Design Space for Space Design

Humanly {S:pace} Constructs Across Perceptional Boundaries

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Design Space for Space Design

Humanly {S:pace} Constructs Across Perceptional Boundaries

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"Galileo Flow Field"
2015
Patinated bronze
H16cm x W11.5cm x D4.5cm
by Tibor Balint

Abstract

In this PhD research by thesis, the author documents his journey that explores modes of operations beyond those predominantly applied at NASA. Specifically, he is looking at designerly and artistic modes of operation, with a research goal to show demonstrable value to enhance NASA's capability to innovate. This exploration is built on cybernetic perspectives and goal-seeking focused on human centered design within NASA's space exploration paradigm.

The author uses a performative approach through real world examples to highlight and substantiate the benefits of novel perspectives, conversations, and boundary objects, which shows their demonstrable value to NASA.

The significance of the research findings is discussed in relations to the state of practice, which is derived from interviews with practitioners across NASA's organizational hierarchy, combined with personal experiences, and independent research on the topics. The two primary application examples examine strategic level organizational conversations in support of strategic decision-making, and a human centered approach to space habitats that utilizes conversations and boundary objects aimed towards higher-level needs of the astronauts. Secondary examples, as added material, explore designing the design environments through human centered conversations with stakeholders, storytelling, multi-nodal and multimodal conversations, designerly modes of operation in engineering-focused environments, and explore the potential benefits of a design education program to change the organizational culture on the long term. These examples are grounded and substantiated using specifically created boundary objects, which are used as communication tools across multiple disciplines.

This research is timely, because expanding humanity into space is an ongoing and inevitable step in our quest to explore our world. Yet space exploration is costly, and the awaiting environment challenges us, the human explorers, with extreme cold, heat, vacuum and radiation—among other conditions—unlike anything encountered on Earth. As a consequence, today's space exploration, both robotic- and human-exploration driven, is dominated by objects and artifacts which are mostly conceived, designed and built through technological and engineering approaches, to support basic physiological, psychological, and safety needs. NASA's activities, products, and processes are controlled by rigid procedural requirements, and are highly dependent on government funding. Since the Apollo era, the annual budget decreased by nine fold and remained virtually flat. Resource constraints, funding uncertainty, and changes in the organizational culture gradually led to innovation barriers, and formed a temporally and spatially coupled cyclical wicked problem for NASA. Yet, the aging workforce, still remembering the golden age of space exploration, is hoping and planning for large "fire and smoke" type missions, which puts NASA on an unsustainable path, while perpetuated by technology and management focus to overcome obstacles. Finding new directions may require a second-order cybernetic transformational change, starting with a changed paradigm, which in turn will impact the Agency's mission and culture, and influence the core processes. In this research the author makes a case to broaden NASA's worldview today, which is dominated by science, engineering, technology, project and resource management considerations. This can be achieved through novel perspectives gained from cybernetics, and other modes of operation through human centered design and art.

While the proposed performative approach is applied to NASA, it is not bounded by it. These perspectives and modes of operation can be applied to any other field, discipline or hierarchical structure within scientific, technological, and social developments. Cybernetic mapping of any environment can provide insights to the connections and the potential for interactions between the various actors within. Understanding the complexities, non-linearity, and competing and often misaligned influences is important to set goals for the system and navigate towards preferable outcomes. Controlling and regulating the variety of these dynamic and responsive systems, in line with the set out goals and objectives, also require considerations and guidance, where cybernetic mapping, conversations and novel shared languages between the actors (in the form of commonly agreed understanding of the meaning), and human center design may play a role. When people are involved in these circular interactions and conversations, human centeredness can lead to transformative psychological impact on a personal level, and strategic advantages at an organizational level.

Key Words: Cybernetics, Design Conversations, Boundary Objects, Human Centered Design, Humanly Space Habitats, Wicked Problems, Innovation, and Strategy

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Acknowledgments

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Author’s Declaration

I certify that during the period of registered study, in which this thesis was prepared, the author has not been registered for any other academic award or qualification. The material included in this thesis has not been submitted wholly or in part for any academic award or qualification other than that for which it is now submitted. The content of the thesis is the result of work that has been carried out of my approved research program. I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Signature:

Date:

Supervisors (in alphabetic order):
Prof. Ranulph Glanville (2012-2014) †
Prof. Ashley Hall (2012-2013)
Prof. Paul Pangaro (2015-2016)
Prof. Miles Pennington (2015-2016)
Dr. John Stevens (2013-2016)

Research Question and Contributions to Knowledge

This thesis documents second-order cybernetic conversations between the researcher and the environment he is a part of, including but not limited to other RCA and affiliated researchers, the design community, NASA personnel at implementation and strategic levels, the artistic community, and the general public. Throughout the research process, questions were raised from observations processed through the researcher's cognitive model, and then these questions were subsequently refined and modified through a forward looking search. These exchanges with the environment helped the researcher to broaden his personal knowledge and refine his understanding of the involved topics. At each iteration cycle, the questions were formulated, posed, reflected upon, answered, then modified and refined through the researcher's evolving cognitive model. The synthesized findings and recommendations are offered back to the environment through conversations and substantiated through case examples.

The research question evolved to ask the following: *"Do modes of operation beyond those predominantly applied at NASA, such as designerly and artistic modes, offer demonstrable value to enhance NASA's capability to innovate?"* Before arriving to this final question, the researcher had to understand the current state of practice by asking, understanding, and answering prior questions about the innovation framework at NASA, and why it represents a wicked problem for the Agency. This understanding also provided the basis for proposing preferred modes of operation that utilized cybernetics and human centered design, as applied to real world examples within the NASA domain.

The contributions to knowledge consist of two parts. First, contribution to the researcher's personal knowledge, where his engineering and technology centric worldview and mode of operation was broadened by integrating cybernetics and human centered design into his cognitive model, which aligned with designerly and artistic modes. Second, as contribution to design research, his performative ontology was applied to NASA through five case examples using cybernetic perspectives. By applying design considerations for these cases, it was shown that the introduction of human centered design, design conversations through shared languages with agreed meanings, and boundary objects, can contribute to preferred outcomes, and can broaden NASA's worldview. The case examples included strategic level decision making processes; space habitat design considerations for long-duration spaceflight; design environments; changing NASA's organizational culture through design education, and boundary objects. Thus, while the work documented in this thesis is situated in design research, the researcher used design and cybernetic considerations, specifically design conversations and boundary objects—including proposed new categorizations—to make contributions to both design research and to the NASA domain. It also included potential contributions to organizational cybernetics related to strategic decision making processes.

Based on the insights gained through cybernetics, it was found that applying designerly and artistic modes of operation to NASA complements its engineering and management modes and offer demonstrable value through design conversations and boundary objects. It has been shown that in an observing paradigm, designers can modify the goals of an observed system, define new requirements for it, and thus broaden the system's variety to enable new options towards preferable outcomes.

While the researcher’s performative ontology was applied to NASA, it is not limited to it. Cybernetic perspectives can be applied to any other field and environment at any scale, by understanding the connections and hierarchies between its actors, and identifying circular paths for their conversations.

Published Work Arising from this PhD

There have been a number of conference papers, posters, presentations, peer reviewed publications, artifacts, and university lectures have arisen from this research. Full versions of the listed papers are available from: <https://rca.academia.edu/TiborBalint> <https://www.researchgate.net/profile/Tibor_Balint>

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(Spin-off: Documentary Film)

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Section 1.
Introduction

Stacked Aeroshells in Negative Space (Butternut wood / 2015)

1.1. Background and Motivation

Today's space exploration, both human and robotic exploration driven, is dominated by objects and artifacts, which are mostly conceived, designed and built through technology and engineering approaches. They are designed, for most parts, through integrated thinking and systems thinking. They are functional, reliable, safe, and expensive, but NASA's current engineering driven operating mode leaves very little room for "humanly" space objects, developed through designerly and artistic modes of operation. Throughout my thesis I will use the term "humanly space object" instead of "human centered space object" to provide a distinction between these terms. With the term "humanly," I refer to every object that is created by humans that is associated with spaceflight. For example, asteroids are space objects, but not human related. Furthermore, not every humanly space object is human centered, or they are human centered to different degrees, depending on their use case. A rocket nozzle is not a human centered space object, but it is a humanly space object.

Space focused organizations, including NASA—typically dominated by engineers, project and business managers—pay limited attention to "soft" disciplines and artifacts coming from design and art. These are considered nice to have instead of identifying a genuine need for them, let alone addressing them through requirements. As a result, when I started my research at RCA's Innovation Design Engineering program, I had a clear view and opinion on what I was trying to achieve. I wanted to understand how to improve technological innovation at NASA. This topic aligned with my interests and work experiences, and planned to deepen my knowledge within my existing mode of operation. However, I have recognized early on that this was an incorrect approach. As a consequence, my research topic has evolved to new and unforeseen areas with new perspectives, making the original research question only a point of departure. Over the past 4 years, through the combined course of my professional career and academic research, my worldview has changed and broadened significantly. As a practitioner at the Jet Propulsion Laboratory I was working as a mission architect and technologist on feasibility studies to robotically explore our solar system. In this capacity my work on observed systems aligned with first-order cybernetics, where the modes of operation is bound and guided by well-defined goals. The requirements for these mission concept studies were well identified, which included science goals and objectives, technological needs and resource allocations. The goal of the system was to optimize the multi-disciplinary concepts (system of systems) for these requirements. As the study lead, my job function on these studies was that of a regulator of the system, keeping the goals, objectives, requirements, and resources within their bounds. Later on, at NASA Headquarters, I worked as the Program Executive for the Game Changing Development Program, where I was overseeing the programmatics of over 60 projects, with an annual budget of $165 million. Moving from the linear project level to a strategic programmatic level also changed my worldview from first looking at an observed system to then being part of the observing system, with a recognition that I was part of the system, influencing it while being influenced by it. This latter position corresponded to a second-order observing system, where I had an opportunity to learn from the observed system feedback and when needed modify its goals. However, in this position I was still embedded in the same system, exposed to the same engineering mode of operation at NASA, while trying to gain novel perspectives. My full-time work provided situated knowledge, but also limited my perspective to the engineering mode of operation. Moving to London after two years of part-time studies and focusing on my research full-time over the past two years allowed me to develop a perspective about new designerly and artistic modes of operations, while still drawing on my past NASA related experiences. Combining past and newly gained knowledge, allowed me to evolve my worldview then reflect back on the NASA environment to identify areas, where my new insights might benefit NASA beyond the current state of practice. This topic-evolution and the broadening of my interests continued throughout my research, and it didn’t stop there. I am confident that this journey will continue over the years to come. The discourse presented in this thesis reflects my performative ontology that consists of an evolving cognitive model of my worldview, which can be applied to any environment. In this research I choose to apply it to various parts of NASA, because it is an environment I am familiar with. However, I believe that the perspectives provided by my constructivist worldview allows me to look at other environments and situations through the same optics of cybernetics and human center design.

It is important to recognize that my research is a personal journey, which allowed me to evolve my own worldview. While I have applied my perspectives to various parts of NASA, substantiated its benefits and provided recommendations, making subsequent changes to a large governmental organization is not trivial. The impact of my research is dependent on the organization’s interest to assess the benefits of my proposed approaches and embrace it. Thus, the value of my research to the Agency will have to be decided by them. Over the past 50 years NASA developed a mode of operation that aligns with its government provided resources. The funding supports space exploration goals, working with civil servants, industry partners and academia. At every level in the organizational hierarchy, from the projects through NASA Headquarters (HQ) to the government, the interests can be localized and misaligned with others. This makes the organizational dynamics a wicked problem with ill-defined, changing and at times incomplete requirements, and without a clear possible solution that satisfies all parties involved. It also introduces barriers, which stem from funding limits and uncertainties, and responses to these from the system, leading to process overload and a risk averse organizational culture. The introduced changes are often first-order based, which means staying within an existing paradigm and maintaining the goals of the system. After the first-order changes are made, things may look different, but the system remains and operates virtually the same way. For example, setting up a new sub-organization with a mandate of being innovative and agile, while having the same organizational structure, reporting requirements, and mindsets as the rest of the organization leave little room for real change. This realization was the motivation for my initial research question. Now I can say that an organizational culture that sets and operates by rigid core processes, and sets its mission accordingly is trapped in its own paradigm. To make real changes to an organization, it needs second-order change (Levy, 1986, p.7), changing from the outside of an organizational system “black box” (Glanville, 1982, p.1), and modifying its goals, and broadening its mode of operation and its paradigm (see Figure 1.1). In turn, the new goals will impact the system; influence its mission, its culture and its core processes. This change is radical, qualitative, and impacts the organization at every level, both spatially and temporally. To embrace paradigm-change, an organization needs to change its worldview, in line with second-order cybernetics. It needs strategic leaders who are integral part of the observing system, influenced by the feedback from the observed system, and willing to change its goals as necessary. Thus, the change of an organizational paradigm, or worldview, is strategic. It is only successful if the need is recognized, and the implementation is enabled and empowered through the organizational hierarchy from the top down.

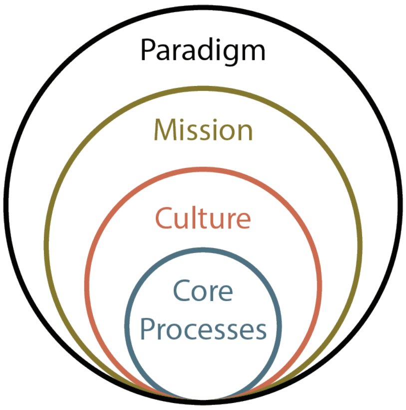


Figure 1.1: Levy's second-order change (Levy, 1986, p.7).

1.2. NASA's Culture and Evolving Paradigm

As this research is seeking modes of operation beyond those applied at NASA, it is important to provide a brief overview about NASA's evolving culture and a rationale why designerly and artistic modes offer demonstrable value to enhance the Agency's capability to innovate.

NASA, the National Aeronautics and Space Administration, was established in 1958—in the height of the Cold War—as a civilian government agency under the US Government's Executive Branch. From NASA's perspective, and as it was messaged to the public, the Agency was tasked to execute and promote the peaceful exploration of space. Concurrently with this, from the US Government's perspective, NASA represented prestige (Jones, 2015, p.6) and provided a political vehicle to openly demonstrate technological superiority over the Soviet Union to the American people and to the world. Being a governmental propaganda vehicle of the Space Race, the US Government provided the necessary budget for it. In 1966, during the height of the Apollo Program, NASA received 4.4% of the national budget. In comparison, today this ratio is about 0.49%. (This is further discussed in Appendix B.1.) The Agency expanded rapidly during this time, and employed the best engineers from the nation and even from abroad. While space exploration required significant technological innovation, the technologies on both sides of the Space Race were routed in technological advancements of World War II. For example, in his book about Wernher von Braun, Neufeld stated: *"Without him, it is hard to imagine that the German army's liquid-fuel project would ever have succeeded in producing the V-2. Although the V-2 was a profound military failure, that vehicle paved the way for the intercontinental ballistic missile… Von Braun's 'baby' went on to influence missile technology in the United States, in the USSR, France, Britain, and China, accelerating the arrival of the ICBM and the space launch vehicle by perhaps a decade"* (Neufeld, 2008, pp.476-477).

Rocket development at NASA was led by the German rocket team under von Braun, which brought a highly detail-oriented, incremental, and controlling culture to NASA. The military nature of rocket technology helped to enforce this approach. Huntsville-based rocket development continued to advance launch capabilities, and solidify this culture. The rocket team's efforts at the Marshall Space Flight Center (MSFC) led to the development of the Juno 1 rocket, which took the Jet Propulsion Laboratory (JPL) developed Explorer 1 mission into orbit. The human space program started with two Air Force-contributed large Intercontinental Ballistic Missile (ICBM) rockets – Atlas and Titan. These were used for the early Mercury and Gemini missions. With the start of the lunar exploration program, the military personnel

– transferred from the large rocket program of the Air Force – further influenced NASA's management culture (McCurdy, 1993, p.15). Focus on details and risk averseness became more dominant with sending humans to space, as *"failure was not an option"* (Kranz, 2000).

The human space flight program led to organizational tension between NASA Centers, as functions and leading roles were redistributed between MSFC, the Langley Research Center (LaRC), the Johnson Space Center (JSC), and the Kennedy Space Center (KSC) (Mccurdy, 1993, p.17). On the science mission side a similar function distribution occurred between the relevant centers, including JPL, the Ames Research Center (ARC), the Glenn Research Center (GRC), and the Goddard Space Flight Center (GSFC).

These divisions between NASA Centers, center traditions, local focus, interests, and expertise led to the emergence of a "confederation of cultures" (McCurdy, 1993, p.22). The resulting culture was driven by individual strategic leaders, with emerging dominant norms, as the power of balance shifted due to emerging missions, related organizational interactions, and leadership changes. This also resulted in a nested second-order system, where at the highest level the government set the goals for the Agency; within that NASA HQ set the goals for the individual programs at various NASA Centers; and the Programs guided the implementation of their Projects. As the Programs and Projects are located at NASA Centers, they are also impacted by center politics. It should be also noted that Programs and Projects represent first-order observed systems, as at the implementation level they only execute, but cannot modify the goals of the system.

Over time, NASA's civil servants became more administrative and less technical. Consequently, the technical culture started to decline, which resulted from contracting out technical work, while increasing bureaucracy and technical oversight within the Agency (McCurdy, 1993, p.133). According to McCurdy, between 1978 and 1989, 83% to 88% of NASA's budget went to contractors (McCurdy, 1993, p.137). But contracting also provided benefits. As a key function for any governmental agency, it is used stimulate growth in industry and academia (see Appendix A.2.7–A.2.8). For NASA, it also broadened the political advocacy base, and the political influence related to its budget. (This will be further detailed in Appendix B.1.)

In the 1960's NASA's culture readily accepted risks. Learning from failures was a normal part of operations; flights were inherently risky; and each flight was treated as a stand-alone event. By the 1980's a shift has occurred, by promoting spaceflight as continuous, routine, and safe (Jones, 2015, p.1). This required realignment from uncertainty to predictability (McCurdy, 1993, p.141), which led to many of today's innovation barriers (see Section 3.5). Continuous programs—compared to stand alone ones—have a desired effect for management, as they require continuous funding from the government, and promises stability over the annual budget cycles (see Appendix B.1). However, this type of change in operational culture introduced an organizational tension. Typically, a research and development (R&D) culture pushes technology boundaries towards new developments, with inherent risks and uncertainty. Yet, the survival of such technical organizations and their leadership is dependent on reducing them, which promotes risk averseness and process overload. The shifting balance between NASA's operational culture and R&D culture led to the periodic emergence and cancellation of various technology programs. The latest incarnation of a technology program is the Space Technology Mission Directorate (STMD). (It was established in 2010 as the Office of the Chief Technologist

(OCT) and split into OCT and STMD two years later.) The Agency level organizational tension is clearly reflected in STMD's funding, which has been stagnant over the years, and it never reached the target cap it was proposing since it was established. (It should be noted that I have worked at both OCT and STMD from 2010 to 2014 in various strategic leadership positions.) Still, regardless of the stagnant funding, space technology development is considered an important contributor to successful space exploration (Jones, 2015, p.6), which is also performed under the other three mission directorates at NASA, namely the Human Exploration and Operations Mission Directorate (HEOMD), the Science Mission Directorate (SMD), and the Aeronautics Research Mission Directorate (ARMD).

As NASA's organizational culture changed over the years, so did the type of work performed by its employees. Before 1970, 84% who responded to an employee survey reported to perform hands-on work. By the late 1980's only 3% reported that they are *"working in a laboratory, test facility, control or tracking center, training astronauts, or working on space flight or aeronautics hardware"* (McCurdy, 1973, pp.156-157). This also illustrates the focus shift between stand-alone and continuous mission operational modes. With more oversight, bureaucracy and risk averseness, and the focus on the "knowing that" aspect of understanding leaves limited room for a designerly approach of "knowing how" (Cross, 2010, p.21), which embraces risks and experimentations.

There are numerous books written about the golden days of NASA, typically referring to the Apollo Program, which was a crash program that responded to urgent political needs. But it also represented enormous human achievements. The accounts by a flight director (Kranz, 2000), former astronauts (Aldrin & Abraham, 2010) (Slayton, 1994) (Lovell & Kluger, 1995), (Cernan & Davis, 2000), historians and authors (Neufeld, 2008) (Burrough, 1998), depicted the historic days, and an environment with heroes and high achievements. (Many of these books and personal accounts were made into movies.) Early astronauts were former fighter pilots, and flight directors acted like dictators. "Failure is not an option" (Kranz, 2000) represented a statement that worked on multiple levels. On a global scale, the Space Race was on (which ended in 1975, as symbolized by the Soyuz-Apollo joint flight between the US and the Soviet Union (Jones, 2015, p.9)). On the mission level, safety became a significant issue after the Apollo 1 fire (NASA, 1967), taking the lives of three astronauts. Even earlier, under the robotic space exploration program, the House Committee on Science and Astronautics conducted an "Investigation of Project Ranger" (McCurdy, 1993, p.186). Following these and other investigations NASA implemented significant changes to hardware designs and processes. As described by Jason Derleth (Derleth, 2015): *"Our culture is a very interesting one at NASA. I think it rises up for the reason we have culture that we have is [that] rockets blow up. So, if you imagine that you are Robert Goddard, back in the days when he was trying to fuel rockets with liquid, liquid rockets, people were laughing at him, the Washington Post said it was absolutely ludicrous, yet he was right. And he found out the hard way that he had to be very very careful with cryogenic propellants. And valves are very tricky. And if the valves are not perfect then the rocket blows up. Well, what do you do when the rocket blows up? You have a whole bunch of pieces. It's a forensics sorts of exercise, where you have to figure out what happened. You can't know, but you figure out as best as possible what happened, then you write down this happened because of 'blah,' then you can do your checklist. You take your checklist and you add a new item to your checklist. Make sure that 'blah' will not happen. Well, over 50 years the checklist called [NPR] 7120.5 [(NODIS, 2015)] is hundreds and hundreds of items long. And* *we check every single one of them. For the human spaceflight side especially. Why? Because if we have an accident, not only we do kill people – which is terrible – not only we lose billion dollar spacecraft – which is terrible – but we also get stopped. Operations stop for two or three years, because we have to figure out what happened. Because we killed people. That leads us to an environment, where we don't even want to put a chart up on the wall because it might kill people. We don't know what kills people, we went through out checklist and its not going to blow up, but when we go, something might happen. So we end up with this culture that is far too hesitant to take risks. Far too hesitant to push the envelope to do something new."* NASA's culture became even more risk averse after the trauma of the Space Shuttle Challenger in 1986 (McCurdy, 1993, p.188), as later programs were not shielded from government criticism and oversight (Jones, 2015, p5).

In comparison, during the Apollo era two key factors overwrote NASA's risk posture. First, it was a political necessity for the US Government to demonstrate space capability, and second, the political distress caused by Uri Gagarin's spaceflight in 1961. Gagarin's flight perceived as an existential threat to the US (Jones, 2015, p.9), which added to the shock created by the launch of Sputnik 1 in 1957. Sage—who looked at NASA through the optics of social sciences—quotes a Washington Post article, which stated: *"the Soviet union has scored a brilliant victory in the race for scientific progress and for leadership on the ideological sphere"* (Sage, 2014, p.34). In response, *"among many options considered, the Apollo program was found to be the most effective and technically feasible"* (Jones, 2015). NASA's Space Task Group (STG) gave a recommendation to President Nixon in 1969, which included a redirection *"from 'crash programs'—a term introduced by the STG—of planetary exploration and develop a "balanced program" where options for human exploration, such as a reusable shuttle vehicle and a modular space station facility, would complement rather detract from scientific goals, international cooperation and military security programs"* (Sage, 2014, p.91). In the post-Space Race era, a number of similar large-scale crash programs were proposed, but without an urgent political necessity and will, they didn't formalize. For example, the Space Exploration Initiative (SEI) and the Constellation Program (CxP) were canceled, Space Station Freedom was descoped and evolved into the International Space Station (ISS), and after the completion of the ISS the Space Shuttle fleet was retired (Jones, 2015, p.3). The canceled programs were lacking clear attainable goals, and were failed attempts to start a new Apollo-style crash program to Mars (Jones, 2015, p.8). Presidents, including Kennedy, Reagan, G.H.W. Bush, Clinton, G.W. Bush, and Obama, all proposed ambitious human exploration plans, from going back to the Moon, to Mars, or to bring back an Asteroid to a lunar orbit, but to date none of these became crash programs like Kennedy's Apollo Program (Jones, 2015, p.4). Without a political will, the Legislative Branch did not approve the appropriate funding for such programs. Furthermore, after the Space Race the space programs lost their high government priority and forced to compete with other discretionary programs in the annual national budget (see Section 5). Currently NASA is proposing an exploration path through the Journey to Mars (NASA HQ, 2015), where the Evolvable Mars Campaign (NASA HQ, 2015) includes the development of the Space Launch System (SLS), the Orion Capsule, and the Asteroid Redirect Mission (ARM), as a stepping stone approach to develop new needed technologies and capabilities for a future human mission to Mars. While scientific exploration is a key driver for robotic space missions, it always took a secondary role behind human exploration (Jones, 2015, p.6), as also reflected in NASA's budget (see Appendix B.1).

Over the past two decades the culture of NASA changed significantly. It is vastly different from the world and culture discussed in the above listed books, set in the apex of the Apollo era. Today's astronauts are no longer selected from military fighter pilots only, and even the approach of the flight directors became more human focused. As Jay Falker (Falker, 2015) pointed it out: *"I used to work at the Johnson Space Center, Mission Control, the 'Houston We Have a Problem' place, and exactly while I was there, they were transitioning the behavior of the flight directors. So, they recognized the mindset that [involved a] military chain of command imperative, no independent thought, do what you do perfectly [and] now, is actually not the best way for humans to work with each other, even in high pressure situations. And they tried to teach their flight directors not to be like Gene Kranz, and he was the hero back in Apollo 13. But, we are proud of technical excellence and proud of being ice cool under pressure, but you are allowed to be human now, and leaders like Jeff Hanley are a new kind of Flight Director (before he became the Constellation Program Manager). [They] were nice people, and they didn't order people around, they talked to them. So, I've already seen within HEO [Human Exploration and Operations Mission Directorate] a change in mindset."*

There are still obstacles to embrace human centered design at NASA. Even today, space exploration uses dual use technologies, which means that it can address both civilian and military needs (Jones, 2015, p.6). Space missions are not yet profitable, require significant government funding, and often driven by non-space-related goals, such as national prestige in the world. NASA's funding for space exploration from the US Government is higher than that of the other space faring nations combined—just like the US military budget. This guarantees a US leadership position in the world related to space exploration, but for the set out exploration goals the provided funding is not sufficient. Today's funding is about 9 times lower than it was during the peak of the Apollo era in 1966. A continuation of a resource limited and technology focused paradigm, combined with an internally evolved engineering focused organizational culture over the past five decades could explain the lower priority of human centered design within NASA. In effect, NASA has a culture problem with incorporating design into its worldview, as it became evident from the conducted interviews (see Appendix F), and from personal experiences. In the meantime, today's most successful commercial non-space related companies hold up design as a key pillar in their paradigms. It can be historically shown that the emphasis on human centered design and art versus utilitarian function-driven form with a focus on hard-core engineering and technology changes between periods of peace and prosperity versus military conflicts and other hardships. During military conflicts human centeredness is taking a back seat in favor of function. In turn, through long peace periods—with increasing prosperity—design, art, and user experience move to the forefront to accompany technological innovation and provide product and service differentiation. The two cycles are in opposing phases, as illustrated in Figure 1.2. These two paradigms coexist in today's world. At NASA, this technology-focused approach didn't change. We still have a predominantly function-driven design worldview for space exploration, and at the same time, a highly influential human centered design focused worldview for consumer products, processes and services.

While there are signs of human centered considerations at various parts of NASA, the current paradigm places an overwhelming focus on engineering, safety, cost, and management approaches (Kennedy, 2015). This paradigm has not changed since the beginning. *"Many aspects of NASA's technical culture were developed at the time that the new space and*

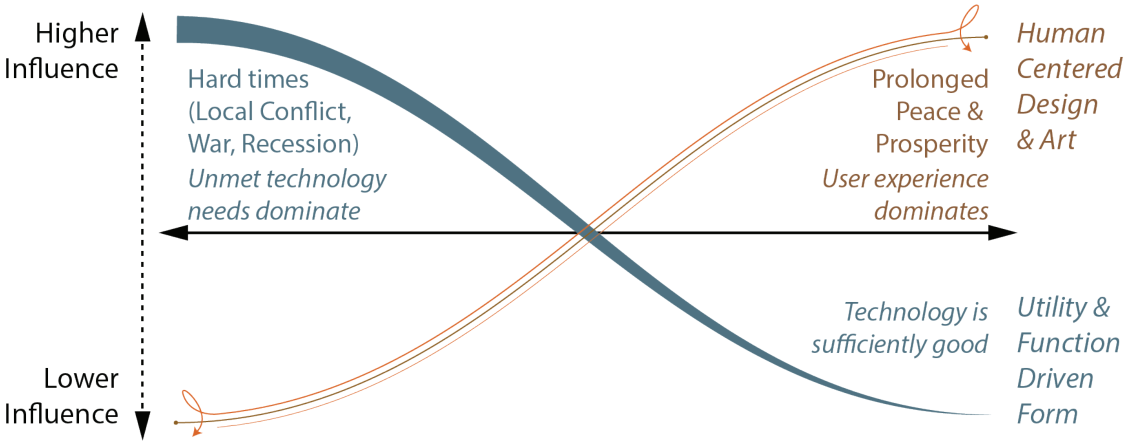


Figure 1.2: Notional cycles of human centered design and engineering driven developments.

aeronautics agency started work in 1958" (McCurdy, 1993, p.90). This was also built on technologies from WWII as discussed above. Cost can impact schedule, and engineering feasibility can drive both cost and schedule. Thus, many consider cost as the biggest challenge to introduce human centered design into the process (Kennedy, 2015) (Davidoff, 2015) (Whitmore, 2015). Human centered design is still viewed by engineers and managers as luxury and fuzzy—in a sense as it is loosely defined, compared to technical requirements, goals, and objectives (Davison, 2015). This pushes back human centered design considerations to a later development phase of the projects. However, this introduces a new challenge, because the engineering point design constrains the system configuration towards the later stages of the development. It makes it significantly more difficult or even impossible to retrofit a finalized configuration for human centeredness, without returning to an earlier development stage, due to cost and schedule limitations. Thus, if human centeredness is not introduced at an early development stage, it will have a hard time to be implemented later on.

In the post-Apollo era NASA's culture evolved into a bureaucratic government agency, competing with other scientific and defense agencies for discretionary funding (see Appendix B.1). Fighting for resources puts emphasis on politics, and the competition for missions can lead to overstated benefits, unrealistically low mission costs proposals, and downplayed risks. In turn, once approved for funding, mission costs tend to overrun, risk levels increase, and science goals are descoped. Without a clear political will and urgency, crash programs will not likely happen. Space exploration will continue in a slow, steady and incremental pace with its shortcomings, especially if the current culture remains unchanged. To address and resolve cultural, organizational, and innovation barriers (which will be discussed in Section 3.5), we can turn to traditional methods, including process, culture, and even the mission changes, in line with first-order change (Levy, 1986, p.10). We can find numerous examples for all of these over the past five decades, from SEI to plans about going back to the Moon, or going to Mars. At best these changes had limited temporal and spatial impacts, but more often the proposed plans "didn't stick." (The challenges related to NASA's wicked problem is detailed in Section 5.) But is there anything else that the Agency can do? To have impactful change we may need to influence the paradigm, by broadening it through second-order change (Levy, 1986, p.7).

Based on these considerations, in my research I am seeking other modes of operations beyond NASA's technology driven paradigm that can influence preferable outcomes. While—according to McCurdy—there is no existing theory to show why organizational culture effects

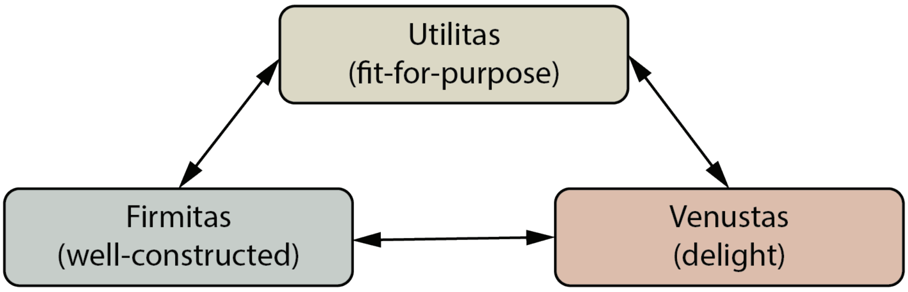


Figure 1.3: The three vitruvian virtues (Vitruvius, 1960); figure after Glanville (Glanville, 2009, p.2).

performance (McCurdy, 1993, p.7), in my research I attempt to address certain aspects that may influence this culture. For example, through the optics provided by cybernetic perspectives, and goals supported by designerly approaches, I will show and evidence how design conversations can support strategic level decision making (see Section 5) and evidence how designerly and artistic boundary objects can support design conversations in the intersection of interacting disciplines (see Sections 6 and 7).

1.3. Evolution of the Research Question

The evolution of my research question was shaped by diverse influences, which were at times unexpected, but in line with RCA's core values. For example, my influences go back as far as the first western text on architecture, called "De Architettura," which was written in the 1st century BC by Marcus Vitruvius Pollio (Vitruvius, 1960). In it Vitruvius declared that architecture (and design) consists of three key elements, namely utilitas, firmitas, and venustas (see Figure 1.3). That is, they have to have utility (or function); they have to be firm (or well built); and need delight. My late supervisor, Ranulph Glanville, called these fit-for-purpose, well-constructed, and delightful, sometimes stated as fabrication, function and form (Glanville, 2009, p.2).

After documenting my initial research findings in two subsequent conference papers on disruptive innovation (Balint, 2013) and wicked problems at NASA (Balint & Stevens, 2016), Glanville posed a question to me: *"…this is all good, but this work could have been done in an engineering or management school… where is the delight?"* In his writings, Glanville (2009, p.3) made a case for delight by stating: *"The significance of delight in design finds expression in another aspect. Design is about doing more than simply satisfying the necessary (being well-built and fit-for-purpose)."* Using the words of the architect Sir Denys Lasdun: *"Our job is to give the client not what he wanted, but what he never knew he wanted till he saw it."* Jessie Kawata (2015) echoed a similar sentiment about design, stating: *"…you know what it is? It's like giving them what they need and not what they want. So you do extra work. It is always extra work. Right? They ask you for … a palette of colors, (you) give them a palette of colors, but then you spend another few hours giving them what they didn't know they wanted. And that extra work is sometimes more impactful."* Glanville was right. His question about the delight element, combined with his frequently repeated advice to *"slow down,"* led me down on two interrelated paths of explorations. On a personal level, it led to the creation of a number of artifacts, in the intersection of design, art, science, and engineering. Making these boundary objects helped me to slow down, and reflect on my research. They provided opportunities to inform my research about boundary objects, while developing conversations across disciplines with them. It also made me question the meaning of delight at NASA. What is delight for engineers, and can it be found in engineering designs? Certain designs, which do not directly address hard requirements, are considered nice to have, and to be addressed at the end of the project, if there are available time are resources. Of course this notion never materializes due to the lack of both. Instead, design is ignored in favor of function-generated forms.

But there is at least another problem that goes against embracing design. The scientific and engineering approaches expect well-defined “hard” requirements, which are relatively straightforward to achieve for these disciplines. Correspondingly, Glanville states: *“Fitness-for-purpose and function are relatively easy to specify and test for. Delight, being harder, is often left out, often with the excuse that it is unscientific”* (Glanville, 2009, p. 2). Heinz von Foerster stated appropriately that *“the hard sciences are successful because they deal with the soft problems; soft sciences are struggling because they deal with the hard problems”* (von Foerster, 2003, p.191). It is difficult to set requirements against soft subjective fields, involving humanly aesthetics, emotions, interactions. In turn, without requirements it is hard to measure if the success criteria are met, and consequently it is difficult to commit a budget to it. Over the past decades sciences and engineering became dominant factors at NASA and design, addressing soft requirements, became an afterthought at best, or trivialized as a waste or distraction, ignoring the fact that there is more to design than form.

Rittel questioned the “form follows function” doctrine, by stating that: *“If this comes together with the ‘need fulfiller’ doctrine, its triumphs are the jeep and other forms of military equipment. If the designer believes that technical perfection automatically provides optimum usefulness, he forgets that ‘technical’ criteria have no independent meaning, and that lists of requirements do not at all determine a solution (otherwise Russian rockets would not look Russian and American rockets American.) The list of requirements maybe long: they either prescribe no solution at all or an infinite number of them. And ‘form’ is no opposite to function: ‘To be looked at’ is just one function of an object, which has many other functions.”* Subsequently Rittel offers a modest-level solution by saying: *“…we might search for tools, techniques and methods which are likely to enhance the designer’s capability to make better plans in view of his commitment. Naturally, as with all tools, such aids are ‘value free.’ A hammer can be used to drive a nail or to hit somebody’s head”* (Rittel, 1971, p.7).

While human space exploration is still limited to the vicinity of Earth, we have plans to send humans to Mars within the next 20 to 30 years. On today’s near-Earth human exploration missions, NASA’s development environments still mainly focus on fulfilling basic functional and physiological needs, while considering higher-level psychological and self-actualization needs (Maslow, 1970, p.46) as nice to have, something that can be addressed towards the end of a flight project, if resources are available. These can’t be ignored on long-duration human missions. Human centered designers and artists address such higher-level needs, yet currently playing only a limited role in our space exploration activities. However, I believe that these higher-level needs will play increasingly important roles in our future space exploration plans. First, on near-term missions to substantiate this approach, then implemented fully on subsequent long-duration human missions. Through this research I am making a case for designerly and artistic modes of operations—two non-engineering domains—to be considered as additions to NASA’s engineering mode of operation.

This overview of the various aspects of my background and NASA’s paradigm echoes the evolution of my research question, and provides a coherent progression of the various research elements. However, this progression became evident only at the end, after synthesizing my research findings into a hierarchy. If I would have known and understood these steps *a priori*, they would not have constituted research, merely an execution of a project path along expected stages. In light of these, my research hierarchy revolves around the final question of: *"Do modes of operation beyond those predominantly applied at NASA, such as designerly and artistic modes, offer demonstrable value to enhance NASA's capability to innovate?"* To answer this question, I have followed multiple research paths:

- For the first example, I was looking at innovation at NASA, followed by the exploration of wicked problems in the US Government framework. Subsequently I looked at the Viable System Model, which led to the development of the Project Assessment Framework Through Design (PAFTD) tool for strategic decision making, leveraging designerly conversations and cybernetic perspectives. (See Section 5.)
- The second example, started with two side projects, the making of the Venus Watch and the Cybernetic Astronaut Chair. These designerly processes evolved into an assessment of today's state of practice related to NASA's space habitats, and designerly and artistic modes of operations to design for these environments. This path also included background research into foundational topics related to philosophy, cognition, perception, constructivism, modeling, communications, Hierarchy of Needs, cybernetics, and boundary objects. The connecting elements through this example path were: design conversations and communications through boundary objects. (See Sections 6 and 7.)
- In the third example, I have looked at design environments at JPL's Innovation Foundry, and the JPL Studio through the optics of cybernetics, and how designerly and artistic processes are benefiting NASA. Throughout this research element I have reflected on my findings by "slowing down" and creating designerly and artistic boundary objects. The connecting elements through this example were: design conversations and boundary objects. (See Appendix D.2.)
- In the fourth example, I was using my research and work experiences at RCA and at NASA, and proposed a new space related design education program between NASA and nearby universities. The goal for such a program was to train a skilled workforce, versed in designerly processes, which is different from the typical skillset of graduates from engineering schools. This proposal is built around design conversations, and project based making experiences for individuals and for interdisciplinary teams. (See Appendix D.3.)
- All of these examples shared the designerly and artistic modes of operations in a NASA environment, with a focus on design conversations, and boundary objects which facilitated these conversations. Furthermore, by creating a significant number of artifacts over the past years, in connection with the various research segments, my research experiences and reflections allowed me to propose new boundary object categorizations, which I feel contributed to the state of knowledge. (See Section 7.)

1.4. Research Scope, Limitations, and Encountered Challenges

In this research I explore NASA's operating paradigm, with a focus on areas where human centered design through designerly and artistic modes of operation can provide demonstrable benefits. The chosen topic is broad, as demonstrated through the number of examples. My research goal was to show that other modes of operation could complement and enrich NASA's prevalent engineering mode of operation. This approach differs from a narrow in-depth research, but potentially can motivate others to choose any of the examples and continue subsequent, dedicated in-depth explorations. However, for each example, I have included a traceable path from current state of practice, as outlined in the previous subsection. An understanding of these connected elements, allowed me to set the goals for my investigations, that linked the state of practice with the proposed modes of operation. For example, starting from NASA's culture, and the current state of innovation, then raising the question to a higher level of wicked problems, allowed me to reflect on innovation barriers, and through the perspectives of cybernetics and the use of design conversations, propose, develop and substantiate a strategic level project assessment tool. This research approach allowed me to have a high level view of different aspects of NASA's paradigm, which is traded against narrowly focused in-depth aspects. The outcomes showed mixed success. For each example I discuss and substantiate my findings to the extent they succeeded or failed. I am also providing a summary of the "wandering" (Glanville, 2007, p.1193) that shaped the course my research.

While the provided examples may seemingly indicate a clear progression path, throughout my research, and due to the nature of research, I have also encountered dead ends and failures on a number of levels.

- After spending my first year looking at innovation in general at NASA, I have developed a good understanding of the practices, and my findings indicated that NASA is already leveraging approaches, which are compatible with NASA's operating modes. I was looking at the problem as an outside observer, through the dominant engineering mode of operation. With this approach I was not yet embracing the key aspect of second-order cybernetics, which acknowledges the presence of the observer (Glanville, 2004, p.1380). It also brought me to a dead end, without actionable steps. Fortunately, Ranulph Glanville, my supervisor, provided a guiding direction by pointing me to constructivism, and wicked problems. Later on Glanville also commented that my assessment approach to innovation could have been done in a business or management school, implying that I was not leveraging my research sufficiently through RCA's culture.
- This direction allowed me to look at NASA's innovation framework and innovation barriers *"as a symptom of another broader issue, by working the problem a level 'up' to the next level of comprehensiveness,"* in line with one of Rittel's seven characteristics for second-generation design method (Rittel, 1972, pp.8-9). While this provided an important insight into NASA's wicked problem for space technology development, it didn't help me with finding actionable solutions to resolve innovation barriers. Again, suggesting a move beyond NASA's engineering paradigm and looking at the problem through designerly modes, including cybernetics, Glanville pointed me to a direction, which eventually led to the development of the PAFTD tool over the last two years of my research. The tool was used to assess a number of NASA STMD projects, but following strategic leadership changes, and the departure of my PAFTD research collaborator from NASA, PAFTD is left without a champion and its future within NASA is uncertain.
- The making of the Venus Watch and Cybernetic Astronaut Chair started out as unconnected side projects. Simultaneously, by the end of the second year Glanville's question on *"where is the delight?"* made me reassess my research direction, and move towards designerly and artistic modes of operations. Insights from the making of these artifacts, and the research into various design aspects for humanly space objects directed my attention to human space exploration. Specifically, looking at interactions between astronauts and

their environments. Due to time and resource constraints the idea of building an interactive mockup was beyond the scope of my research. In hindsight it would have been the wrong approach anyway, as it would have represented yet another of the many designs by an individual. While it would have added a new data point to the existing ones, its impact without broadly accepted guidelines (which currently do not exist) would have been an academic exercise. Instead, I used my background research into the current state of practice, and supported it with the making of boundary objects. Through this approach I am advocating the development of new guidelines, which can be derived from future dedicated analog missions, then included in the development of future designerly or artistic humanly space objects and space habitats.

- While making the case to include designerly and artistic modes of operation in Innovation Foundry processes, my initial assumption was that these aspects are not yet recognized nor implemented at NASA. However, based on interviews and background research I have found that JPL's Innovation Foundry and the JPL Studio already started to implement some of these approaches over the past 4 years. While this finding invalidated my initial assumptions, it allowed me to look at organizational and operational aspects of the Innovation Foundry through the optics of cybernetics. This helped to uncover areas for improvements, which would have not been evident by looking at it through an engineering perspective. Furthermore, existing processes allowed me to reflect on boundary objects, which led to my proposed categorizations.
- In connection with NASA's culture, I have developed a white paper about setting up a space focused design education program to develop the next generation of experts in designerly ways of thinking and operating. (A generalized version is documented in Appendix D.3.) The negotiations to initiate it have failed. It was not resonated with the potential university partner, maybe because today's educational institutions are highly influenced by resource constraints. However, I still believe such a program is needed and I will continue to advocate for it.
- Related to designing, the making of boundary objects required me to learn new skills. The circular process of sense-giving and sense-making often resulted in failures, or unwanted outcomes. To illustrate this, I have given a step-by-step example of making the cybernetic astronaut chair by learning through failures, echoing Glanville's paper title on trying again, failing again, and failing better (Glanville, 2007).
- Translating my cognitive model into a symbolic mathematical model so far did not yield an outcome. Looking at past works from Boole (Boole, 1847), Spencer-Brown (Spencer-Brown, 1972), and Glanville (Glanville, R., 1975), and the approach of Wittgenstein (Wittgenstein, Russell, & Ogden, 2007), I felt that any such attempt would need significantly more research and formulation, and thus it was beyond the scope of my current research.
- Shortly after my arrival to London, two years ago, the passing of my supervisor, Ranulph Glanville, created a void and a yearlong gap in my supervision related to cybernetics. His guidance through my first two years has significantly shaped and benefited my research, and his knowledge was unmatched within RCA. Fortunately, for my final year Paul Pangaro became my external supervisor to advise me on cybernetics related aspects of my research. (It should be noted that both Pangaro and Glanville had Gordon Pask as their supervisors.)

The challenge for this type of research is that proposing and implementing changes through different modes of operations beyond the existing one, requires an adjustment to the system goals. While from my academic research level I can propose and advocate for these goal modifications, their implementations require strategic level decision authority. Without that, the recommendations may remain parts of an academic exercise.

1.5. What is in the Thesis Title?

The title of my thesis is *"Design Space for Space Design."* It echoes Glanville's subtitle for a paper, *"cybernetics in design and design in cybernetics"* (Glanville, 2007, p.1173), which is concerned with the close link between cybernetics and design. Similarly, in the title I am highlighting the need for designerly modes of operations within space exploration, while hinting a circular cybernetic approach to achieve it. In this context, space can refer to physical spaces, design spaces, process spaces, and hybrid spaces, where circular interactions are facilitated between individuals and their environments. The subtitle is *"Humanly {S:pace} Constructs Across Perceptional Boundaries." "Humanly"* refers to some level of human centeredness related to space exploration and *"constructs"* to a constructivist approach. We construct our cognitive models based on the phenomenal world, aided by our sensory organs, which form a boundary. I termed this *"perceptional boundary."* Per its standard dictionary meaning, *"perceptional"* refers to our cognitive process of perception; this is chosen in opposition to *"perceptual,"* which is used for biological processes. This boundary provides a distinction between the outside phenomenal world and our cognition. Finally *{s:pace}* distinguishes the spatial and temporal characters of design. This title may sounds complex, but it is intended to provoke a conversation about its framing and meaning, which may lead to a shared common meaning, and create new variety in a discourse.

1.6. Thesis Structure

In its final form, the structure of my thesis consists of four integrated segments.

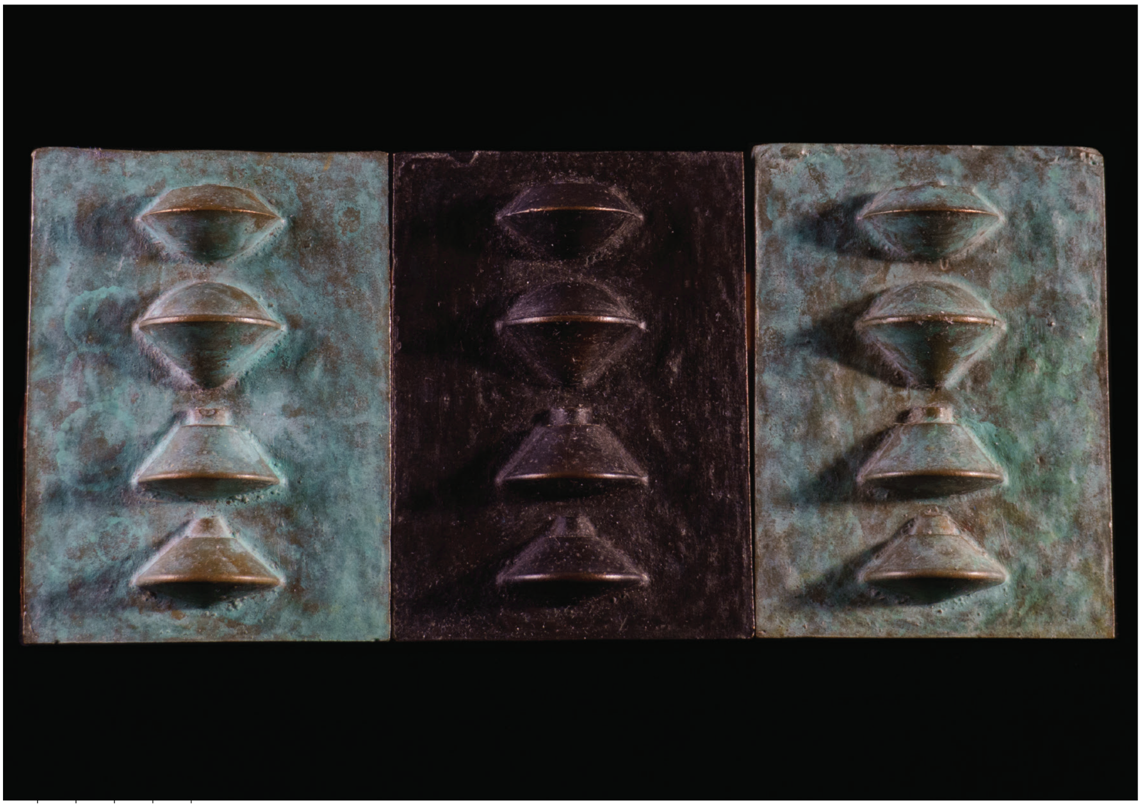
The first segment includes the front matters, such as the copyright statement; abstract; acknowledgments to people who contributed to the success of my work; the author's declaration; a statement on the contribution to knowledge; a list of the various publications that arose from this research; an introduction (Section 1); a summary of the methodology and approach used to carry out the research (Section 2); and an introduction to foundational concepts and terminologies, which are needed to establish a baseline for the discourse (Section 3).

In the second segment, in Section 4, I am providing a concise description of my performative ontology. Ontology refers here to personal knowledge, which is rooted in concepts from the fields of philosophy, epistemology, perception and cognition, cybernetics, design and art. It is becoming performative by applying it to real world situations.

Thus, in the third segment I am applying the performative ontology from Section 4 to various examples at NASA. In these examples, cybernetics provides the perspective, combined with design to guide the designer through design conversations and human centered design considerations. The level of human centeredness varies between the examples. The first example relates to a strategic assessment tool using an organizational cybernetic approach and design conversations, which was developed in support of strategic decision-making (see Section 5) The second example makes a case for developing self-actualization related human centered guidelines to long-duration space habitat designs (see Section 6). (Two secondary examples are provided in the Appendices.) In Section 7, I am proposing new categorizations for boundary objects and use the artifacts to ground the previous examples from Sections 5 and 6, and illustrate how these objects bridge the discourse between disciplines, ranging from design through science and art to engineering.

The final (fourth) segment includes the conclusions and future directions (Section 8), the appendices with supporting material, a glossary, abbreviations, and the bibliography. The appendices provide details on innovation in general (Appendix A); on NASA's budgetary process, the PAFTD question set, and PAFTD related testimonials (Appendix B); on the artistic and design examples related to human centered considerations for space habitats (Appendix C); on secondary examples addressing designing the design, through design environments, storytelling, boundary objects, and design education at JPL (Appendix D); on making the boundary objects (Appendix E); on the semi-structured interviews and their mapping into subject topics (Appendix F); and on the mapping of the research domain (Appendix G).

Section 2.
Methodology and Approach



Alvin Seiff Memorial Award Medals, obverse side (Patinated bronze / 2016)

2.1. Prologue to Methodology and Approach

My thesis-based PhD research is concerned with the exploration of designerly and artistic modes of operation that can offer demonstrable value to enhance NASA's capability to innovate. In my approach I am using second-order cybernetic perspectives and human centered design driven goals, utilizing *design conversations* and *boundary objects*. My examples are applied to real world situations to influence the discourse, which may lead to preferable outcomes. Subsequently this can broaden the system's paradigm. I have carried out this design research to understand the current and relevant state of knowledge (SoK) across disciplines, which included philosophy, epistemology, perception, cognition, cybernetics, design, and art. In addition, I have researched the current state of practice (SoP) at NASA, related to human centered design, technological innovation, innovation environments, innovation processes, wicked problems, strategy and management.

Calling my research "design research" first requires me to define these two component words, namely "design" and "research."

2.2. Design—According to Archer and Frayling

The word "design" has multiple meanings, from verbs to nouns. It can depict actions by practitioners and characteristics of artifacts. It can address singular aspects or can be interdisciplinary. First, let's look at design through the optics of two former thought leaders from the Royal College of Art, Bruce Archer and Christopher Frayling, with a hint of Theodor von Karman (Goldstein, 1966, pp.334-365).

"Scientists study the world as it is, engineers create the world that never has been" (NSF, 2016). This statement by Theodore von Karman, the renowned founder of the Jet Propulsion Laboratory (von Karman & Edson, 1967), has created some controversy half a century ago. It was praised by engineers and criticized by scientists. Yet, in light of the categorization of Bruce Archer (Archer, 1978, p.5) this may make perfect sense, as he not only grouped anthropocentric activities into the typical Sciences and Humanities, but also proposed a third discipline, that he called *"Design with a capital D"* (Archer, 1978, p.6)(Cross, 2007, p.17). He placed scientists into the Science category, while putting artists, designers, engineers, and other practitioners who create novel parts, into the Design category. Archer's categorization of science describes the phenomenal world of natural laws to be independent from humanity. In the empirical tradition of Hume (Hume, 1739), its exploration is done through controlled experiments, classifications, and analysis of its sub-disciplines. It is an objective and rational approach that is concerned with how things are, and with uncovering the "truth" through empirical methods. Humanities explore the human experience through evaluations, reflections, analogies, and metaphors, and it is concerned with justice, commitments, and subjectivity from an anthropocentric point of view. Design requires an active participation by humans, and it is concerned with the artificial world, creating the new, through pattern-formation, modeling, and synthesis, through practical and innovative ways. It focuses on appropriateness, empathy, and other human centered design considerations about how things ought to be. It introduces novel options and forms. Furthermore, Design, including design education, is a non-linear discipline (Hall & Child, 2009, p.2), where in a cybernetic sense the feedback broadens the regulator's understanding and knowledge (or variety (Ashby, 1956, p.124)) allowing the designer to identify new previously unseen options from an added human centered perspective. In comparison, engineers typically take the initial requirements as bounding rules, and linearly converge

towards a point design solution. These lines are often blurred within NASA, as science instruments are designed between the overlapping disciplines of science and engineering, designed by subject matter experts, who are well versed in both specialized fields. Designers and artists can also overlap between these categories. For example, creating new processes or materials can bring together design and art with material sciences. Reflecting or artistic activities may connect the Design category with Humanities. These lines and connections are often overlapping, but the importance of Archer's categorization is to identify a distinction and to show why creative disciplines, such as design, are different from Sciences and Humanities.

Christopher Frayling took a different angle to categorize design and art, by discussing research activities about-(or into)-design & art, for-design & art, and through-design & art (Frayling, 1993, p.5). Research about-design and art is based on theory, looking at aesthetics, perception, ethical, cultural, historical aspects, among others. For example, my brief documentary about making the Galileo Flow Field artifact would belong to this category (see (Balint, 2016a) and Appendix E). Another example, for-design, is the Venus Watch 1.0 concept project, which was the focal point about storytelling related to space exploration, extreme environments and the evolution of manufacturing innovation (Balint & Melchiorri, 2013) (Balint & Melchiorri, 2014). Research, through-design, is practice based, which may involve developmental research, artifact creation, contextualization, and communication of the results. It is a conversation between the practitioner and the artifact, involving both sense-giving and sense-making, while facilitating the emergence of communicable knowledge. In my research I have applied my performative ontology to making physical artifacts and developing a virtual tool (PAFTD) (see Section 5) (Balint, Depenbrock, & Stevens, 2015). All of these examples are related to facilitated conversations. Research for design and art involve practice, where thinking is contained in artifacts, where implicit knowledge is communicated iconically. My research is theoretical, with applied research elements, connecting them to NASA's modes of operation, from engineering to designerly and artistic modes. Furthermore, in the process I have made several artifacts to serve as conversation focal points. I refer to them as boundary objects (see Sections 3.4 & 7). Examples include: the Cybernetic Astronaut Chair (Balint & Hall, 2015); the Venus Watch 1.0 concept (Balint & Melchiorri, 2014); the Galileo probe sculpture and medals; and the IPPW conference posters in Section 7 and Appendix E. A mapping of my research examples into Frayling's categorization is further explored in Section 7 about boundary objects. It can be seen that my research addresses all three categories, namely about-design, for-design, and through-design. (A detailed mapping of the research domain is provided in Appendix G.)

2.3. Defining Research and Its Link to Cybernetics

The word "research" originates from the late 16th century, from the now obsolete French noun "recerche" and verb "recercher." Also, in Old French "re-" represents an intensive force, which is combined with "cerchier," "to search." Research is looking at the yet unknown. As Albert Einstein stated: *"If we knew what it was we were doing, it would not be called research, would it?"* (Kitchin & Freundschuh, 2000, p.214). Related to this, another statement is attributed to Einstein: *"problems cannot be solved with the same mindset that created them."* (While the original source for this quote is not clear, it can be traced back to a New York Times Magazine interview on 23 June, 1946 titled: *"The real problem is in the hearts of men,"* where Einstein stated: *"A new type of thinking is essential if mankind is to survive and move to higher levels"* (Rowe & Schulmann, 2007, p.383).) Research is an active process that is circular, between the

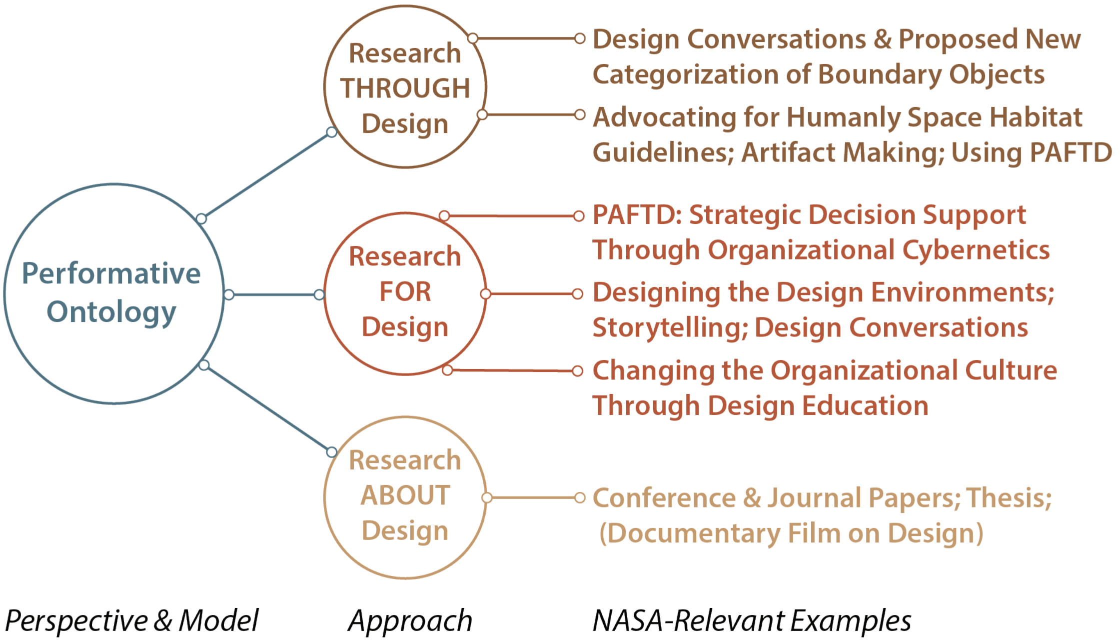


Figure 2.1: Research topic areas, mapped into Frayling's categorization.

researcher, the research process or methodology, and the environment. Here the environment is the phenomenal world, with infinite variety. The research process, which provides feedback from the environment, enhances the researcher's understanding of the problem. In a cybernetic sense, feedback information increases the researcher's variety. The researcher can assemble this gained information into new cognitive models, and a resulting new worldview. Through this process the researcher's tacit knowledge emerges into communicable knowledge, which is expected to reach beyond the state of practice (SoP), and the state of the art (SoA). (Section 3.2 provides further discussions on cybernetics and tacit knowledge.) According to Gregory Bateson, *"creative thought must always contain a random component"* (Bateson, 1978, p.182). Thus research is an action to seek novel information that we don't yet know at the outset of the research. As a consequence, it often results in the reformulation of the research question, as the researcher's cognitive model evolves throughout the research process.

2.4. Finding the Appropriate Research Method

Selecting the appropriate research methodology is rather important, as the searching procedure influences the findings. In the Western Rationalist Tradition, researchers establish the rules for their own processes. This empiricist approach was advocated by David Hume (Hume, 1739), and has a strong tradition in the British educational system. It is a regulatory construct, which tends to reduce the variety of the research, and thus limits its outcomes. A positivist approach requires validated empirical evidence before a theory or hypothesis is being accepted. When employing a positivist research method, the researcher selects a theoretical framework then gathers information if the theory matches the researched phenomena. This method can be problematic. As stated by Karl Popper, *"it is easy to obtain confirmation or verification for nearly every theory, if we look for confirmations"* (Popper, 1962, p.36). In comparison, a rationalistic approach argues that all knowledge can be derived from foundational principles, which are known *a priori*, and using logic. Gottfried Leibniz, a contemporary of Isaac Newton, argued that reason alone is sufficient to derive new knowledge and understanding, although admitted that it might be difficult to use it beyond the field of mathematics (Leibniz, 2013). The question also arises, where is *a priori* knowledge coming from? Immanuel Kant offered a method where both empirical and rationalist approaches are valid (Kant, 1781). Thus, the Kantian approach—preferred in my research—is inclusive, that affords a broadened variety for the system it is applied to. In this Kantian tradition, for example, Einstein derived his relativity theory (Einstein, 1916) from rationalistic thought-experiments, where the theory on gravitational waves took 100 years to validate.

Jumping forward from Einstein by about half a century, during the early stages of space exploration NASA was known for its innovative approaches to engineering, technology, design and process development. Designers took notice. Design methodology emerged in the late fifties and early sixties thinking that civilian and other design areas could benefit from the ways NASA and the military approached large-scale projects. Design benefited from the systems approach or mission-oriented approach, and it was contrasted against the modifying approach of engineering design. NASA helped this through spinoff activities of its technologies and processes to civilian use—which is still ongoing today. At the same time, industrial designers became interested in the systems approach, because they *"were dissatisfied with their ways of doing things."* So as engineers and architects. Industrial designers started to move beyond cosmetic improvements to engineering hardware and addressed the interfaces between the user and the object (Rittel, 1972, p.5).

When Horst Rittel explored design methods, he differentiated between first-generation and second-generation methods, where the latter deals with underlying difficulties, which were taken as inputs for first-generation methods (Rittel, 1972, p.7). He summarized the second-generation design method through seven characteristics (Rittel, 1972, pp.8-9), which also have relevance to my research. These are:

1. The "symmetry of ignorance," which assumes that the expertise and ignorance about a given problem are distributed among all participants. Nobody can claim superior knowledge over others; the "I know better" statement is not applicable. This approach attempts to develop maximum participation, activating maximum knowledge (see design team environments at JPL's Innovation Foundry in Appendix D).
2. An argumentative structure of the planning process, which assumes that the design activities involve the selection of a favored position against various other positions about the issue (see habitat design considerations today, discussed in Section 6).
3. Looks at a given issue as a symptom of another maybe broader issue, thus working the problem level "up" to the next level of comprehensiveness (see wicked problems, innovation barriers, and innovation in Sections 3 and 5 and Appendix A).
4. Assumes the ideal of transparency, as design steps leading to the present time require the understanding of prior design steps (see, for example, the evolution of the research question, from innovation, through wicked problems, to PAFTD in Section 5).
5. Uses objectification to (a) minimize knowledge loss over time, and (b) to stimulate doubt. That is, it allows for stating the objectives with increased clarity and subsequently casting stronger doubt and criticism. Objectification also helps to raise the right issue, which can stimulate stronger divergence of the opinions (see the proposed categorization of boundary objects with examples in Section 7).
6. Assumes the control of delegated judgment from the planner (regulator) to the designer. Here the planner requests the designer to identify all of the assumptions, then casts deontic judgment and guides the designer towards a subset of the desired assumptions

(see organizational hierarchy and decision-making between project and strategic levels in Section 5; and the example of designing the IPPW posters in Section 7).

7. Calling it the conspiracy model of planning, which deals with the implementation problem, where the planner shows both the expert and the client how to plan for themselves. (This is exemplified by this thesis, which introduces designerly and artistic modes of operation, in order to advocate for these new modes to both subject matter experts and strategic leaders operating within NASA's engineering paradigm.)

Bruce Archer gave a simple definition of research by stating: *"Research is a systematic inquiry, the goal of which is knowledge"* (Cross, 2007, p.124). Building on Archer's notes and "best practices," Nigel Cross identified five characteristics for design research (Cross, 2007, p.126). He stated that good research has to be:

1. *Purposive:* by finding a worthy problem to investigate;
2. *Inquisitive:* by seeking the acquisition of knowledge;
3. *Informed:* by being aware of previous related research; state of knowledge (SoK); state of practice (SoP); and state of the art (SoA);
4. *Methodical:* where the research is planned and disciplined;
5. *Communicable:* that is generating and reporting knowledge that testable and accessible by others.

These characteristics align with my research approach, as detailed below.

2.5. Method Developed for this Research

In his first PhD research Ranulph Glanville (Glanville, 1975), did not set out a methodology or formulation at the beginning. Instead, he allowed it to evolve throughout stages, as questions were answered, while raising new ones. This is a performative approach (Pickering, 2010, p.6), with a forward-looking search (Pickering, 2010, p.18), where new findings are abstracted and incorporated into the person's cognitive model through deduction, and then the evolved model is used to propose new possible research goals. This is also a constructivist approach, which builds on circular conversations with the environment.

"The main purpose of design methodology seems to be to clarify the nature of the design activity and of the structure of the problem" (Rittel, 1972, p.5).

Today, NASA's paradigm is engineering, technology and management driven. Systems thinking and integrated thinking provide an efficient way to develop systems and system of systems. Meanwhile, the commercial world embraced human centered design, design thinking and designerly thinking as a key differentiator in a competitive environment. Yet, there is not a single design methodology that one can fit for all circumstances. Horst Rittel (Rittel, 1971, p.6) describes the difficulty with "grand approaches" by stating: *"all these difficulties are different expressions of the basic dilemma of human existence if one tries to be rational (i.e., tries to anticipate the consequences of one's doing) there is no beginning and no end to reasoning. One can think a further step 'backward' and also another step forward. The more one tries to anticipate and to justify one's actions the more difficult it becomes to act. On the other side, nonrational spontaneous action on a large scale is likely to get the actor and the others into trouble. It is irresponsible. Thus both extremes have little survival value. For all of these reasons there cannot exist anything like 'the' design method which smoothly and automatically resolves all of the difficulties. Those people who claim the existence of such a device postulate* *nothing less than the solution of all present and future problems of this world. They are likely to produce nothing but 'platonic' schemes impossible to implement."* Thus, instead of proposing a methodology with step-by-step instructions, in my research I develop perspectives through cybernetics, identified goals through design, and then applied them to various parts of NASA. This approach is built on my research, my personal experiences, and my evolving cognitive model.

Furthermore, my experiences echoed the findings of Nigel Cross on design cognition (Cross, 2007, p.113), where he stated that *"there has been a number of striking similarities identified in design activity, independent of professional domain, suggesting that design cognition is indeed a domain-independent phenomenon."* Good designers, including engineering designers, use similar methods to find the best outcomes to their set out goals. They formulate their concepts, analyze and synthesize goals, frame the problem, focus on the solution, include alternatives, and use structured processes. They are creative and innovative. The differences between good and bad designers may come from some of the shortcomings, including narrowly focused understanding of the problems and their fields, inflexibility and rigid fixation on single solutions, inexperience and lack of creativity. These aspects are further detailed in (Cross, 2007, pp.99-116). Beside these similarities, there are also identifiable differences. Engineers tend to focus on the requirements and solve the set out problem through predominantly analytical processes. Designers tend to use synthesis, and the solution develops through the process of solving it. For designers the design brief represents a point of departure for an exploration (Cross, 2011, p.14). For engineers a brief represents hard requirements, which bounds the problem.

Similarly to Glanville, I have not set out a methodology at the start. This allowed me to "wander" (Glanville, 2007, p.1193) and explore different disciplines, problem spaces and evolve both the research question in response of the findings of prior research phases. This approach is constructivist, where the new knowledge is gained and meaning is constructed through circular conversations with the environment. Acknowledging to be explicitly incorporated into the system, that describes and observing paradigm, I was able to modify the goals of the system after each cycle, by adjusting the research question (see Figure 2.2). This second-order cybernetic perspective stems from looking at NASA as a subjective observer, who is

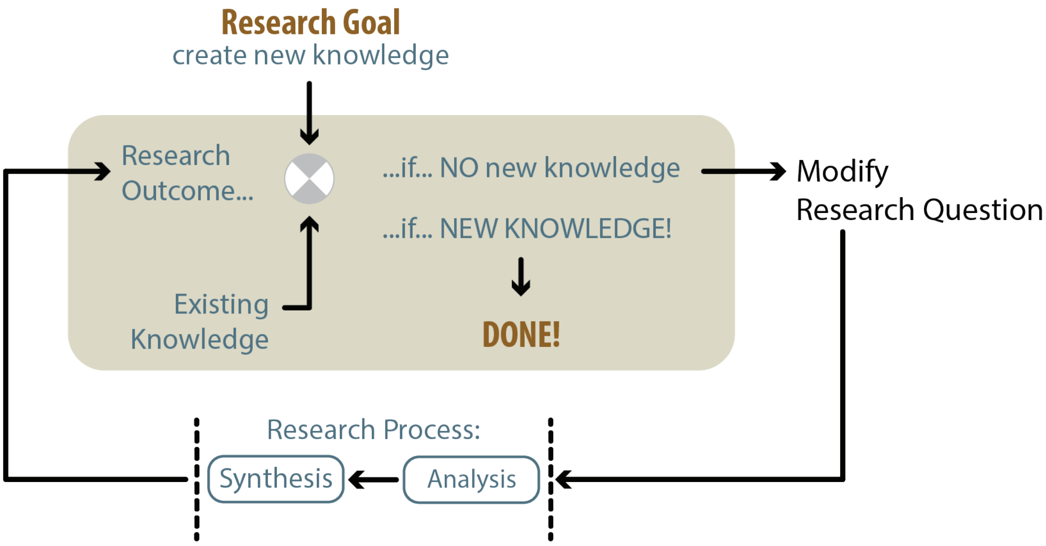


Figure 2.2: Researcher's model of the research process (developed from conversations with Paul Pangaro).

temporarily engaged in designerly and artistic modes of operation (i.e., a practice from within). These modes of operating outside of NASA's typical engineering mode allowed me to seek modified goals for the system throughout the research cycles. These cycles repeated until a stopping criterion was reached, which addressed a research question worthy of exploration. As this circular conversation with the environment is continuous, the stopping criterion for the research is arbitrary. For example, if a satisfactory outcome is found, or the research reached a dead end, or the researcher exhausted the available time and resource allocation, and needed to close out the research. Therefore, this thesis documents a snapshot of my research findings as of now, which is expected to keep evolving over time. New findings will inevitably reshape my cognitive model, leading to new perspectives, which can reinforce or contradict the findings documented here.

2.6. Co-Evolution of the Research Method and Research Question

Over the past four years the problem (my research question) and solution co-evolved (see also (Cross, 2007, p.102)). Accordingly, I have modified my research question on a yearly basis, through a process shown in Figure 2.2. The research timeline, shown in Figure 2.3, provides information on the research outcomes responding to those questions at each stage. The list represents communicable knowledge, in the form of conference and peer reviewed publications, artifacts or boundary objects, exhibitions, and art competitions. A detailed full list is provided in the preamble.

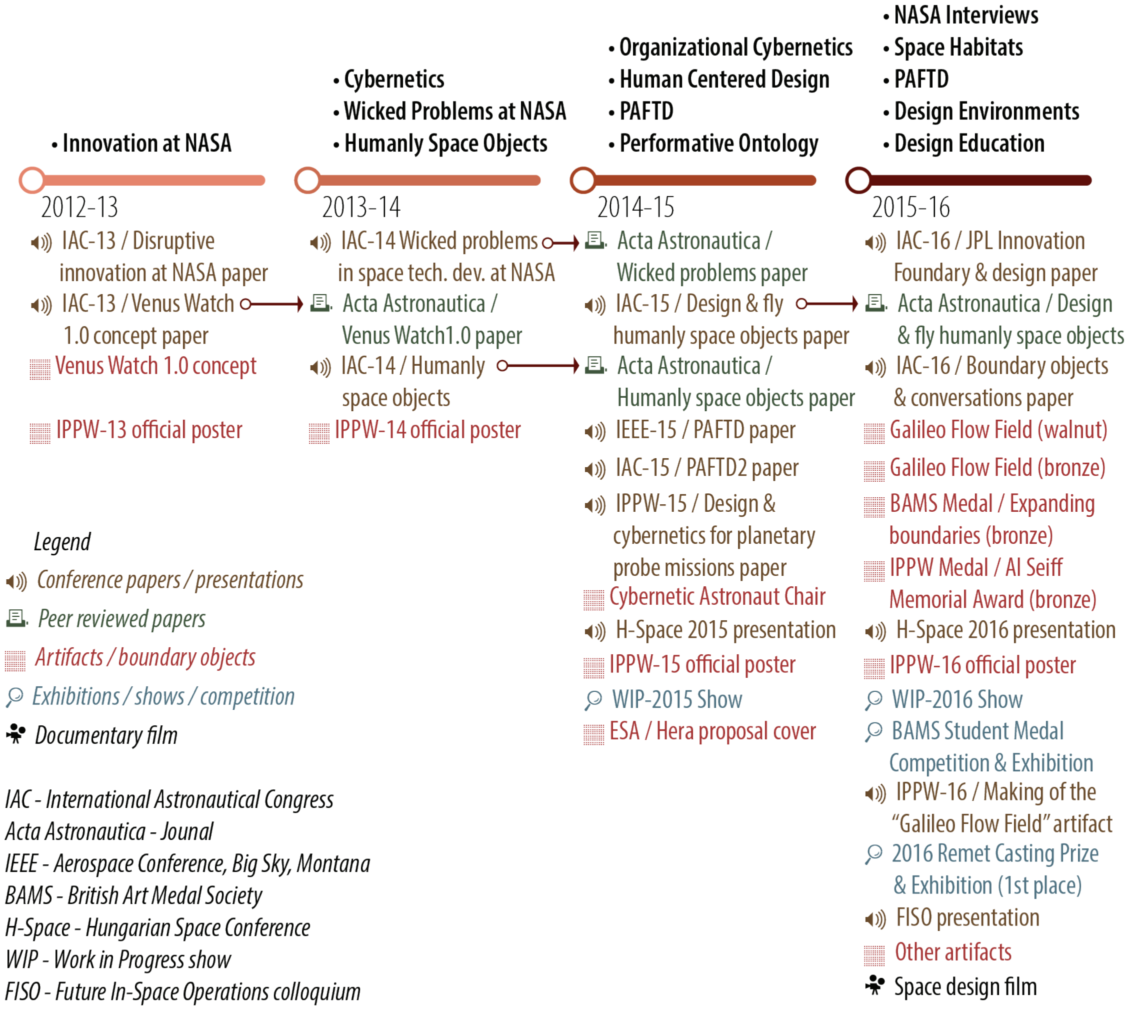


Figure 2.3: Research timeline, showing topic evolution and arising communicable outputs.

When I started this research at RCA on a part-time correspondent basis, I was working at NASA Headquarters (HQ) as the Program Executive for the Game Changing Development (GCD) Program under the newly formed Space Technology Mission Directorate (STMD). The goal of STMD was to develop innovative new technologies for NASA and I was interested in finding novel ways to advance the state of practice. Correspondingly, my initial question asked *"what is the innovation framework at NASA, specifically at STMD, and how can I improve it?"* I have documented my findings in (Balint, 2013) on innovation at NASA, through an engineering perspective. My findings brought up new questions related to the understanding of broader issues of this complex and non-linear environment, which reached beyond the bounds of the GCD Program, STMD, and even NASA. The outcome painted an incomplete picture of the issues and motivated me to further explore the root causes.

After discussions and guidance from my supervisor, Ranulph Glanville, I have modified and updated my research question and asked, "*what are the wicked problems for space technology development at NASA?"* This formulation of the question aligned with the third characteristics of Rittel's second-order method (Rittel, 1972, pp.8-9), that is, looking at innovation and innovation barriers as the symptom of a broader issue. This stage of the research allowed me to construct a model that included concepts from cybernetic conversations, and organizational hierarchy from branches of the US Government to NASA projects and external stakeholders. The findings were communicated to the public and subject matter experts in (Balint, & Stevens, 2014) (Balint & Stevens, 2016).

The next revision of my research question was motivated by Glanville's guiding question: *"This is all very interesting, and you could have done this research at a management or business school. But you are at a design and art school. So, where is the delight in your research? That is, delight in a Vitruvian sense"* (Vitruvius, 1960). He also explored this same question about delight in (Glanville, 2009, p.3). Delight is not only referring to the joy of research, or my research topic addressed to that point. It can also represent a new perspective, a random element, a new mode of operation beyond my original engineering mode, which can change the discourse on the addressed topic, and may lead to new models. Thus, in the final cycle I have reformulated the research question to explore the innovation issue from a new perspective, but keep it sufficiently open not to lead the solution by the question. The question, which I ultimately addressed in this thesis, wile building on the hierarchy of the previous research cycles became the following: *"Do modes of operation beyond those predominantly applied at NASA, such as designerly and artistic modes, offer demonstrable value to enhance NASA's capability to innovate?"* The formulation of this question benefited from two side projects from the first two research years. These were the Venus Concept watch (Balint & Melchiorri, 2013) (Balint & Melchiorri, 2014), and the Cybernetic Astronaut Chair (Balint & Hall, 2015a) (Balint & Hall, 2016). Making these objects provided an opportunity operate in designerly and artistic modes, and help me to develop a performative approach, where I utilized my evolving cognitive model and subsequently applied it to real world cases through circular sense-giving and sense-making cycles. The designing and making of these artifacts also helped me to *"slow down"*—a Glanville term—and cognitively process complex theoretical concepts, and translate them into conversation focal points.

Throughout my research I have broadened my understanding on the topics, from innovation, wicked problems, cybernetics, to designerly and artistic modes of operation. These experiences enriched my cognitive model, which allowed me to identify areas within NASA where these modes of operation can add demonstrable value. I have chosen four areas for this, which included strategic level decision making within an organizational structure; human centered space exploration; designing the design environments; and design education. For each subtopic I have conducted background research, using primary and secondary sources, including semi-structured interviews, assessed and documented the state of practice, and developed related physical or virtual products. These included the PAFTD tool for strategic decision-making (see Section 5); and a number of artifacts with sufficient variety for me to propose novel categorizations for boundary objects (see Section 7). All of these examples provided a demonstrable value of designerly and artistic modes of operation to enhance NASA's capability to innovate. For example, the Project Assessment Framework Through Design (PAFTD) tool is based on design conversations and cybernetic circularity. It supports strategic level decision-making and helps to mitigate innovation barriers. Space habitats, when designed with a focus on higher-level needs, aid interactions between astronauts and their environments, and promote discovery and learning through conversations and interactions. Boundary objects facilitate conversations between astronauts and their environments; across discipline boundaries; within design environments; between proposing teams and sponsors; and between NASA and the public. Design education helps to develop the next generation of design thinkers and makers, who are trained in these designerly and artistic modes of operation and over time can influence NASA's paradigm.

My examples fall into three categories, as shown in Figure 2.4. The state of practice cases have been already implemented at various places within NASA. For example, JPL's Innovation Foundry puts a strong focus on storytelling and involves designers in the mission concept generation process. The state of the art examples include: a strategic level project assessment tool I have developed with a NASA collaborator, and making the case for space focused design education. The space habitat example includes the case for new guidelines through dedicated analogs. It is speculative, as it requires acceptance and implementation from NASA.

The primary information for my research was based on reports, personal experiences and observations, and interviews. The interviews were semi-structured, with predefined questions, but allowed for open and fluid conversations, depending on the topic, previously gained

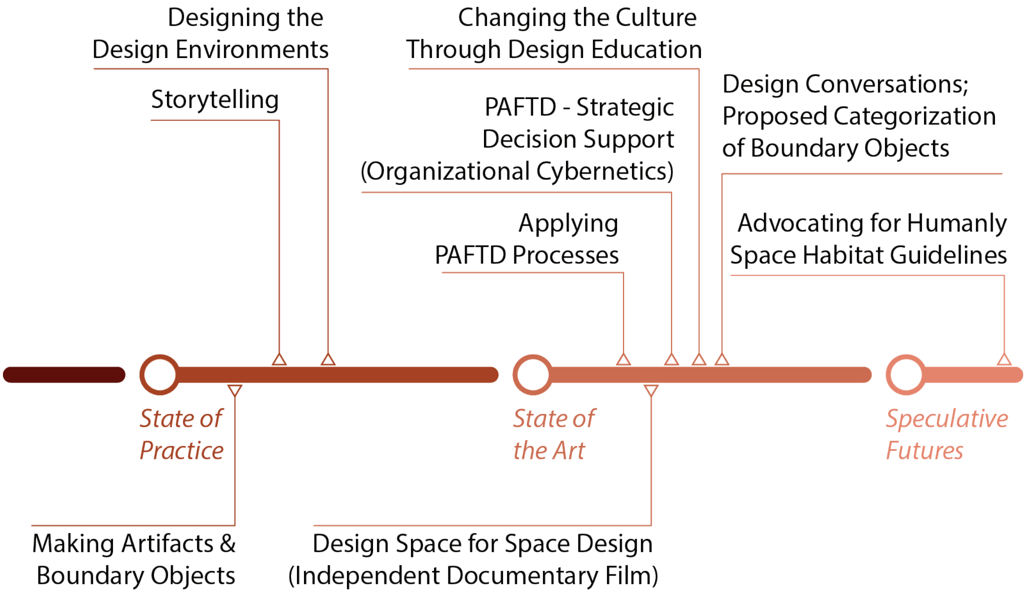


Figure 2.4: Topics addressed in this research, mapped into development stages.

information from prior interviews, and the dynamics between the interviewer and interviewee. The professional backgrounds of these 32 face-to-face interview participants ranged from senior Program Executives at NASA HQ to design practitioners and subject matter experts (SME) at NASA Centers. I have focused my research on primary information sources, through interviews and personal communications, and accessing original data sources, including reports, historical records, NASA Procedural Requirements (NPRs), statistical data on government spending. My research also included the making of artifacts, which are used in this research as boundary objects in the intersection of disciplines. The research was complemented by secondary data sources, such as on-line articles, journal articles, research reports and research books.

Creating models, tools and artifacts through design conversations played an important role in my research. I have used them to communicate aspects of my theoretical discourse to the observers or readers through my thesis, publications and objects. For each example I have substantiated my findings and documented them in the appropriate sections. I have also reported aspects and stages of my research in conference papers, journals, and exhibited artifacts at RCA WIP (Work in Progress) shows, workshops, and art competitions.

My goal was to learn about designerly and artistic modes of operations, cybernetics, and integrate them with my past experiences from the fields engineering and science.

2.7. *Epilogue to Methodology and Approach*

In summary, this thesis documents my qualitative research (Robson, 2011, p.24) that evolved over the past four years. Not setting out a method from the start provided the needed flexibility for "wandering" with a purpose of finding the appropriate research question. Due to the inquisitive nature of acquiring knowledge I have leveraged primary and secondary information sources, including semi-structured interviews, and applied designerly and artistic modes through the creation of artifacts, which I referred to as boundary objects. These performative actions informed me about the current state of practice at NASA, from human spaceflight to design environments and organizational aspects. It was a methodical approach, that included goal seeking through identifying research questions, and conducting background research, analyzing the options, synthesizing the findings, while comparing the progress at each stage against the research question. I used these processed findings at each stage of the research to reformulate the goals of the system, which led to subsequent research questions. This is in line with cybernetic circularity. With and acknowledgment that I am exclusively incorporated into an observing system, this goal seeking approach allowed me to explore seemingly unconnected aspects of NASA's predominantly engineering mode of operation. My second-order cybernetic perspective also provided the means to adjust the goals of my research, and advance my cognitive model that included a hierarchical and abstracted model of the phenomenal world. Purposively applying this model to real world examples and artifacts allowed me to modify the research question to the next level of progression. Then the synthesized findings helped to identify other modes of operation, namely designerly and artistic modes, which can offer demonstrable benefits to NASA. At each stage of my research I have generated communicable knowledge through conference papers, peer reviewed journal papers, and exhibited artifacts that facilitated conversations between diverse communities and disciplines. This approach aligns with the design research characteristics discussed by Cross (Cross, 2007, p.126).

Section 3.
Foundational Terminologies, Definitions, and Background Concepts

Abstracted Terrain (Recycled mahogany wood / 2015)

3.1. Prologue to Foundational Terminologies, Definitions, and Concepts

Designers and artists create artifacts, which interact with the observer. In effect, they communicate through their objects. Through this communication knowledge is transferred in both directions. But the process also raises several interesting underlying questions. For example: What do we know? How do we know what we know? What is real? Who decides what reality is? These can lead to further questions in connection with the application-target of this research, namely NASA and human spaceflight. Thus, we can also ask: What is the minimum desirable level of daily humanly interaction on long-duration spaceflight? Does this vary between different cultures, races, sexes, life stages, and other factors? These are just some of the fundamental questions that drive our understanding and search for meaning. Over our human history, branches of philosophy were dedicated to answer them, which also included other connected and derived fields, such as epistemology and ontology.

In this section I will introduce foundational terminologies, definitions, and background concepts from literature, related to this research. These are relevant for the development of my cognitive models, and its applications to real world examples. Under foundational terminologies and definitions I discuss two primary topics, namely cybernetics and design. Several subtopics are connected to these concepts, including constructivism, perception, cognition, tacit knowledge, schema, modeling, hierarchy, communications, design thinking, design conversations, and wicked problems. Under the background concepts I will also discuss innovation, innovation barriers at NASA, and identify touch points where changes can be introduced towards preferable outcomes. Terminologies for these are defined in this section, and in the Glossary.

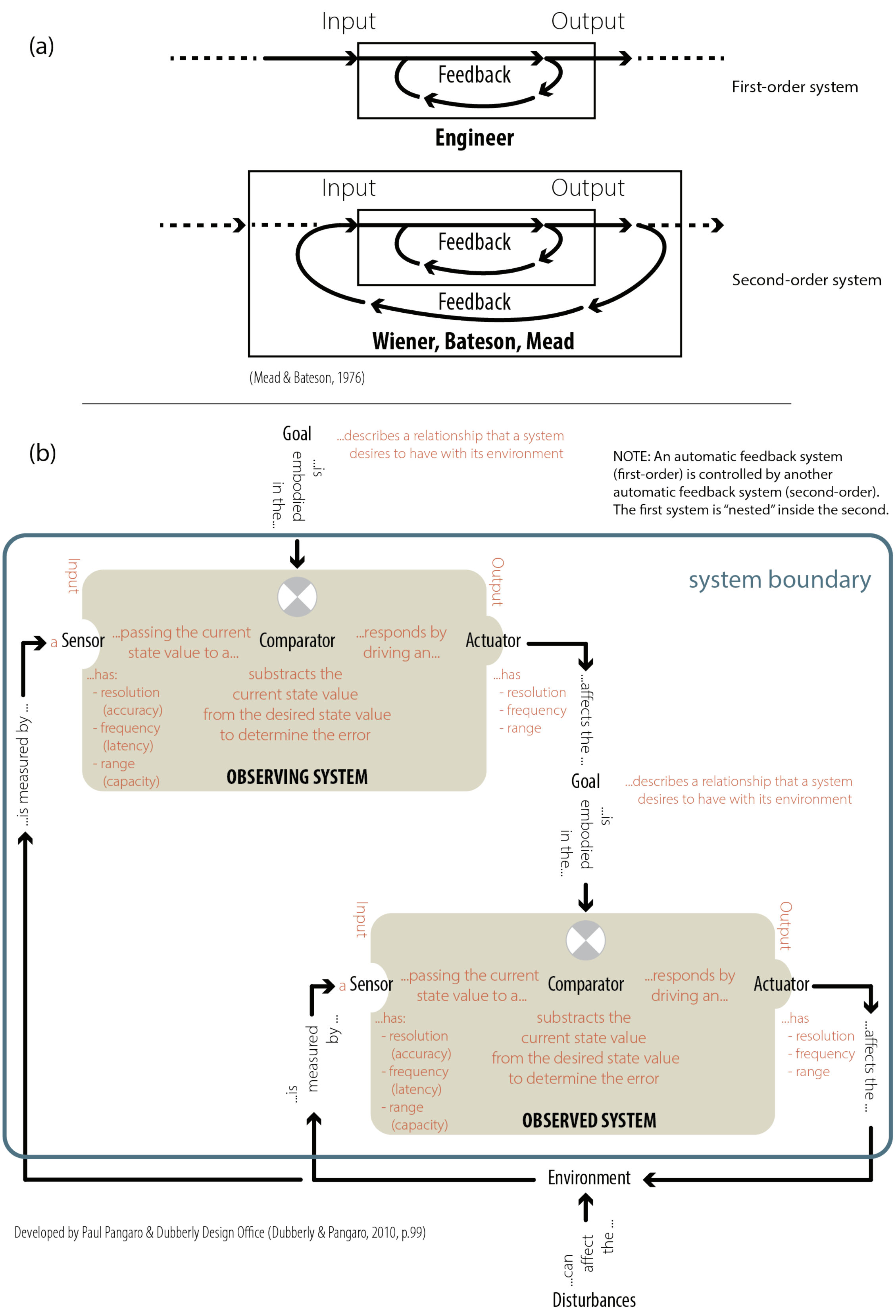
3.2. Cybernetics

3.2.1. What is Cybernetics?

Cybernetics can be described simply as circularity. It is a trans-disciplinary field, first introduced by Norbert Wiener in 1948, as “Control and Communication in the Animal and the Machine,” in his book with the same title (Wiener, 1948, p.62/549). The origin of the word, cybernetics, traces back to the Greek word Kybernetike (κυβερνητική), in relation to governing, steering a ship, and navigating. The words government and gubernatorial also refer back to this Greek word.

Cyberneticians study—among other things—a broad range of fields, including philosophy, epistemology, hierarchy, emergence, perception, cognition, learning, sociology, social interactions and control, communications, connectivity, mathematics, design, psychology, and management. These areas can overlap with other disciplines, such as engineering, computer science, biology, and anthropology, but instead of regulation (that is rapidly converging towards a single solution), cybernetics focuses on an abstracted context to find underlying dynamics and understanding.

Margaret Mead characterized cybernetics as a common language shared between disciplines (Glanville, 2004, p.1380). While many of today’s disciplines from control and network systems, to systems engineering, and project management find their roots in cybernetics, they are typically associated with *first-order cybernetics* (see Figure 3.1a upper image). In this “observed” paradigm, the rules are set, and the observer treats the cybernetic loop as a completely independent system, such as when looking at an artifact. The observer is



(Mead & Bateson, 1976)

NOTE: An automatic feedback system (first-order) is controlled by another automatic feedback system (second-order). The first system is "nested" inside the second.

Developed by Paul Pangaro & Dubberly Design Office (Dubberly & Pangaro, 2010, p.99)

Figure 3.1: Depiction of circular first-order and second-order cybernetic systems: (a) after Mead and Bateson (Mead & Bateson, 1976); and (b) second-order feedback system after (Pangaro & Dubberly, 2010, p.99).

not present in this representation of the system as a single loop, and supposedly unchanged by the observation. *Second-order cybernetics* explicitly incorporates the observer into the system, thereby shifting to an “observing paradigm.” (See Figure 3.1.a lower image and Figure 3.1.b.) The loop of the observed system (in the prior example, looking at an artifact) forms an inner loop where the observer explicitly couples with the inner loop at the inner loop’s goal: the goals of the inner loop can be modified and/or changed by the actions of the outer “observing” loop. This broadens the paradigm of the inner loop in a way that is irreversible, that is, once opened to this shift, observers can never go back to their former state of supposed separation (Glanville, 2004, p.1380) (Dubberly & Pangaro, 2010, p.9). Second-order cybernetics is lesser known than first-order cybernetics, yet due to its potential to enable transformational changes, it is currently undergoing a renaissance among researchers. It allows us to evolve new shared languages and discourses through designerly and artistic modes of operations, leading to new options, insights, and outcomes.

NASA’s paradigm is dominated by systems engineering, which can be described through first-order cybernetics. It is an observed paradigm and can be described through objectivism, linear causation, and reductionism. To demonstrate other modes of operations, such as designerly or artistic modes, we can turn to second-order cybernetics, as it has produced a strong design theory for observing systems, which includes variety amplification (or attenuation) (Ashby, 1956, p.124), mutual circular causation, non-determinism, and the subjective observer (Dent & Umpleby, 1998). Therefore, SoC provides a suitable method for exploring designerly strategies.

3.2.2. Models and Modeling

We can construct cybernetic models through the reduction of complex observed systems to simple ones (Weinberg,1991, p.501), but as George E.P. Box pointed it out, we need to be aware that *“essentially, all models are wrong, but some are useful”* (Box & Draper, 1987, p.424). This modeling is not trivial and it applies to our processes of creating cognitive views of the world. Furthermore, the fidelity of these models varies between fitting and matching our observations. Simplifications may lead to loss of fidelity, and understanding what can be ignored can significantly impact the usefulness of the models. For example, Newton derived his theory on gravity and mass (Newton, 1687) without accounting for comets, asteroids and small bodies in the solar system, yet his model provided highly accurate predictions on planetary motions compared to other predictions to that date. Einstein used mass differently in his model, describing the general theory of relativity (Einstein, 1916). To draw meaningful conclusions from models, our simplifications have to capture and weigh all of the key influencing factors, and ignore those which have secondary effects on the modeled system. As stated by Laurence J. Peter (Peter, 1982), *“some problems are so complex that you have to be highly intelligent and well informed just to be undecided about them.”*

I believe that my simplifications and resulting models capture key elements of the complexities of this research, which then are applied to initiate new conversations. Subsequently these can benefit human exploration and technology development related activities, drivers and influences at NASA. It can also help to elucidate the implementation challenges at hand. Applying new models and shared languages can also help to create a novel worldview. This broadened approach can facilitate unlearning and re-learning how we operate, and can lead to novel and preferable outcomes. The models we develop range from personal cognitive models to organizational models shared between its members. We can change both personal and organizational models through learning. Within an organization this need to be supported from the top down, from senior leadership, through conversations and cybernetic loops between organizational entities with appropriate regulatory and feedback loops, where the variety at each element of the organization is adjusted through conversations.

3.2.3. Constructivist Philosophy of Cybernetics

Cybernetics helps us to construct novel worldviews through circular conversations. The worldview is part of our cognitive model. In this context, the “metaphysical world” is a philosophical and epistemological abstraction of the “real world,” concerned with its nature. (von Glasersfeld referred to this “real world” as the “realm of the phenomenal” (von Glasersfeld, 1984, p.23), thus subsequently I will be using the term “phenomenal world.”) It asks, “what is there?” and “what is it like?” Our interactions with the phenomenal world provides feedback on these questions. The perceived variety of the world helps us to develop our cognitive models about it. From an abstracted philosophical perspective the variety of the world is broader than we can perceive at any given time. Thus, openness to variety afforded by the construct of the phenomenal world animates us to evolve our constructs to achieve better and better correspondence—that is, enables more effective action—with the world we experience. This is part of our epistemological exploration and ontological development. By definition, it is routed in a constructivist philosophical view, which theorizes that all knowledge is constructed by humans, by iteratively refining the cognitive models of our environment while interacting with it. It requires participation, opposed to a rationalistic view where the world is observed and discovered neutrally and objectively. As knowledge can be described as justified true belief, Immanuel Kant pointed out that we need both empiricist experiences and rationalistic reasons. *“Thoughts without content are void; intuitions without conceptions, blind”* (Kant, 1781, p.148/1165). We need experiences to create our cognitive models, while creating a model without validation can only lead to theoretical illusions. Radical constructivism was introduced by Ernst von Glasersfeld (von Glasersfeld, 1984, pp.17-40) (von Glasersfeld, 2001, pp.31-43). According to radical constructivist theory, knowledge is personal, and not transferable between people. Instead, new ideas and models are constructed by each individual, from external inputs, combined with personal knowledge. These emerging constructed models are influenced by a person’s subjective interpretation of an experience and ongoing interactions with the “world” and its other participants, instead of observing an objective reality. This model is formed through a circular conversation with the environment, thus it aligns with the principles of cybernetics. Following a constructivist or radical constructivist approach over other philosophical schools of thoughts is a personal choice, based on a subjective belief in this process. Through selectively choosing arguments it leads to constructing our own ontology, our personal knowing, and our own cognitive model of the phenomenal world. Creating and designing require circular conversations with the environment, coupled with the concurrent internal conversations of designer or artist. Through these circular loops the available options influence the freedom to create.

3.2.4. Tacit Knowledge and Hierarchy

In his book, titled “Tacit dimensions,” Michael Polanyi introduced the term “tacit knowledge” (Polanyi, 1966, p.9-11) as opposed to explicit knowledge (Polanyi, 1966). As Polanyi stated: *“we can know more than we can tell”* (Polanyi, 1966, p.4). Polanyi discussed Meno’s paradox by Plato, about the search for a solution to a problem, where we either know what the problem is, then we know the solution, or we don't know what the problem is, then we wouldn't know what we are looking for (Polanyi, 1966, p.22). Tacit knowing addresses this hidden knowledge. Tacit knowing can account for a) a valid knowledge of a problem; b) the person's capability to pursue it, guided by its sense to approaching its situation, and c) a valid anticipation of the yet indeterminate implication of the discovery arrived at in the end.

We have underlying unprocessed and interconnected pieces of information, which we may call intuition or gut feeling. Kahneman called it "fast thinking" (Kahneman, 2013, p.32/1307). Tacit knowledge is unarticulated and intuitive, that can't be communicated easily. It can be acquired only through experience within a relevant context. It is considered personal knowledge, but it can be transformed into explicit knowledge by codifying, articulating or specifying it. Connecting experiences with tacit knowledge can play an important role for the designer in the design process, where prototyping can result in new insights and the emergence from tacit to explicit knowledge. It can also play a role for the observer when looking at the actions of the designed object. Tacit knowledge can be also a great benefit for strategic decision making, as this interconnected set of underlying insights can signal plausible directions even before expressed properly.

Polanyi also discussed the hierarchy and emergence of knowledge. Hierarchy is a differential construct of a perceived ranking order related to a given subject matter. It has relevance in model formulation and generation, and can influence the order of actions. We develop models of the phenomenal world at various scales, which are both spatial and temporal. Some of these may include importance models, personal cognitive models, and organizational models. Unlike using a language, where we are forced to communicate in a sequence, and follow a logical order, tacit knowledge is non-sequential. It can emerge through a hierarchy where the various levels of interfaces build on the top of each other, the same way as sounds, words, sentences, and prose are structured. By appropriately assigned structuring and hierarchy, tacit knowledge may emerge into communicable personal knowledge.

3.2.5. Communications and Shannon's Law

Claude Shannon introduced his general model of the communication process in 1948 (Shannon, 1948 , fig.1). Shannon's Law, which relates to information theory, is a flexible model that deals with "incessant fluctuations" or noise in the communication system, and can be applied to a broad range of disciplines, from design and art to engineering, computer science, cognitive sciences and various means of interactions.

The model parses communication to piecewise components as shown in Figure 3.2. The shown eight parsed elements can be used to explain the process of communications, including associated challenges. These elements are:

- *The Information Source:* refers to the person (Cognition A) who generates and wishes to transmit the Message. It may also refer to a scientific instrument on a space mission, collecting data for transmission.
- *The Message:* is initiated by the Information Source, and acquired by the Destination. For a message to have meaning, both sides are required to share a common code, such as the same human language, or data encoding. The information has to have entropy in order to provide a meaningful distinction.

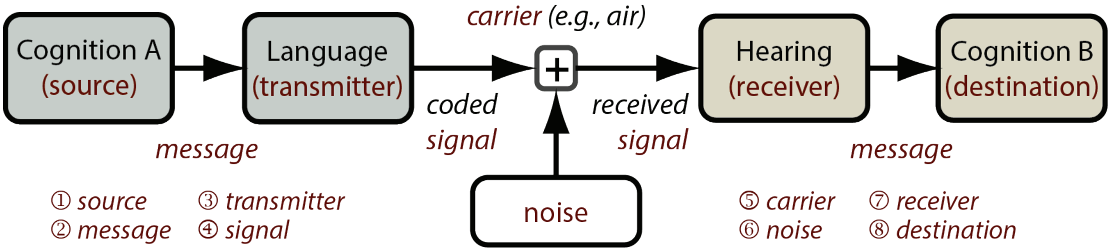


Figure 3.2: After Shannon's schematic diagram of a general communication system with its eight elements (Shannon, 1948). The shown interpretation also includes cognitive and perceptional components relating to human language. (This clearly remains within first-order cybernetics.)

- *The Transmitter:* may refer to a broad range of options, from a person in a conversation to various electronic media, including transmitters on planetary probes. The Transmitter converts the Message into a Signal, such as the human voice and gestures during personal interactions, or electronic signals with appropriate encoding, magnifications, filters, and antennas.
- *The Signal:* is what propagates through the carrier. This can involve a single channel or multiple channels, for example a combination of voice interactions with gestures, or parallel data channels from a descending planetary probe, as was designed for ESA's Huygens probe, which descended to the surface of Saturn's moon, Titan, in 2005.
- *The Carrier:* represents the signal channel, and typically refers to air, electric current, electromagnetic waves, media for printing, and even currier services. Space missions typically use electromagnetic waves, either in the radio- or light-frequencies; however, X-ray communication is also in developments. Carrier signals can be transmitted in multiple channels simultaneously.
- *The Noise:* is an added and unintended signal from the environment, which introduces undesired variety. Interplanetary communications often include noise correction and data redundancy to minimize noise. Depending on the desired outcome, noise can be also introduced to the system to confuse the message, and to create doubt, as seen by counter-messaging of certain media outlets in support of political gains for their affiliates.
- *The Receiver:* represents the bodily perceptional sensors, such as the ears, eyes, sensory receptors for the skin (for pressure, texture, vibration, heat, pain, itch), smell receptors or from the world of engineering, receiving antennas that converts the signal into a message, based on the common code between the source and the destination.
- *The Destination:* is the person (Cognition B) who cognitively interprets the message.

Shannon's model was created through the reduction of complex systems into a simple one. Abstracted and simplified models typically do not capture all details of reality (Weinberg, 1991, p.501), yet they proved to be useful to capture mechanical components of communication flow in a broad range of disciplines, from engineering and computer science to cognitive sciences, design, and various means of interactions. Models can provide a meaningful representation of, and insights into the phenomena they represent. Models can be also modified or augmented to represent more complex systems. Using communication systems as an example, the system between the sender and the receiver has numerous intertwined parts (transmitters, receivers, antennas), combined with multiply serial or parallel signals and carriers. Nevertheless, Shannon's abstracted model captured all the key elements of a one-way communication system. One of the shortcomings of this model is that it treats information as a free flowing property, without accounting for the differences in personal knowledge and cognitive differences between the two actors, namely the sender and the receiver of the message.

3.2.6. Perception and Cognition

Perceiving and interpreting our surroundings at varying scales, from an artifact to the universe, are highly influenced by our personal cognitive models. That is, to create cognitive models of the phenomenal world, we first need to perceive it through our sensory organs (i.e., eyes for vision, nose for smell, ears for hearing, tongue for taste, skin for touch, and vestibular sensors for balance and movement). This will be addressed in more details below. The information input, in the form of energy from the environment, passes through these bodily sensors, and translates into perceptional experiences by cognitive processes.

The steps of this incoming information flow seems obvious, yet explaining particular details of perception and cognition occupied psychologists for a long time. The theory of cognition and human intelligence development was first constructed by Jean Piaget, a Swiss developmental psychologist (Piaget, 1952, pp.357-417) (Singer & Revenson, 1996, pp.1-11). Piaget was also a constructivist, focusing on the cognitive developmental stage theory of children, including logic, language, space and time, and play, but also addressed knowledge acquisition, construction and use. Children think about what they perceive as the world around them differently from adults, as they learn and acquire knowledge differently through cognitive development. For example, in this process—at times—they may talk to animals and inanimate objects, and attribute life to them. Piaget labeled this animism. He also explored other concepts about childhood development processes, related to logic, language, space and time, and play, among others. Piaget contributed experience and interaction as key elements of cognitive child development.

Through a constructivist approach he theorized that knowledge is developed gradually, in stages, and by constructing and understanding of the world through sensory experiences and interactions. Furthermore, alignments and discrepancies with building blocks of intelligent behavior and knowledge (schemata) influence interpretation and learning.

In one's mind each schema relates one aspect of the observed world, which can be artifacts, actions, or abstract concepts. Formation of the schemata starts at an early age. Piaget stated: *"…the baby begins by constructing, in coordinating his actions, schemata such as those of the unchanging object, the fitting in of two or three dimensions, rotations, translations, and superimpositions that he finally succeeds in organizing his 'mental space' and, between preverbal intelligence and the beginnings of Euclidian spatial intuition, a series of 'topological' intuitions are intercalated as manifested in drawing, stereognosis, the construction and assembling of objects etc.; that is to say, in the areas of transition between the sensorimotor and the perceptual"* (Piaget, 1952, p.x). The interaction between the object and the observer is achieved through a sensory perception path, which includes three distinct yet interconnected elements: 1) the object itself; 2) the observer's sensory system (including vision, auditory (hearing), somatic sensation (touch), gustatory (taste), olfaction (smell) and vestibular (balance/movement)); and 3) the neural pathways of the brain involved with sensory perception. Cognitive processes include perceiving, remembering, believing, reasoning. These steps may evoke emotions, which constantly intertwine with cognition. Interactions between the object and the observer are achieved through three complementary processes,

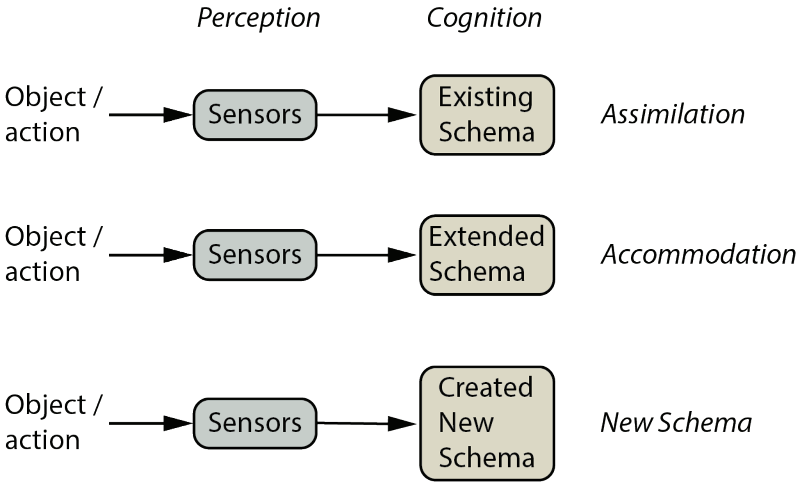


Figure 3.3: Illustration of sensory perception and cognition, including assimilation, accommodation and creating a new schema, after (Piaget, 1952, pp.357-417).

namely assimilation, accommodation, and creating a new schema. In the case of assimilation, interaction with the object is approached through previous experiences of the observer, and if there is an alignment, then the new experience will become part of the existing schema. Accommodation requires revision of the old schema to fit the new experiences. When these two approaches do not work, the observer is required to create a new schema to interpret the new experience (see Figure 3.3). The sequential process of assimilation, accommodation and creating a new schema is part of the process of experiencing and learning, and may evoke a range of emotions in the observer, including surprise, joy, and frustration. Designers and artists utilize this approach, either consciously or subconsciously, and use it to build artifacts. We can also use this approach for humanly space objects where the astronaut interacts with the local environment.

One of the key considerations of perception and cognition is to identify if perception of our phenomenal world relies on a) information received directly through the bodily sensors, or b) if previous knowledge by the person and expectations also adds to the cognitive interpretation. James Gibson, the American psychologist, proposed a direct “bottom up” theory of perception, discussing it under “the optical information for perceiving affordances” in (Gibson, 1986, p.40). His theory of direct visual perception is detailed in Chapters IX to XII related to vision (Gibson, 1966, pp.154-255). This approach is raw sensory data driven, and linearly unidirectional through visual processing, and it initiates with the sensory stimulus. (For example, when objects are superimposed, one object blocks the view of another; or the relative sizes of the same type of objects change as we move them to different distances from the eyes.) In comparison, Richard Gregory, a British psychologist, proposed an indirect “top down” constructivist theory. He states: *“The brain makes sense of the world by making predictions”* (Gregory, 1970, p.162). His approach combines sensory and contextual information to recognize patterns. For example, in a noisy environment we may understand a word when included in a sentence more than the word alone, as our cognition can provide the appropriate filtering and interpretation. This is also a guessing process through the formulation of a perceptual proposition between the sensory input and our knowledge, as a word may have many meanings. Thus a priori knowledge can be very influential in the cognitive processes.

In this constructivist approach there is circularity between guessing cycles that refines our initial assumptions of a meaning towards a shared understanding, where our internal model

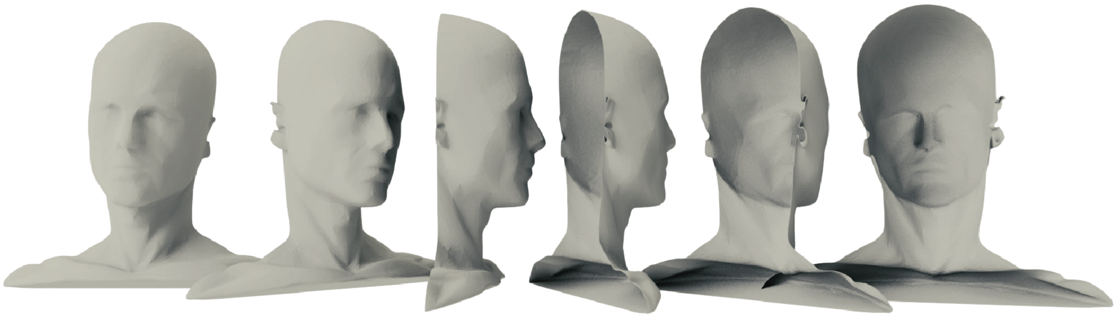


Figure 3.4: Visual perception error with convex and concave faces, after (Gregory, 1970, p.128).

aligns with the received information. Incorrect interpretation can lead to perception errors. A visual perception error example is the concave face illusion, shown in Figure 3.4, illustrates how our cognition interprets a concave face as convex, even though it is clearly shown otherwise. This "unconscious inference" is based on our previous experiences, supporting Gregory's theory that the information is not simply based on direct input data. Gibson opposed Gregory's top down approach arguing that Gregory's examples are taken out of context, while a full sensory input provides sufficient environmental information to make sense of it, and to justify a raw sensory data driven direct approach. He pointed to flow patterns (or outflowing optic array), invariant features (or invariants of structured simulation that specify surfaces), and affordances (Gibson, 1986, p.139,140,127). Flow patterns inform us about motion parallax, that is relative speed as a function of distance. Invariant feature refers to the different perceived size of the same object as a function of distance. Affordances are interaction possibilities between a person and objects. (This is further discussed in a subsequent sub-section.) Yet, Gibson's theory doesn't account for perception errors (Figure 3.4), or naturally occurring illusions, for example looking at stationary objects out of a train's window, which appears as the train starts to move, while the fixed environment with the observer and the train cabin feels stationary. None of these two theories can explain all of the perceptional experiences under all circumstances. To resolve this impasse, Ulric Neisser proposed a model, he called it a "perceptual cycle," where the top down and bottom up processes work in a circular way (see Figure 3.5) (Neisser, 1976, p.20). He pointed out that purely data driven approach would make people mindless robots, while a purely prior knowledge driven approach would make them dreamers without physical grounding. (This combined approach is reminiscent of Kant's philosophical work, where he pointed out the need for both rationalistic

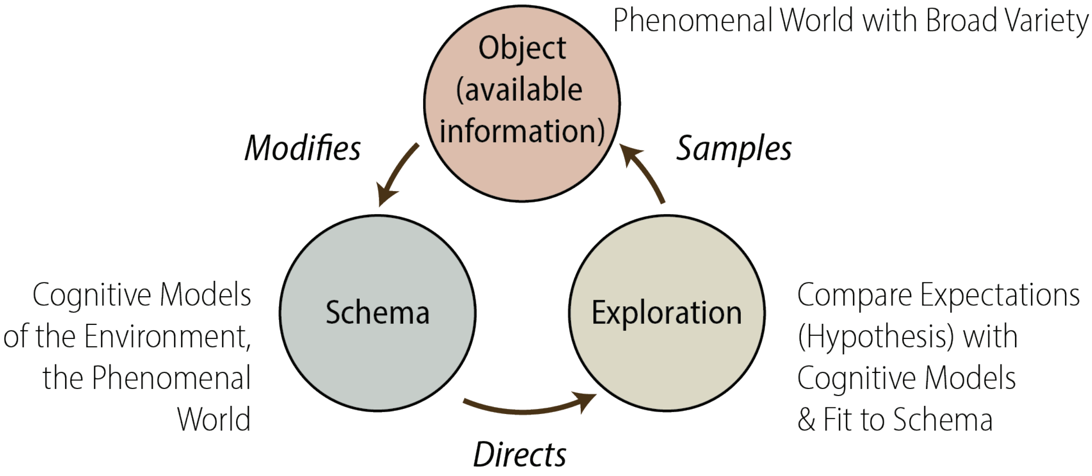


Figure 3.5: Perceptual cycle of perception and cognition, based on (Neisser, 1976, p.20).

and empiricist approaches.) Thus, in a circular process our cognitive models (or schemata) provide expectations (hypothesis) for given contexts. If the sensory input disagrees with this hypothesis, then it does not fit an existing schema, and in line with Piaget's approach the schema is either extended, or a new schema is created for a new experience. Neisser's perceptual cycle model, shown in Figure 3.5, combines the cognitive psychology models of Gibson and Gregory. It plays an important role in understanding how we think, create, invent and innovate, and in general interact with the world. It also implies that the complexity and fidelity of our abstracted cognitive model of the world improves through circular conversations with our environment. The guessing and interpreting phases of a broadened cognitive model may stimulate a larger number of innovative ideas, where designers and artists can translate them into novel real-world artifacts.

The worldview, which on the individual scale is the cognitive model of the world, represents a subjective social reality and understanding, which influences the perception and cognitive processing of the received information. The information only has meaning if it is differentiated and decoded by the observer. "Cognitive bias" represents a subjective "noise" which influences the interpretation of the received message (Kahneman, 2013, p.1059/1307). Just like subjective perception and cognition, the scientific progress can be also viewed as discontinuous. Changing a worldview can lead to epistemological rupture, overcoming the block, as demonstrated by the influence of Newton and Einstein on technological and societal changes. Gaston Bachelard used a similar construct for the history of science, proposing that science is coupled with the concept of progress (Idlas, 2011, p.10). In this scientific evolution the worldview is converging towards an increasingly better approximation of the world in our cognitive models, which also represents a subjective reality. When the way of thinking encounters limits, these limits manifest as "epistemological obstacles." Overcoming such obstacles through an "epistemological rupture" requires new knowledge, and new variety in a modified cognitive model, that is, a new worldview. Thus an epistemological rupture represents changes in both the psychology of the subjective individual and the collective worldview.

3.2.7. Maslow's Hierarchy of Needs

Abraham Maslow developed his motivational theory between the early 1940's and 1970's (McLeod, 2014). Maslow's Hierarchy of Needs (HoN) initially included five levels (Maslow, 1943, pp.372-383), which were subsequently extended to eight (Maslow, 1970, p.2&104). His initial five hierarchical stage model included physiological needs (e.g., metabolic, shelter, reproduction), safety needs (e.g., security, stability, health), love and belonging needs (e.g., family, friendship, intimacy), esteem needs (e.g., achievement, respect, recognition), and self-actualization needs (e.g., personal fulfillment, growth, creativity). At the lower levels, basic or deficit needs motivate people to meet them. For example, hunger or thirst becomes an increasingly strong motivator as time passes, until they are met. He proposed that once a need is met at a certain level of this hierarchy, the person moves to fulfill the next level above it, towards self-actualization.

The eight stage model included the initial five needs listed before, but Maslow added between esteem needs and self-actualization needs: the *"cognitive needs for sheer knowledge (curiosity) and for understanding (the philosophical, theological, value-system-building explanation need)"*; and aesthetic needs related to *"the impulses of beauty, symmetry, and possibly to simplicity, completion, and order"* (Maslow, 1970, p.2). Maslow topped the list with

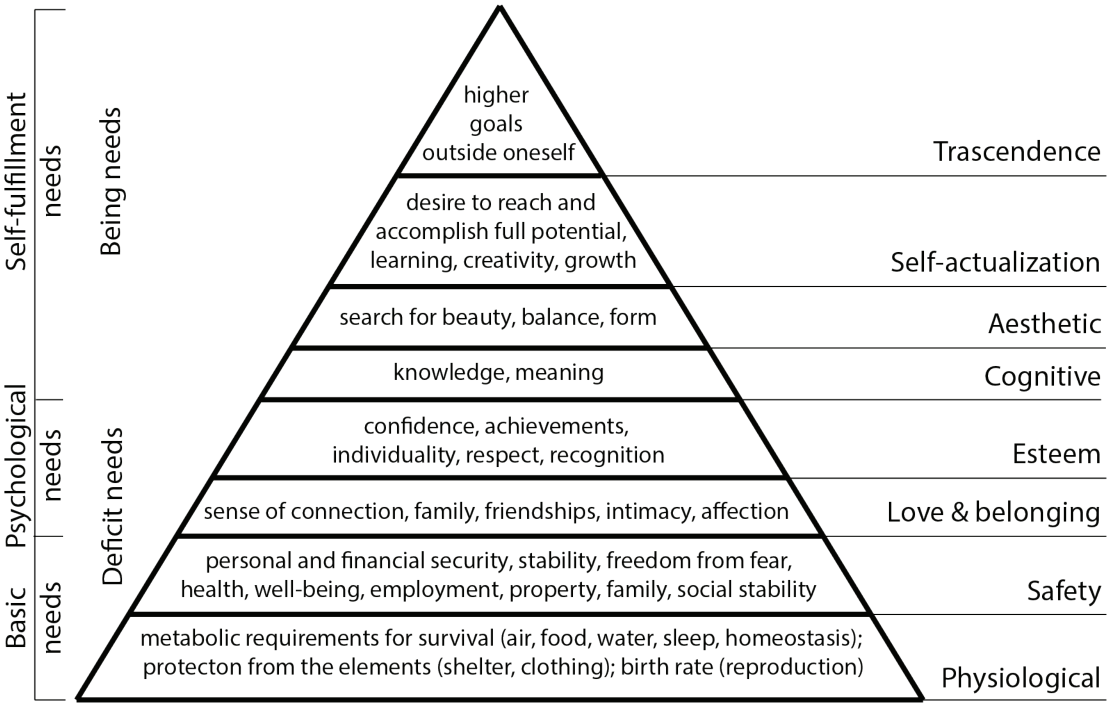


Figure 3.6: Illustration based on Maslow's hierarchy of needs (HoN), described in (Maslow, 1970, p.2&104).

transcendence needs, by which he meant *"for the person to grow toward full humanness, towards actualization of his potentialities, toward greater happiness, serenity, peak experiences"* (Maslow, 1970, p.104). The hierarchy, based on Maslow's work, is shown in Figure 3.6.

Maslow's approach was criticized by stating that his findings were based on qualitative methods, specifically on biographical analysis, which is often subjective and can be biased by the researcher. Thus, self-actualization might work better as a proposed concept than a scientific fact, as it is not derived and validated through rigorous analysis and synthesis. Recent research with a larger control group of 60,865 participants from 123 countries has indicated that the list is reasonable, but the order of the needs may change (Tay & Diener, 2011). Furthermore, the same research by Tay and Diener pointed out that *"the balance in life is desirable; this follows from the fact that each of the needs makes separate contributions to SWB"* (or subjective well-being) (Tay & Diener, 2011, p.363). This is in line with my assertion that human centered design and cybernetics should be part of NASA's culture. They also confirmed Maslow's hypothesis that *"people tend to achieve basic and safety needs before other needs"* (Tay & Diener, 2011, p.363). This finding can also describe NASA's engineering and safety focused paradigm. Since Maslow's findings are based on the sampling of only 18 biographies of highly educated individuals, from a scientific perspective this might be a small pool and can be considered biased. However, in this research the HoN is applied to highly trained astronauts, which makes the comparison relevant, as they have much in common with Maslow's selection pool. For example, Palinkas found that long-term isolation and confinement has minimal impact on the health and well being of the crew, and for this he suggested *"one of three possibilities: a) isolated and confined extreme environments are no more stressful than other environments; b) highly motivated, self-selected individuals who volunteer for such long-term missions are capable of maintaining high levels of performance in such environments over long periods of time; or c) some highly motivated individuals simply do better than others"* (Palinkas, 2001, p.26).

3.2.8. *Variety in Cybernetics*

Within the field of cybernetics, the term “variety” was introduced by W. Ross Ashby (Ashby, 1956, p.124), referring to the degrees of freedom of a system (Ashby, 1956, p.129) or more specifically to the distinct states of a given system and its environment. Stafford Beer referred to variety as *“the measure of complexity in a system, defined as a number of its possible states”* (Beer, 1974, p.5). For a stable system in dynamic equilibrium, its regulatory mechanism has to have greater or equal number of states (variety) than the environment it is striving to control, otherwise the control is ineffective; this is the definition of his Law of Requisite Variety (Ashby, 1956, p.206). Ashby states his Law as: *“only variety in R (regulator) can force down the variety due to D (disturbance); variety can destroy variety”* (Ashby, 1956, p.207). That is, variety absorbs variety, defines the minimum number of states necessary for a controller to control a system of a given number of states.

3.2.9. *Cybernetic Circularity*

In the simplest way, cybernetics can be described through its circularity. Cybernetics provides a way to look at things—a perspective—and focuses on communications in addition to control, but addresses them both in a circular way with forward and feedback loops.

Communication aspects are different from the language, which is the required shared encoding and decoding requirement of the signal. These make communications between humans significantly more complex than data communications between electronic transmitters and receivers discussed by Shannon (Shannon, 1948, fig.1). Thus, to refine and develop a shared meaning between individuals, we need to include circular and iterative feedback loops. In other words, we need to construct and refine meanings through conversation loops.

Real-life communications are often bidirectional, with feedback loops, as addressed in cybernetics. The models shown in Figures 3.2 can be expanded to show a circular communication loop between two actors (see Figure 3.7). It is an expanded interpretation of Shannon’s unidirectional model. Here the message is formulated and transmitted by the sender (Actor A), but the meaning of that message is interpreted by the receiver (Actor B), regardless of the intended meaning by the sender. This is an important observation, and it echoes Heinz von Foerster’s point about *“the reader, not the writer, determines the meaning of a sentence”* (von Foerster, et al., 2014, p.13/276). The response from Actor B to Actor A, in the form of a feedback, follows the same process, and the conversation may continue until a commonly agreed understanding is constructed. Environmental noise and *“cognitive biases”* (Kahneman, 2013, p.1059/1307) can interfere with the communication loops, and the need to be compensated for by the actors. These aspects are different from the language, which is the required shared encoding and decoding requirement of the signal. These make communications between humans significantly more complex than data communications between electronic transmitters and receivers. Thus, to refine and develop a shared meaning between individuals, we need to include circular and iterative feedback loops. In other words, we need to construct and refine shared and agreed meanings through conversation loops.

We can also apply this approach to designerly and artistic creative processes. In this sense, starting with an individual, the act of making consists of iterative circular conversations between the designer/artist and the environment. The information from the environment crosses the sense organs, and is processed through cognition. Feedback is returned to the

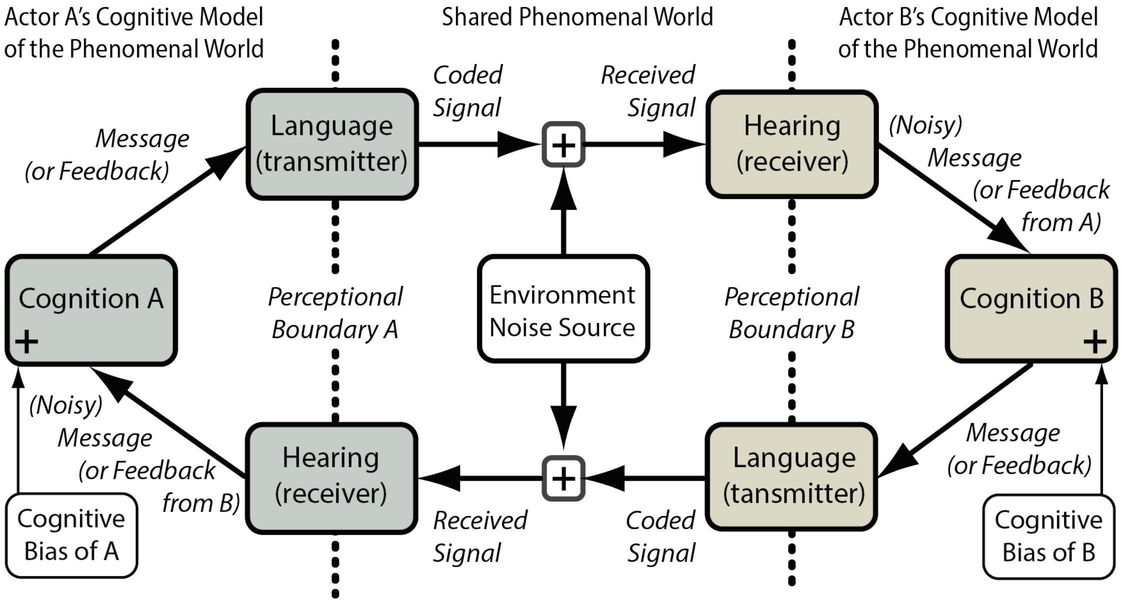


Figure 3.7: An interpretation of Shannon's model of information flow between two actors, adding cognitive and perceptional components relating to human language (Balint & Hall, 2016). "Everything said is said by an observer" (Maturana & Varela, 1980, p.xxii) and "everything said is said to an observer" (von Foerster, 2003, p.283). The illustrated circular conversation promotes the evolution of the discourse towards a shared and agreed understanding, while the personal knowing of the two actors is expected to differ.

environment via language, gestures, and actions. The making process involves a cognitive conversation with subsequent cycles of sense-giving (i.e., creating subsequently evolving versions of the object) and sense-making (i.e., critically assessing the outcome), until a satisfactory outcome or a stopping criterion is reached, where the variety is balanced and the system becomes stable (see Figure 3.8). The variations and random outcomes from the sense-giving phase can result in an object that is different from the initially conceived one. Therefore, the incoming observed information during sense-making phases combines the initial intent of the designer, and the noise from the environment that can lead to often-unexpected outcomes.

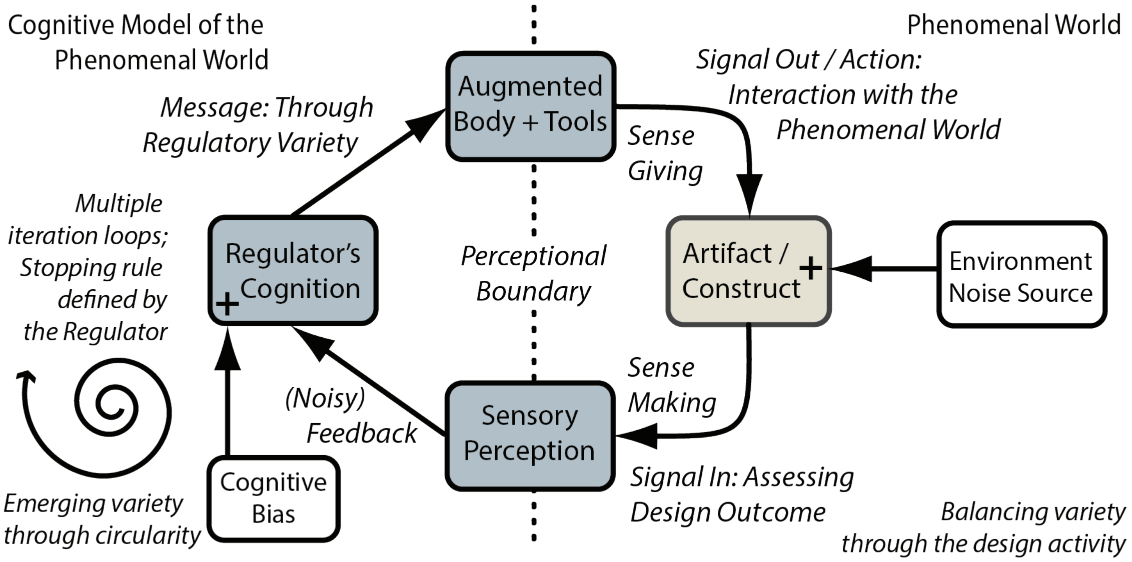


Figure 3.8: Schematic diagram of a constructivist dialog between a designer/artist and the artifact or construct, based on cybernetic circularity; also showing the designer's perceptional boundary and cognitive bias (Balint & Hall, 2016).

The designer now has an opportunity to reassess the artifact and make modifications in a subsequent iteration step and give sense to a new prototype. (Practice-based research places the main focus on this approach.)

3.2.10. Circular Conversations Across the Perceptional Boundary

As discussed above, the communication exchange between the cognitive mind and the environment is bi-directional, and it is performed across—what I termed—a "perceptional boundary" (see Figure 3.9). (Note: I use the term "perceptional" instead of the typical "perceptual" term, as I am referring to the cognitive process combined with perception instead of the biological sensing process.) The steps of this incoming information-flow seems obvious, yet explaining particular details of perception and cognition occupied psychologists for a long time. It conjures images of Ranulph Glanville's "Zero Space" (Glanville, 2010, p.98) and George Spencer-Brown's distinction and crossing in the "Laws of Form" (LoF) (Spencer-Brown, 1972, p.1-2). Glanville's example of the thick wall on the top of the Mayan pyramids, and Spencer-Brown's line of a circle on a sheet of paper, both provide a distinction between the inside and the outside. My perceptional boundary aligns with these concepts, where the circular loop includes unidirectional incoming information from the environment through sensory perception;

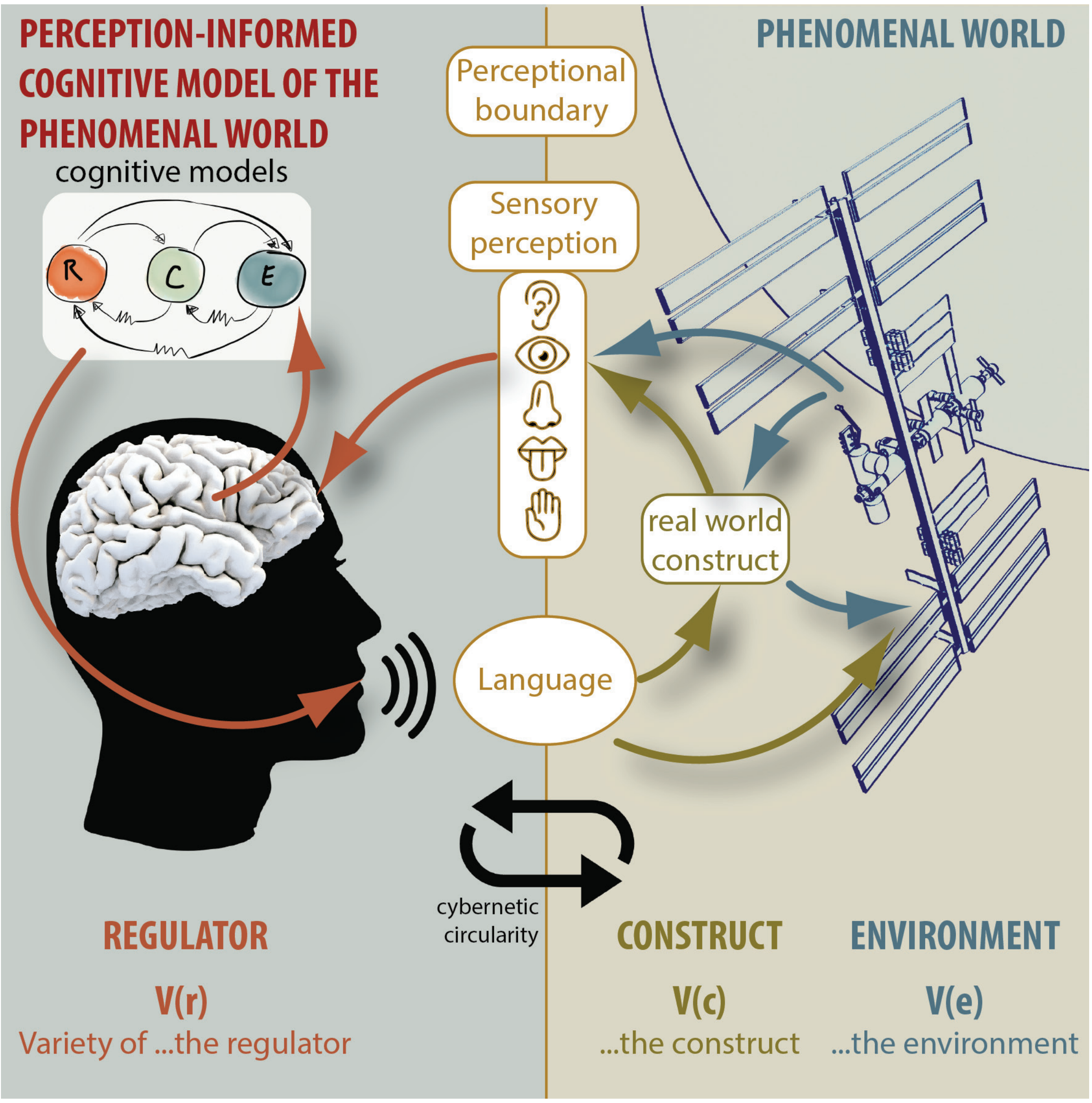


Figure 3.9: Illustration showing communication across the perceptional boundary (Balint & Hall, 2015a).

cognitive processing; and outgoing information through language (which may or may not be augmented with gestures or other means). This circularity completes a conversation loop, which is sequential, as the perceived information needs to be processed, then responded to (see Figure 3.9). The interpretation of the incoming signal is dependent on the cognitive model of the person, and may align with Piaget's three complementary processes. For the outgoing signal, language is used to communicate meaning, representing the condition of realness (e.g., is this carp a fish? Yes, it is.); and falsehood (e.g., is this dolphin a fish? No, it is a mammal.). Meaning is defined by its truth-value, but also by its use-value. Wittgenstein introduced truth condition (truth-function) theory early in his career (Wittgenstein, Russell, & Ogden, 2007, p.64/151), proposing that only a strict definition of the language is required to represent meaning. Later in his career he revised this position and introduced the use theory, where both the strict meaning of the language and the context are important. For example, making a sarcastic comment changes the strict meaning of a message. Therefore, when communicating, we need to account for both the truth and use conditions. Conversations and interactions are further developed by Gordon Pask through his Conversation Theory (Pask, 1976, p.27). Pask considered any interaction with our environment as a conversation. We interpret our sensory input as part of the conversation and respond through our cognitive processes. Even if the process is internal, without the outgoing verbal message, it has the structure of a conversation with the environment. Designers and artists utilize these approaches of learning, interacting, conversing with others or having a circular conversation with themselves, while creating through prototyping cycles. These activities are done either consciously or subconsciously, and are subsequently can be built into artifacts.

It should be noted that the concepts introduced in the Laws of Form has much in common with Boolean logic and Boolean algebra by George Boole (Boole, 1847), who described it over a hundred years before LoF was written. Spencer-Brown simplified Boole's algebra, and discussed it through a new language (Spencer-Brown, 1972), which resonated with his audience. He reflected on the works of both Boole and Wittgenstein, and related it to logic and cognition. His work was greatly influential among cyberneticians, including Heinz von Foerster (an important catalyst for second-order cybernetics)(von Foerster, et al., 2014), and Humberto Maturana and Francisco Varela from Chile, who introduced autopeiesis (referring to self-reproducing and self-maintaining systems as will be discussed next) (Maturana & Varela, 1980, p.xvii-xxiv). Many who were influenced by LoF developed their own variants on Spencer-Brown's primary algebra. In effect, their introduced their own language to open up new conversations and enable novel outcomes. Connected concepts related to perception and cognition are further discussed in my research, for example, how this relates to tacit knowledge, cognitive models, communications, hierarchy, cybernetics, design, affordances, and human centered approaches.

3.2.11. Autopoiesis

The term, autopoiesis, was introduced in 1972 by two Chilean biologists, Humberto Maturana and Francisco Varela (Maturana & Varela, 1980, p.xvii-xxiv). While their originally used it to define self-maintaining biological systems at the cell level, the concept has been adopted by other disciplines including sociology, systems theory, and cybernetics. They invented the term after stating: *"If indeed the circular organization is sufficient to characterize living systems as unities, then one should be able to put it in more formal terms…" "…a formalization can only come after a formal linguistic description… yet we were unhappy with the expression 'circular* *organization,' and we wanted a word that would by itself convey the central feature of the organization of the living, which is autonomy." "…analyzed Don Quixote's dilemma of whether to follow the path of the arms (praxis, action) or the path of the letters (poiesis, creation, production)…" "I (Maturana) understood for the first time the power of the word 'poiesis' and invented the word that we needed: autopoiesis"* (Maturana & Varela, 1980, p.xvii). According to Maturana and Varela, unity, organization, structure, structural coupling, and epistemology define an autopietic system.

It is an observer-dependent approach to cognition, in line with second-order cybernetics. In connection with design and design education, Dubberly and Pangaro (Dubberly & Pangaro, 2010, p.9) described autopoiesis as: *"One of the great challenges facing the design profession is how it can create sustained learning about design practice. In recent years, several universities have begun to grant PhDs in design, but design research is still young and relatively unformed. The feedback systems necessary to sustain it are not yet in place. Designers need a self-sustaining, learning system whose components make and re-make itself: the curricula must contain "the practice" while also capturing processes that learn while also sustaining those that already exist. Inherent in the seven cybernetic frameworks are mechanisms to make such activities explicit for the design community and for the institutions (schools, consulting studios, and corporate design offices) that support it."*

3.2.12. Viable System Model (VSM)

Management cybernetics is a subdivision of cybernetics, established by Stafford Beer in the 1960's (Beer, 1974, p.22) (Beer, 1981, p.157). It looks at the regulatory and guidance mechanisms that govern the operations of organizations at any scale, from companies to societies. Organizations are autopoietic systems, which are dynamic, self-organizing, can reproduce and survive their changing environment (Maturana & Varela, 1980, p.xvii-xxiv). They can be viewed as living and dynamic systems. Consequently Stafford Beer based his model on the human body, where body parts, the nervous system, and various parts of the brain are represented by the five systems of VSM, which are listed below and shown in Figure 3.10. Because they are dynamic, they are in constant flux, which is influenced by their variety (Ashby, 1956, p.124) of its elements. For example, higher variety leads to greater flux. Following any perturbation stability can be achieved through regulatory control, where over a control-driven relaxation time the system balances itself and its variety returns to an overall equilibrium. To limit perturbation, that is the variety generated by the system, regulatory controls can be used to attenuate it. Another way to achieve stability is by amplifying the variety of the regulatory component of the system. If done incorrectly, and too many variety attenuators are built into the system, it can result in rigid organizations with suffocating restrictions, and leading to innovation barriers, as seen at NASA. Beer referred to cybernetics as *"the science of effective organization,"* and variety as *"the measure of complexity in a system, defined as a number of its possible states"* (Beer, 1974, p.5). He identified three ways institutions typically employ to reduce variety:

1. Regulatory management control from the top down;
2. Rigid connections between organizational structures and employees, constraining the interactions;
3. Rigid organizational structure, requiring uniform responses for incoming influences and interactions.

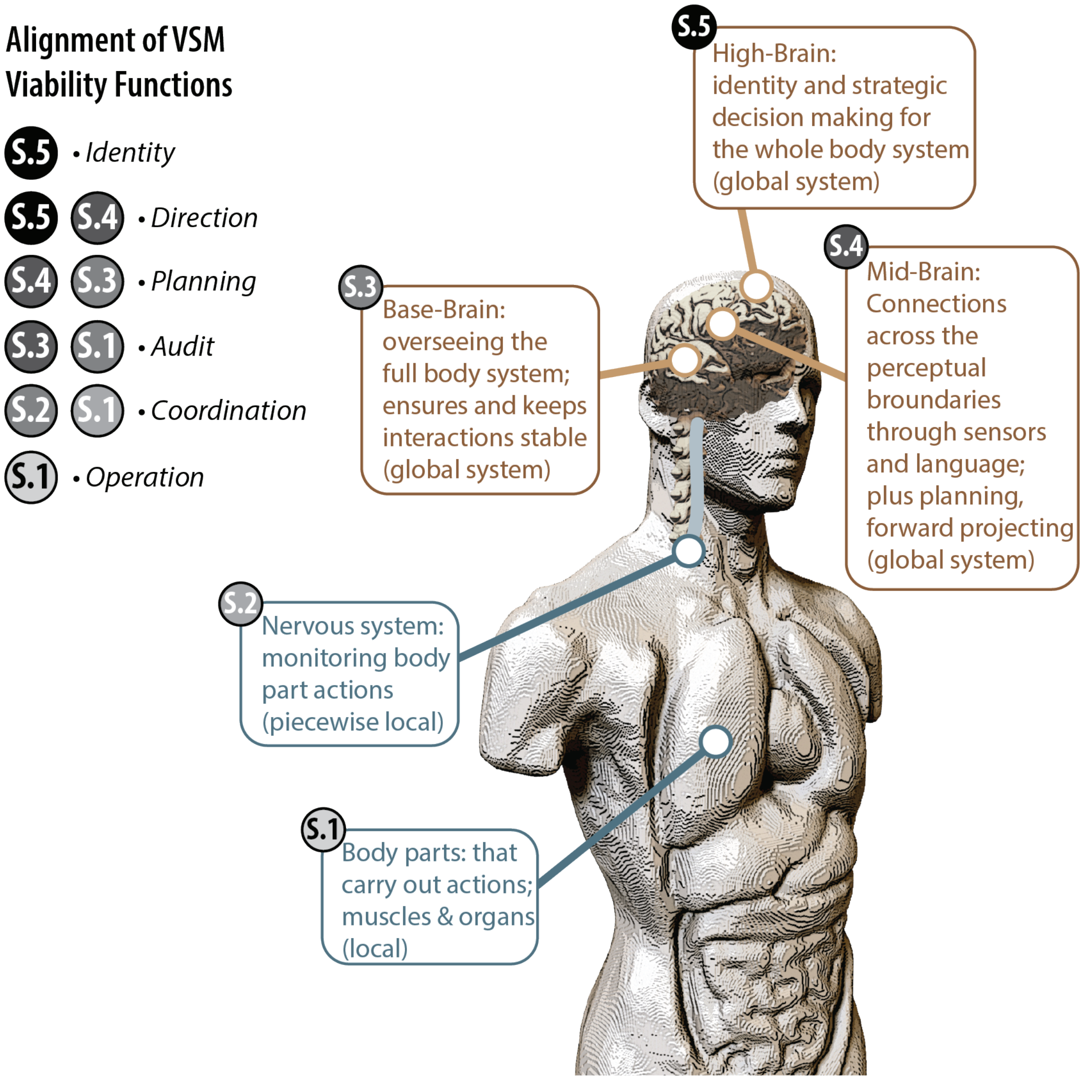


Figure 3.10: VSM draws comparisons between an organizational structure and the human body.

None of these approaches are ideal, and may lead to rigid structures. Thus, to manage an effective organization, regulators should not simply impose variety controls, but need to be aware of the variety distribution and how they impact the various departments and individuals. The organization's senior leadership also need to be aware of the dynamics of these control measures. Too much oversight can lead to micro-management, while too sparse feedback results in delayed or late regulatory responses in case of perturbations. These interactions are reflected in Stafford Beer's Viable System Model (VSM) (Beer, 1981, p.157), shown in Figure 3.11. It is a conceptual model to understand organizational structures and rules, and to identify touch points, where changes and alignments can be made to benefit operations. As organizations have less variety than the environment they operate in, they need appropriate strategies to be responsive. Organizations are autonomous (that is, viable) systems, and in line with VSM, they require five key system functions to operate effectively. These are, in decreasing hierarchical order:

- System 5: Strategy / Policy / Identity
- System 4: Intelligence
- System 3: Control
- System 2: Management / Coordination
- System 1: Executions / Operations

These organizational functions are recursive, where the same generic types of hierarchies between regulators and controlled elements can be applied at all scales. (We all have managers, and we all work with peers or subordinates.) This recursiveness provide strength, robustness, and integrity to the organization. Thus, cybernetics related considerations play important roles in introducing new conversations to any organization, including NASA, and in effect to its space exploration goals. This recursiveness can provide a distinction between first and second-order cybernetics. First-order cybernetics describes an observed system. For example a project manager observes and controls the execution of the project, while keeping it on track to achieve the set out project goals within the available resources. Second-order cybernetics describes a cybernetic circular loop around the first-order loop, and can be described as an observing system. That is, observing the observer. For example, at the strategic organizational level senior leadership can observe the first-order project execution loop, and compare the execution progress with their own higher-level strategic goals. The strategic level observing system can subsequently reset the goals of the project level system, as required.

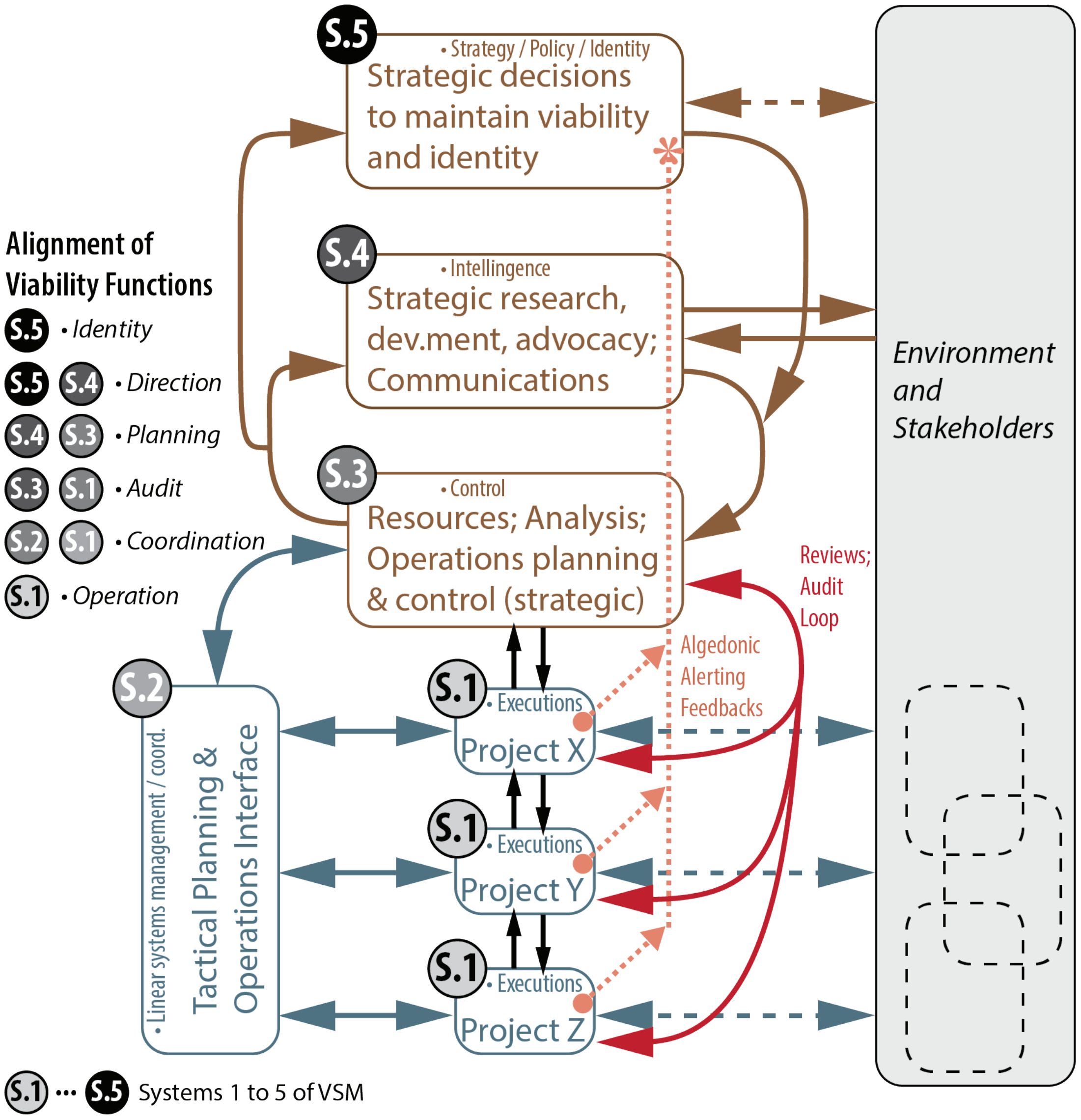


Figure 3.11: Illustration of VSM, after Stafford Beer's Viable System Model (Beer, 1981, p.157).

3.3. Design

The word “design” has a broad range of meanings. Among others, it can be a noun or a verb. It can describe a discipline, an activity or an object. While design is a rather broad subject, there is an agreement on the fundamentals, which was captured simply, and elegantly by the authority of Herbert Simon. In (Simon, 1996, p.111) he stated: *“Engineers are not the only professional designers. Everyone designs who devises courses of action aimed at changing existing situations into preferred ones.”* Glanville presented cybernetics as a theory of design, and design as cybernetics in practice (Glanville, 2007, p.1173).

One way to describe design in the present context—after leveraging cybernetics-based perspectives of a system—is that it is a utility driven response towards a need. To this end, designers may invent new requirements to address this need with an added focus on the users. The introduced new requirements add variety to the system, which opens the possibilities to novel outcomes and can lead to disruptive innovations. The benefit of a design approach with its non-linearity is that it can always break through its bounds, step outside its current paradigm. These breakthroughs happen in stages. A new breakthrough establishes a broader design paradigm. Once it is codified, it is easy to incrementally exploit it until the gained options are exhausted. Subsequent breakthroughs restart these broadening /exploiting cycles. Therefore, design described at any given time can only provide a snapshot of its existing paradigm, which is expected to evolve from its present state.

The types of design can range from artifacts through processes to services, or the combination of them. Each of them can be the focus of multiple PhD research projects and other academic work, where topics are advanced and re-framed.

It is beyond the scope of my research to provide a comprehensive overview of the field of design research and design practice. Instead, I am focusing only on the aspects, which are relevant to my discourse. Thus, following some introductory words on design in the previous section, I will give a brief discussion here on design thinking, design conversations, and artifact-specific affordances and signifiers.

3.3.1. From Design Thinking to Design Conversations

Space exploration introduces significant technological challenges, where incremental developments can fulfill near term needs, but future missions will require new alternatives, and new ideas. Existing solutions are becoming obsolete and design thinking can provide a new approach to tackle these emerging problems. Design today is often viewed as a discipline focusing on aesthetics, image, and fashion. However, design accounts for more then simple ergonomics and packaging. Therefore, we should focus less on the resulting artifacts and more on the approach to achieve the desired goal. This design thinking approach allows us to address challenges through transformational innovations.

Design thinking follows two parallel paths. One is “designerly thinking” (Cross, 2011, p.7/150) and the other is “design thinking” (Brown, 2009, p.21). Designerly thinking is an academically routed approach, that looks at a designer’s skills and competence, and links it with the theoretical complement of the designer’s competence from an observer’s perspective.

In contrast, design thinking is a simplified version of designerly thinking, as it focuses on practice of design and management, placing less emphasis on the theoretical elements

(Johansson-Sköldberg, Woodilla, & Çetinkaya, 2013, p.123). Design thinking begins with integrative thinking to exploit opposing ideas and opposing constraints, and to create new solutions. Design thinking organizations apply both deductive reasoning—moving from the general to the specific—and inductive reasoning—moving from the specific to the general (Martin, 2009, p.69/188). In the case of design that means balancing desirability (what humans need), (technical) feasibility, and (economic) viability. The design and creation of new artifacts and processes can benefit from design thinking and systems thinking, through a combination of observational research, brainstorming for new solutions, and rapid prototyping. Design thinking also looks at a broad range of considerations, including the understanding of culture, aspirations, motivations and context, at every level contributing to the framework. This approach can be beneficial to derive strategies in the government framework, where multiple stakeholders have diverse sets of drivers and expectations.

Design thinking requires learning by making, and building in order to think. In effect, it often builds on tacit knowledge (Polanyi, 1966, p.9-11), which uses prototypes to speed up the process of innovation, because creating them will allow the practitioner to understand the strengths and weaknesses of the artifact or the process being designed. Faster turnaround results in faster evolution of ideas, which can result in better outcomes while saving resources. Socializing prototypes also results in an inclusion of stakeholders at an early stage, and encourage feedback for faster iteration, acceptance, and dispersion of the new technology. This is in line with the collaborative approach of solving wicked problems.

Design thinking is important for all levels of innovation, from incremental to the development of transformational technologies. Instead of making the best choice out of available alternatives, which is the current linear approach at NASA, it encourages us to take a divergent approach, create new options, explore new alternatives, find new solutions and new ideas, that didn't exist before. The process and use of divergence and convergence cycles, and their application for technology development at NASA are discussed in (Balint, 2013).

Good design, may it be a process, an artifact, or service, can provide distinct advantages over purely technology driven developments, because of its multi-disciplinary nature. Its transformative characteristics involve four major elements (Norman & Klemmner, 2014), namely:

- *Design Thinking:* to identify and solve the right problem;
- *Systems Thinking:* to account for the crosscutting multiple disciplines;
- *Integrative Thinking:* where both design theory and practice are accounted for; and
- *Human Centered Design:* to assure harmonious synergies between the user & technology.

At today's most innovative companies, including Apple, Google, 3M, Dyson, design is not limited to simply engineering and management, but included as an all-encompassing approach, involving other fields such as social sciences, design, and the arts. In comparison, NASA is currently using systems thinking and integrated design approaches, but can benefit further from these commercial practices by moving beyond its current state of practice, which is mostly driven by rigid engineering, technology, and project management considerations. In engineering, once the initial needs (usability or desirability) are identified, technology goals and requirements (feasibility) are given, and the resources (viability) are provided, a project is being developed through a mostly linear fashion. In a cybernetic sense, throughout project execution, at each stage, feedback is provided to the engineers and project managers (regulators). They

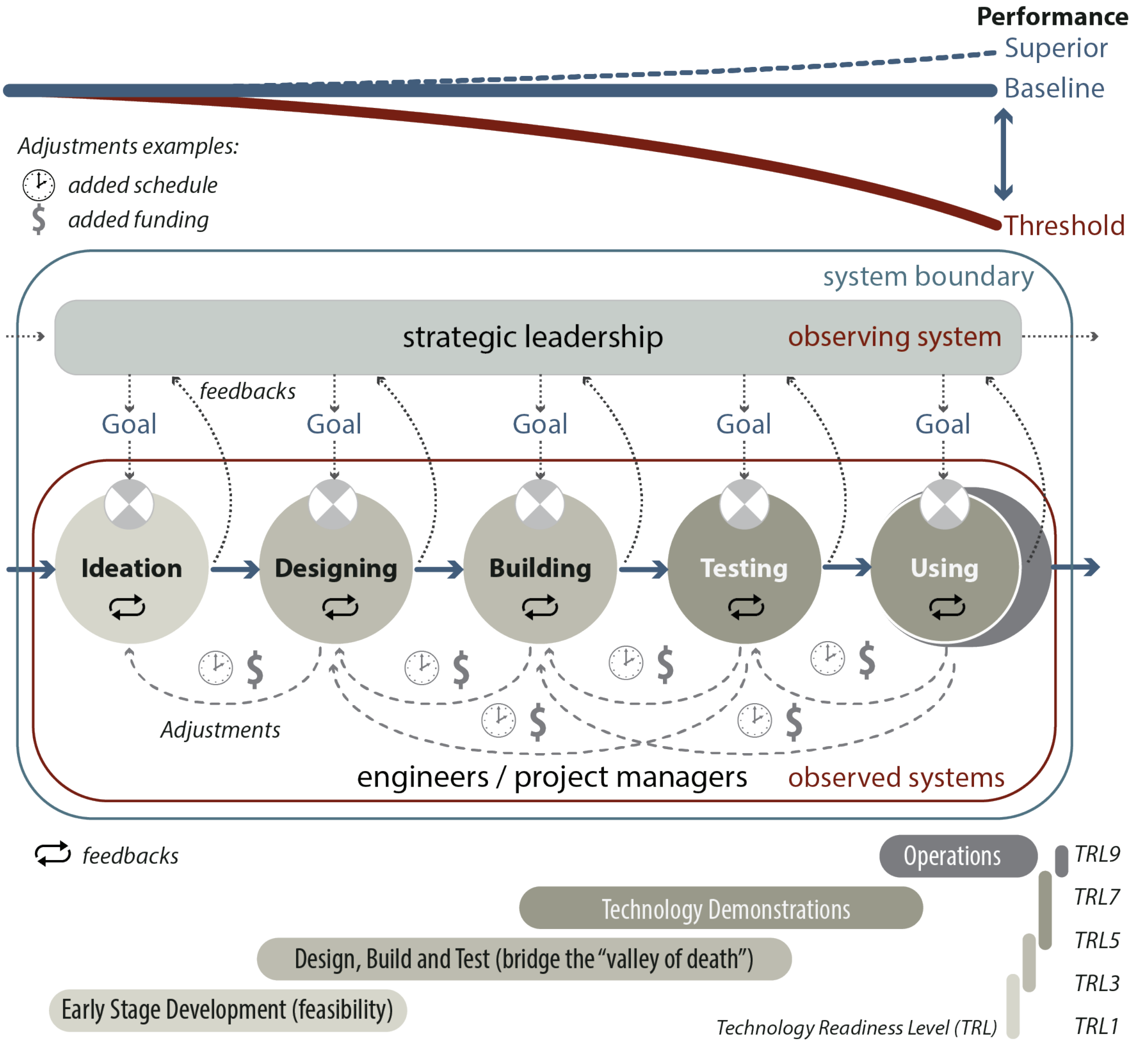
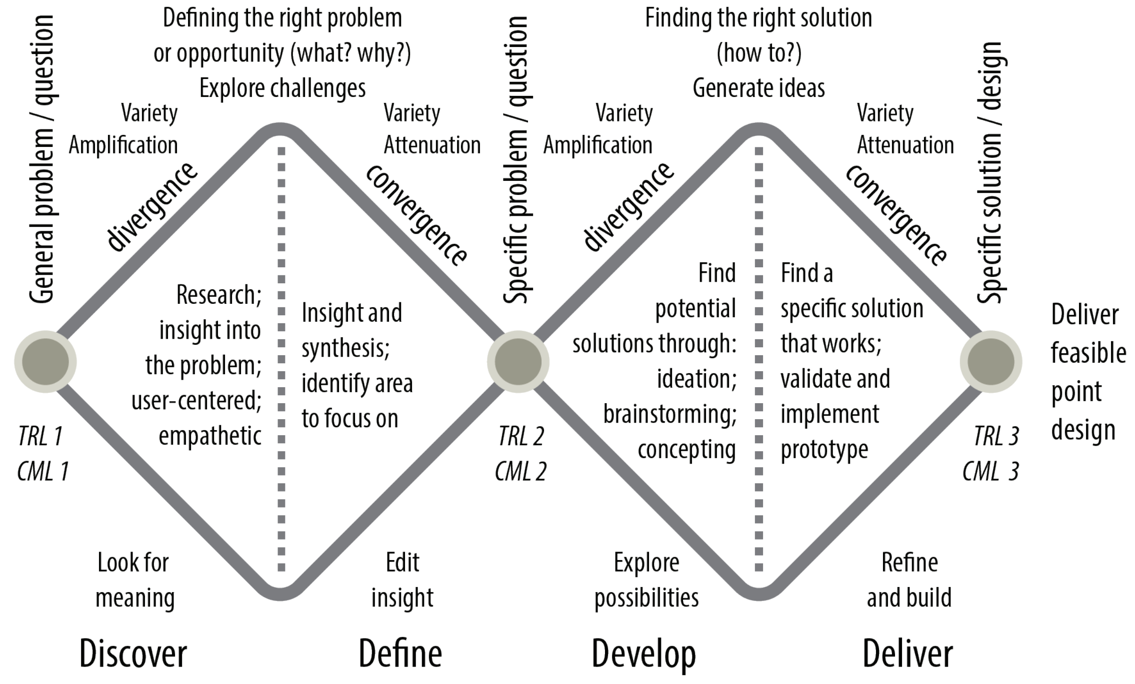


Figure 3.12: Linear project execution of a technology under development, in line with a first-order observed paradigm (updated from (Balint, 2013)), and its connection to a second-order observing paradigm—shown in the outer loop—where senior leadership can modify the goals of the first-order system.

are not present in the representation of the system as a single linear loop, and it is expected that they be not changed by the observations. In such a linear engineering and management framework the gathered information allows the regulator to make required adjustments to achieve the set out technical development goals within the available resources. This is first-order cybernetics, with an "omnipotent observer" (the project manager or engineer), who is designing and executing a project. An example of a linear project implementation process is shown in Figure 3.12, where a project progresses through a chain of linear stages, from ideating and designing, through building, to testing and using. During the early stage of project development, consisting of ideation and an initial design phase, feasibility is demonstrated at low Technology Readiness Levels or Concept Maturity Levels, from TRL/CML1 to 3. Subsequent steps include building of an engineering model or developing the concept of a point design in the mid-TRL/CML range form 3 to 5, testing and demonstrating it in relevant environments from TRL/CML 5 to 8, until using it on spaceflight mission at TRL/CML 9. These technologies and mission concepts are conceived from the beginning with a performance goal, represented in the baseline requirements. Strategic leadership members are explicitly incorporated into the observing system, and are part of the observing paradigm. They define these requirements. During project execution, within the observed system, the expected technology performance of a component may creep from the expected baseline performance, but as long as it is above a threshold, the project development continues under the control of the project managers or engineers. At each execution stage the project manager reports on the health of the project to strategic leadership. When the project encounters barriers within a development stage, including minor cost overruns or technical problems, the project manager acts as a regulator to keep the project on track. The typical way to solve larger issues is through an iterative process, which may involve stepping back to an earlier development stage; modifying or redesigning the technologies; or reassessing the mission concept. These iteration steps can cost both time and money, and may require intervention from the strategic level if the resource needs exceed the initial allocation (and margin). Under these conditions the project manager needs to request additional funding and/or time from strategic leadership, who can modify the goals of the project. For example, they can further support or cancel the project. The rigorous technology development at NASA can also lead to exceptional performance outcomes, above the initial baseline performance. For example, one of the Mars Exploration Rovers, Opportunity, was designed for 90 days and up to 1.5 km of traverse. (Both rovers were.) It operated for 11 years and 2 months, and traversed 42 kilometers (26.2 miles). Such complex multi-part systems, and mission architectures require Systems Thinking and Integrative Thinking, where circular iterative methods are used. *“Many of the interconnections in systems operate through the flow of information. Information holds systems together and plays a great role in determining how they operate”* (Meadows, 2008, p.14). Integrative Thinking brings forward opposing ideas and opposing constraints, to find new solutions. These approaches are currently employed at NASA, where the process includes defining and building systems, system of systems, but with a strong technology focus, where human centered designers, industrial designers and architects only play roles at the early stages—corresponding to low TRL and CML—of the developments. This will be further discussed in Section 5 and Appendix D.

Design thinking represents an approach, which looks at a broad range of considerations, including understanding the culture, aspirations, motivations, and context at every level of the system. This approach can be beneficial to drive strategies in the government framework, where multiple stakeholders have diverse sets of motivations and expectations, pointing to NASA’s wicked problems (see Section 3.5.3). Design thinking can be important for the development of transformational technologies. Instead of the current linear way of making the best choice out of available alternatives, it encourages us to take a divergent approach, create new options, explore new alternatives, and find new solutions and new ideas that didn’t exist before. There are numerous design process models in existence; well over a hundred of them are compiled by Dubberly (Dubberly, 2005). For illustrative purposes, in my thesis I discuss the “double diamond” design process model by the Design Council (Design Council, 2005, p.6), shown in Figure 3.13. It represents two linearly connected dynamic divergence and convergence cycles, as also described in Bela Banathy’s 1996 model (Dubberly, 2005, p.24). The double diamond model highly simplifies the design process, into only four stages, around a single system goal, which limits open exploration. The system goal (for example the design question) is fixed, and the process resembles a linear waterfall model rather than a cybernetic circular exploration. It is a compromise, which works against the notion of circularity and openness. A further inadequacy of this model is that it doesn’t show how it leads to questioning the question, and the option for its reformulation in line with second-



TRL: Technology Readiness Level; CML: Concept Maturity Level

Figure 3.13: Illustration of the "double diamond" design process model after the Design Council (Design Council, 2005, p.6) and Banathy's 1996 model (Dubberly, 2005, p.24), showing two linearly connected dynamic divergence and convergence cycles, and approximately aligned Technology Readiness Levels (TRL) and Concept Maturity Levels (CML) (Balint et al., 2015).

order cybernetics. While acknowledging these limitations, this double diamond approach is used within NASA's design environments during early stage concept developments to address two key questions. At the initial part of the formulation phase, first we need to define the right problem or opportunity for our generic question, using both technological and strategic insights. The second phase is set out to find the right solution to a specific problem. Both phases include a divergence stage, to identify and create options, and a second convergence stage to make choices.

The process starts with posing a question. In the first phase research is being carried out to find insight into the question, discover the meaning of the posed problem, then the identified options are synthesized to define a specific problem or question. In the second phase a potential solution-space is developed through ideation, brainstorming, conception or other means. From these generated ideas a specific solution or design is selected, and validated through a prototype (e.g., breadboard, brassboard). This process is best suited to an early development stage, from Technology Readiness Levels (TRL) or Concept Maturity Levels (CML) 1 to 3, where feasibility needs to be proven. Design thinking requires learning by making and building in order to think. In effect it often builds on tacit knowledge, which uses prototypes to speed up the process of innovations, because creating them will allow the practitioner to understand the strengths and weaknesses of the artifact or process being designed. This strategy should start with a human centered approach, balancing and harmonizing desirability or usability, with technical feasibility, and economic viability. Design thinking and this double diamond process are already being used at NASA's Jet Propulsion Laboratory, where the Innovation Foundry employs designers and architects along with managers, engineers, technologists, and scientists. These designers are contributing to the early stages of the process, when novel design processes need designing. The approach already proved to introduce more creativity, beyond the purely analytical approaches. It also helped to "deep dive" into stakeholder needs, through discussions and observations, with an added focus on humanly interactions. Further details on JPL's Innovation Foundry and its design processes are provided in Appendix D.

While we can point out the benefits of design thinking, there are also some insufficiencies with this approach alone. "Thinking" might not be sufficient; we need to put emphasis on the communicating and doing phases. Brainstorming is a vaguely defined concept, which should be replaced with design conversations (Pangaro, 2010). To address this, instead of only focusing on the harmonization of usability, feasibility and viability, we pay added attention to the actual interactions—called design conversations—within the organizational hierarchy, including both internal and external stakeholders, and also when working in a design environment. This type of design methodology should incorporate circular and dynamic cybernetic interactions between stakeholders, starting at ideation and prototyping throughout all development phases, with strong considerations for the Law of Requisite Variety (Ashby, 1956, p.206). (At later development stages of a technology project, trades to alternative options are no longer open due to fiscal constraints, and the project is managed through engineering and project management principles.)

Both within a design environment and at the strategic level, iterative cybernetic feedback loops are expected to amplify the variety of the regulator (e.g., the designers, or the strategic decision makers), who in return can make increasingly informed choices in subsequent iterations, with a set out goal to benefit the users/stakeholders. Building on these conversations, the outcomes can be evaluated through a systematic approach to harmonize the strategic opportunities and constraints. A relevant model discussing design conversations is depicted in Paul Pangaro's model of co-evolutionary design (Pangaro, 2010). As shown in Figure 3.14, the model consists of four conversationally and circularly interconnected elements:

- A conversation to agree on the goals;
- A conversation to agree on the means;
- A conversation to design the design (for example, designing a preferred design process); and
- A conversation to create a new shared and mutually agreed upon language.

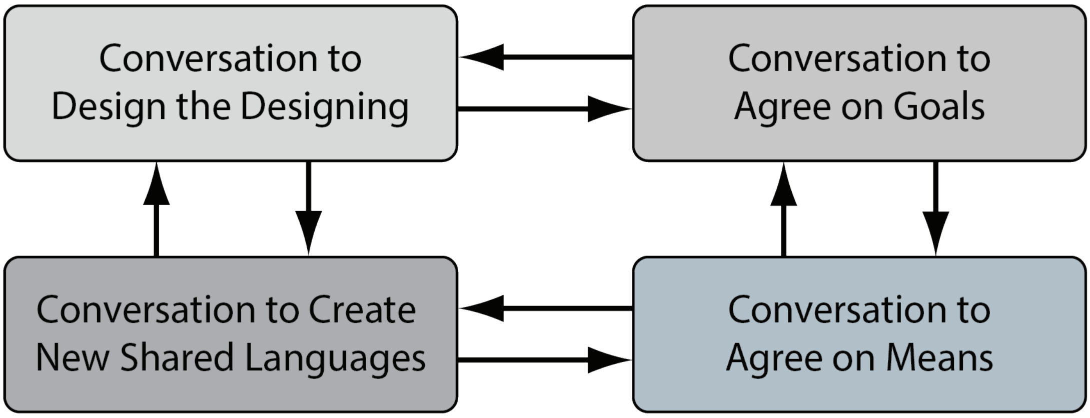


Figure 3.14: Adapted model of co-evolutionary design, after Pangaro, with influences from Dubberly, von Foerster, Pask, and Geoghegan (Pangaro, 2010).

These cybernetically circular conversations are the basis for reaching agreements, which in a team environment can subsequently strengthen the team and can lead to trust, and establish the ground for change. Change is a foundational requirement for innovation, but to think outside an established framework and its bounding options, new shared languages are needed. Such new shared languages with agreed meanings are created in these conversations. Therefore, the important part of a design framework is not to simply "dream up" a new language and present it as a given solution, but to introduce a new process that facilitates these design conversations, leading to shared meanings, new discourses, and subsequently arriving to preferable outcomes. Adopting design conversations within the aerospace sector can open up the mission and technology design trades beyond today's options, which are limited by and increasingly specialized language. These conversations could be enhanced by using boundary objects, which will be discussed below and in Section 7.

To turn this trend around, we need to look for novel approaches. While pointing these out, the intended purpose of my research is not to provide firm answers, recipes, and plug-in point solutions, but to identify touch points within the established processes, were realignments can be realized using new perspectives through cybernetic and designerly approaches to augment the current state of practice. In addition, I also highlight the need for novel shared languages, emerging from design conversations. As a potential outcome, these new shared languages can be used to initiate and advance the design discourse, potentially leading to novel and preferred outcomes from an initial ideation phase, through the development and mission design, to the various operations phases.

3.3.2. Affordances and Signifiers of Objects and Environments

The term "affordance" was introduced by the American psychologist, James Gibson in his article, titled "The Theory of Affordances" (Gibson, 1986, p.127). It refers to one or multiple opportunities or possibilities for interaction, provided by a particular object or environment. These action possibilities can be measured objectively in a latent environment, and does not have to be known or recognized by the observer. Also, they don't have to be visible, perceivable or even desirable. Affordances are always expressed through their dependences on the observer. They are circular relationships, relating some types of attributes of the environment to interactivity potential by an agent, which in turn aligns and relates back to the environment, which has relevant affordances. For example, a high bookshelf provides affordance for a tall person. The same bookshelf is out of reach for a child, without having the same affordance. The concept of affordance has been very influential in a number of fields, including design, visualization, human-computer interactions, ergonomics, and others. It also influenced how we consider visual perception. Looking at it from the environmental psychology point of view, perceiving the environment leads to action, and affordances provide clues for the observer indicating possibilities for an immediate action without requiring sensory processing. For example, a lamppost provides an affordance of walking into it, while the moving observer subconsciously can avoid the collision, based on existing knowledge of the potential outcomes. (Gibson's breakthrough idea was the realization that "our heads are in the world" as our interpretation and construction of it are triggered by affordances, rather than "the world is on our heads" as it is perceived.) Other examples include buttons, knobs and levers, where the observer instinctively knows how to operate them.

Don Norman developed an extended view of the concept of affordance, assuming dependence on culture, prior knowledge, and personal expectations (Norman, 1999). Compared to Gibson, Norman uses perceived affordances (which may not even actually exist), where the appearance of an artifact can provide critical clues about it.

During interactions with artifacts it is expected that the user's variety is different from the designer's variety. As a consequence, the interpretation of the artifact may differ from the intended use envisioned by the designer. Designers can provide built in clues to the users about artifacts, which would not necessarily limit their variety, but would highlight the recommended and intended ones. This can be achieved by employing signifiers (Norman, 2013, p.18/499) that would highlight the intended way and use of the artifact during interactions. These clues are part of the conversation between the user and the artifact, and in a decoupled way between the designer or artist and the user.

Designers and artists create new shared languages, which emerge from design conversations. These conversations can be external or internal, and the used novel shared languages can lead to new options and outcomes. Through the artifacts, designers and artists communicate a message, which can broaden the variety of the users and observers, creating novel experiences beyond today's function driven objects and artifacts.

Designers have to consider how to create a perceivable conceptual model to fit the artifact into the observer's schema; what type of guidance should be provided about its usability; and how to align the artifact's affordance to the knowledge of the observer, especially if the observer has not seen the artifact before. The designer/artist can also introduce "false affordance," where no affordance is implied, but no action is possible (e.g., having a thin wire chair that does not support any weight). Design feature can also connote cultural differences, differentiation or entertainment. Another option is using "hidden affordance" where the information about the affordance is not available (e.g., a hidden drawer). This approach can be a useful tactic on a long-duration spaceflight, slowly revealing hidden affordances to enable continuous stimulation from humanly space objects. They can be stimulated over time or by user expertise, and even by boredom levels.

3.4. The Origin of Boundary Objects

Boundary objects, in the intersection of various disciplines, help us to initiate conversations towards a shared understanding of our environment or the problems at hand. Conversations may lead to shared novel languages and options. These conversations could occur in different contexts, for example, between individuals; team members; teams and their sponsors; institutions and the public; and others. Boundary objects can be used to communicate across any discipline, from the general public, artists, and designers, to scientists, engineers, and managers.

The term "boundary objects" was originally introduced under social sciences by Susan Leigh Star and James R. Griesemer (Leigh Star & Griesemer, 1989, p.388). These objects can be simultaneously:

- Concrete and abstract;
- Specific and general;
- Conventionalized and customized.

Boundary objects are often internally heterogeneous. Leigh Star and Griesemer have identified four types of boundary objects. For the first type, they used the example of a museum curator, who collected objects from a broad set of contributors with different backgrounds. The curator set the rules for the collectible objects, and then derived theories from them. We can look at this as a reflective practice, where the initial set of rules bound the derivable theories. The second type of boundary object is an "ideal type," which consists of an abstracted object, such as a map. It can have meanings to multiple user groups. It can be used by tourists, experts, geologists and others, all using the same symbolic representation and abstraction. The third type refers to a coincident physical boundary, for example the boundary of California, where the object collectors all operate within its perimeters. The fourth type refers to standardized forms, which helps communications between the participants. For example, this may refer to common interfaces between spacecraft designs, where both NASA and ESA are developing subsystems, which are connected through a standard connection at their interface boundary.

Leigh Star and Griesemer were interested in boundary objects, which contained different elements or aspects in different worlds, considered magical to those worlds. They called them boundary objects, where the mismatch, caused by the overlap between worlds (or disciplines) becomes the problem space for negotiations.

The conflict resolution could be done by oscillating (or, more precisely, moving circularly and recursively) across the boundaries of the disciplines, and in the process forming a new social world. Subsequently, the object forms a common boundary between the worlds, inhabiting them simultaneously. In a cybernetic sense, a common meaning is constructed through conversations across the disciplines.

Throughout my research I have created a number of boundary objects that I am using to evidence design conversations between me, as the designer, and the environment.

Furthermore, the insights gained from my research and combined with my design practice of making these artifacts, led me to propose new categorizations for boundary objects, while using them as representative examples (see Section 7).

3.5. Innovation Barriers and Wicked Problems

In my research the purpose of introducing cybernetic perspectives and human centered design is an intended application to NASA's current worldview, driven by engineering, technological innovation, and related management practices. This necessitates the inclusion of NASA-relevant topics, such as the definition of innovation, which is discussed in Appendix A, and NASA specific innovation barriers, and the concept of wicked problems, which are discussed below.

3.5.1. Barriers to innovation at NASA.

The National Research Council (NRC) in its 2011 review (NRC, 2012, p.1-1) has stated that *"NASA's technology base is largely depleted, and few new, demonstrated technologies (that is, at high technology readiness levels) are available to help NASA execute its priorities in exploration and space science"* and *"a strong advanced technology development foundation is needed also to enhance technology readiness of new missions, mitigate their technological risks, improve the quality of cost estimates, and thereby contribute to better overall mission* *cost management...”* Subsequently, an internal NASA study identified barriers to innovation. Top level conclusions from this unpublished study (NASA, 2013a) are in line with classical barriers and risks described in numerous literature sources, including (Bennis & Biederman, 1997, pp.117-141), (Brown, 2009, p.111), (Christensen, 1997, pp.207-210), (Dodgson, Gann, & Salter, 2008, p.10), (Dyer, Gregersen, & Christensen, 2011, p.47/338) and (Kelley, 2005, p.52). Specifically to NASA, McCurdy identified similar corresponding barriers almost a quarter of a century ago (McCurdy, 1993), illustrating how quickly NASA’s culture changed and solidified following the Apollo era (see also Section 1.2). The list includes the following findings related to NASA (Balint, 2013):

- *Risk-averse culture:* while this has been true for NASA throughout its existence, and largely driven by the trickle down effect of astronaut safety, today’s NASA is much more risk avert than it was during the Apollo era. Over time this culture found its way into other parts of the Agency as well, creating an overly structured and regulated environment. (See also (McCurdy, 1993, p.61).)
- *Low priority on innovation combined with short-term focus:* budgetary pressures and constraints often drive this. NASA Mission Directorates are leaning to select low-risk missions, which then drives the use of flight qualified heritage components, thus not creating the immediate need for next generation technologies. Furthermore, the limited resources—multiple times over the Agency’s history—resulted in the cancellation of technology programs, thus curbing innovation. To remedy this, The Office of the Chief Technologist (OCT) was established in 2010 to take an Agency wide view of the technology portfolio, and STMD to develop the next generation of technologies currently not in the pipeline. (See also (McCurdy, 1993, p.142).)
- *Instability:* funding uncertainties can adversely impact projects and workforce. Projects can be descoped, canceled, postponed, or slowed down significantly. All of these have an impact on creating an innovative workforce, work environment, and bringing forward new innovative ideas. (See also (McCurdy, 1993, p.102).)
- *Lack of opportunities:* flight projects can provide a cadence to drive new ideas and approaches. However, lower Cost Cap missions (for example Discovery class missions) rely on existing technology solutions and do not promote innovation. Large-scale space missions, such as multi-$Billion class Flagship missions, may occur once or twice a decade, where a larger budget can support the development and infusion of new technologies. Unfortunately these missions are too few and far apart to provide the foundational drive to establish and maintain an innovative organization. (This connects back to the second point.) (See also (McCurdy, 1993, p.101).)
- *Process overload:* innovation implies being agile and responsive. Current management practices dictate significant oversight for most activities, driven by process and reporting requirements. These activities can become significant burdens on projects, while providing limited return value, beside the desire to track execution to a large extent. While Agency processes would allow for customization, their implementations may introduce real or perceived barriers. (This also connects back to the first point on risk-averse culture.) Agency processes allow for customization, and process tailoring which can reduce real or perceived barriers. (See also (McCurdy, 1993, p.111).)

- *Communication Challenges:* since projects are performed across ten research centers, and at times through collaboration with industry, academia and other government agencies, dispersed teams often experience communication challenges. Recently introduced restrictions on travel and conference attendance further limit teams to interact and exchange ideas, which is key to drive innovation under normal circumstances. (See also (McCurdy, 1993, p.22).)
- *Organizational inertia:* internal politics within research centers, non-project specific drives and considerations, bureaucratic processes can all contribute to limiting innovation within an organization. (See also (McCurdy, 1993, p.99).)

Innovation theory and practice provides recommendations to solve these issues (Bennis & Biederman, 1997, pp.117-141) (Christensen, 1997, p.209) (Dyer, Gregersen, & Christensen, 2011, p.161/338) (Dodgson, Gann, & Salter, 2008, p.315). Thus, innovation in industry and government agencies (including NASA) can be encouraged in a number of ways, including:

- *Creative ideation:* this is similar to the industry approach called Bootlegging, where a certain percentage of the work hours (e.g., 20%) can be used for developing innovative projects and ideas. In the past this approach was used at Google and 3M.
- *Innovation laboratories and creative spaces:* this approach is used widely within industry, including the concurrent design facilities of large automotive and oil and gas companies. Even within NASA most of the research centers established similar innovation related facilities (e.g., JPL's Innovation Foundry) (NASA, 2012).
- *Innovation funding:* this approach is used in industry through independent research and development (IRAD) funding, prizes (e.g., XPRIZE), awards, and grants. Within NASA's Space Technology Mission Directorate the Center Innovation Funds (CIF) Program provides seed funding to NASA Centers, where the Center Chief Technologist allocates these funds to low technology readiness level development projects, typically with a one-year development life cycle.
- *Skunkworks:* this approach was established under Lockheed Martin's Advance Development Program (ADP), called Skunkworks. With only a dozen key rules, a collocated small team with sufficient funding, and using a rapid prototyping approach, designed and developed iconic flight hardware, like the Blackbird, in record time. A similar approach can be adopted at NASA to stimulate innovation, while aligning innovation pathways with NASA challenges. One current example is the Swamp Works at NASA's Kennedy Space Center (Fox & Mueller, 2013).
- *Process streamlining:* within NASA, technology and research projects, as well as flight projects, are governed by NASA Procedural Requirements (NPR 7120.8 and 7120.5, respectively) (NODIS, 2015). These guidelines allow for tailoring, which can reduce reporting requirements, the high number of key decision points, and other deliverables through the project's lifetime. While this is an available approach, its implementation is not that straight forward.
- A *combination* of some of these approaches can be used by merging Bootlegging (i.e., using time the allocation of civil servants) with innovation funding (by providing a small amount of procurement) and by providing creative spaces and Skunkworks type environments (i.e., by providing a suitable work space to carry out the project).

These barriers can be further explored through the field of cybernetics, which involves research into interdisciplinary fields, including power relationships and structures, constraints and possibilities. These multi-directional interactions can be modeled through closed signal feedback loops, which may provide invaluable insights into this problem space. It is particularly useful and important, because these barriers at NASA span across numerous fields from financial, regulatory and governmental, through management, individual interactions and center politics to science, technology, education, and outreach.

3.5.2. Technological Innovation for Space Exploration

Space exploration related innovation and technology development in the government sector, but also in the private enterprise, face many challenges. The technologies are often experimental and one-offs and the rewards are harder to measure than those for profit driven commercial terrestrial organizations. Space related project life cycles can be significantly longer than those for terrestrial technologies. At times the development cycle from idea to use can measure up to a decade or more (NRC, 2011, p.9-5), therefore, by the time of infusion these technologies may look somewhat obsolete compared to similar terrestrial technologies. However, space technologies often encounter extreme environmental conditions and mitigating these can be significantly more challenging than operating in terrestrial environments.

Innovation in the space field is a necessity. Pushing the boundaries for both human and robotic exploration requires technologies beyond terrestrial needs. While the space sector can build on commercially developed terrestrial experiences, pushing the requirements beyond those needs require significant investments, which often can be only afforded by the government sector.

In order to look beyond near-term space exploration needs, and enable future missions, it is essential to dedicate a portion of the space technology funding to radical, disruptive and transformational technologies, as will be discussed in Section 5. Consequently, setting up an organization, such as NASA's Space Technology Mission Directorate, is a highly important element to advance our future space exploration goals (Balint, 2013).

Spin-offs from these developments often benefit other government agencies, the private sector, and the nation in general. Therefore, investing in space technology developments and exploration is key to also advance US national capabilities and address US needs. Similarly, the same statement is valid for other nations with space exploration activities.

Commercial space activities in the near term play a role through providing valuable services and product development under contract to the government sector. In the future, it is expected that commercial space activities will find a market to make their operations not only self-sustaining, but also profitable (Balint, 2013). Potential activities may include space tourism and space exploitation through asteroid mining, but the self-sustainability of these is yet to be seen.

In the meantime, the high cost of space exploration and the related development of innovative, disruptive, radical, transformational and crosscutting technologies require dedicated organizations and funding to advance exploration goals and support US national needs, without the pressure for profitability.

3.5.3. Wicked Problems

The phrase "wicked problem" was first used in social planning to describe a problem, which does not have an obvious solution, due to changing requirements, and incomplete or contradictory bounding conditions. Furthermore, as a result of the often-complex interdependencies, a chosen solution to a wicked problem can result in subsequent new problems. Horst Rittel and Melvin Webber introduced ten general rules to describe wicked problems (Rittel & Webber, 1973, pp.160-167). These are:

1. There is no definite formulation of a wicked problem.
2. Wicked problems have no stopping rules.
3. Solutions to wicked problems are not true-or-false, but good-or-bad.
4. There is no immediate and no ultimate test of a solution to a wicked problem.
5. Every solution to a wicked problem is a "one-shot operation"; because there is no opportunity to learn by trial-and-error, every attempt counts significantly.
6. Wicked problems do not have an enumerable (or and exhaustively describable) set of potential solutions, nor is there a well-described set of permissible operations that may be incorporated into the plan.
7. Every wicked problem is essentially unique.
8. Every wicked problem can be considered to be a symptom of another problem.
9. The existence of a discrepancy representing a wicked problem can be explained in numerous ways. The choice of explanation determines the nature of the problem's resolution.
10. The planner has no right to be wrong.

Conklin synthesized and reduced these ten rules to six general characteristics (Conklin, 2006, pp.7-8). These are:

1. You don't understand the problem until you have developed a solution;
2. Wicked problems have no stopping rules;
3. Solutions to wicked problems are not right or wrong;
4. Every wicked problem is essentially unique and novel;
5. Every solution to a wicked problem is a "one shot operation";
6. Wicked problems have no given alternative solutions.

Wicked problems cannot be simplified to hard or complex problems and cannot be solved by incorporating additional considerations or by including more stakeholders, as will be discussed in Section 5 through NASA's example. For these, the initial problem definition and the outcome are bidirectionally linked, and the stakeholders may have radically different perspectives, motivations, and drivers towards the issues. Hence, an optimal outcome is dependent on the perspective of a stakeholder, instead of being universally correct. Wicked problems are often ill defined and over-constrained, and cannot be solved through analytical thinking. They may require innovative solutions and good strategies.

Roberts identified three strategies to tackle wicked problems (Roberts, 2000, p.2). Their implementations are influenced by management styles and institutional approaches, and can be described as follows:

1. *Authoritative:* This strategy places responsibility of solving problems to one or a few people. This is perceived to reduce the complexity of perspectives as competing views are being eliminated. The disadvantage is that key perspectives might be eliminated, or not appreciated, which may lead to less favorable outcomes.
2. *Competitive:* This strategy brings opposing views against each other. It requires stakeholders to hold their views and propose their preferred solutions, so the different solutions can be compared and weighted. The disadvantage is the potential of creating confrontations and discouraging knowledge exchange. In turn this may disincentivize the stakeholders to propose solutions.
3. *Collaborative:* This strategy involves all stakeholders working and converging towards a common best solution, agreed upon by all parties involved.

NASA operates in a framework with a broad variety of stakeholders, where the associated problems and challenges go beyond a strictly rational, scientific and technical approach. (Balint & Stevens, 2016)

An understanding of wicked problems for space technology development at NASA is important to justify our Project Assessment Framework Through Design (PAFTD) model and strategic assessment too, which will be further discussed in Section 5 and Appendix B.

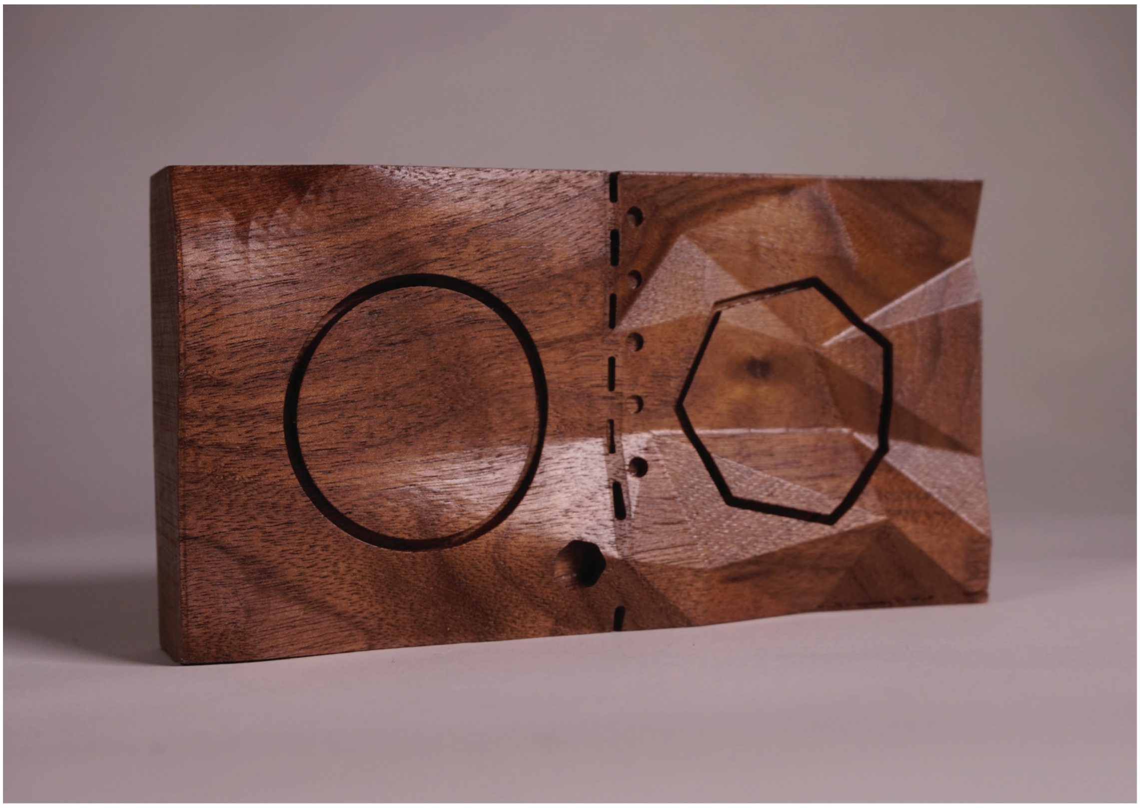
3.6. Epilogue to Foundational Terminologies, Definitions, and Concepts

The terminologies and foundational concepts introduced in this section were concise with a goal to lay the grounds and support the discourse presented later in this thesis. (Further discussion on these terms are given in the Glossary section.)

In summary, cybernetics-related considerations play important roles in introducing new conversations to space exploration through designerly and artistic modes of operations, which can be applied at various touch points at NASA (see Sections 5 and 6, and Appendix D).

In my research I used cybernetics to provide perspectives, and considered language and conversations as the basis to construct shared meanings. Such conversations can occur across disciplines—for example, between art, design, science, and engineering (Ito, 2016)—and can be aided by objects as focal points. In this context, these objects are in the intersection of discipline boundaries, and can be referred to as boundary objects, which will be discussed further in Sections 7.

Section 4.
Performative Ontology



Crossing the Perceptional Boundary (Walnut wood / 2015)

4.1. Prologue to Performative Ontology

"Cogito ergo sum" (Descartes, 2011, p.22). According to René Descartes, the only thing we can be sure of is that we exist. Therefore, the exploration of our world has to start with the self. By observing the world we develop certain knowledge about it, which manifests itself in our cognitive models. But, "how do we know what we know?" and "how can we be sure that something is true or false?" These are the concerns of the philosophical field of epistemology. Echoing Descartes, we personally wish to understand "what exists," and "what's its nature?" These questions are related to the study of reality, which belongs to a branch of philosophy, called metaphysics. Exploring these questions is essential to advance personal knowledge through ontological reflections.

An ontology can be defined as a narrative of being; or a systematic account of existence through categorization and relationships. It defines entities and entity types within a framework, and seeks to describe how these are grouped according to similarities and differences, how they correlate within a hierarchy. According to Marianne Talbot from the Faculty of Philosophy at Oxford University, ontology is part of metaphysics. A person's ontology is a list of what exists or may be said to exist for that person. If I believe in unicorns, it is on my list of what exists. It is part of my ontology. (Is it justified true belief? That is a different question.) While an aspect of ontology is concerned about knowability, there is a counter element of unknowability, which can motivate the performative brain to explore the unknown and uncertain.

In this section I will briefly describe components of my ontology. My cognitive model can be traced back to concepts and theories from the fields of philosophy, epistemology, perception and cognition, cybernetics, design and art. It is dynamic and constantly evolving, thus it represents a snapshot at the time of writing this thesis. Thus, the discourse presented in this section is, in essence, a bridge that reflects my personal understanding and beliefs to date, which builds on foundational concepts from Section 3, with a focused scope that will be relevant to the rest of my research. Subsequently, the action of applying this ontology to real-world situations is used to demonstrate this performative ontology. (Andrew Pickering introduced the term "performative ontology" in (Pickering, 2010, p.22).) The application examples—discussed in Sections 5 to 7 and Appendices D and E—span across NASA, from organizational cybernetics, through human space exploration, to design environments, design education, and boundary objects. Some of the examples are substantiated, some are speculative in the form of recommendations for further action, which may or may not be implemented by NASA. Applying my ontological model is not limited to NASA, and it is sufficiently general for being easily used within other fields and disciplines.

4.2. Performative Ontology Overview

Pickering observed that modern sciences are concerned with causation, description, and prediction. In comparison, the cybernetic vision represents a forward-looking search (Pickering, 2010, p.18).

Science is not static, and the descriptions and predictions are based on a temporal snapshot of current knowledge. The descriptions are abstracted models developed by the observer (the scientist), and these models allow for predictions. Scientists acknowledge that their knowledge and models are not complete they are derived from observations to that point. That is why scientists call their models "theories" no matter how well these are understood or proven. (Just because all the observed swans are white, and the theory states that all swans are white, one can potentially come across a black swan.) Examples include the theory of gravity by Isaac Newton (Newton, 1687), the theory of evolution by Charles Darwin (Darwin, 1872), and the theory of relativity by Albert Einstein (Einstein, 1916).

The observations inform scientists about new research directions, and the findings may refine or contradict existing theories. For cybernetics, reality is always in the making. It is evolutionary, rather than causal (Pickering, 2010, p.18). It is non-dualist, that is, it does not separate physical and immaterial properties. For example, the dualist lines are becoming blurred for a homeostat, which is not only a physical object. Through its fixed goal towards its internal state, it adjusts to the environment through circular and explicitly coupled interactions.

Engineers create a world that typically relies on first-order change, where the goals of the observed system are set and the observer in the inner loop is closely coupled with the goals of the system. The regulator of this system is (supposedly) not changed by the observation.

Designers are explicitly coupled with the system through an observing paradigm, and they can modify the goals of the observed system. Designers, architects, and artists can create and invent new rules, thus broaden the system's paradigm by adding variety to it. This leads to new perspectives and can lead to novel outcomes beyond what an existing paradigm can accommodate.

Our cognitive model of the world is personal, in line with von Glasersfeld's radical constructivist model (von Glasersfeld, 1984, pp.17-40) (von Glasersfeld, 2001, pp.31-43). The structured hierarchies of personal knowing (Polanyi, 1962, p.720/8888) of our models form our ontology. Yet our model is not static, not a simple cognitive reflection of the phenomenal world. It evolves through new observations, tacit knowledge (Polanyi, 1966, p.9-11) emerges to communicable personal knowledge as novel experience patters form and incorporated into our schemata. Our cognitive models are performative. They are not merely informing us about our environment through incoming information, but they help us reassemble novel concepts. This makes our ontology performative. This nonmodern performative aspect of our being is not representable in modern science that builds on modern ontology of our environment, which is both knowable and representable (Pickering, 2010, p.20).

After discussions with my supervisor, Paul Pangaro, I have adopted the term performative ontology and defined it as an epistemological approach to my cognitive model, applied to real world situations. It relates to the dynamic and adaptive evolution of my cognitive model of the perceived phenomenal world, including how these are grouped into my schemata and hierarchy. It also looks at distinctions that differentiate one thing from another, or highlight similarities between them. The performative aspect takes this cognitive approach further and defines the cybernetic brain an acting machine and not a thinking machine (Pickering, 2010, p.49). It refers to a brain that interacts with the world and can perform in any new situation it encounters, instead of cognitively processing the incoming information. An example for the performative brain (Pickering, 2010, p.13) is the emergence of a novel concept through a "creative leap" (Cross, 2010, p.65). It refers to the creative cognition in design.

My model can be summarized as follows:

- *Cybernetics* provides a perspective to understand the dynamic connections and conversations between actors, processes, objects, and their environments. It is a constructivist approach. According to von Glasersfeld: *“Constructivism necessarily begins with the (intuitively confirmed) assumption that all cognitive activity takes place within the experiential world of a goal-directed consciousness”* (von Glasersfeld, 1984, p.10).

- *Design* provides an approach to translate the insights from cybernetics, related to the issue(s) at hand. In a first-order observed system the designer or engineer is coupled with the goals of the system in an inner loop (see Figure 3.1b). This is not very different from the current state of practice at NASA, using systems thinking and integrated thinking. We need to go one step beyond. In a second-order cybernetic system the designer is part of the system through an observing paradigm, which is an outer loop (see Figure 3.1b), and can invent new requirements, modify system goals for the observed inner circle. This can lead to new options, introduce and evolve novel agreed upon shared languages, and in the process can influence existing paradigms.
- From an observer’s perspective—and we are all observers—*communications* between personal cognition and the phenomenal world—the environment—are achieved *across a perceptional boundary*, using sensory inputs and language or gesture outputs.
- A *conversation* is a circular mode of communication between actors, that allows them to construct and converge towards an agreed upon shared meaning, which can also lead to shared novel languages.
- Conversations are temporally sequential. Through each cycle the role of the actor and the environment changes. That is, the *roles in a conversation are relative*, where the actors are both regulators and observers at various temporal stages of this circular interaction.
- *Boundary objects* in the intersection of disciplines, can be used to aid these conversations. These objects can be static, or can evolve dynamically through the conversations.
- Novel shared *languages* with agreed meaning broaden the variety of the system, which can lead to new options, preferable outcomes, and may lead to a broadened paradigm.
- In *human centered design* (HCD), the designer embraces the perspective of the user(s). This is facilitated through conversations, interactions, and participations.
- The *level of human centeredness* for humanly space objects *may vary* from case to case. For example, a rocket nozzle is less human centered than a space habitat, while both are necessary elements of human space exploration.

The sub-sections below follow a logic that starts with the phenomenal world, the environment, then steps across the sensory organ boundaries to address cognition. Closing the feedback loop through communications and language we arrive to cybernetic circularity that provides a perspective to look at the world, which affords forward-looking searches and actions. This is then followed by a brief discussion on the need for human centered design, to complement the cybernetic perspectives (see Figure 4.1). While these may sound obvious, their implications for my research were far reaching, and allowed me to identify examples within NASA’s organizational and operational paradigm, where strategically chosen insertions may lead to novel options and preferable outcomes.

4.3. The Environment

The variety of the phenomenal world, which I will refer to as the environment, is postulated to be infinite. Each variety represents a distinct state of the environment. Therefore, if there is no distinction between varieties, then it is the same variety. If an observer can’t make a distinction, then it is considered the same variety (Wittgenstein, Russell, & Ogden, 2007). The

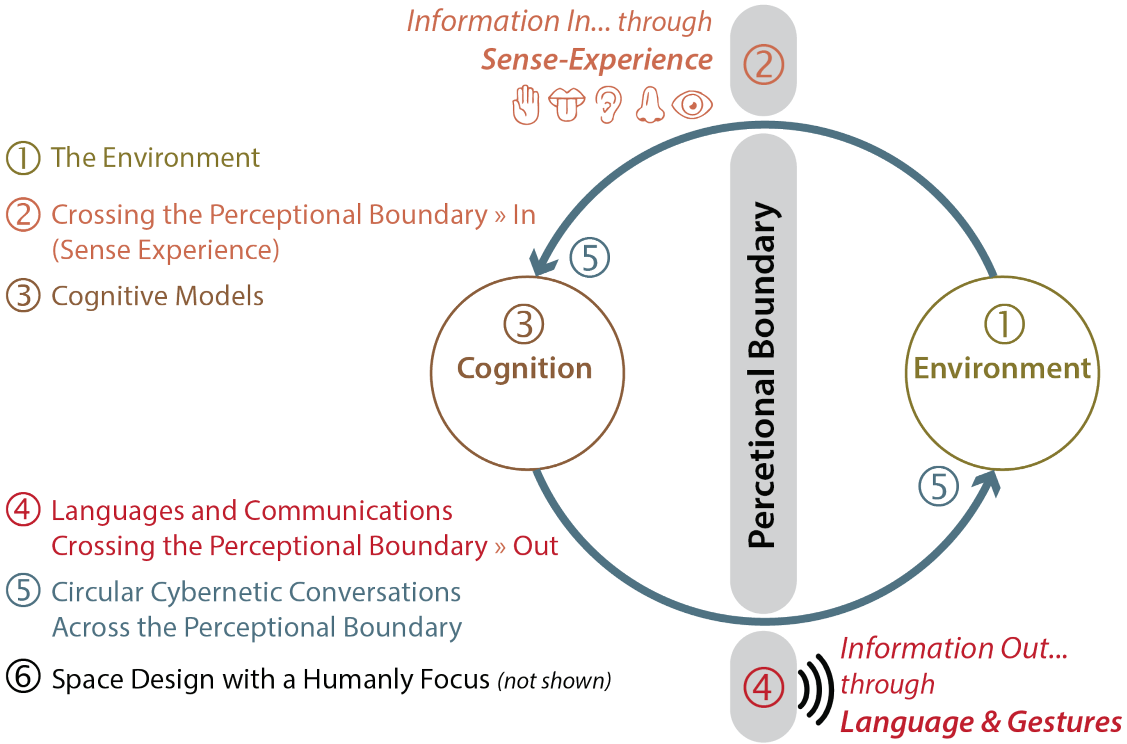


Figure 4.1: Circular conversation with the environment across the observer's perceptional boundary.

environment—the phenomenal world—is non-hierarchical. It simultaneously allows for mutual contradictory beliefs about its facts—which include objects. These contradictory beliefs are the reflections of diverse cognitive models of the observers.

4.4. Crossing the Perceptional Boundary

A distinction exists between the environment and our cognition. This distinction is defined by a boundary (Spencer-Brown, 1972, p.1-2). I call it a "perceptional boundary." It represents a distinction that affords crossing. We communicate across our perceptional boundary, utilizing our sensory system, which sets limits to the information flow and the perceived variety of the environment. The sensing organs allow us to differentiate one thing from another, which is the source of information. A distinction between signals translates to information entropy. Sense organs facilitate signal flow from the environment to our cognition. (Language and gestures provide the feedback from our cognition to the environment, as discussed below.) In our quest to broaden our understanding of the environment, added sensors can broaden our physiologically bound sensory perception, leading to further perceived distinctions (or perceived variety) of the environment. We can use this amplified information entropy from the combination of our sensory organs and augmented sensors to refine our cognitive models. For example, from light sensors beyond the visible range and sounds sensors outside the audible frequencies, to the detection of gravitational waves, recently confirming Einstein's theory, the broadened variety provides new perceived distinctions about our environment. Beside amplification, we can also attenuate information entropy by limiting the variety of our sensory perception. Earplugs can reduce sound pollution, or filters can remove unwanted noise from the environment, while highlighting meaningful information.

4.5. Cognitive Models

We continuously perceive unidirectional signals from the environment through our sensory organs. Our sensors bring information from the environment to our cognition. These signals can become meaningful information, if we can decode and process them through our cognitive models. We create cognitive models of the environment we live in, and in effect all of our perceived knowledge is an abstracted model. They consist of perceived subsets of the environment's variety and provide a distinction in accordance. Cognitive models are abstractions of the environment, based on its perceived and processed variety. Our understanding of the environment is bound by the fidelity of these abstracted models (Weinberg, 1991, p.501). The creation of these models relies on the combination of reason and experiences (Kant, 1781, p.148/1165), in line with rationalistic (Leibniz, 2013) and empirical (Hume, 1739) approaches. Cognitive models are expected to be dynamic and evolve continuously. As cognitive models are subjective, they can be influenced by external or internal paradigms, which can lead to distortions and prevent the evolution of the models. (Belief systems, social norms are examples for these types of cognitive biases (Kahneman, 2013, p.1059/1307).) These models can also develop in stages or discontinuously. Cognitive models define paradigms, where new information is used to validate them. Variety that is uncognized or does not fit the model is not seen, as it is not made sense of yet. This translates to an epistemological block. Looking at the same information and processing it differently can lead to novel cognitive models that overcome such a block, causing an epistemological rupture (Idlas, 2011, p.10). For example, moving from a geocentric to a heliocentric view of the universe, or looking at mass differently in the theories of Newton (Newton, 1687) and Einstein (Einstein, 1916). (This will be further discussed below under cybernetic conversations.)

The incoming signals are not always processed through cognitive models, as the models may not accommodate distinction for the incoming variety. Variety that exists in the environment, but outside of the fidelity of the model to recognize the distinction may contribute to tacit knowledge. Tacit knowledge (Polanyi, 1966, p.9) is unprocessed underlying knowledge (*"we know more than we can tell"* (Polanyi, 1966, p.4)). It is not reliable and it is hard to assess (e.g., I have a gut feeling). Continuous tacit accumulation of this type of variety can be processed subconsciously into hierarchies, which can lead to emergence of this tacit knowledge to communicable personal knowledge. The term, "personal knowledge" was also introduced by Polanyi in (Polanyi, 1962, p.409/8888). Hierarchies are relevant to formulate cognitive models, and can influence the order of actions. Emerged knowledge provides insights and understanding, and influences our cognitive model or schemata, which consists of a collection of schema. It amplifies conscious variety, ready for application.

Perceived information also influences the schemata (Piaget, 1952, pp.357-417). In a process of rapid guessing (McLuhan, 1977, time: 4:47), the information is compared to existing schemata regarding its "sameness," which is then processed through assimilation, accommodation, or creating a new schema. McLuhan states: *"…speech is a cool medium of low definition, because so little is given and so much has to be filled in by the listener"* (McLuhan, 1964, p.23), which again points to the process of guessing. This suggests cognitive processing in line with a top down approach (Gregory, 1970, p.162). Yet, some information processing can be bottom up, based on direct input from the environment (Gibson, 1966, pp.154-255). Neisser's perceptual cycle (Neisser, 1976, p.20) attempts to reconcile these two approaches. It offers a circular process (see Figure 3.5) that includes sampling the environment, consulting or modifying the schema, and directing exploration for a subsequent sampling, until a convergence criterion is reached. This is a preferred approach in my ontology as it is in line with circular cybernetic constructivist conversations with the environment.

Accommodation and assimilation of a schema amplifies the variety of a cognitive model, but within the existing paradigm. New schema broadens the variety of the schemata, and could also used to rethink and broaden the paradigm. In my research, this led me to add new disciplines and related modes of operation to my cognitive models, which included—among others—cybernetics and human centered design, with designerly and artistic modes of operation.

4.6. Communications and Languages

Personal knowledge is potentially communicable—which is different from transferable. It has to be received and understood as well as formulated and transmitted. (It is important to point out that understanding a message does not guarantee a correspondence between the sent—intended—and received—interpreted—meanings, as it is influenced by the non-transferable personal knowledge of the actors (von Glasersfeld, 1984, pp.17-40) (von Glasersfeld, 2001, pp.31-43). *"The reader, not the writer, determines the meaning of a sentence"* (von Foerster, et al., 2014, p.13/276).) Communicable information is bound by language. The cognitive model and communicable knowledge is predominantly verbal (e.g., spoken or written), where language provides distinctions for the cognitive model. Language is a code for encoding the message, which must be shared between the sender and the receiver. Language can be defined in a broader sense, beyond spoken words. It can be interpreted through its truth condition (Wittgenstein, Russell, & Ogden, 2007, p.64/151), that is, by its literal meaning. Literal meaning is precise, and limits variety. Language can also be interpreted through its use condition, that is, by its contextual meaning. Contextual meaning can be vague and allows the observer to interpret it subjectively, through a broader variety than that for truth condition. Communicated language provides a distinction in a message from the sender's cognition to the environment. If the language-based message does not provide a distinction, it does not exist. Disciplines develop specialized languages, making communications more efficient. Specialized languages bound the variety of a cognitive model. A system with bounded variety can lead to barriers. To overcome barriers, the variety of the system has to be increased. Introducing new disciplines with new agreed upon shared languages and meanings can broaden the variety of a system, allowing for new insights and more options.

4.7. Circular Cybernetic Conversations

Cybernetics is circularity. It is concerned with the connections and conversations between an actor and the environment. It builds on a constructivist approach (Piaget, 1952, pp.357-417). We construct our knowledge through conversations and experiences with the environment. Instead of relying only on rationalism (Leibniz, 2013), or empiricism (Hume, 1739), we account for both (Kant, 1781). (In rationalism, reason without validation remains an idealistic illusion. In empiricism, experience alone stays subjective, if not processed through pure reason.) We need both, which amplifies the variety of this inclusionary approach. However, rational and empirical elements can be spatially and temporally decoupled. That is, a rational construct, based on pure reason, can add variety to the cognitive model and to the environment, which can be validated later. For example, the gravitational waves were validated 100 years after Einstein introduced his theory of relativity (Einstein, 1916). In turn, gained variety from the environment through experiences can be rationalized later, as it may become tacit knowledge first.

In cybernetics, variety represents the number of possible states of a system (Ashby, 1956, p.124). Under cybernetics, radical constructivism postulates that knowledge is personal (von Glasersfeld, 1984, pp.17-40) (von Glasersfeld, 2001, pp.31-43). Personal knowledge as a whole is not transferable between people, although parts can be communicated through conversations. People construct their own ideas and cognitive models. New ideas emerge and evolve from a combination of received information and personal knowledge.

Conversations provide the circularity for substantiation and to refine the correlation, knowledge, and agreed upon shared understanding between the environment and our cognitive model (Pask, 1976, p.27). Conversations are circular and involve an actor (as the regulator), a process, and the environment. Conversations always have to have at least one actor with cognition involved. (Pask proposes that the same person can have multiple personae, and have internal conversations.) The environment can be a person or an artifact. A conversation consists of two phases, a forward phase and a return phase or feedback. In a conversation between the regulator and an artifact, or more specifically in a conversation with the self through an artifact, the conversation consists of two phases. A sense-giving phase from the regulator to the artifact, and a sense-making phase from the artifact to the regulator (see Figure 3.8). These forward and feedback cycles can be utilized in design, when goals are applied to attenuate or amplify controls. In a conversation between two actors, Actor–A and Actor–B, the role of the regulator changes back and forth (see Figure 3.7). When Actor–A communicates an intended message, its meaning is defined by Actor–B. The message passes through the perceptional boundaries of both Actor–A and Actor–B in the first time-step. (For this discussion let us ignore the potential influence of a noise source in the environment.) In the second time-step Actor–B decodes and processes the information. Now being in a regulator position, Actor–B formulates a response and sends the encoded message to Actor–A, in the third time-step. The intended meaning of Actor–B's forward message becomes Actor–A's received and interpreted feedback message. (The intended and interpreted meanings may differ.) During these conversations the applied controls from the perspective of each actor can amplify or attenuate variety. Over time the system balances itself, and the system variety reaches equilibrium. At this time-step a shared and agreed upon meaning is constructed between the conversing actors. Spatial and temporal shift can occur at any of these three conversation phases, which can be leveraged when designing immersive, interactive, and participatory environments. Boundary objects, in the form of objectification of ideas, can facilitate these conversations, bridge discipline boundaries, and support the convergence towards an agreed meaning between the actors (see Section 7).

Conversing systems are recursive, they work at many levels. As systems are dynamic, they are in a constant flux. The greater the system's variety, the greater the flux. System stability requires equilibrium after any perturbation. Regulators can implement regulatory control to attenuate variety, which can lead to stability on one hand, but can over-constrain the system and limit outcome potential. Under first-order cybernetics, where the observed system operates within a given paradigm, this approach can keep projects on track. At a strategic level, which is an observing paradigm, new requirements can be created and enforced to modify the goals of the first-order system, thus broadening the organizational paradigm. A scientific approach to make an organization effective is codified in the Viable System Model (VSM) (Beer, 1981, p.157). VSM deals with regulatory and guidance mechanisms, operational hierarchy, and viability functions. VSM's viability functions support these, by addressing operations, coordination, audit, planning, direction, and identity. Organizations—similarly to the human body—can also be compared to dynamic, living evolving and adapting and self-sustaining autopoietic systems (Maturana & Varela, 1980, p.xvii-xxiv). To understand the organization and regulate it, the system needs a regulator. Furthermore, the organization has to have a model otherwise the regulator can't be effective to control it.

Understanding cybernetics and design conversations and applying them to real-world scenarios can lead to new insights, as will be discussed in subsequent sections.

4.8. Space Design with a Humanly Focus

Within the space exploration paradigm our interactions with the environment and with each other are dominated by technology, and related requirements and procedures. In this paradigm, even for the human exploration segment, humans are considered to be participatory elements of the overall system of systems model. This approach demonstrated functional outcomes in the past and can still work for near-term human exploration and robotic missions. However, long-duration deep space missions will require a new paradigm, as the crew is isolated for an extended period of time that is measured in years. Designing for the crew presents a simplification regarding certain aspects of terrestrial designs. That is, astronauts represent a well-defined subgroup of the population. For example, the astronauts have closely similar physical and psychological makeup, which is further refined through years of training. This reduces the variety of the system from a designer's perspective. As humans are the ultimate autopoietic systems, their viability functions should not be limited to only basic physiological and psychological needs. Inverting Maslow's Hierarchy of Needs (Maslow, 1970,p.2&104), we can place human centered considerations ahead of technology considerations, based on each member of the crew, while maximizing (optimizing) his/her variety for the best interactions and circularity with the environment. This is required to support higher-level human centered viability functions, namely identity through self-actualization, direction to keep interactions stable, and planning through delegated autonomy. (The remaining viability functions on audit, coordination, and operations, target physiological and psychological deficit needs—see Figure 3.11 (Beer, 1981, p.157)—which are already being addressed at NASA.) Satisfying these higher-level crew needs might not considered necessary from a functional engineering perspective under today's paradigm, but neglecting them can significantly impact the mission's risk posture. Thus a human centered perspective strongly aligns with a strategic perspective, which requires broadening today's paradigm. However, there is an implementation challenge. Engineering disciplines are well established, with well-defined "hard" requirements, which can be assessed objectively. Higher-level "soft" requirements are more subjective. These are significantly more difficult to codify and measure their implementation success. For example, growing plants onboard a space habitat can address harder to measure psychological needs and wellbeing, while also providing food for the crew (Whitmore, 2015)(Connors et al., 1985, p.78). They also require second-order considerations, where the crew's can shape its interactions with the environment and change the goals of the system. This may require new modes of operation, such as designerly and artistic modes, facilitating—among other considerations—conversations, learning, and discovery. Advocating and finding support for new modes of operation within NASA is a continuation goal for this research.

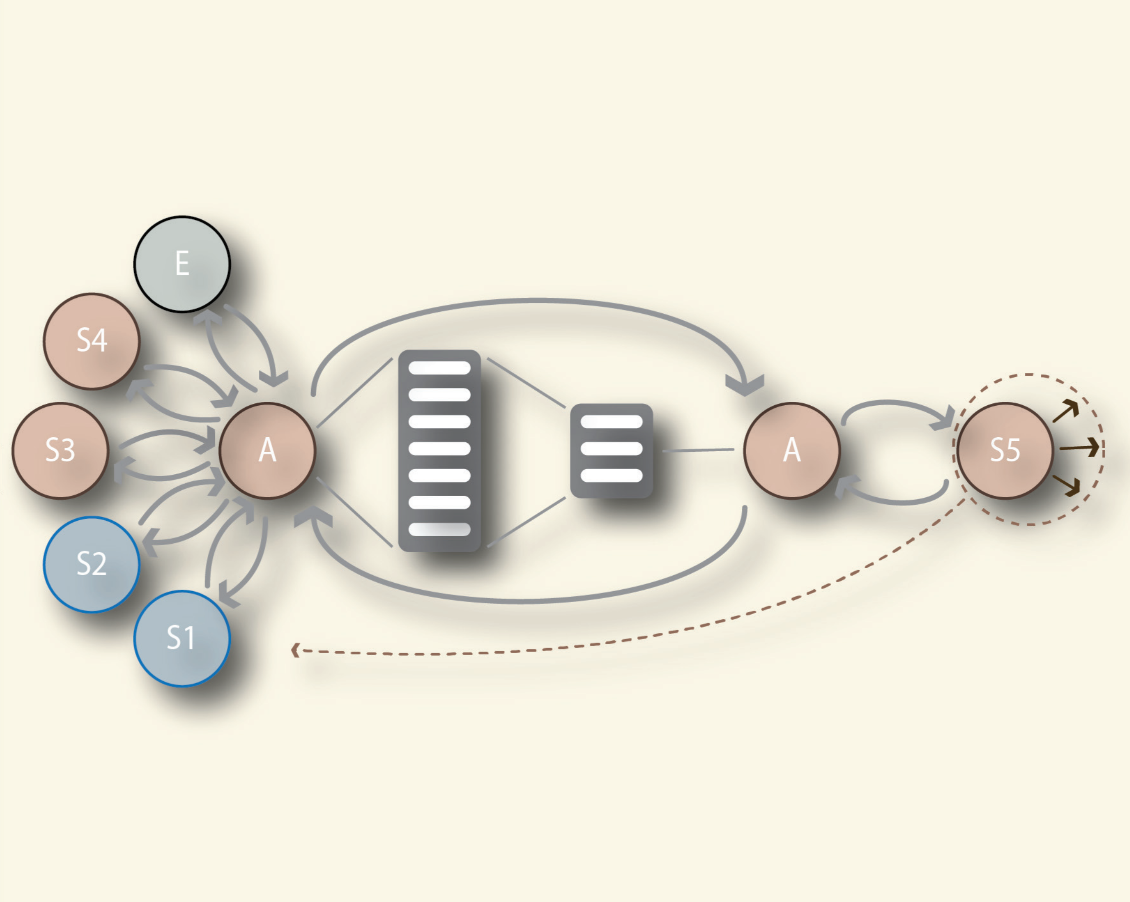
4.9. Epilogue to Performative Ontology

In my research I have employed cybernetic perspectives—a keystone of my performative ontology—in combination with a human centered design focus, and applied them to real-world examples at NASA.

But why should we care about space? Because space changes the language for humanity. It expands the discourse, provides new options, new conversations, stimulates imagination, broadens understanding, finds new meaning not only in space, but also back on Earth. Every step forward creates a new baseline for the upcoming generations. Pressing knowledge forward can happen in many fronts and disciplines. NASA’s current paradigm is dominated by engineering and technology driven practices, but in the future—hopefully starting sooner rather than later—we need to include new disciplines to advance the discourse. Given this stance, for true participatory ontologies we need to find novel perspectives and make our space exploration practices more human centered, with a focus on the human experience. This can be achieved by complementing NASA’s engineering mode with designerly and artistic modes of operation, through design conversations and boundary objects.

The views presented in this thesis reflect my cognitive model I have developed through my research. It represents only a snapshot in time, and I expect that it will evolve in the future, just as it evolved to this point. There is also a likelihood that aspects of my model may not fully align with views held by a number of others on these topics. Subsequently I have provided definitions for the introduced terms to highlight why they represent a distinction for me compared to other more commonly used terms (see Section 3 and the Glossary).

Section 5.
Example-1:
Organizational Cybernetics and Conversations for Strategic Decision Making



PAFTD Conversation Cycles (2015)

5.1. Prologue to PAFTD

Space exploration faces many challenges, where near-term goals can be addressed through incremental technology development approaches. However, future missions beyond the current mission implementation horizon will require new alternative ideas and solutions, which should be reflected in space technology portfolios. Within NASA's technology and process driven environments (non-technical) design is typically associated with aesthetics and image creation, but design should account for more than simple ergonomics and packaging that might be addressed at the end of a development cycle as an add-on, only if time and resources are available. Good design, may it be a process, a service, or an artifact, can lead to distinct advantages over purely technology-driven developments, because of its multi-disciplinary nature. Furthermore, at a strategic level, a well designed process that builds on cybernetic perspectives combined with design thinking and design conversations can provide insights to decision makers, leading to actions and subsequently to preferable outcomes for the non-linear wicked problems they face.

Problem definitions are derived from specific points of views. In turn, the resulting solutions are inherently defined by the same problems at hand. An overly regulated problem-space can only result in incremental outcomes, but not transformational or disruptive ones. In contrast, transformational and disruptive space technologies, and related mission architectures can have a significant impact on future space exploration directions. Consequently, strategic considerations and directions of a space technology organization have far reaching impacts on future exploration plans. To find differentiating strategic directions we may need to look beyond traditional project management and systems thinking approaches, and look at the development environment through the eyes of a designerly thinker. Design is a creative approach towards non-linear problem solving with the power to tackle complex multi-disciplinary and pressing social issues. Linear disciplines, for example engineering, tend to downplay the advantages provided by design. This way of thinking may work at the linear project and program execution levels of an observed system, where the goals of the system are set. However, at higher levels in the organizational hierarchy, strategy needs design and design needs strategic considerations.

Over the past 50 years NASA's operations became increasingly influenced by NASA Procedural Requirements (NPR) (NODIS, 2015). These NPRs impact projects, portfolios of projects, operations and processes. Each mishap or failure added new requirements to the already lengthy NPRs. (Derleth, 2015) It was enforced by risk averse managers, and resulted in documentation overload. NASA's innovation barriers are detailed in Section 3.5.1 and (Balint, 2013, p.5). Most of the barriers can be traced back to NASA's budget, and NASA's organizational hierarchy. The uncertain annual budgets also necessitate strategic decisions on the portfolios of projects. Based on my experiences at both linear project and non-linear strategic levels within NASA, I have identified a touch point related to strategic decision making. This is a touch point where a novel perspective is needed to make beneficial changes. Thus, I had to look beyond the state of practice of project reporting, gain a broader understanding of NASA's place in the U.S. governmental framework, assess its internal organizational structure, and develop a new perspective that can supersede the prevalent worldview within the Agency.

To make a case for a new strategic decision making support tool, I am providing a brief overview on NASA's budgetary processes, the structure of its internal and external hierarchy in Appendix B, and discuss the reasons why I consider the Agency's operational dynamics and operational complexities within the US Government framework a wicked problem (Section 5.2), where the motivations and interests vary at each level in the hierarchy (Balint & Stevens, 2016, p.97). This understanding provides the foundation to argue for a novel perspective that draws on Stafford Beer's Viable System Model (VSM) (Beer, 1981, p.157). In turn, VSM introduces an organizational perspective, novel to NASA, that can be leveraged to identify a specific touch point to facilitate change (Section 5.3). Touch points can occur at any of the bi-directional circular conversation loops between the entities, including organizational groups or individuals. Introducing changes at touch points can help to overcome epistemological obstacles and result in an epistemological rupture locally, which then can propagate through the whole organization. The present example for a process-change at a touch point involves the use of a project assessment tool, that my collaborator and former colleague at NASA HQ, Brett Depenbrock, named Project Assessment Framework Through Design (PAFTD) (Depenbrock, Balint, & Sheehy, 2015). (The discussions on PAFTD represent shared views and opinions between Depenbrock and I, arising from our design conversations during the development of the tool. It is built on my research related to cybernetics and design; on my experiences as a Program Executive and Senior Technical Advisor at NASA HQ; and Depenbrock's business experiences at STMD's Resource Management Office.) PAFTD is an Excel-based software tool that frames conversations with stakeholders. It is used by an analyst to synthesize the information from conducted semi-structured interviews. These interviews broaden project related variety beyond technical feasibility and fiscal viability. The processed information package helps to inform senior leadership on key project performance drivers and strategic issues in support of their decision making process, related to technology portfolios (see Section 5.3) (Balint, Depenbrock, & Stevens, 2015).

This example is at the intersection between human centered design, design conversations, organizational cybernetics, project management, resource management, organizational management, modeling, and social sciences. It also involves systems thinking and integrated thinking. To understand what roles cybernetics and human centered design may play in this environment, we need to have an understanding of all of the related and relevant fields, for which I am providing an overview below.

5.2. Why is Technology Development a Wicked Problem for NASA?

Making project level decisions requires the project manager (the regulator) to keep cost, schedule, technical performance on track, and deliver an artifact/technology that performs to requirements. At a strategic level there are additional considerations, which goes beyond linear project execution. The mismatch between goals, expectations, resources, personalities and other drivers at every organizational level makes the problem non-linear and often with no clear solution. This aligns with the characteristics of wicked problems, which was introduced in Section 3.5.3. In this sub-section I discuss why NASA has a wicked problem when developing space technologies. This understanding helps to develop a more holistic view about the roles and complexities of space technology development within NASA, and points to the desire towards reassessing its worldview about how strategic decisions are made, and how they can be advanced further.

5.2.1. Measuring NASA Against Conklin's Characteristics of Wicked Problems

Looking at the six characteristics of wicked problems (Conklin, 2006, p.7-8), which are also listed in Section 3.5.3, and referring to them as "wicked problems by Conklin 1 to 6," or WPC1 to WPC6, I have found the following:

WPC1—Problem non-linearity: For NASA—and for all government agencies—the annual budget is unknown until it is appropriated. The appropriation at the beginning of the fiscal year is far from certain, and can stretch through the full fiscal year. Regularly included earmarks and changing content from the PBR introduce further uncertainties. Once the appropriation is done, NASA HQ updates the plans and allocates resources in the best suitable way. (Details on NASA's PPBE process is provided in Appendix B.)

WPC2—No stopping rules: Projects may encounter difficulties due to changing resource allocations, reflecting internal and external changes from the environment. They may need further interventions from the strategic level to resolve these issues (see Figure 3.12).

WPC3—No right or wrong choices: Operating in a resource limited environment, strategic decisions are needed on a number of issues, focusing on subsets of the problem, which can be addressed under the circumstances. For example, program execution can target short- or long-term technology needs, incremental or transformational technology developments, or a mixture of them. Any of these approaches and choices can be justified at a given time, based on strategic considerations. Subsequently, the outcomes may be declared successes or failures as they propagate to the future.

WPC4—Problem uniqueness: NASA's technology portfolio is changing continuously, with projects being completed and new projects starting. Program resources are influenced by budget allocation uncertainties year after year. While past experiences may help to resolve these issues, every year a new set of variables are introduced, making the problems at hand always novel and unique.

WPC5—One shot operations: Once the budget is appropriated, NASA HQ responds to allocate the needed resources to the performers (see Appendix B). This has to be done swiftly to limit negative impacts to the continuity of the programs and projects. Once the resources are allocated, the projects are responsible to perform at the expected level. Pushing technology boundaries can result in project overruns, requiring additional resources at any time of the year, complicating the process and introducing stress points.

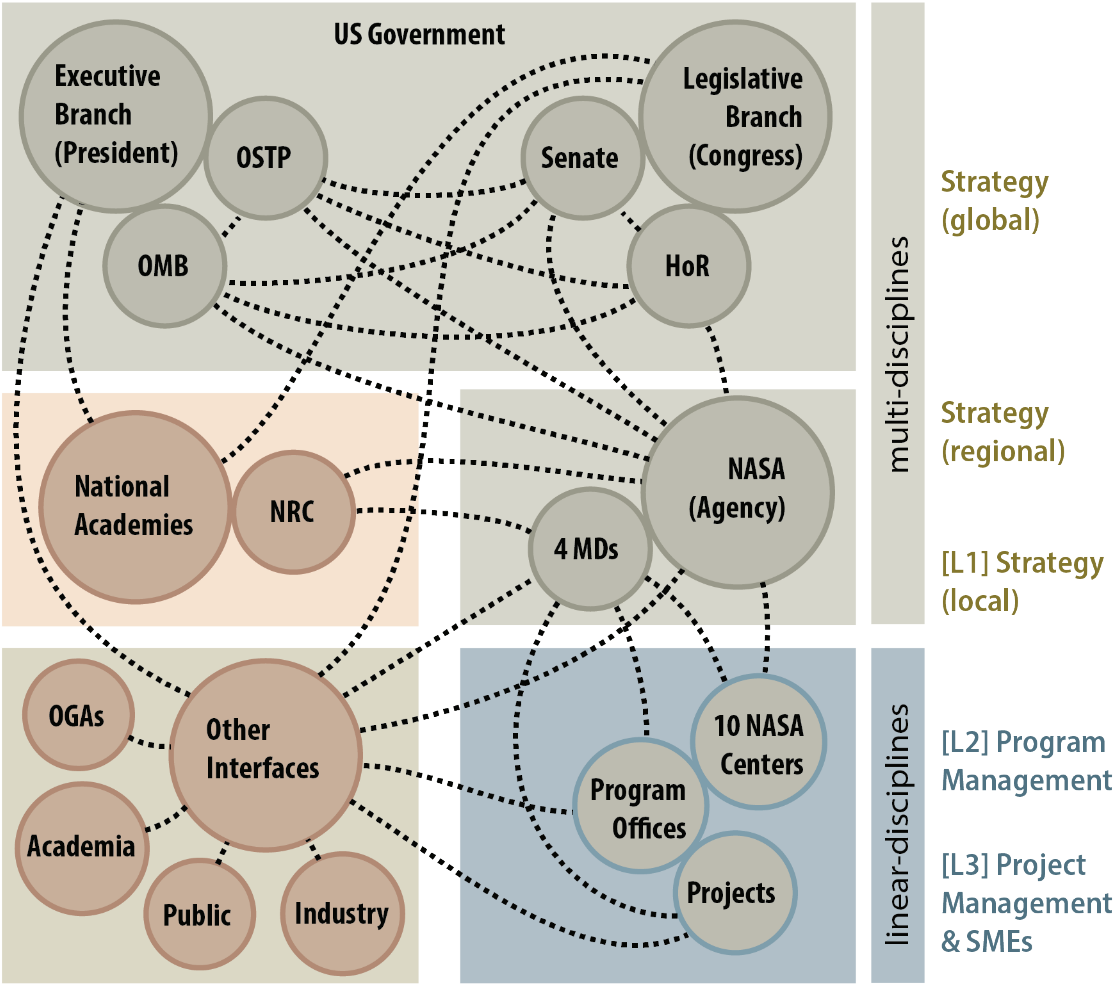
WPC6—No given alternatives: NASA's resources are constrained and uncertain within bounds. Project risks can be mitigated through reserves to a point, but the continuous interplay between the full portfolio of projects and their uncertainties, constrained by a limited budget, makes the outcomes unique. Driven by strategic decisions, some projects might be impacted more than others, without alternative solutions.

5.2.2. Cyclicality, Temporality, and Spatiality

Based on the discussions above, I can further refine the wicked problems model for NASA, to account for its temporally and spatially coupled cyclical nature. I have identified cyclicality due to the annual budget appropriation cycle, governmental mid-term elections in every two years, and presidential elections every four years. Furthermore, some of the technologies may take a decade to develop, which introduces an additional layer of an even longer timeframe. The annual budget cycle often introduces resource-related uncertainties, driven by appropriated budget levels and time delays. When the budget is not appropriated by the first day of the fiscal year, the Agency operates under Continuing Resolution (CR) guidelines, when new projects cannot be started, and spending is held at the level of the previous fiscal year. An extended length of the CR (and other compounding factors, such as sequestration) may also lead to continuous re-planning cycles, resource reduction to the projects, or at times to rush spending at the end of the fiscal year. In addition, appropriated budgets are frequently lower from the PBR amount, requiring further re-planning activities. The national election cycles contribute to the temporality of the wicked problem. At mid-term elections new House of Representatives and Delegates can be elected for two-year terms, and new Senators for six-year terms. Some are re-elected, but even partial turnovers in committee membership can change the voting balance, and influence appropriation outcomes when combined with the dynamics of national politics, and perceived national budgetary priorities. As I have stated before, NASA's budget is below 0.5% of the national budget and it is in the discretionary funding category, which means that it can be adjusted based on other national or regional priorities. Thus, the appropriated budget can include earmarks, which are specified changes or added constraints to the PBR. These earmarks are often spatially aligned with the Congress-person's regional interests to bring resources to their home states. Depending on local economies, the importance of space related investment and jobs vary between states, translating to earmark-based resource distributions. Depending on the balance between congressional party affiliations, and that of the President (elected every four years), the appropriation committees may support, oppose, and/or modify the PBR. All of these can result in budgetary uncertainties and instabilities for NASA's appropriation process and outcomes, including continuous re-planning cycles, project de-scopes, delayed milestones and missed deliverables. These have a significant impact on technology development and related strategies. Consequently, I have extended Rittel and Webber's model (Rittel & Webber, 1973, p.160) and termed it: "NASA's temporally and spatially coupled cyclical wicked problem." The complex interconnections between NASA organizational entities and outside organizations are detailed in Appendix B.1.3 and visualized in Figure B.4. In support of this discussion, the same figure is shown here as Figure 5.1. Understanding the influences to this wicked problem at various levels can help identifying areas where design, design thinking, designerly thinking can be leveraged for strategic decision making at both micro scales (for project and programs) and macro scales (for mission directorates and the Agency).

5.2.3. Strategic Considerations

As an example, NASA's Office of the Chief Technologist (OCT) was established in 2010, after identifying the need for a protected and self-contained entity focusing on the development of future transformational space technologies for the Agency and the Nation. The office was envisioned with an annual budget of 1 billion dollars, and a matching workforce of about 900 civil servants. In 2013 the Office was divided into a small office for the Chief Technologist, addressing Agency-wide policies and strategies, while the majority of the resources was allocated to the Space Technology Mission Directorate. However, the initially requested annual funding level never materialized, and after these years it was $576M in FY14, yet with approximately the same original civil servant complement, which is overly high for the current funding level. This limits procurement for competed new technology projects, and requires hard choices about how resources are allocated. For this type of organization a desired portfolio balance would include projects targeting both explorational (or transformational)



OSTP........Office of Science and Technology Policy
OMB........Office of Management and Budget
HoR.........House of Representatives
OGAs......Other Government Agencies

NRC...........National Research Council
MDs...........Mission Directorates at NASA
[L1]-[L3]...NASA Organizational levels 1 to 3
SMEs.........Subject Matter Experts

Figure 5.1. Connections between NASA and its stakeholders (Balint & Stevens, 2016).

and exploitational (or incremental) technologies. (Note that the terms explorational and exploitational are used differently in the innovation context from those used in the habitats section—Section 6—related to human exploration of space.) The former would open up new approaches for the next generation of missions, while the latter would support existing near term stakeholder needs, both within NASA and for the nation. However, the constraints may require to assess original assumptions, reflect current performance, and seek out new opportunities and threats, and by asking strategic questions along the line of:

- Is the current technology portfolio addresses the appropriate needs?
- Is the organization developing the right technologies, to the right stakeholders, for the right infusion timeframe?
- Can the budget support funding all the technology areas identified in the Space Technology Roadmap (NASA, 2010)? If not, where should the focus be?
- Can the budget support developments across all Technology Readiness Levels, from early stage to flight development?
- Can the budget support technology development both inside and outside of NASA?

- Should the investment be near term focused with incremental technologies, or far term focused with more transformational technologies? What is the right balance between the two types of investments?
- How to infuse new transformational technologies into stakeholder needs?
- How to deal with non-performing projects? Would cancellation be warranted to free up resources?
- How to best communicate strategies, related to technology development activities, to key stakeholders and to the broad community? What is the best organizational structure to achieve a desired outcome?
- How to customize the message to various stakeholders—e.g., at various levels from project implementation through strategic management at HQ, to the funding sources of the government, while also including external companies, academia, and the public? How to be consistent with the messaging, while maximizing the knowledge transfer to the broadest set of audiences?
- How to motivate members of the organization, and how to leverage their talents?
- What are the biggest challenges facing the organization?
- What are the new opportunities and threats that strategies should consider, both short and long term?
- How to overcome innovation barriers, including NASA's risk-averse culture; low priority to innovation; short-term focus; instability; lack of opportunities; process overload; communication challenges; and organizational inertia?
- How to leverage non-traditional approaches that may not require significant investment yet may greatly enhance project performance, visibility, and awareness both inside and outside of NASA? For example, NASA's Advance Exploration Systems (AES) under HEOMD worked with the Topcoder community on NASA's Asteroid Grand Challenge, leveraging the skills of the broad code developer community. AES also received 233,431 votes for the new Z-2 spacesuit outer shell design, in effect involving the public at virtually no cost to advertise the technology and design activities of that organization. These strategic approaches can provide added dimensions and resulting benefits to an organization by extending strategic thinking to multiple disciplines beyond linear project and program management lines and practices.

Further details and potential approaches to some of these questions can be found in (Balint, 2013).

5.2.4. Knowledge and Hierarchy

As discussed in Section 3.2.4, tacit knowledge (Polanyi, 1966, p.9) can emerge through a knowledge hierarchy where the various levels interface, the same way as sound, words, sentences, and prose build on the top of each other. Through an analogy and redirection, this hierarchy system can be applied to organizations within NASA's framework, building up from linear Project and Program levels, to strategic levels, including Mission Directorates, and subsequently to Agency and Government levels. This model is shown in Figure 5.2, which is simplified from Figure 5.1.

I consider project and program level activities at NASA Centers to fall under first-order linear cybernetic disciplines, driven by highly constrained and goal-oriented practices. They operate

Figure 5.2. NASA's notional knowledge hierarchy, updated from (Balint & Stevens, 2016).

within their established paradigms. At these levels engineering and technology drivers address feasibility, while set management practices, planning and execution processes deal with viability (see Figure 3.12). The usability aspect, related to NASA or National needs, are driven by higher-level strategic considerations. Strategic level organizational entities, at HQ and higher can overwrite project and program level goals and requirements, thus these are operating under second-order cybernetics. At the Mission Directorate, Agency and Government levels decision-making is multi-disciplinary, involving future opportunities, threats, and a broad input from stakeholders, as discussed above. The strategies are also hierarchy specific, which I describe as local, regional, and global, respectively, as shown in Figures 5.1 and 5.2. Influences and drivers vary at each level, and coupled through their interfaces (for example between project and program; program and directorate; and so on). In this hierarchical setup, a mismatch between the levels and associated drivers can be detrimental to the organization. For example, if the strategic (L1) Directorate level focuses too much on linear (L2) Program and (L3) Project oversight, it may impact the organization in multiple ways. It spends its resources away from strategic thinking, while forcing the Directorate to operate in a linear discipline mode. Subsequently this may limit the organization's success and competitiveness, especially if contemporary organizations simultaneously leverage their own strategic advantages. Operating within an organizational hierarchy at a lower than its actual level also negates the effectiveness, roles and responsibilities of that level, which may propagate through the organization. This can result in reduced effectiveness and lower workplace morale. While I am only addressing this on a notional scale, it is important to point out that there are potential risks, coupled with less optimal outcomes, when an organization does not assign and delegate its roles and responsibilities across its hierarchy. Through a notional example, if an organization at the strategic level spends its efforts only on planning and execution, it potentially uses its resources away from strategic work at the strategic level. On the short term it may lead to the appearance of a functioning organization, and may even perform a significant amount of work, but at the same time may go down the wrong path, or unnecessarily spends efforts to cover all bases and broad option trades. Performing endless planning exercises further narrows the option trades from a narrow foresight to an even smaller but meaningful number of scenarios. A better approach is to focus on a strategic understanding of the environment at the strategic level, and select the best perceived option based on a broadened view about the opportunities and threats. At the same time, strategic levels must delegate planning and execution to the linear disciplines within the hierarchy, where these belong.

People in strategic leadership positions play important roles to create and lead a successful and dynamic organization. NASA has strict procedures that, in general, lead to the selection of the most qualified person for a given position. This is important, because there is a risk to promoting people to increasingly higher positions in the organizational hierarchy without the suitability for the new position. This can be illustrated through the hierarchy construct, coupled with the Peter Principle, which states that: *"In a hierarchy every employee tends to rise to his level of incompetence"* (Peter, L.J., Hall, R., 1969, p.25). According to this principle, at times the selection for a new position may be based on the applicant's performance in the current role, instead of the requirements of a new position. At higher strategic levels, the linear disciplines, such as project management, and program management practices are replaced with strategic thinking, requiring a multi-disciplinary skill set. Strategy is vastly different from linear planning and execution, especially in engineering and technology fields at the project implementation level. Strategy involves assessment and analysis of the situation, identifying options, then setting policies, and combining them with coherent actions (Rumelt, 2011, p.456/633). Strategic leaders leverage tacit knowledge based on analysis and foresight of multi-disciplinary future opportunities and threats, combined with reflections of the ongoing activities and constraints. Design thinking, systems thinking, and integrative thinking, including scenario prototyping can stimulate new ideas, resulting in an emergence of tacit knowledge to communicable knowledge, new options and strategic advantages. This can be further illustrated through Ashby's Law of Requisite Variety (Ashby, 1956, p.206), which is discussed in Section 3.2.8. As stated there, a controlling system can only avoid being restrictive if it has equal or greater variety than the system it wishes to control. For a linear engineering discipline, the system's variety is filtered by the regulator's variety, which leads to a well-controlled outcome. When promoted to a strategic level, if the regulator maintains its prior limited variety, inherited from a linear discipline, the outcomes are over-constrained and controlled down to the same level as that for a linear discipline. While this system produces outcomes, the regulator might not be aware of variety imposed limitations, and the system under-performs and not competitive. If there is too little variety in the controlling system (regulator), the control becomes restrictive, rather than facilitative. On the other hand, if the regulator at the strategic level operates with a broadened variety, new options may emerge from the absorbed strategic level information, allowing the regulator to select from a broader set and maximize the success of the outcome. Thus, if we want proper enabling control—not restrictive—we must have sufficient variety. In other words, the approach that makes a manager successful in a linear discipline is not sufficient to be successful at a strategic level. Without adjustment, the success of the organization can be adversely impacted.

Looking at regulatory control through a circular cybernetic loop, shown in Figure 3.1, it becomes clear that the regulator can impose goals to the system to reduce the variety of the process, and in a subsequent step reduce the variety of the environment. Feedback from the environment and the process can increase the variety of the regulator, providing a broader understanding of the environment to make regulatory choices. The regulator can also broaden the variety of the process and the environment. For example, a micro-manager or a dictator would regulate the environment from the top down, exercising full control. A good manager would delegate to lower levels, and in effect increase the variety of the environment, opening the possibility for new options, and benefiting from the creativity of the people from the environment. Thus, cybernetics is not used to provide answers, but to gain insights and perspectives into the connections between the various actors, then use other means, such as design, to "turn the various knobs" to achieve the desired outcomes. Ultimately a system and its environment tends to move towards equalizing the variety across its elements. The outcomes are reflected on how this balancing is achieved, namely, through top down control, or through delegation.

Through mapping NASA's wicked problems for space technology development (Balint & Stevens, 2016) (Balint & Stevens, 2014), a system of hierarchy emerged, building up from linear project and program levels (Level 3 and Level 2), to strategic levels, including Mission Directorates (Level 1), and subsequently to higher Agency and Government levels (see Figure 5.1). At strategic levels within this hierarchy, there are misaligned contributing factors to projects, turning a linear engineering project development into an incomplete problem with changing requirements and without a clear possible solution. This needs strategic considerations for effective decision-making.

5.3. PAFTD—A Novel Strategic Decision Support Tool

Technology development organizations face numerous challenges related to the planning, execution and optimization of their portfolios through the staggered lifecycles of their projects. Particularly when these portfolios consist of loosely coupled projects. Typical engineering and project management approaches are effective to solve well-focused control problems leading to convergent regulated outcomes. (For example, developing a certain technology within the allocated resources.) In comparison, strategic non-linear problems can't be solved easily, and may require novel approaches, where feedback is used to broaden the variety of the decision makers, providing better insights into the opportunities and threats, allowing a broader set of options to choose from. There is a risk of operating an organization at the strategic level through project management approaches used at the linear project execution level. It may lead to outcomes, but such an overly regulated environment would highly limit the potential of the organization. Strategic considerations related to portfolio elements reach beyond technical feasibility, fiscal viability and schedules, where the various trade-offs form wicked problems (Rittel & Webber, 1973, p.160). NASA's wicked problems related to space technology development are discussed above in Section 5.2.

Organizations can be viewed as dynamic cybernetic systems, especially when characterizing and modeling them through the Viable System Model (VSM) (Beer, 1981, p.157). Beer states: *"To remind ourselves: a level of recursion is a level at which a viable system is in operation, as an autonomous part of a higher-level viable system, and containing within itself parts which are themselves autonomous viable systems"* (Beer, 1974, p.31). (VSM is introduced in Section 3.2.12.) Through this dynamic model the technology portfolio elements are expected to change throughout the lifecycles of projects. At the same time, the variety of the overall system (Ashby, 1956, p.124) is being continuously balanced through circular regulatory and feedback processes between management, the projects and the environment they operate in. Consequently, regular strategic-level project performance assessments are required to understand strategic level opportunities, threats, stakeholder needs, in addition to linear project level reporting.

Why are we concerned about all of these? Because technology organizations, including NASA, are expected to be innovative. Yet, the National Research Council (NRC) in its 2011 review has stated that: *"The mission-enabling activities in NASA's Science Mission Directorate (SMD)—including support for scientific research and research infrastructure,* *advanced technology development, and scientific and technical workforce development—are fundamentally important to NASA and to the nation"* (NRC, 2011, p.10-1). Related to Thermal Protection Systems specifically, NASA's technology base is largely depleted, and future successes will depend on advanced technology developments (NRC, 2012, p.1-1). Developing these new technologies requires the management of technology portfolios, which are governed by rigid processes documented in NPR 7120.5 for flight projects and NPR 7120.8 for technology and research projects (NODIS, 2015). These activities often face innovation barriers, which can be reduced or mitigated through various recommendations provided in an internal NASA study, which are discussed in Section 3.5.1. However, these recommendations, and the project oversights through NPRs are linear and procedural. They are not addressing the means of strategically managing and optimizing technology portfolios. In the government sector, including NASA, organizational inertia and resource requirements discourage riskier investment choices (see Section 1.2). Furthermore, the organizational structure and traditional reporting requirements and processes restrict the ability of managers to diagnose root causes of performance. NASA implements rigorous oversights for its projects, but these processes only provide insights to the project performance, related to technical advancements and resource usage (NODIS, 2015). These linear project level metrics don't provide information about strategic level considerations, which do not directly relate to project executions, yet are important to strategic decision-making. Currently strategic level information is accumulated through meetings between the leadership. For example, strategic level information is often exchanged between members of the senior leadership of mission directorates and stakeholders at the same strategic management level from other organizations. These meetings can be regular or *ad hoc*, with gained insights, which are not always transparent, complete or traceable. Furthermore, current project management tools interrogate project execution, but do not provide insights to broader strategic level issues. Good strategy involves focus that propels organizations to confront challenges, to make the logic of strategy explicit, and to force managers to see if desired outcomes are being achieved (Martin, 2014).

Therefore, to fill this gap between the current state of practice (SoP) and a traceable strategy-driven approach, with my collaborator, Brett Depenbrock, we have developed a qualitative modeling tool, called Project Assessment Framework through Design (PAFTD). PAFTD provides the means for independent project assessments, and enables a quick and efficient approach to measure key factors surrounding the strategic performance and dynamics of selected investments (Depenbrock, Balint, & Sheehy, 2015). It was designed to address this need for high- and mid-TRL system level projects, that is, above TRL 4. It is easy to use and customizable. PAFTD can be used to assess internal and external root causes of project performance at NASA Centers, Federally Funded Research and Development Centers (FFRDCs), and outside of the organization. PAFTD comprises of a number of strategic questions based on design thinking (Brown, 2009, p.13), as related to usability/desirability, technical feasibility, and fiscal viability. It gives quick and diverse insights into strategic issues. The synthesized information from a PAFTD evaluation allows senior leadership to contemplate comprehensive and thoughtful scenarios and to drive out deeper and more obscure root causes related to the health of the projects within their technology portfolio.

The PAFTD framework is built on cybernetic perspectives, and aligns with the Viable System Model (VSM) (see Section 3.2.12). The approach used to create this latest iteration of PAFTD moves beyond design thinking considerations, employed in the first version (Depenbrock, Balint, & Sheehy, 2015). Subsequently we are advocating design conversations between the various stakeholders in order to uncover root causes, which contribute to the understanding of the environment surrounding the project. PAFTD-based assessments enable dynamic performance trend modeling, and assessment of strategic option trade spaces. (Trade space assessment is similar to the design term "generation of alternatives" (Cross, 2010, p.106).) Findings from these assessments, based on design conversations with stakeholders, analysis and synthesis, can inform senior leadership on strategic aspects of the projects in a consistent, transparent and traceable manner. Armed with such broadened set of information senior leadership can prioritize investments that contribute to well-calibrated choices and may lead to preferable outcomes. For these choices to make sense, senior managers can benefit from a documented set of relevant information and justified true beliefs about the stakeholders, the environment, threats and opportunities and the capabilities of their organizations. I am also providing a brief discussion on the advantages of PAFTD against other project assessment methods, and state how its use may reduce organizational barriers through strategic assessments and decision making, thus leading to an effective and dynamically responsive organization. PAFTD was applied to a number of mid-to-high Technology Readiness Level (TRL) projects within NASA STMD's technology portfolio. It provided project relevant information to senior management, and substantiated the PAFTD tool and highlighted its benefits.

While the tool was used to assess internal and external strategic level root causes for projects performed at NASA Centers, Federally Funded Research and Development Centers (FFRDCs), PAFTD is not limited to NASA, and can be readily applied to technology portfolios at other organizations within the government and commercial sectors (see Section 5.3.6).

5.3.1. Mapping NASA STMD into the Viable System Model

From a cybernetic perspective, typical organizational charts provide a structural breakdown of organizational elements. The boxes represent people and their positions with links, revealing system and reporting hierarchy. However, these connecting lines—where the cybernetic control and feedback loops are rolled into singular connections—do not provide information on dynamic working connections, interactions, and communication links. Figure 5.3 illustrates a simplified organizational chart for NASA STMD (NASA STMD, 2015). As part

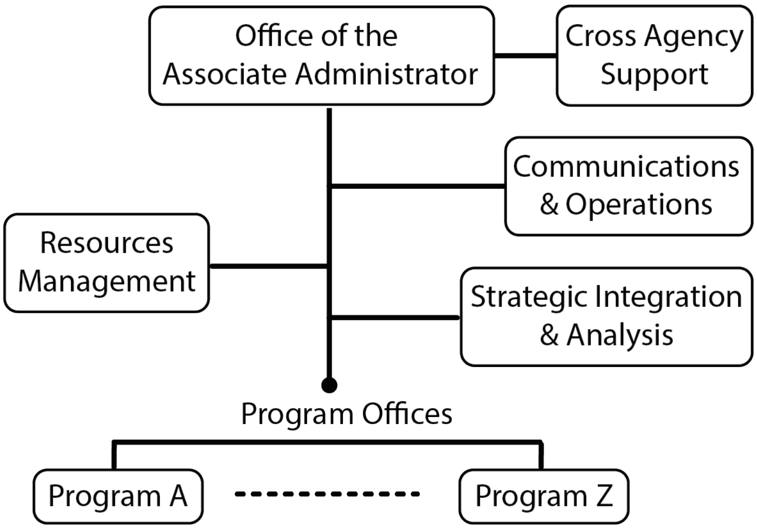


Figure 5.3: NASA STMD organizational chart (simplified from (NASA STMD, 2015)).

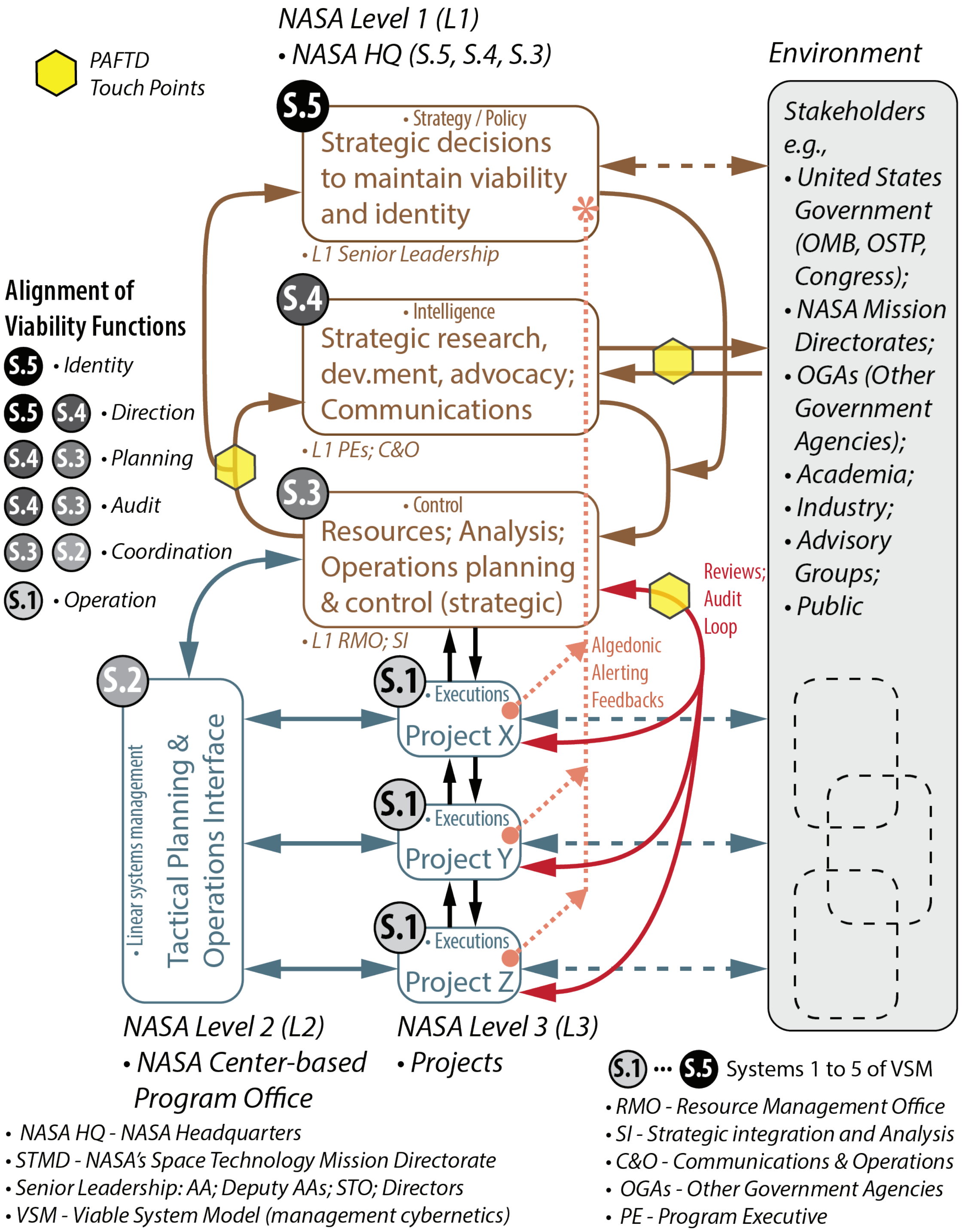


Figure 5.4: Notional mapping of NASA's Space Technology Mission Directorate into Stafford Beer's Viable System Model (Balint et al., 2015).

of the development effort of PAFTD, I have mapped NASA STMD's organizational structure into the Viable System Model (Beer, 1981, p.157), as shown in Figure 5.4 (Balint et al., 2015). Organizational entities at NASA are well established over the past five decades, which means that all of STMD's various departments and system functions have found an appropriate place within VSM. (As discussed in Section 3.2.12, organizations can be viewed as living and dynamic systems. Consequently Stafford Beer based his model on the human body, where body parts, the nervous system, and various parts of the brain are represented by the five systems of VSM, as shown in Figure 3.10.) While the mapping of STMD aligned with VSM, it became evident that certain organizational functions were missing. At the time of this assessment, at a strategic level STMD was focusing more on short-term tactical activities, than delegating that to lower levels, and dedicating resources to strategic considerations. Furthermore, the audit loops from System 1 (the project level) to System 3 and above (strategic levels) were mostly aligned with project performance reporting at various Key Decision Points (KDPs), as dictated by NASA's Procedural Requirement documents, NPR 7120.5 and 7120.8 (NODIS, 2015). In this process, a project reports its linear level activities to the strategic level, focusing on technical feasibility and resource related viability. However, as shown in the wicked problems visualization (Figure 5.1), there are other influencing factors to strategic understanding of the environment, which is not provided from the linear project level. PAFTD is designed to address this, by collecting complementary strategic level information, while positioned at VSM's Systems 3 and 4 levels. From here, the PAFTD analyst can provide synthesized and attenuated data to senior leaders, thus supporting them to make more informed decisions.

5.3.2. Using Design Conversations in PAFTD

In the model that forms the foundation of PAFTD, strategy starts with a human centered approach, balancing and harmonizing desirability or usability, with technical feasibility, and economic viability. As government organizations and corporations are living entities, and projects change dynamically throughout the formulation and implementation phases, we need to assess project performance continuously, at every level. Information on feasibility and viability is regularly obtained from the projects through required reporting events, such as in monthly reports, mid-term and end of year reviews, continuation reviews and project Key Decision Points (KDPs) (NODIS, 2015). These are delivered from the linear project level to the strategic level. Strategic level information, which may impact these projects are not readily captured in these reporting cycles. Yet, to make appropriate decisions at the strategic level, related to both projects and the overall technology portfolio, these need to be collected, processed, and made available to senior leadership for their strategic considerations. Currently external input from stakeholders is obtained during KDP reviews, where they verbally express their opinions. This information is often incomplete, limited to the meeting attendees, and based on their subjective opinions. I believe that with the introduction of the PAFTD tool, the gathering of strategic level information becomes more complete, traceable and transparent, and advances the current state of practice. It helps us to "deep dive" into stakeholder needs, through conversations and observations.

At the strategic level, iterative cybernetic feedback loops are expected to enhance the variety of the decision makers, who in return can make better choices in subsequent iterations, with a setout goal to benefit the stakeholders. Building on circular design conversations, which is discussed in Section 3.3.1 and (Pangaro, 2010), the outcomes are evaluated through a systematic approach to harmonize the strategic opportunities and constraints. The PAFTD tool helps to re-design the auditing process by first mapping the organization into the Viable System Model, based on cybernetic principles (see Figure 5.4), then using design conversations from the strategic level to augment information reported from the project level. The strategic level information is systematically collected from internal and external stakeholders. By re-designing the processes at the strategic level, we introduce new means to effectively influence the optimization of the technology portfolio. Information gathered through PAFTD broadens awareness of stakeholder needs and other loosely coupled factors of NASA's wicked problems, which goes beyond needs and goals, technical feasibility and fiscal viability.

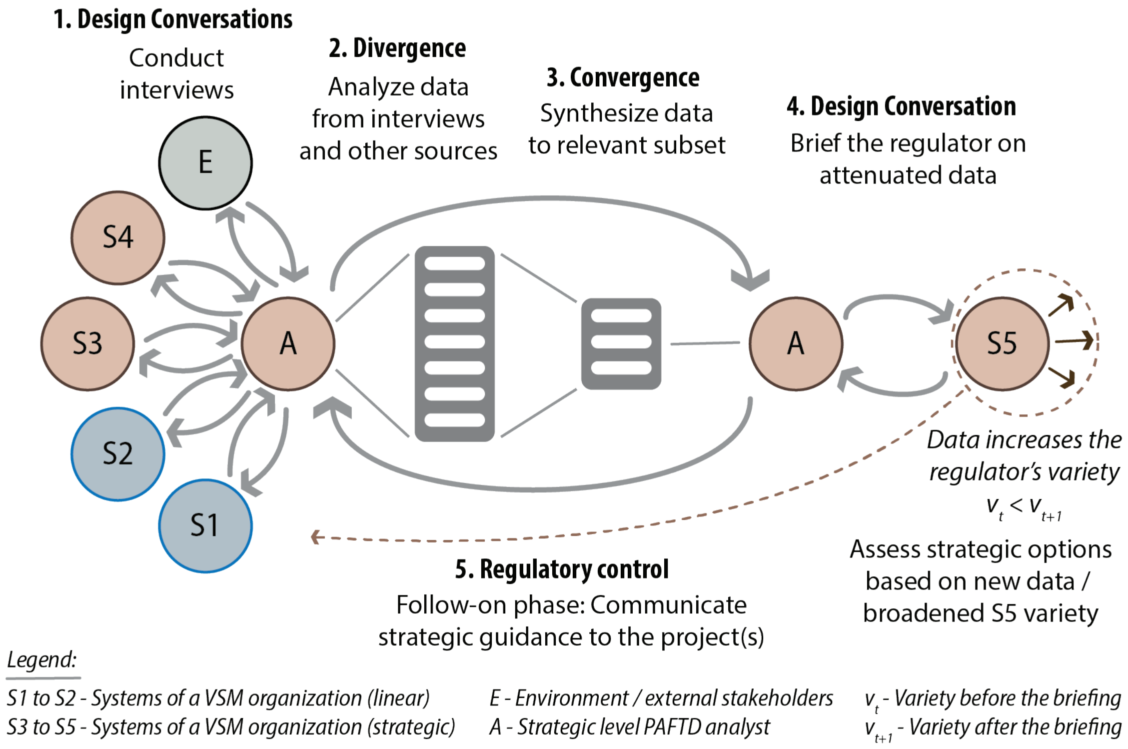


Figure 5.5. PAFTD process steps, based on cybernetic circularity and design conversations (Balint, Depenbrock, & Stevens, 2015).

To demonstrate the PAFTD process, we need to look at it from the perspective of a PAFTD analyst who gathers and synthesizes the information, and members of the senior leadership (the regulators), who use the presented information to make strategic choices. Traditionally, project reporting is conducted from Systems 1 & 2 to Systems 3, 4 and 5 (see Figure 5.4). In the PAFTD process, the system analyst resides at the strategic level, and while conducting the design conversations, interfaces with Systems 1 to 4 within the organization, and with the external environment consisting of stakeholders (see Figure 5.5). Design conversations in the form of semi-structured interviews were conducted by Depenbrock, related to address three topic areas on usability, feasibility and viability (Depenbrock, 2015). (Details on these topic areas are provided in the following sub-section.) While some information was collected from the project level to verify and validate the project-presented progress, the main focus is placed on gathering strategic level information to augment linear project data. Conversations related to the project environment are performed with:

- Members of the Resource Management Office (RMO) related to the overall funding environment;
- Program Executives (PEs) about their views on programmatic and strategic directions;
- Project and Program Office members;
- External contractors supporting the project; and
- Stakeholders (e.g., from other Mission Directorates), where the developed technologies are planned to be infused; here the analyst explores potential changes in stakeholder needs.

This analyst-collected data represents information, or variety, related to the strategic and project level status of the project at the time of the conversations. In this unprocessed form the information would be overwhelming to senior leadership. Therefore, it requires an additional step to synthesize it to salient points which would inform senior leadership about strategic issues without the burden of having them process the large amount of diverse data. It should be noted that PAFTD is not a linear formulaic tool, where anyone can step through the process based on a manual, and come to the same conclusion. At the strategic level we deal with non-linear wicked problems and the choices made upon the available strategic information are impacting the outcomes. Therefore, to identify the most relevant information, the data synthesis needs to be performed as objectively as possible, with attention to factual accuracy and focusing on the key strategic elements of the findings. This can be best achieved by utilizing the expertise and experience of the analyst who performs the interviews and synthesizes the data, then presents unbiased information to senior leadership for further considerations. It should be pressed that the PAFTD analyst does not make decisions, only provides strategic information to leadership. From the perspective of senior leadership, strategic decisions are made in light of the best available information. Project reporting provides updates at given key project performance stages on the progress-related technical areas and resource usage. However, individual projects represent elements of the overall portfolio, which in turn characterizes the strategic directions and goals of their organization. Thus, there can be times, when changes are required to the portfolio, based on strategic considerations, regardless of the potentially exemplary performance of a given project. For example, in the first years of STMD's history, the organization funded the development of multiple Entry, Descent and Landing (EDL) technologies, with a goal of infusing the most promising one to the upcoming Mars 2020 mission, as a precursor demonstration to a future human mission to Mars. When the Science Mission Directorate announced the heritage-technology based re-flight of the Mars Science Laboratory (MSL) mission in 2020, this decision locked in the EDL technology to the same one, as used on MSL. This negated the need to fund the development and mission infusion timeline for the emerging EDL technologies, and required strategic decisions to reassess the goals of technology developments related to this area. Limited resources combined with a strategic direction change from the stakeholder, necessitated rapid response, independently from project level performances. From this example it is evident that strategic level decision-making cannot be reliant only on project level information. Thus, the synthesized data presented by the PAFTD analyst to senior leadership broadens their true and justified knowledge on the project environment, allowing them to explore more options, and to make regulatory choices based on them, which are in line with their organization's strategic direction. The second-order cybernetic loop from the perspective of senior leadership includes identifying regulatory choices, setting out strategic directions, and delegating roles and responsibilities to lower system levels to plan and execute according to these goals. In effect, overwriting or modifying the first-order implementation rules, as needed. The feedback from lower system levels (and observed system) to senior leadership (a second-order observing paradigm) is a key part of the decision making process, where the presented information is used to broaden the variety of the leadership by gaining better insights into strategic level opportunities and threats, and allowing them to set the goals of the observed system towards preferable outcomes.

PAFTD advances current organizational management approaches, which looks at humans as noisy, fuzzy, and uncertain system elements that need to be risk mitigated. In current views, humans are more of a nuisance in the system that competent process and systems engineers need to factor in, to minimize uncertainties of the system. Humans are virtually animated systems, integral parts of the machinery, but can often perform tasks poorly, which negatively impacts system performance. This systems approach is far from being human centered. In comparison, PAFTD is a positive effort system, facilitating preferable outcomes, instead of squeezing more out of the impersonal machinery with fuzzy human elements. I believe that the simplifications and resulting model in PAFTD captures key elements and complexities of NASA's wicked problems, which then can be applied to initiate new conversations, and subsequently benefit technology development activities, drivers, and influences at NASA. Applying new models can also help with looking at the world from a new perspective, and improve conversations with the environment. This approach can facilitate unlearning and re-learning how we operate, and can lead to novel and preferable outcomes. The models we develop range from personal cognitive models to organizational models shared between members. We can change both personal and organizational models through learning. Within an organization this needs to be supported from the top down, from senior leadership. PAFTD represents a new strategic project assessment approach, where circular feedback loops through conversations—with internal and external stakeholders—aid a more systematic decision making process than used in todays project management practices.

The following sub-sections and Appendix B.2 consist of detailed discussions on the PAFTD tool, including a comparison of its capabilities with other project assessment methods and tools.

5.3.3. PAFTD Assessment Categories and Questions

A PAFTD assessment consists of semi-structured multi-nodal interviews with internal and external stakeholders from strategic and project levels, who are connected to the project being evaluated. Brett Depenprock, my collaborator on PAFTD and a Booz Allen analyst, who worked at the STMD Resource Management Office, compiled the standardized question sets for these conversations. The questions are derived from discussions with NASA STMD Senior Technical Advisors (including me at the time) and mid- and high-TRL Program Executives (Depenbrock, Balint, & Sheehy, 2015). The PAFTD categories addressed the design thinking categories of usability, feasibility, and viability. Subsequently, Deperbrock cross-mapped these categories to IPAO criteria, as it demonstrated alignment with existing NASA assessment processes, instead of creating yet another new evaluation process. (IPAO is NASA's Independent Program Assessment Office.)

Details about these PAFTD categories, IPAO criteria, and the cross-mapping of questions are provided in Appendix B.2.

5.3.4. Synthesizing and Scoring

Following the semi-structured interviews, consisting of the information-gathering phase from various stakeholders on the project performance, the PAFTD analyst scores the responses in order to quantify the results. For each question and response, a score of 3 denotes a "successful" rating, 2 is given for "partially successful" rating, and 1 for "not successful" rating. The success criteria are framed around the expectation that the maturity for a project under evaluation reflects efforts either approaching or already in an implementation phase. To use this Excel-based tool during the evaluation phase, the PAFTD analyst selects a key differentiator from each question via the drop-down menus in the "Success Level" column to characterize the success of the project across the three design thinking categories (i.e., usability, feasibility, and viability). Through the evaluation process, an updated snapshot of the raw scores captures the cumulative total of these questions, in a normalized form (i.e., dividing the accumulated points by the total points possible, and multiplying it by a weighting function for the three categories).

Weighting is the distribution of the category scores by percentage of the total score. Weighting impacts the overall assessment score of a project. PAFTD has been flexibly developed to allow the assessor (the analyst) to assign specific weight distributions, based on project development phase or assessor expertise. Because weighting can be changed, depending on the project phase or assessor subjectivity, the insight gleaned from the tool is most available in the categories and the questions that comprise them. As the framework evolves, and a number of projects are evaluated using it, the larger sample size will enable a fairer comparison of total score significance. Senior leadership must think critically when determining the significance of overall scores, as desired outcomes that comprise PAFTD may not be the optimized outcomes.

The main benefit of using PAFTD lies in the willingness to introduce novel methods, in this case through design conversations, that broadens the organizational paradigm and accommodates new processes that can provide strategic insights, and through it advance the success of the organization.

5.3.5. SoP Management Tools Used Inside and Outside of NASA

Monthly Reporting, Mid-year / End of Year / Continuation Reviews, and Earned Value Management (EVM): The PAFTD framework is a comprehensive platform for evaluating strategic areas of project performance. It is not intended to replicate or replace current proposal or reporting criteria. Proposal cost estimates tend to be overly optimistic, and financial and technical project reporting tend to be reactionary and to create linear tracks for management thinking. (*"In the competition for funding, it is expedient to exaggerate benefits, minimize costs, and downplay reliability and safety issues that hint at risk of failure or injury" (Jones, 2015, p10).*) Traditional methods of effect project management like monthly reporting, mid-year reviews, and Earned Value Management offer effective ways to track the financial and technical performance of a project, but do not provide the level of depth or scrutiny that PAFTD's provocative analysis yields. Given the complexity of managing technology development at a strategic level, STMD ought to rely on an innovative model to enable the creation of options for creative investment selection and assessment. STMD managers, especially at the strategic HQ level, delegate execution to a project, and consequently exercise less control over the day-to-day cost and schedule management. Once requirements are laid out, a project is selected and moves into an implementation phase. At times, reporting may overburden projects with limited resources (e.g., related to workforce and budget). PAFTD provides strategic level assessment that fills a gap and need for analysis performed at a HQ level, that complements project reporting from the project level.

Management Tools Used Outside of NASA: Management consulting firm Bain in its 2013 Management Tools and Trends publication offered that *"among the key lessons we've learned over the past 20 years is that executives need to champion an enduring strategy, find the right tools and then adapt the tools to the companies, not vice versa"* (Rigby & Bilodeau, 2013, p.8). The five tools that were used most often were Strategic Planning, Customer Relationship Management, Employee Engagement Surveys, Benchmarking and Balanced Scorecards (Dodgson, Gann, & Salter, 2008, p.125). PAFTD can also be viewed as a balanced scorecard.

It is a tool that helps managers to measure and improve performance. Robert Kaplan wrote in “Conceptual Foundations of a Balance Scorecard” that the *“balanced scorecard approach starts with strategy and then identifies the inter-relationships and objectives for various stakeholders, the stakeholder approach starts with stakeholder objectives and, in a second step, defines a strategy to meet shareholder expectations”* (Kaplan, 2010, p.14). Strategy is about choice.

5.3.6. PAFTD Outcomes and Testimonials

The PAFTD tool can be used to capture and identify strategic knowledge, related to the health and performance of a given project. It can also help to formulate Mission Directorate level strategy and communicate key aspects about the project to stakeholders at strategic levels. That is, locally within the Mission Directorate; regionally to the Agency, and globally to the Government. In addition, the captured knowledge can be used to communicate key findings from strategic levels to lower linear discipline levels (i.e., to the Level 2 Program Offices and to the Level 3 Projects). Due to its systematic and multi-disciplinary structure—addressing usability, feasibility and viability—it is less biased than findings, which are focusing on just a few aspects, such as project management and resource use history. Consequently, decisions based on the added knowledge through the use of PAFTD can drive strategic understanding and the subsequent actions to respond with the appropriate approach. Thus, risks to both the project and to the overall mission directorate portfolio can be minimized.

At STMD, PAFTD was briefed to senior leaders within the organization and used in 2015-16 by Depenbrock—a Booz Allen Hamilton analysts at the time, under contract at STMD—to aid organizational investment decision-making. Beside STMD, Booz Allen Hamilton has also leveraged the PAFTD framework to direct research, involving robust data collection and extensive interviews related to specifically identified technology projects. The weighted questions provided a guide to scrutinize collected data, and the analysts used key differentiators to identify the most thoughtful and defensible grades to judge a technology’s performance and projected health.

PAFTD has fostered a greater awareness of the need for STMD senior leadership to examine the external technology environment and to develop a focus on a mid- and high-TRL technology pipeline that would harness increased flexibility and broader impact now and into the future. The comprehensive nature of PAFTD has facilitated more stringent technology readiness assessments, established more defined thresholds for enforcing reviews of poor project performance, and instituted clearer and more consistent processes for traceability. For example, PAFTD informed one senior manager about the need to have constraints set into a Center-led project, that would not allow it to be continually pushed out (i.e., senior management identified the need for setting a hard launch date for the project). In another instance, PAFTD informed a senior manager about a competing and similar technology development effort, being conducted by the European Space Agency (ESA), which may have had an effect on STMD value proposition regarding a ongoing and similar investment in the portfolio.

To substantiate the utility and benefits of PAFTD, I have obtained testimonials from three people closely connected to the development or the use of this project assessment tool. They are:

- *Brett Depenbrock*—former Booz Allen contractor who worked at the Resource Management Office of the Space Technology Mission Directorate at NASA HQ, and was a collaborator on developing PAFTD;
- *Patrick Murphy*—Director of the Project Management Office, and Member of STMD's Strategic Leadership Team; NASA HQ Space Technology Mission Directorate;
- *Frederic C. Baker*—Director of Space and Missile Systems, Meggitt PLC.

I am providing relevant extracts from their letters, and including the unedited testimonials in Appendix B.7.

Brett Depenbrock, my collaborator on the PAFTD tool development, explained (Depenbrock, 2016):

- *"Booz Allen and NASA endorsed the use of the framework, and its name was formally utilized on Statement of Work (SOW) documents. These SOWs required the use of PAFTD as part of specified deliverables on two different task orders."*
- *"Depenbrock conducted interviews, analyzed and synthesized the collected information, and presented it to senior leadership."*
- *"It is apparent that the work was valued, because Depenbrock was asked to return for a second task order from July 2015-July 2016, to continue providing a similar value stream."*
- *"It is important to note that within NASA a number of factors drove decision-making surrounding technology investment projects. Although Depenbrock's deliverables provided substantial influence, the insights gained from PAFTD assessments could not control the ultimate decisions leaders might make regarding a certain project. Those final project-related management decisions were made as a result of multiple inputs, including project reporting, PAFTD analysis, organizational strategies, and others."*

Patrick Murphy, the RMO Director stated (Murphy, 2016):

- *"The PAFTD tool shows real promise." It "… went beyond the typical project assessment approach…"*
- *"A large sample of our Space Technology Projects from both the Technology Demonstration Missions (TDM) and Game Changing Developments (GCD) projects were assessed by the PAFTD analyst (Brett Dependbrock). Using the PAFTD tool, the interviews were synthesized and briefed senior leadership on the findings."*
- *"The real value of the PAFTD tool was that the design was NOT to replace this project reporting, but to augment project related information from a strategic level, independently from project reporting." "The unique feature about the PAFTD tool is it used interview data from project team members at both a project and strategic level."*
- *"The results were significant, they provided additional insights, independently from project reporting and gave a broader understanding which helped senior leadership to make better informed choices. The biggest value of the PAFTD is that it does not replace traditional project reporting processes, but rather, it augments it."*

In the capacity of a "user" of the tool for future applications external to NASA, Frederic Baker—the Space and Missile Systems Director at Meggitt PLC—provided a testimonial about the influence of this design and cybernetic approach on his strategic activities (Baker, 2016). He first met with Depenprock at the IEEE Aerospace conference to discuss the PAFTD framework presented in (Depenbrock, Balint & Sheehy, 2015). Subsequently I had a meeting with him at the IAC-15 Conference in Jerusalem to further discuss the tool and its strategic potential, which was also documented in (Balint, Depenbrock & Stevens, 2015).

- Baker was interested in the tool, for *"…leveraging our corporation's competencies and capabilities across divers business units (5, in this case), to optimize growth, performance, market capture and portfolio prioritization within the sector under my responsibility as Director – Space and Missile Systems and I was fortuitous enough to have noticed this paper within the proceedings."*
- *"My attention was drawn to the potential of the tool to support my intention as a Swiss-based subsidiary of a FTSE-100 corporation to drive our Space sector strategy and vision."*
- *"The 'usability', 'feasibility' and 'viability' focus category questions provided an excellent place to start for holding this inter- and intra-SBU conversation and for communicating its importance to upper management. Where necessary, I replaced the TRL-relevant and US government offices (i.e., OMB, GAO, OSTP) questions applied to the NASA context with related technical maturity level and governance driver questions based upon our product heritage and development approaches. This was necessary due to the fact that we're a publicly-traded corporation and not a government agency."*
- *"Personally, the 'viability' questions were the most important part of the tool for me (pertaining, particularly, to the multiple 'wicked problems' I was facing) related to my corporate strategic needs since the management, budget, schedule and risk topics/areas would be the most challenging toward growing the sector for the corporation as the execution mastery of the answers arrived at would prove to be the 'nexus' of success of the health and performance of our future Space projects' and products' ecosystem. The prioritization success of our Space project and product executions were greatly reliant upon the effective communication, management strategies and subsequent 'buy-in' of the diverse decision makers across the management hierarchy within the five different SBUs of the corporation, ergo, successfully addressing the 'viability' topics provided the highest-weighted arguments to move this into the realm of development priority."*
- *"As my employer was in the middle of a 10-year strategy and future growth 'search and deploy' frenzy, beginning in March of 2015 and extending through June of the same year, the contents presented within this paper were fortuitously of direct value to me and I began implementing its approach."*
- He stated: *"I was particularly intrigued by your notion of integrating a cybernetic approach within the process. This is what you call, if I've understood it correctly, the 'cybernetic circularity and design dialog' process of the PAFTD tool. I had not yet been aware of this unique approach to successfully establishing a more focused and coherent process toward developing a company's strategic technology and market-driven portfolio and believed it had great merit to explore."*
- *"The dialog aspect of the tool was of particular interest containing great value as the majority of strategic directions embarked upon by many corporations are based on but a few human interactions from within their ecosystem and, generally, by those with "quantified" heritage,"*

- *"This approach supported the conversations I had already begun across the SBUs with a coherence, focus and practicality to which I could point for credibility and consistency."*
- *"Since the company's greatest challenges were/are to prioritize, select and manage technology and internal R&D investments within an annually-constrained financial system, I was excited to leverage the insights gained from the PAFTD tool to facilitate this selection and decision-making process."*
- *"With respect to having 'validated' the tool, I can unequivocally state that I, through the best of my abilities within a resource-constrained and limited "big-picture" ecosystem within which the Space sector is not the company's primary focus, effectively applied and implemented the PAFTD tool and its relevant questions from the three different categories, 'usability', 'feasibility' and 'viability' with successful results."*
- *"The importance to applying this new 'technology' of incorporating both a design dialog and cybernetic approach is invaluable as it addresses a comprehensive environment of human relational, resource-driven, management and externally-driven data points, imperative for the successful prioritization of strategically-driven technology investments."*
- *"The PAFTD tool, as presented within the references cited, opens the door for a new process while empowering all team members with a participatory, contributory, effective and, dare I say, 'holistic' perspective to improving the overall chances of success of this engagement and its end results. The tool's implementation provides for a successful path away from the simply linear and often ineffective prioritization approach toward incorporating a cybernetic, multifaceted, relational, empowering, conscious, dynamic and optimized approach enhancing the overall chances of success of the stated objectives."*

5.3.7. Current Status of the PAFTD Tool

Within NASA STMD: *"Since the demonstration of the PAFTD tool, the PAFTD analyst, has left STMD to pursue gradschool at the University of Maryland. In tandem the STMD leadership continues to remain dynamic and has changed; currently there is no champion to push help PAFTD tool* (Murphy, 2016)*." "Without a champion, the future of PAFTD is currently uncertain at these organizations* (Depenbrock, 2016)*."*

Outside of NASA: *"Given the fact that I had just, single-handedly, begun the process for effectively defining and prioritizing the Space sector's future directions across the next 10-15 years, both internally and in conjunction with our external partners, I can also state that we were off to a great start. Among the successes is a multi-national, multi-stakeholder, cross-SBU program for an external client which would not have been materially possible without my having come across this new approach of a design dialog and cybernetic 'technology' (Baker, 2016)."*

5.4. Epilogue to PAFTD

Innovation focused technology development involves funding and managing a portfolio of loosely coupled projects through their project life-cycles. An organization and its projects are influenced by diverse internal and external factors, often beyond the institutional needs, and the typical linear disciplines of technical feasibility, cost, and schedule. Within an organization, at a higher strategic level, for example at NASA HQ and at Meggitt PLC, the influencing factors and trade-offs form spatially and temporally coupled wicked problems, and are often unique and not understood until a solution is formulated. This presents a touch point, where a novel process can advance the state of the art. Thus, to overcome these challenges, a combination of cybernetics, human centeredness, design thinking and design conversations were introduced to the project assessment process, which benefited senior leadership with portfolio management, future planning, and resulted in closer ties with stakeholders. Organizations are dynamic systems, where the performance of the projects frequently deviates from the initial plans throughout the projects lifecycle, due to the unmatched variety between management (the regulators), the projects, and the environment. Thus regular strategic-level project performance assessments are required, which go beyond linear project management and reporting approaches. To achieve this goal, with my collaborator, Depenbrock, we have developed the Project Assessment Framework Through Design (PAFTD) tool. PAFTD addresses the need to dynamically assess the performance of high- and mid-TRL technology projects. It is easy to use and customize. PAFTD can be used to assess internal and external root causes of project performance at NASA Centers, at Federally Funded Research and Development Centers (FFRDCs), and at external organizations. The PAFTD framework aligns with the Viable System Model (VSM). PAFTD-based assessments enable dynamic performance trend modeling, and assessment of option trade spaces.

PAFTD is typically executed by a resource analyst or strategic analyst. The tool is based on conversations with various stakeholders, where the analyst inquires into aspects of the project from a strategic perspective. These conversations are semi-structured interviews. The analysts converses with Project Management and team members to validate the information presented to the strategic levels by the project. The analyst converses with Program Executives at the strategic level to understand internal strategic considerations. Also, conversations are conducted with external entities, such as contractors, strategic policy makers, and stakeholders to understand potential strategic changes, trends, threats, opportunities related to the project. Once all the information is collected from the interviews and other primary and secondary sources, the analyst processes the information (attenuates variety), and presents it to Senior Leadership at VSM's highest System 5 level. The attenuated information augments the linear project level reporting with strategic content, which broadens the variety of the strategic decision makers, who in turn can have a broader understanding of the project environment at a strategic level. This approach makes strategic decision-making more transparent and traceable, compared to the current *ad hoc* approach where strategic level information is covered at the discretion of senior leadership. Based on PAFTD's performance measures, senior leadership can reassess and if needed modify the goals of the system, and prioritize investments that contribute to well-calibrated and optimized outcomes.

One criticism of the PAFTD tool and process is related to the cognitive bias of the analyst, who collects the information through conversations, then analyzes and synthesizes the data, and presents the relevant information—representing the broadened strategic variety—to senior leadership. It is a valid point, and it draws attention to the importance of employing analysts with a broad variety, who are familiar with all aspects of the projects in the technology portfolio.

Looking at the future of PAFTD, as it evolves, both Depenbrock and I believe that the tool would benefit from assistance from data science and machine learning that have made CB Insights' Mosaic tool an extremely valuable resource for venture capitalists, corporate strategists, and entrepreneurs. Mosaic is an evidence-based, statistically driven software that ingests large amounts of data to objectively assess and predict private company health. The Mosaic score uses dozens of signals, including the quantity and quality of job postings, web traffic, social media chatter, executive turnover, customer signings, mobile app data, and news sentiment (CB Insights, 2015). PAFTD's approach—based on usability, feasibility, viability, design conversations, and cybernetics—was found to accurately assess and predicts space technology investment health. It should be also noted that the applicability of PAFTD is not limited to NASA, as attested by Baker (Baker, 2016). The questionnaires can be reworked to any other organizational environment to support strategic decision-making at other disciplines. This is second-order cybernetics related decision-making, where the observing system at the strategic level can modify the goals of the observed system at the project level. It should be noted, however, that the PAFTD analysis interviews, data analysis and synthesis, are performed by the analyst within the first-order observed domain.

Ultimately, PAFTD aims to harness the multitude of options that managers can employ to influence optimized outcomes. In effect, its goal is to improve the management of the system. Central to the model's backbone is the ability of an organization to diagnose its success criteria. Given the tendency for technology development leaders to set ambitious goals, PAFTD supports a useful mechanism to foster increased accountability, communications, traceability, realistic expectations about organizational capabilities, and competition. It serves to provide a simplified means of performance measurement to create urgency for innovation and to begin the diagnosis of appropriate strategies to achieve lasting success.

Section 6.

Example-2: Towards Humanly Space Habitat Guidelines

Cybernetic Astronaut Chair (Steel rods–Paracord–Canvas / 2015)

6.1. Prologue to Humanly Space Habitats

In a broadened sense, for human spaceflight we can identify four distinct paradigms with very different characteristics (Sherwood, 2015). These are paradigms for:

- *Exploration:* where the goal is to take a small trained professional crew of 4 or 6 to distant and unexplored parts of our solar system. In the past, the Apollo program took astronauts to the Moon, today we are planning for a human mission to Mars within a few decades.
- *Exploitation:* where planetary resources can be extracted for commercial gains. It is building on the scientific findings that asteroids and the Moon has diverse material resources, which under this paradigm are expected to provide economic returns for commercial ventures. This activity would involve groups of construction and maintenance workers, measured in the tens to hundreds, who would be stationed at geostationary orbit.
- *Experiencing spaceflight by everyday people:* where tens or hundreds of thousands of people could take trips to low Earth orbit.
- *Colonization:* where the metric is the number of families taken from Earth to their new space-based or planetary surface-based homes, leading to an initially small colony of hundreds of families living on the Moon, within less than a century.

Each of these paradigms has different characteristics, requiring different technologies and investment strategies. Since my research focuses on NASA's activities and related touch points, I will limit my discussions to the exploration paradigm, discussing the state of practice, and arguing for a more prominently integrated use of human centered design and space mission architectures for future human spaceflight.

Looking at NASA from an organizational point of view, human exploration related activities are performed at the Human Exploration and Operations Mission Directorate (HEOMD). Within HEOMD the Advanced Exploration Systems (AES) champions new technology solutions, which will enable future human exploration missions. AES is currently involved with the development of over two dozen technology projects, including habitat technologies on the International Space Station (ISS), and habitation systems to Mars (Moore, 2015). HEOMD recently completed a document titled "NASA's Journey to Mars" (NASA HQ, 2015), which highlights a human spaceflight strategy to Mars with a flexible and evolvable path. This is a top-level strategy at this point, which targets decision makers both in Washington DC and at other space agencies around the world, and the aerospace industry. The report only focuses on top level strategy for the next 20 years, without much details, but it informs the Executive and Legislative branches of the US government on NASA's proposed plans, which subsequently will be negotiated for funding. Details on funding processes are provided in Appendix B.1.

Also within HEOMD, the Human Research Program (HRP) focuses on the mission crew and their interactions between their space habitats, the broader space environment, and the ground-based support. Within HRP the researchers look at space human factors and habitability, the next generation human exploration vehicles by addressing crew autonomy, isolation and communication, medical care and healthcare (may these be preventative or treatment related), environmental factors in terms of the air, water, acoustics, or other factors like the impact of external terrestrial dust on the crew. They also look at behavioral health and performance, team composition and cohesion, biomedical or metal health aspects, the circadian rhythms and sleep deprivation, workload, and scheduling. The research identifies research gaps, requirements, and standards before establishing a new program for it, in a budget limited environment (Davison, 2015).

HRP addresses crew related issues through evidence-based risk evaluation architecture, with approximately 30 sets of risks. These risks are then broken down to a set of research areas and are being addressed systematically. The current approach addressing these risks within HRP is similar to an engineering method, with a structured breakdown of the research gaps, leading to mitigating technologies and countermeasures. The work is done nationally through competitions, utilizing the National Research Infrastructure for research announcements, then work is carried out with subject matter experts to mitigate the risk areas. These risks can be categorized in multiple ways. There are external medical risks of sending a human into space where they are exposed to the extreme environments of space, and the internal risks of being a human, where they can get sick naturally during the mission. The risks and research areas address both physiological and psychological needs of the crew, including risks they encounter on a deep space mission, from food, water and toxic buildups to isolation and confinement hazards. Through integrated solutions and approaches some of the resulting technologies may address coupled risk elements. For example, growing plants onboard a space habitat can address psychological needs and wellbeing, while providing food for the crew (Whitmore, 2015)(Connors et al., 1985, p.78). HRP also has a human health risk board, with two identified risks. One is associated with human system interaction design and the other is related to behavioral health. Team cohesion on a long-duration autonomous mission beyond earth orbit is a red (high) risk. Once a risk is identified as a requirement, the designers and engineers have to account for it (Davison, 2015). Thus, to account for new HCD needs—for example self-actualization needs—we have to include well-defined HCD requirements into the set of considerations, which can be derived from new guidelines, based on terrestrial analog studies (e.g., HI-SEAS and Antarctic stations), and human spaceflight related past experiences.

The challenge for designers, architects, and even experts from the Human Research Program is to convert the guidelines and requirements meaningfully, so engineers can understand them, and subsequently can design systems that are verifiable in an engineering sense (Whitmore, 2015). Engineering requirements conform to pass / fail decisions. Human aspects are considered fuzzy, not black or white. It is difficult to put numbers against them, and they are context dependent. The current research focus is related to the minimum acceptable habitat volume for the crew. The test volumes have to be tested against tasks, which range from working, eating, social aspects, and crew size. The answer will drive the next generation of habitat designs (Craig, 2015). Thus, the program not only focuses on volumes and tasks, but also address processes thorough computational tools for engineers that can aid them to assess the trade space through “what if” scenarios. Providing tools, methods or processes to the engineering team may ensure that the human centered requirements are accounted for and implemented in the final point design.

Under HEOMD and support from STMD, HRP coordinates with the Spaceflight Program and Crew Health and Safety Program. (On a side note, which will be further explored in Appendix D.2.3, language plays an important role within organizations. For example, beside the information provided in the previous sentence, this sentence also encapsulates a specialized language used continuously at NASA. This shorthand aids communications; it also locks in the variety to a paradigm that proves to be a barrier for new ideas. In a way, this language and associated paradigm leads to an epistemological barrier, where certain aspects of human centeredness are not observed and accounted for.)

In response, for this example I discuss human centered design related aspects of space habitats, the current state of practice, and propose areas where designerly and artistic modes of operations can be used to augment NASA's current operating mode. Introducing these new operating modes can broaden today's paradigm by addressing higher-level needs in Maslow's Hierarchy of Needs, such as self-actualization needs (Maslow, 1970, p.46). As a caveat, in this section I am not intending to provide a comprehensive overview of technical solutions and architectures for human missions. Instead, I am making a case for the development and inclusion of new guidelines for long-duration human space habitats that focuses on higher-level needs through new modes of operations. In doing so, it needs to be recognized that adding any new guidelines and requirements to the current modes of operation would contribute to the combined effect caused by physiological, psychological, interpersonal, and habitability related stressors (Connors et al., 1985, p.94-104), which will have to be addressed and resolved in subsequent research.

6.1.1. Space Architecture and Design

Engineers are often excellent analytical thinkers, as their work demands that kind of approach. They can break down problems to sub-categories, find solutions, and address well-defined requirements. In their regulatory role, they converge to optimal solutions within well-defined bounds. The work of engineers on system architectures, systems engineering and space architectures are closely related, as all of these disciplines have to consider the whole. However, systems engineering works on component technologies then integrate them into a system of systems as the development progresses. Engineering tends to focus on the hardware and software part of the spacecraft, leaving out human systems engineering or human systems integration. This leads to an outcome where adjustments and corrections are required at the end of the process to account for some humanly aspects of the design, at a development stage when the system is already being designed, built and tested towards its engineering requirements. A good example is the International Space Station (ISS), where we have learned and understood through over 16 years of operational experience that including human centered considerations in the system of systems provides a better living and working experience for the crew. The ISS was built as a space laboratory, with its focus and configuration to serve that function, while lacking the attention on the human experience. In a terrestrial environment our working and living spaces are clearly separated and configured differently. That is, we work at and live in different places, customized and configured for those specific human needs (Toups, 2015). Similarly, long-duration spaceflight must build on both terrestrial and ISS experiences, where the crew's human centered space habitat accounts for the human experience aspects as well, beyond mission goals related scenarios and functions.

This is where designers and architects can add significant value to the design and development process, because they are complementary to engineering, while looking at the same problem from different perspectives and different strategies. They propose changes to the goals of the system by inventing new requirements, often think outside a given paradigm, consider integration from the earliest development stage, and prototype solutions through iterative means and synthesis. This conversation through multiple iteration cycles of sense-giving and sense-making guides the designs towards novel and desired outcomes, aligned with the system goals. They start with the big picture about how the various elements are connected. A space architect looks at three closely interwoven areas, the human crew, the hardware, and the software (Kennedy, 2015). Designers and architects by definition have a human centered approach. When architects design a house, they design it for the people who live in it, without dictating a personal architectural style. Instead, they work with their clients, making them the center of the design. Many of the architectural principles used by space architects are based on terrestrial experiences, which evolved over thousands of years (Kennedy, 2015). Thus, when designing for space, designers and architects look at it from the perspective of the crew, and how they interact with the various aspects of the mission. They place importance on the interfaces between the astronauts and their habitats, ranging from transfer vehicles to the habitation systems and environment. They design for the psychological and physiological wellbeing of the crewmembers, and how the habitation volume is used (Bannova, 2015). In comparison, hard core engineering does not have requirements for psychological needs—such gray and fuzzy disciplines—which are lacking clearly defined metrics and requirements compared to engineering (Guidi, 2015).

From a stylistic point of view, some may cast space architecture under modernism or post-modernism, but historically, over the past 50 years, human space exploration mission architectures have been predominantly driven by engineering, including the transportation system capabilities to deliver assets to space, and mission costs (Kennedy, 2015). Science missions helped us to better understand the environment, and technologies supported mission functions and provided needed capabilities. Current and future technologies will be able to keep us on this trajectory, but it is becoming increasingly insufficient as we march towards a long-duration human mission to Mars. This mission will require new considerations, which should make human centered design the focal point, leveraging technological solutions around human needs, addressing both basic and high level needs on Maslow's hierarchy. The interactions between humans, their artifacts, immediate environment, habitat, and broader space environment will become crucial to achieve mission success.

Space architecture brings a holistic picture to the entire end-to-end mission. NASA is in an early conceptual development phase for these future human exploration missions to Mars, where the mission trades are still open, and without looking at the fine details. At this stage the variety has to be kept as broad as possible, to allow for flexibility down the road. At this stage it is important to have the appropriate guidelines and requirements for the missions, and systematically work towards addressing them. Having the right guidelines is key, as it allows the teams to develop the mission architecture elements. For example, the ISS included governing documents with requirements on the "flight crew integration habitability hardware," such as the crew quarter and the galley. Today these are called human factors requirements (Whitmore, 2015). Thus to have any new aspects of human centered design incorporated into future habitat designs, we need to have guidelines, which subsequently can be converted into requirements. Then, these have to be included in the governing documents as part of the habitat designing and building process.

In the commercial world, designers and architects are working in an interdisciplinary environment. In their "umbrella function," they oversee and guide the development process. They have a very different strategy from the one used by engineers and scientists. *"The essential difference between these two strategies is that while the scientists focus their attention on discovering rules, the architects were obsessed with achieving the desired* *results"* (Cross, 2007, p.23). Similarly, engineers operate within the well-defined rules of the phenomenal world. Accordingly, the engineering design process places an emphasis on analysis and works towards something that actually is operative. In comparison, the architectural approach is more aligned with synthesis and responds with an outcome that satisfies the system's goal. For example, an architect coordinates with engineers, the mechanical systems, accommodates design, and works with structural experts (Toups, 2015) and converges towards a desired outcome. It is different at NASA, where in line with its current worldview, space architecture related activities are predominantly systems engineering and integrated thinking driven. The engineering approach led to a subdivision of disciplines, guided by hard requirements and implemented by engineers and managers. The small group of designers and architects at NASA do not have an umbrella function overseeing and guiding the end-to-end design process (Kennedy, 2015). They need to speak the language of the engineers to be understood. They are involved mostly in the early formulation phases, but only as yet another represented discipline and not in guiding and leading positions. They work as integrators, not as designers of the habitat. Furthermore, due to resource constraints, which necessitates keeping the development cost low, detailed human centered considerations are not included in the early feasibility assessments and mission concepts studies, although, crew health and performance related research is ongoing. According to this approach, once the mission costs, bounding engineering, and technological aspects are understood, follow up design iterations are expected to look at more detailed designs. This includes increasingly more human centeredness. Larry Toups (Toups, 2015), a space architect at NASA JSC, compared it to building the foundation of a cathedral. If architects are involved with creating a strong foundation, then there is a hope that the cathedral will be built successfully. This analogy, however, is wistful thinking. Design and architectural guidance is required throughout the full process, involving conversations and coordination between the various disciplines. A systems approach with sub-systems developed within their own disciplines then integrated into system of systems propagates margins, requirement mismatch, and other undesired effects, and can lead to over-designed, expensive and sub-optimal outcomes. They may fulfill individual functional requirements, but can lead to complications, unwanted complexities, and cost overruns. Yet these designs would miss out on key aspects, such as human centeredness, which are hard or even impossible to retrofit.

While mission critical, functional, and safety aspects of the crew are included in the design reference architectures and mission studies, these requirements don't account for higher-level human centered needs (Craig, 2015). Space architects, designers, and even top managers acknowledge the need for more human centeredness, but refer to them as something that needs to be addressed at a later development stage, when a point design for a Mars mission is chosen. This affords me to propose a case now for new guidelines and requirements for higher-level self-actualization needs. These can be considered, adopted and further developed for NASA, to benefit future long-duration human deep space missions.

6.1.2. Human Centered Design

At NASA, human centered design addresses ways to mitigate the risks and challenges for the users involved with space exploration, with a focus on their mission goals related productivity and well being. HRP, through its risk-based architecture, looks at the capabilities and constraints of these users, including not only the crew who are living and working in space, but also their terrestrial counterparts, such as the maintenance and support personnel, engineers, and controllers involved with the missions. Over the past decades a significant amount of work has been carried out both inside and outside NASA to incorporate HCD into the formulation, development and operations phases of the mission (Davison, 2015). My intent is not to duplicate this effort, but to augment it with a seemingly missing dimension related to the vitruvian delight, discussed in Section 1.3. In the context of this example, this refers to higher-level needs in Maslow's hierarchy, which is relevant to the crew on long-duration spaceflight.

Engineering optimizations and designs often claim to be human centered, because they include some of the design considerations used by designers. For example, engineers may consider separation and co-location of objects and habitat elements inside a habitat-volume to map the option trades. These software-based trade space exploration tools are still engineering solutions, solving optimization routines. Yet, they barely scratch the surface of human centeredness at best, and at times they can be misleading or misrepresenting HCD. While engineering systems perform to specifications, humans are more diverse. They come with different mindsets, physical conditions, health, yet can complement each other, and provide expected or unexpected solutions to solve problems, which can greatly benefit a mission. Human centered designers can prototype these interactions through multiple divergence/convergence; analysis/synthesis; and sense-giving/sense-making cycles, and converge to a desired outcome through conversations with the users, designers, and even through objects during the prototyping process. HCD is a non-linear development process. At the same time, the level of human centeredness varies across NASA. Clearly, a robotic mission to a planetary destination has limited human centeredness, but it can focus on the user experience and interaction design elements between the received information and the scientist or engineers. In turn, on a human exploration mission the crew's interaction with the habitat is fully human centered.

It is evident that the basic needs for safety and survivability of the crew are required, regardless of any other consideration. These requirements are well-defined and straight forward to address through engineering means. On a deep space mission, it can be expected that mission success related workloads on the crewmembers will vary throughout the trip. Around critical mission events, such as departure from Earth, arriving to Mars, landing and ascending, the workload and mission critical activities will dominate the crew's time (Bannova, 2015). These can be addressed through technologies and HRP-developed solutions. During the cruise phase, between the planets, and for parts of the surface mission there will be additional personal time, which is important for the crew's psychological wellbeing. Mission planners believe that free time will be highly limited, during which time astronauts can be gainfully kept occupied with training and learning for the upcoming Mars surface mission (Davison, 2015). This assumption can easily introduce difficulties for the highly educated crew, forced into an existence where only their basic needs are met, and combined with non-stop work over a multi-year long trip.

This work/sleep/train paradigm is not addressing the crew's higher-level needs, which can be called their vitruvian delight. Astronauts have to be in an appropriately balanced environment that also caters to their higher-level needs. Consequently, designers and architects and subject matter experts from other human centered disciplines have to work with the engineering community to include opportunities and variety for the crew that enables self-actualization. A well-established balance between work and personal activities maintains a performative, active brain and psychological wellbeing thus reduces the risk of negative impacts to the mission.

Requirements and guidelines for specific higher-level needs should have a different metric from basic physiological needs and functional psychological needs. To address the vitruvian delight element for the crew, these higher-level needs should not be explicit point-design requirements. Instead, the delight element can be achieved by building variety into the system that affords discovery by the crew. Designing and accommodating system elements inside the habitat with a humanly approach opens up the creativity, and enables the delight elements to be discovered, explored and experienced. It facilitates the conversations between an astronaut and the environment, and between crewmembers, at a higher-level in Maslow's hierarchy. For these considerations it is challenging to gain acceptance from engineers and managers, who are operating within the current engineering paradigm. But it can be foreseen that without a paradigm shift to incorporate a higher-level of human centeredness, future long-duration missions can lead to unforeseen complications from the crew's perspective.

The key aspect to achieve human centeredness in space design and space architecture is to embrace it in the early stage of the design, allowing to guide it toward the principle of human integration from the beginning, and establish NASA standards for human systems engineering and integration. This has to happen through the forcing function of new NASA Procedural Requirements (NPR), and an updated NASA Systems Engineering Handbook, which mandates compliance with the requirements by the projects.

The benefits of human centeredness on these missions are bifurcated. So far, the discussion focused forward on the impact on the crew and the mission. But there is an inverse benefit from these humanly space experiences. In certain ways, space architecture and design are more challenging than those for terrestrial applications. This is due to the engineering constraints to deal with the extreme environments and the need for sustainability (Bannova, 2015). But there are other differences as well. On exploration type missions, the crew would not be a typical representation of a broad cross-section of the terrestrial population. The astronauts would be in peak physical and mental conditions, about the same age, well trained to deal with the harsh environmental conditions, psychologically balanced. Yet, they will still be individuals with differences, which would make the spaceflight a human centered experience. Tracking human behavior and conditions in high detail, over a multi-year mission, in a highly demanding extreme environment, would teach us about being human. Applying these experiences back to terrestrial design and architecture can lead to unexpected new directions. This can range from personal spaces in overpopulated areas, to remote scientific stations in arctic regions. It can impact the designs of elderly homes, hospital wards and even correctional facilities.

6.1.3. Physiological, Psychological, and Self-Actualization Needs

When addressing the impact of spaceflight conditions on crew behavior, it is important to identify the relevant stressors, and how these interact with each other. There are four known types of stressors in space: physiological, psychological, interpersonal, and those related to habitability (Connors et al., 1985, p.94-104). These stressors can hypothetically interact in three different ways: *"by addition, when the physiological effects of multiple stressors are equal to the linear sum of the single effects; by synergism, when the combined effects are greater than the simple sum of effects; or by antagonism, when the total effect is less than the linear sum, of the single effects"* (Connors et al., 1985, p.95). It has been also recognized that conditions of isolation and confinement can intensify the impact of stressors on long-duration spaceflight. Palinkas also reported on three psychological domains of behavior: the individual domain (e.g., stress related performance, emotions, cognitive performance, coping styles); the interpersonal domain (e.g., crew and ground dynamics and interactions, diversity, leadership); and the organizational domain (e.g., impacts of organizational culture, managerial requirements) (Palinkas, 2001, p.25). (A comprehensive list of stressors is tabulated in (Morphew, 2001, p.75).) These stressors for astronauts are not different from those related to general human needs, which range from basic physiological needs through psychological needs to self-actualization needs (Maslow, 1970, p.46), as described by Abraham Maslow, and discussed in Section 3.2.7. Building on this, in Figure 6.1, I have mapped Maslow's HoN into relevant astronaut support systems. Basic needs can be addressed through engineering and technological means. Metabolic needs, including food, water, and air, are sustained by the Environmental Control and Life Support System (ECLSS). The habitat and the space suit provide protection against the extreme environments. Astronaut safety is provided by shelter from radiation, sensors and alarms, system autonomy, health monitoring, communication systems, an escape pod on short-duration missions (which is not an option on a long-duration mission), and support from ground control. These technological solutions, however, may not sufficiently alter the perceived risk of living in this hostile space environment, which also includes various internal and external environmental hazards and limited supplies (Palinkas, 2001, p.25).

Today's mission planners recognize the importance and address the crew's psychological wellbeing. Growing plants and maintaining a greenhouse would not only address food and nutrition needs, but also contribute to psychological well-being, emotional satisfaction and team dynamics with lots of mutual benefits. Plants or even fish can make the environment more delightful for the astronauts (Davison, 2015). Love, belonging and esteem are also addressed through activities and interactions, in HRP researched risk mitigation. It is recognized through the current habitat design paradigm that the habitation environment has to be efficient, practical, comforting and accommodating in terms of the crew's behavioral needs. NASA is looking into the medical effects on an 1,100-day space mission. Recent HRP studies identified the need to go beyond basic needs, and design a system that keeps humans happily

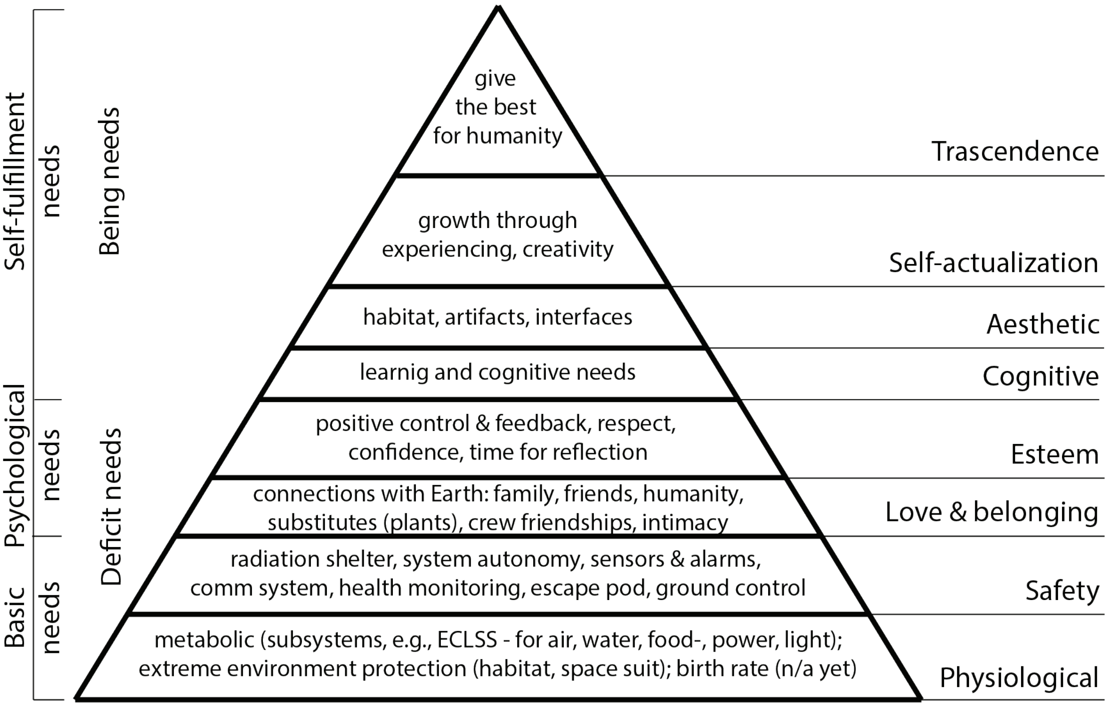


Figure 6.1: Maslow's HoN mapped into astronaut needs and risk mitigation responses (Balint & Hall, 2016).

alive and productive during the two years mission to Mars and back. NASA also has metrics on usability, operability, and fatigue (Whitmore, 2015).

Astronaut needs include response capabilities to medical emergencies, without taking an emergency room on the mission. Space human factors and habitability looks at human-system interactions, motor performance, how astronauts interact with the spacecraft, the computer systems, and displays. It includes basic ergonomic layout, reconfigurability of the habitat for certain activities within a limited volume, while maintaining a multi-use capability. Food emerges as an important habitability consideration in many confinement situations (Connors et al., 1985, p.98). Nutrition and food intake is another key element, not only to have the right nutrition, but also to provide tasty and enjoyable food experiences, which in turn translates to good health and a good psychological team environment during the mission. From these perspectives NASA addresses human centeredness, but these are still at the lower end of Maslow's Hierarchy of Needs.

Psychological wellbeing of the astronauts has to be addressed as it may result in mission failure, or loss of the mission, although not necessarily the loss of the crew. The Apollo mission was driven by hard-core engineering, with little attention to human centered design. It involved relatively short-duration missions with military fighter pilots, who were trained for harsh and regimented routines. A future Mars mission will have a mixed group of non-military astronauts, combined with long mission duration, while being isolated from Earth. The emerging psychological stressors can be influenced among other options by scheduling and planning, recreational activities including personal and group times, group dynamics and hierarchy, the habitat environment, including lighting and noise, meals, odors, hygiene, exercise. Designing for a multi-cultural and multi-national crew has its own challenges. Signifiers often vary between cultures, which introduce different meanings. Certain colors, words, behavioral responses can influence crew interactions. Many of these challenges can be overcome by training the crew together over a long period of time.

The current mindset on crew activities assumes that they will have limited time to spare. Crew training is expected to use up much of their free time during the mission (Davison, 2015). At the same time, temporal and spatial aspects of spaceflight present psychological, cognitive and perceptional challenges to the crew. The concept of Home will shift from the Earth to near-Earth, then to no-man's land during transit, to near-Mars, and on Mars. This can become a psychological stressor, that can be addressed through humanly design of the habitat. The diurnal cycle has to be artificially maintained during the long transits through artificial lighting. On Mars the day-night cycles are slightly longer than that on Earth. The crew has to adjust to it, against their lifelong terrestrial experiences. The constrained habitat volume can be mitigated through the use of visual and augmented reality, and artificial or real windows. Design and art should play a significant role in developing these solutions, as these can heighten emotional crew responses (see Appendix C). These can provide a delight element, and contribute to the psychological wellbeing of the crew during the long-duration mission.

Happiness and delight are not part of HRP's research elements. HRP's main focus is on behavioral health and performance. However, some discussions notionally identified the need for self-actualization related considerations (Davison, 2015) (Whitmore, 2015)(Howard, 2015). While it is not yet studied at NASA, it will be the focus of the discussion below.

6.2. Today's Space Design Elements

Today's human space exploration involves ongoing near Earth missions, and preparations for future deep space missions, leading to a crewed mission to Mars. Human space missions are not routine. They are complex, extreme, risky, and expensive. They require transport systems from Earth to orbit, and habitation assets in space. Today, we use human rated chemical rockets to take astronauts to orbit and back, and utilize the International Space Station as both a habitat and a research laboratory. Deep space missions need similar functions, but different configurations and engineering systems from the ISS, with increased reliability and enhanced habitability. For example, the Orion capsule, under development, is designed to go around the Moon on a weeklong or longer mission. It will return on a higher velocity trajectory compared to returning from the low Earth orbit of the ISS. The ISS return is also shorter, less than half a day. This necessitates a different habitability solution from an ISS transfer capsule, better protection for the crew, including high g-loads and vibration. Surface habitat designs for the Moon and Mars, and Mars transfer habitats need to address yet other mission requirements, from longer mission durations, higher system reliability, lowering risk to the crew, and radiation protection, to name a few. NASA's Commercial Crew program is designed to deliver astronauts to the ISS, through the development of US commercial capabilities by SpaceX and Boeing. This will solve today's dependence on Russian launch vehicles. Regarding commercial habitats, the Bigellow inflatable module is designed for an initial ISS demonstration, with plans to evolve it into a future commercial space hotel. NASA's approach is analogous to those used in the early days of aviation, where the government—fulfilling its role to support foundational research—was heavily involved, then subsequently handed it over to private enterprise. This model is working for space as well, which resulted in aerospace giants like Boeing and Lockheed, followed by others, including SpaceX, Orbital ATK, Sierra Nevada, Blue Origins, Virgin Galactic, and others.

Designing these future multi-disciplinary missions requires strategy, planning, engineering, science, architecture, design, and a host of other diverse disciplines. Space architects and designers are currently involved with foundational feasibility aspects of these plans, which includes design reference architectures to demonstrate feasibility-specific aspects of the concept studies; design processes; prototypes and mockups; terrestrial and underwater analogs; human performance focused research by HRP, and ISS experiences.

6.2.1. Design Reference Architectures and Other Mission Architectures

A future human mission to Mars is understood to be complex and costly. To understand and frame the scope, mission goals, technological challenges, the impacts on the crew, and resource requirements, NASA carries out end-to-end mission concepts studies, called design reference missions. These documents serve as assessments, building on the state of practice, identifying existing and new needed capabilities, and are used as a document to communicate a feasible mission architecture to internal and external stakeholders. For planning purposes, the Mars Design Reference Architecture, or DRA 5.0 (NASA, 2009), was developed in the last decade, followed by two revisions.

These studies evolve as we learn more about our space environment. For example, in DRA 5.0 the assumption on the radiation environment for the crew and electronics was higher than we understand it today from sensor measurements on recent robotic missions on Mars, including on the Curiosity rover. This finding opened up the mission architecture space to separate the human part from the cargo, where humans will use a chemical rocket to get to

Mars in months, while the cargo will take years, using electric propulsion on a more mass efficient trajectory to deliver hardware and supplies before the arrival of the astronauts. This precursor cargo mission can deliver the surface habitat with all subsystems, landers, rovers, and return systems. This is a radical change from the single delivery Mars mission architecture. Similarly, technologies advance both for space and terrestrial applications. This allows us to incorporate these into future architectures, which will likely introduce beneficial improvements over the next two decades. Therefore, committing to a point design today, for a mission that will fly more than twenty years from now, would limit us from the benefits of these future technological innovations and solutions.

A subsequent higher-level overview document, called “NASA’s Journey to Mars” (NASA, 2015) identified an evolvable path to Mars with three exploration phases, shown in Figure 6.2. These are:

- The *Earth Reliant phase*, of yesterday’s and today’s human exploration missions, with short 6 to 12 hours missions and returns within hours.
- The emerging *Proving Ground phase*, which utilizes the ISS, and commercial cargo and crew delivery capabilities to lower Earth orbit. This will be followed by intermediate capabilities towards a deep space mission. This will still target cislunar space (i.e., between Earth and the orbit of the Moon), with the Space Launch System (SLS) to deliver more mass to orbit, the Orion capsule to take astronauts as far as the Moon, and a deep space habitat, which can be a precursor for a transit habitat to Mars. These mission durations will range from 1 to 12 months, allowing the crew to return in days.
- The *Earth Independent phase*, which will build on the capabilities of the previous phases. This will also utilize the high-power solar electric propulsion element of the proposed Asteroid Redirect Mission (ARM), for cargo delivery. A Mars Transit Habitat will take humans to Mars or to its moons Phobos and Deimos. Other mission elements may include orbiters and landers.

The evolvable Mars campaign is not a point design mission. Instead, it looks at options, making the modular approach more attractive, as it allows flexibility to redesign future missions to any destination as driven by other drivers, some of which might be related to national policies, and funding allocation earmarks from the budget appropriators (see Section 5.2).

The mission developments are expected to be incremental, which involves spending a significant time and effort in cislunar space. As it is in the vicinity of the Earth, it is relatively quick to get there, while it will allow us to test out systems, making sure that the crew will be kept alive and safe on a subsequently planned 1,100-day round trip mission to Mars. Even if our life support systems are made 99.9% reliable, a failure can result in a “bad day” for the crew on a long-duration mission. This can’t be tolerated, thus we need to perfect all systems in the vicinity of the Earth before committing a crew to a Mars mission. These technology and mission architecture studies are currently carried out by HEOMD and STMD within NASA. In support of NASA’s commitment to a future human mission to Mars, its FY2016 budget—with a $55M line item allocation—mandates the designing and building of a space habitat by 2018.

NASA’s evolvable Mars campaign focuses mainly on surface missions to Mars in the 2030s, with end-to-end architectures, which also includes a habitation strategy. The cargo element

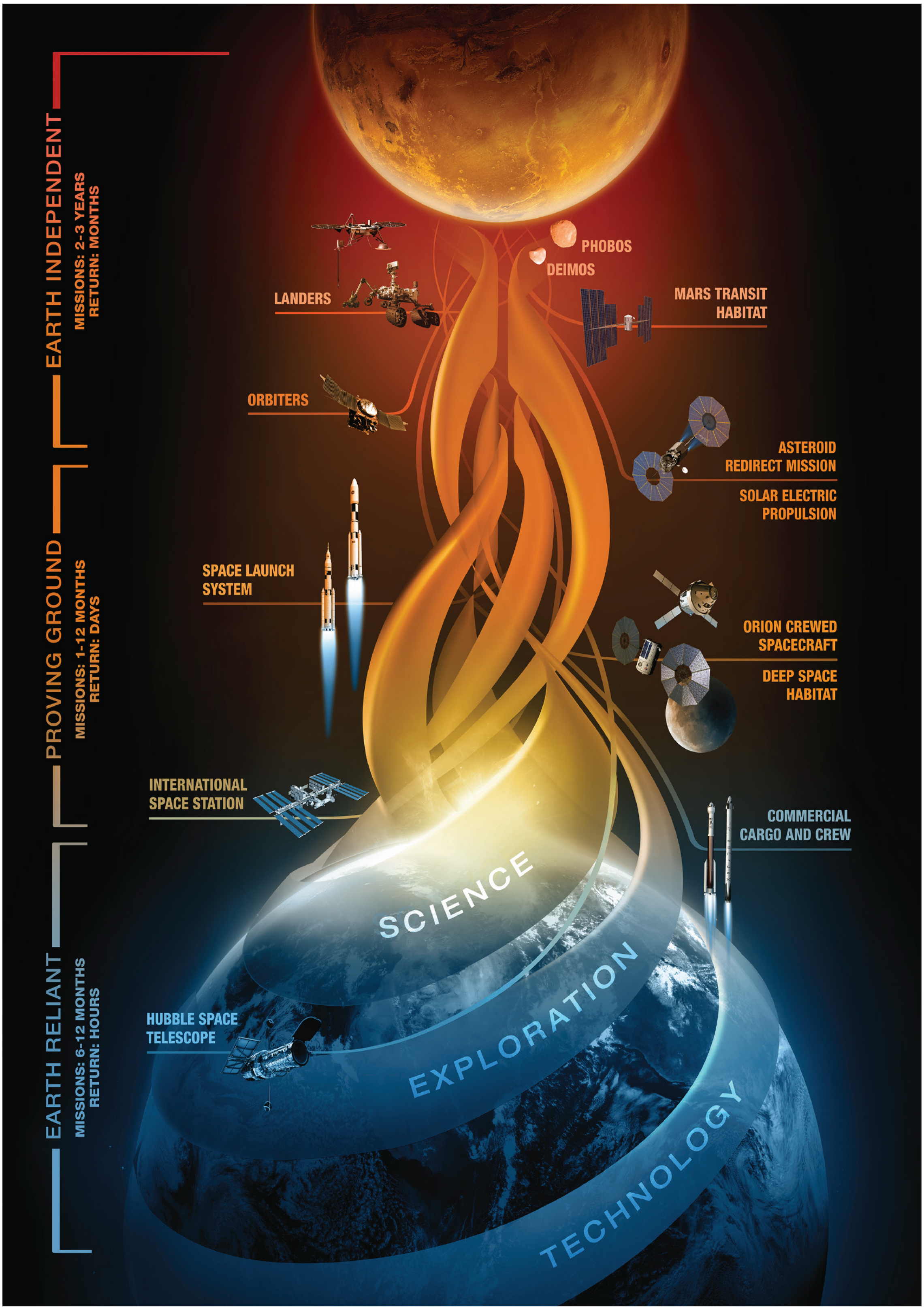


Figure 6.2: Notional phases of NASA's Journey to Mars (NASA HQ, 2015).

of the architecture delivers the Mars surface habitat, with its subsystems and supplies for a surface mission on a highly efficient, but slower multi-year low-thrust trajectory, utilizing a high powered solar electric propulsion system. The astronauts are delivered on a fast 6 months trajectory, using a high-thrust chemical propulsion system. The evolvable Mars campaign starts with missions to cislunar space, where key technologies can be perfected towards a long-duration Mars mission. This also allows NASA to go beyond the ISS, and evolve the transportation habitat to take people to Mars or a moon of Mars. One of the options to achieve this is through a modular configuration, that focuses on the common elements between the three phases of habitation, which are:

- Getting to Mars;
- Living and working on the surface of Mars or one of its moon; and
- Returning back to Earth.

The cargo delivery part of the mission is robotic, but once the crew arrives, the mission is expected to become very human centered.

Ongoing mission architecture studies provide iterative inputs into future updates to the design reference mission, which eventually will lead to a point design habitat for a future human mission to Mars. These mission architecture studies help to identify near-term investment needs and long-term design requirements.

NASA's Mars plan is not a simple flagpole planting exercise, combined with returning the crew safely to Earth. It requires planning for all the activities, astronaut needs, and designing their interactions with the environment, and developing appropriate support systems. The planned mission architectures account for operational scenarios for the habitation systems, supporting robotic systems, and mobility platforms on the surface. These surface assets will dictate the lander requirements, and the design of the Mars Ascent Vehicle, which brings the astronauts to their in orbital rendezvous with the return spacecraft. Mass and volume limitations of the launch vehicle impact the overall mission architecture, including the habitation volumes for the launch capsule, the Mars Transfer Habitat, the lander design, the surface asset, and the ascent vehicle. Current studies are assessing the minimum volume for humans, which are mostly focusing on basic physiological needs and to a lesser extent to psychological needs. For example, if a crew of four needs to survive for 48 hours until they reach the Earth orbiting spacecraft, what are the minimum functions and volumes they need in order to accomplish the tasks. It shows that the various mission architecture elements are strongly interrelated. The launch vehicle defines the available mass and volume for the habitat, which in a functional way have to support the astronauts during the Earth to Mars transit, and at Mars (either on the surface or on its moons).

The current design reference architecture is bound by a mass limit of 43 metric tons with a baselined crew size of four—although mission trades considered crew sizes between two and six. This mass and related mission cost limitation favors a multi-mission habitat, which can be used on each stage of the mission. These designs are proof of concept studies, not at the point design stage yet. The design activities also include astronauts early on, building on their experiences from prior spaceflight. It is a cognitive challenge for designers who never experienced spaceflight and with a deeply routed terrestrial experience to design for the space environment without the experience of zero gravity and its associated psychological factors.

The lessons learned from these multiple concepts and activities are subsequently integrated into future habitat designs.

Once the crew arrives to Mars, they have to enter the atmosphere, descend, and land (EDL) on the surface. Various configurations of the space transportation system and EDL technologies can deliver either 18 or 27 metric tons, depending on the transportation system and EDL system constraints (Craig, 2015). This can lead to either a very modular configuration on the surface, or it may employ a monolithic one-piece element. These landed habitat sections can then be customized by the crew once they arrive.

NASA's Mars Design Reference Architecture (or DRA5) (NASA, 2009) dedicates only a few pages to ergonomics and higher needs in Maslow's hierarchy, with a caveat that it will be addressed at a later time. The rest of the thousand or so pages documents aspects of engineering, technology, mission architectures, and resource requirements. Similarly, the Journey to Mars document (NASA, 2015) only mentions, in bullets, the human crew in connection with basic needs and operations, namely crew health, performance, and mission protocols. To read more about the human element for these future missions, we need to look at other documents, including the "Human Integration Design Handbook" (NASA, 2010a). While it addresses human ergonomics, perception, cognition, and habitat architecture related issues, it is still less human centered design, and more of an engineering and human performance related document. Even the title implies looking at humans as fuzzy elements in the system, which has to be mitigated, guided, managed, so they will not interfere with technology and engineering.

Such predominantly engineering and resource driven habitat designs primarily account for technical functionality, life support, and safety, in line with Maslow's basic needs. Today's engineering and resource driven trends are influenced by some of the barriers NASA faces, related to resource limitations and a risk averse culture (Balint & Stevens, 2014). This wasn't always the case. We may recall that during the Apollo era, in the late sixties and early seventies, NASA worked with Raymond Loewy, the French-born American industrial designer (Loewy & Snaith, 1972). Many of the ideas and concepts from his full size mockups fed forward to subsequent designs, including the food storage racks (Loewy & Snaith, 1972, p.2&10) on the International Space Station. He looked at habitat designs from a human centered perspective, making the environment more comfortable for the astronauts (see Figure 6.3).

In recent decades, this early attention to humanly designs have been shifted towards the demonstration of technological feasibility and costs. None of the design reference studies used an integrated approach between hard-core engineering, space architecture and human centered design that demonstrated the benefits of aesthetics, crew appreciation, at no cost to the habitat design. However, I believe that to be successful in our endeavor, the future evolution of long-duration human exploration mission architectures should reassess this technology-focused approach, and augment it with an emphasis on human centered design. This should include special attention to the higher-level self-actualization needs of the crew.

6.2.2. Prototyping & Mockups

Prototyping and building mockups is a typical iterative design activity, which are currently utilized at JSC's Habitability Design Center (HDC) in support of planning human exploration missions, and at JPL's Innovation Foundry for planning robotic missions (see Appendix D).

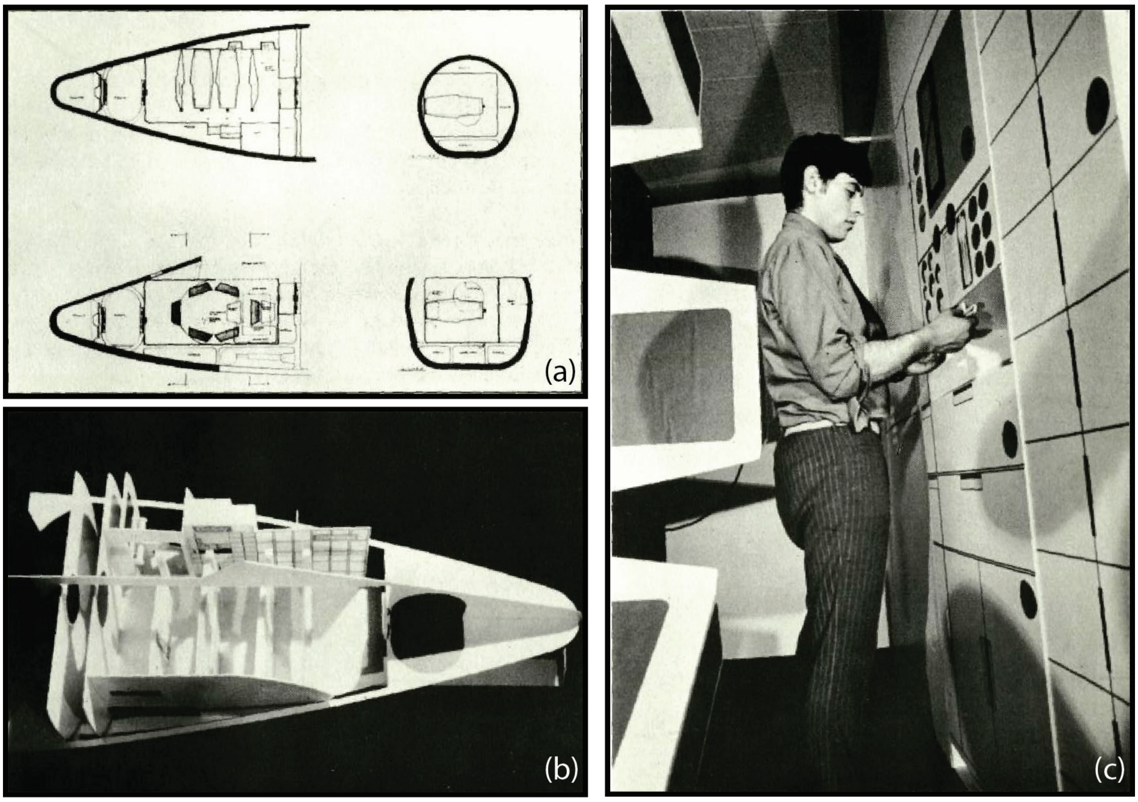


Figure 6.3: Raymond Loewy, William Snaith concepts: (a) Crew compartment configuration of X-axis docking concept; (b) Shuttle orbiter model of couches in the launch orientation; (c) Full size mockup of a crew management compartment (Loewy & Snaith, 1972, p.2).

During the design process the study teams identify functions, then brainstorm with a broad group of experts, including astronauts as users. (This aligns with co-design methods.) This helps to flush out a few concept designs. The best concept is then translated to a mockup, which becomes a point of departure for a new iteration. One example is JSC's Habitat Demonstration Unit (HDU), which was developed through rapid prototyping. In this design the working and living space were separated, with an attempt to make the living environment more pleasant for the crew. Another example is the Orion capsule, which has design heritage from the Apollo capsule, but it is somewhat larger. Since it is designed for a 21-day mission for a crew of four, it has to have a toilet (see Figure 6.4). Experts at JSC's HDC built several wood and foam-core mockups to prototype configurations within a full sub-scale section of

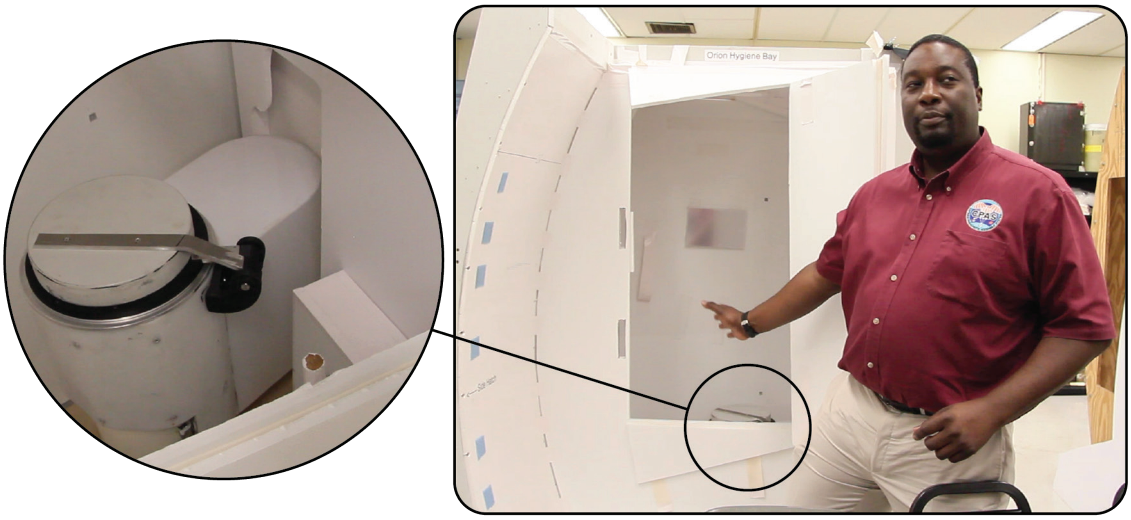


Figure 6.4: Mockup of the Orion Capsule's toilet compartment at NASA JSC's Habitability Design Center.

the aeroshell. These were used to demonstrate a feasible configuration that supported access, function, maintenance, and moving around inside a restricted isolated sub-volume (Howard, 2015). Such iterative prototyping activities help to keep humans in the development loop, and try out scenarios, which can't be done through paper studies and engineering considerations. Mockups can be built to different levels of fidelity. HDC developed mockups can be further advanced by submerging them in neutral buoyancy tanks to simulate a zero gravity environment, and conduct studies to see if the crew can access the facility and perform the designed function under more relevant environmental conditions. While the benefits of these prototyping activities are acknowledged, budgetary constraints still limit the roles of humanly designs under today's technology and budget-focused paradigm.

6.2.3. Analogs

Terrestrial analogs are important to gain experiences for operational scenarios, logistics, group dynamics, co-habitation, among others. (Prototypes become analogs when they are put into simulated operational scenarios. They refer to full systems instead of stand-alone artifacts.) Today's habitat analogs accommodate human crews up to months at controlled extreme environments. While they can't simulate the effects of space environment as a whole, they can be used to simulate subsets of the experiences that astronauts may face on their journey.

Analogs are part of the design iteration process. They provide human centered operational insights to subsets of the expected future experiences. Since these analogs are terrestrial based, they can't simulate the long-duration zero gravity environment, although zero gravity can be experienced on parabolic flights over short and repeated 25 seconds bursts.

In the past, there has been a grassroots effort to address human centeredness for habitats. Kriss Kennedy, a space architect at JSC, started a tiger team (consisting of subject matter experts to work on a specific task), which turned into a project to develop the Habitat Demonstration Unit (HDU) (Figure 6.5). Starting from a PowerPoint presentation, originally it was planned as a prototype for a lunar habitat, with a diameter of 5 meters. The built analog was subsequently taken out to the Arizona desert for analog demonstration and field-testing (Kennedy, 2015). This prototyping approach and analog demonstration allowed the designers to test out the human interactions elements with the habitat and the interactions with crew members within, which was originally not accounted for in the engineering designs. (Including crewmembers in analogs aligns with co-design methods.) This also demonstrated the advantages of a circular and iterative prototyping approach against the typical engineering method where systems are driven to a finalized point design with high specificity on paper first, then built and tested. HDU was returned from Arizona, renamed to HERA, or Human Exploration Research Analog. It currently resides back at NASA JSC. HERA/HDU provides a controlled environment within NASA JSC, where astronauts can spend weeks or even months, living and working inside a small reference size habitat. It is being used to study the psychological and physiological impacts of crew confinement. HERA has been advanced towards a modular habitat system, which can be augmented and reconfigured according to study requirements. This is an Earth-based test facility, which might be configured with crew quarters for one study, or a logistics module for another, or a maintenance module next. It is achieved through reconfiguring the interior. Through partnering with the Rhode Island School of Design (RISD), the team built several reconfigurable workstations that can fit into the HERA profile and volume, to achieve the desired co-located spaces. For example, placing

Figure 6.5: HERA/HDU analog module. Clockwise: External view, inside view, and CAD model.

the medical station next to maintenance, or teleoperation next to entertainment (Howard, 2015). These analog prototypes and active studies will provide a better understanding of the optima layout of a habitat. Therefore, this level of human centeredness is already part of the practice at NASA JSC. Similarly, under the eXploration Habitat (X-Hab) studies, AES was funding academic work to find novel innovative and integrated concepts for habitat layouts and designs. These university teams—including the Pratt Institute with a human centered design focus—incorporated a broad set of disciplines: built mockups, and rapid prototypes to try out various configurations (Moore, 2015)(Pratt, 2016).

NASA's analogs are not limited to HERA/HDU. Both stationary and mobile habitats in the Arizona desert or Utah desert simulated a Mars-like environment, isolation, small habitat volumes and team dynamics. NASA's Space Exploration Vehicle (SEV) concept turned the design paradigm around to achieve both mobility and habitation in one vehicle. It was developed in collaboration with the Rhode Island School of Design (RISD). It was designed to support two astronauts for up to 14 days. The first generation SEV focused on functionality (see Figure 6.6 (left)). Lessons learned from using it in a desert analog environment were incorporated into the second generation SEV, shown in Figure 6.6 (right). Its redesigned layout for the hatches minimized interference with the suit port, providing better access and mobility for the astronauts. The rover cabin housed the astronauts, with a cabin layout that is

Figure 6.6: (left) First generation SEV with suitport. (right) Second generation SEV at NASA JSC.

analogous to the curved walls of sailing boat layouts, with tiny nooks and crannies all around. The cupboards were small, but efficiently utilized within the small ten cubic meters of habitable volume. Efficiency was a guiding principle. The driving seat turned into sleeping benches, and a separating curtains' structure—similar to a berthing on a train—helped to achieve privacy and sound proofing between the two crew members. This allowed them to have a good night sleep. The activities included an hour of exercise, and the multi-functional volume had a toilet and a galley. A highly relevant finding was the importance of the crew selection over the interior design of the habitat, which will become exceedingly impactful on long-duration missions (Bluethmann, 2015). These design considerations and insights from the analog tests will feed forward to future designs and contribute to the psychological wellbeing of the crew. A different type of mobile habitat carrying platform was developed at JPL, called ATHLETE (All-Terrain Hex-Limbed Extra-Terrestrial Explorer). It is a flexible and scalable robotic mobility system. The current prototype was designed as a concept for lunar exploration. A half-scale version of the ATHLETE rover with a habitat was successfully built, as shown in Figure 6.7. The habitat accommodated a small bathroom and galley as well. For a Mars mission, under the evolvable Mars campaign, ATHLETE could carry multi-purpose construction elements, or could

Figure 6.7: Half-scale ATHLETE rover, carrying a habitat mockup.

be equipped with attachments or mechanisms on its limbs (Wilcox, 2015). HDU, SEV, and ATHLETE where tested on NASA's Desert Research and Technology Studies (or Desert-RATS) analog demonstration series for Lunar, Mars, and rocky planetary bodies explorations. Other analogs can simulate a variety of aspects for future space missions. In 2007, Scientists and researchers participated in the Arctic Mars Analog Svalbard Expedition (AMASE), in Norway. This two-week long analog mission studied harsh and isolated Mars-like environmental conditions, while using techniques and instruments designed for a future Mars mission. They lived on a converted ship, which was used as a scientific laboratory. Analog field campaigns to Rio Tinto, Spain, and on Ellesmere Island in the Canadian High Arctic tested Mars deep drilling capabilities. The HI-SEAS habitat is located in Hawaii's Mauna Loa volcano, and it stands for "Hawai'i Space Exploration Analog and Simulation," which is designed to simulate a long-duration Mars mission. The purpose of the research is to learn about crew behavior, dynamics, nutrition, performance, roles and hierarchy within the group. The team members also perform Mars specific scientific tasks, from geological explorations to bio-signature detection. Underwater analogs include the NEEMO projects, (short for "NASA Extreme Environment Mission Operation"), and neutral buoyancy tanks JSC, which can train astronauts to perform tasks in zero gravity environments. NEEMO's Aquarius research station in Florida is the only underwater facility where a group of astronauts, engineers and scientists can live and work up to three weeks inside.

Analogs play an important role in habitat designs. They encompass the philosophy of human centeredness, and cybernetic circularity through design iterations, prototyping and user experience design. The combination of these analog studies provide piecewise data, which can be combined to a more complex model, in support of future habitat designs. These, however, are still task focused, representing an environment which is designed by engineers to understand systems behavior with the humans in it.

Combining prototyping methods with analogs and training of NASA's engineering and management community are important factors to establish a human centered paradigm. Actions and conversations can help to raise awareness and to embrace human centeredness from practitioners, but it will only be successful if enabled and mandated by senior leadership. The current requirements have to be augmented or overwritten from a strategic level. Initial steps have been made by putting human system integration into NPRs, which will highlight human centered design. But, to make it successful, awareness and education of a broad community is also required, to support its understanding and implementation (Whitmore, 2015).

Therefore, to address the delight element, we need to conduct human centered analog studies, specifically targeting higher-level needs, while allowing the process to modify the habitat environment accordingly. In this approach the environment and processes adopt to the astronauts' needs. In comparison, today's human centered studies involve designing the environment that the astronauts need to adjust to. In a way, we need to turn Maslow's hierarchy of needs on its head, by starting with the addressing of the higher-level needs, then wrapping the basic needs around it. Adopting a new paradigm along this line requires a top down approach, that makes higher-level needs mandatory.

6.2.4. ISS and Other Current Experiences

Today's human exploration missions primarily revolve around the International Space Station (ISS). It is the ninth human occupied space habitat. Previous stations included 6 Soviet Salyut

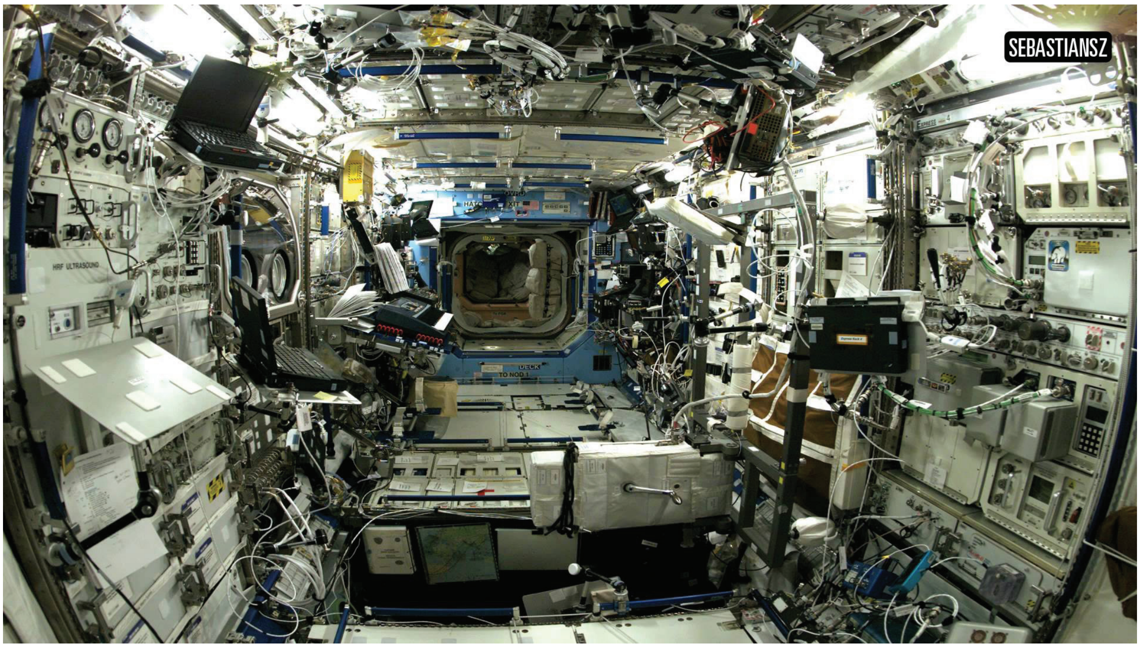


Figure 6.8: Inside the ISS.

stations, the Soviet-Russian MIR station, and the US Skylab. The ISS was designed as a national laboratory; hence it is a noisy work environment with bright lights, and people living in it (see Figure 6.8). The ISS is a multi-functional environment, merging the work environment with private spaces (e.g., for sleep), public places (e.g., the galley), and hygiene (e.g., toilet, cleaning). Some of the functions overlap, for example the work environment and the exercise equipment. The galley is situated within the workspace. Sleep areas and the toilet are separated from the workspace, but allocated within the same continuous volume. Since the launch of its first module in 1998, with the first crew in 2000, it has been permanently occupied for over 15 years. The ISS was completed in 2011, with a final pressurized volume of 916 cubic meters. Beside its scientific missions, NASA and its international partners have accumulated decades of human spaceflight experiences on board, related to health, interactions, collaboration, communications, psychological stressors, group dynamics—without providing a complete list of these.

The activities on ISS are overseen by Mission Control in Houston, and are highly procedure driven. It is easy to implement, because the communication distances are short and the time delays are negligible. In comparison, on a long-duration Mars mission the one-way communication delay can be as much as 20 minutes, making real time communications impractical. This necessitates a different communication paradigm between the crew and Earth. For this, NASA is developing and testing a software tool that allows the astronauts to write their own procedures, plan their daily work schedules, identify when the equipment needs to have maintenance and servicing. This, in turn, will give the crew more autonomy and place them in charge of their daily activities, instead of getting instructions from Houston. NASA is testing this tool on the ISS, which includes automated scheduling, and servicing of the water contamination sensor. In the past they tested the ISS computers with this software, using it for computer network maintenance, and automated the express rack. In the future, software can be used as an advanced cautionary system that alerts the astronauts in case of failures, and help diagnose potential faults. Software tools can be further developed into intelligent systems that can learn from experiences. For these, various processes and procedures are being developed on the ISS. For example, the ultrasound imaging was developed through

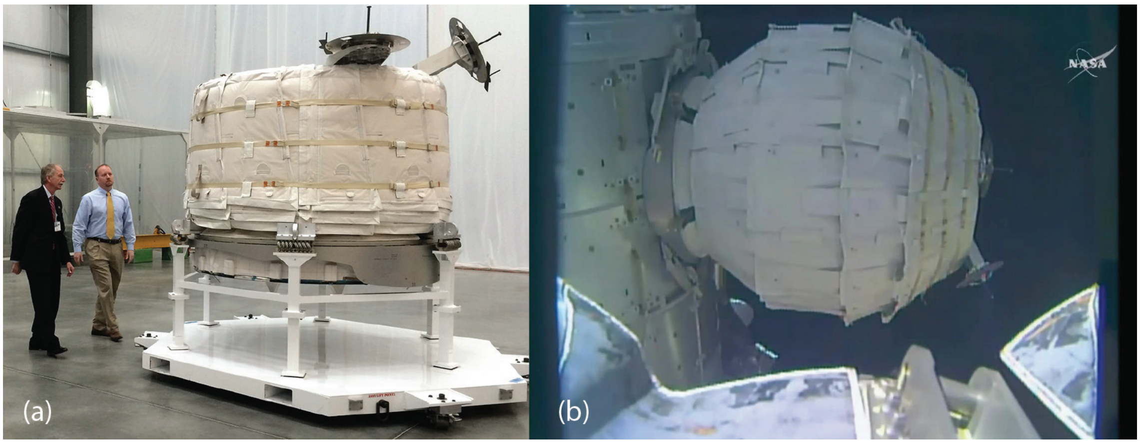


Figure 6.9: BEAM (Bigelow Expandable Activity Module), an inflatable habitat demonstrator by Bigelow Aerospace. (a) Stowed configuration. (b) BEAM deployment on the ISS in 2016.

experimentations on astronauts, in support to develop telemedicine diagnostic strategies in space, but also on Earth (Davison, 2015). Furthermore, astronauts performed telerobotic rover operations in Germany, from the ISS, which provided operational experiences for operating rovers on Mars from orbit or from Phobos.

Space transportation provides access to space and crew delivery capabilities to the ISS. The Russian Soyuz capsules are still being used for crew transfer from the Earth to the ISS and back. The US completed several Moon missions with the Apollo Capsules, which were designed to survive more demanding entry conditions from a lunar trajectory, than those experienced by capsules returning from low Earth orbit. Starting in 2017, NASA will contract crew delivery to two US companies, SpaceX and Boeing. These capsules are designed for short-duration missions, lasting for up to 12 hours. Consequently, many of the design and habitability considerations for in-orbit or deeps space habitats are not required on them.

The ISS and these capsules provide invaluable operations experiences for human centered designs of future habitats and other spacecraft. These short-duration spaceflight experiences can benefit emerging commercial developments for earth orbiting habitats. For this, NASA AES is funding four commercial teams, including Bigelow Aerospace, Lockheed-Martin, Boeing, and Orbital ATK. These are designed as cislunar habitats, but potentially can be developed further into a Mars transit habitat (Moore, 2015). Bigelow's inflatable habitat—shown in Figure 6.9—was delivered and deployed on the ISS in 2016, after being launched on a SpaceX supply mission.

However, these accumulated experiences can't provide all the information for long-duration missions, even when combined with new scientific knowledge, analogs, prototypes and mockups. But, as elements of the evolvable Mars architecture, we can build incremental knowledge and confidence to mitigate risks encountered by the human crew. ISS-based experiences are predominantly mission operations and mission goals driven, where the crew's schedule have been fully controlled and prescribed. On these historic missions self-actualization needs were not accounted for. Yet, I believe it needs to be an important consideration on deep space missions, where the crew is isolated from the Earth for years with similar characteristics to solitary confinement.

6.3. Habitats and Habitation

The word “habitat” can be easily misconstrued, due to its generality, the same way as referring to something as a “car” (Howard, 2015). We have an abstracted personal cognitive model on what this might mean, but there are countless ways to design them to accommodate humans in a space environment. Any change from the initial assumptions, such as the crew size or special functionalities, will ripple through the design, resulting in a different final outcome.

Architects and designers must learn about the constraints and nuances of zero gravity, and the different reduced gravity environments on the Moon with sixth-g, or on Mars with a third-g. Understanding and designing for the space environment beyond our terrestrial experiences provides both constraints and opportunities. We accumulated our experiences from past human missions, ranging from orbiting space stations (e.g., Skylab, ISS, MIR, the Tiangong Space Station, the Soyuz-Apollo mission), to the Apollo missions to the surface of the Moon. Habitation planning activities are largely influenced by our operational experiences on the International Space Station. But, it is recognized that it is not the same system as the one for a two-three years Mars trip, which requires us to incorporate advanced human needs, psychological needs, the mitigation of solitary confinement type of feelings, and ISS based experiences related to living and working on a space-based outpost.

Based on the evolvable Mars architecture, the next destination beyond ISS might be cislunar space with 30 to 60 day missions, acting as a testing ground for a Mars Transfer Habitat. The capability needs are highly different between cislunar habitats and subsequent deep space habitats, and will require significant developments to advance the designs. NASA’s evolvable Mars campaign includes a planned human mission to Phobos around 2030, which can be used as a stepping-stone to the Mars surface. This means that initially NASA doesn’t have to develop a lander for the Mars surface systems, those can be teleoperated. This simplifies the mission architecture, as it is significantly easier to reach Phobos, than landing on Mars.

Designing a multi-purpose habitat to be used at different destinations and in a broad set of mission architectures has significant cost benefits. This flexibility is preferred by a number of experts over a perfectly designed habitat for just a destination and single use. Yet, operating in different environments has drawbacks too. They can’t be optimized for a single environment, for example for zero gravity or on the surface of Mars, which results in overheads and over designed configurations with duplicate systems if an equipment can’t operate in all the encountered environments (e.g., heat exchangers work differently in vacuum and in the Martian atmosphere).

It is given that a habitat must support the basic needs of the astronauts, by providing a living space, radiation protection, and life support system functions (e.g., water, air, food), and safety. Recycling is an important aspect of deep space missions, as resupply is no longer possible, while the mass and volume constraints impact storage and logistics. The astronauts have to maintain their habitat both inside and outside during the round-trip. On the surface, various mission scenarios assess the activity ratio between surface operations, extravehicular activities (EVA), the use of robotics versus human exploration, and the related system needs. Current design reference architectures focus on these aspects of the mission.

Today’s spacecraft and habitat designs are predominantly engineering driven, based on technological perspectives. However, it is widely acknowledged within the space architecture and design community that NASA needs to include more human centeredness and involve human factor specialists, designers, and artists, to complement the technical developments. While human factors specialist were involved with the Orion capsule development, this can't be said for the deep space habitat concept developments, because the fidelity of these latter studies are not at the point design level. Yet, these developments must address aspects of crew satisfaction and behavioral health and the psychological impact of the living space.

Demonstrating compliance with higher-level needs in Maslow's hierarchy is done differently from meeting technical requirements. For example, a requirement on crew productivity can be demonstrated iteratively through prototyping, testing and demonstrating a certain approach that is related to a certain habitat configuration, and compared against similar tasks in a different or more traditional environment. But this is still a function and mission operations related approach, which only forms a part of human centeredness. Having a good office layout that makes someone productive does not guarantee a happy employee, especially if one needs to live in the office too. The confined volume and mission tasks introduce certain constraints to the design. Yet a habitat also has to provide a home away from home for the crew with the mindset of a traveler (Toups, 2015). It has to provide intimacy, warmth, privacy, and community in a multi-functional space with a built in variety that allows operating as an office or a home. *"Privacy is a balance between forces to affiliate and forces to withdraw. This balance helps an individual define himself and his relationship to others. An important question is just what this balance implies in space"* (Connors et al., 1985, p.101).

6.3.1. Personal Space, Public Space, and Total Volume

Throughout their ISS missions, the astronauts routinely claimed and personalized spots on the station (see Figure 6.10). The privacy needs of the crewmembers present important considerations, related to the level of privacy, auditory impacts, visual isolation, eating and hygiene. On smaller capsules, like on the Orion module, space is limited, providing very little separation between the astronauts. On long-duration missions it is important to find a balance between protecting the privacy of the crewmembers, while fostering effective crew functioning (Connors et al., 1985, p.102). In a larger habitat, designers need to consider the layout from a

Figure 6.10: ISS sleeping arrangement, serving as a personal space.

human centered view. For engineers placing all piping in the same area is a logical solution. From the perspective of a user, a designer, or an architect, placing the galley and the toilet next to each other in a small volume is not acceptable as it interferes with the user's wellbeing, regardless of the cost savings from an engineering approach.

Having a small crew in a closed environment over a 2-3 year period has to be designed not only for basic needs, but also for individual and team behaviors, their interactions, and team dynamics. Separation between living and workspaces are also very important. Historic terrestrial examples are the houses where the shops and workshops were at street level, and living spaces above them.

NASA's is in the process of identifying the minimum volume requirement for the crew on long-duration missions, and use this information as a point of departure for habitat designs. Starting from a minimum volume, these contained spaces will inevitably include overlaps of functional spaces. These can be mitigated with deployable elements, for example deployable sleep stations, which can collapse during the day then opened for sleep. This still create a private space, but only used when needed.

Small habitat designs can and did draw inspiration from terrestrial analogs, for example, from recreational vehicles to boats, from submarines and naval vessels to underwater diving platforms, and people living in isolation on arctic stations, oil rig platforms, and even in incarceration. Experiences from these environments can provide understanding of the psychological and medical impacts on the crew. In return, a successful space habitat design can benefit future concepts of these mentioned terrestrial examples, or create new terrestrial design spinoff opportunities.

The most popular place on ISS is the galley (see Figure 6.11) where the astronauts get together to eat and socialize. Accommodating even a small crew in a limited habitat volume

Figure 6.11: ISS galley in action.

can be a design challenge, but it is important to provide a place, where they can assemble and interact as a group.

The volume of solid framed habitats—which are virtually aluminum or composite cans—is defined by the launch vehicle fairing diameter. For example, ISS modules launched on the shuttle were limited to a fixed maximum diameter of 4.5 meters, which represented a design constraint.

Inflatable habitats provide flexibility to achieve larger volumes, dictated by human needs. These also have constraints, as superpressure inflatables in vacuum are trying to be spherical. Achieving a non-spherical shape is possible, but at a mass penalty. This shape is also differ from terrestrial experiences, where we build walls under gravity conditions, which defines a two dimensional layout for a living space (Kennedy, 2015). Designing for a floor space differs from designing for a volume space, and architects with Earth-influenced cognitive models for gravity conditions have to re-imagine human centered functions and uses in zero gravity without having the experience base for it. Conversations with astronauts and experiencing zero-g on parabolic flights can partially fill this gap, but these only provide limited exposure to develop these needed cognitive models for designers and architects. Long-duration Moon or Mars surface habitats for future uses are easier to envision, as they are in a (partial-)gravity environment, and building underground removes volume constraints and allow for terrestrial-like architecture concepts to be implemented. However, the first surface habitat on Mars or on Phobos will still be limited to surface-based “cans” or inflatables.

For descent vehicles the human centered design element is relatively limited. The crew is primarily a passenger, with some piloting and operational tasks. The flight is typically less than 12 hours; therefore the accommodation does not have to provide an overnight functionality. The ascent vehicle might require accommodation for about 5 days, where the living functions will include sleeping, eating, trash operations, similar to a habitat, but for a shorter period of time (Howard, 2015). A long-duration habitat must also include medical response capabilities, which covers both preventative and emergency medicine, and maintenance workstations. Design heritage for a deep space habitat is drawn from the ISS. Similarly, the Orion capsule and future ascent and descent vehicles are drawing on Apollo and Space Shuttle heritage. Yet all of these designs are predominantly technology driven solutions for short-term missions, addressing basic needs and functionality in support of mission goals. Future long-duration human missions have to provide more advanced technological capabilities, higher reliability, and more importantly an added focus on human centeredness.

6.3.2. Communications and Autonomy

Communications between the ISS and ground control are virtually instantaneous, and in any case of emergency, the crew can return back to Earth within hours. In comparison, on a long-duration Mars or deep space mission rapid Earth return, evacuation, and resupply of resources and new instruments are not possible. The available mass and volume at Earth departure sets limits for resources, and must be carefully chosen (Craig, 2015).

Communication delays will necessitate high levels of autonomy and a redesign of the interaction strategies between the crew, their families, and mission control back on Earth. Instantaneous communication will no longer be possible, but a model used by Facebook could work (Davidoff, 2015). Instead of picking up a phone and calling someone, a message could be sent, knowing that a response will not happen for at least 8 to 40 minutes, depending on the phasing between Earth and Mars. In a Facebook communication paradigm, people still feel connected without the expectation of instantaneity.

From a medical perspective it translates to autonomous medical care. The astronauts will be able to consult with experts from Earth, who can provide assessment and advice on a needed procedure, but given the communication delay, the needed procedure will be performed by crew members in real time for themselves. In this operational environment autonomous systems will support an independent decision making capability.

There are many attempts to automate and optimize habitat designs. The difficulty can be explained through first and second-order cybernetics. Identifying guidelines and reducing them to requirements reduces the variety of the system, and makes their implementation a first-order linear problem. This process does not account for second-order cybernetics, where an astronaut, as the regulator can reset the rules of the first-order system.

6.3.3. Modular Habitats and Reconfigurability

Near-term precursor missions can be accomplished using modular architecture elements, with small pieces, and habitation, which is somewhat bigger than the Orion capsule, and can be scaled with the duration of the mission. Cislunar missions might accommodate a crew for 60 to 90 days, or a deep space mission for 100 days. With a modular approach, these habitats can be scaled up for a long-stay 1,100-day Mars mission, which will also include a 500-day surface stay.

On deep-space missions, Earth-independence allows the crew to be autonomous, and shape their environment the same way as buying a house and personalizing it from the previous owner. For this, providing variety to the crew through modularity, and combining it with autonomy and self-determination, the astronauts will inevitably adopt their personal space to their needs. This will likely expand to the public spaces during the mission. Tracking the evolution of the habitat configuration over a long-duration mission can provide an unparalleled insight into the human psyche (Bannova, 2015). This approach—by allowing reconfigurability of the personal and private spaces—can be used on precursor analog missions as well. It helps to demonstrate the need for human centeredness for habitat designs, and move beyond HRP's risk based requirements.

While turning Maslow's hierarchy of needs upside down, and addressing higher-level needs first, designers and architects are still bound by fundamental mission constraints, which include physical dimensions and mass allocation. Furthermore, *"although astronauts are provided with a 360° world, they continue to operate as if they lived in a modified two-dimensional world"* (Connors et al., 1985, p.97). Learning to use all surfaces is an important aspect to deal with the psychological impacts of living in a constrained space. This can be also aided through design. Having a modular habitat system makes the environment adaptable to personal user needs, and reconfigurability benefits from the zero-gravity environment where repositioning objects are not impacted by their weights. Similarly, without gravity, partitions can be set up using light fabric, which can be stored in a small volume, but using it to creatively can break down the living space. Space partition can also be achieved through nonphysical means, for example using creative lighting configurations with a similar psychological impact. A self-defined environment gives autonomy and self-determination to the crew. A new configuration of the living environment has to comply with mission and personal safety requirements, but this can be achieved through conversations between the crew and mission control on Earth. Monitoring systems inside the habitat, for example with RFID tags, can inform ground control about the configuration of the habitat objects, allowing them to identify response plans for mission emergencies. Configuration conflicts with procedural requirements can be resolved through conversations with the crew, while reinforcing their self-determination and autonomy. This approach caters to the highest level of adaptability.

A modular and reconfigurable design with design considerations and commonality can be used to afford crew autonomy. For example, ongoing research at NASA included a project called "logistics for living" (Toups, 2015). It looked at packaging material for supplies, which can be re-purposed for other desired uses. The team took packaging material, specifically the single-use crew transfer logistics bags (see Figure 6.12), which are currently used on supply missions to the ISS. These are made out of flame resistant Nomex material, filled with heavy foam. These bags were redesigned to be unzipped and unfolded into a flat sheet for subsequent use by the crew to reconfigure their living space with internal partitioning and other personalizations. This is still in an early phase, but demonstrated a human centered design approach for these future-long-duration missions.

With an increased mission duration, and long-term separation from Earth we need to address psychological stressors, such as confinement, isolation, separation, and stresses from the outside extreme environment. Many of these can be addressed and mitigated through a creative and human centered designing of the habitat interiors. The importance of human centeredness will rise in the priority list as these design reference architectures evolve from top-level feasibility studies towards a final point-design. The inclusion of human physiological and psychological needs is listed in the considerations and mitigated through identified risks, but higher-level needs are not yet incorporated as hard requirements.

Experience has shown that in zero-gravity habitats astronauts can be easily disorientated while traversing between modules. Mixed orientations of the environment caused motion sickness due to mixed visual and inner ear cues. The habitat interiors need to adopt to the crew needs to mitigate these physiological responses, for example by not switching orientations. The humanly focus have to make it easier for the crew to live in a long-duration habitat. The living space must differ from a laboratory or work setting, separated from the bright lights and noise. This brings aesthetics, décor, and pleasantness into the design considerations. Connors indicated that the importance of décor is influenced by crew gender makeup and if there is meaningful work to be performed during the mission (Connors et al.,

Figure 6.12: Transfer logistics bags.

1985, p. 98). These considerations, however, are often subjective and include hard-to-define needs, with fuzzy requirements. While the environments afford us to create and use unique designs, from artifacts to full habitats, it will also take time to adapt to these environments by the crew who will occupy them. Dividing large module volumes by creating corners where astronauts can't see the full extent allows them to go around corners, see only parts of it, and have changes over time. This may make them feel more comfortable because the subconscious mind is always trying to explore the environment. Surprises can keep the mind active.

Looking at it in an abstracted way, people are dynamic constructs who evolve over the mission duration. In response they may want to reconfigure their environment, rearrange their crew quarters, or adjust the designs. It is desirable to separate the noisy work area from the quiet living and sleeping zone, and separate public places from private ones, allowing the astronauts to withdraw at times. They may wish to adopt the habitat to different situations. Through activities during their personal time they can address psychological issues, including boredom, and stay intellectually active and keep the brain alert in a positive way. Combined with exercise routines, the astronaut can balance psychological and physical health, which go hand in hand. This balance is important, as a psychological breakdown can jeopardize the crewmember and maybe even the mission.

6.3.4. Cupola, Magic Window, Display Walls, and Lights

The minimum required volume of a future habitat is still under consideration, but once it is agreed upon, the design teams can start working on various configurations that can impact the crew's perception of the volume and architectural layout of the habitat. This will include all of the key functional modules, from the workstation and passageways to personal and shared spaces. The design teams can influence the astronauts' spatial and temporal perception using windows, projected images on the walls, covering the walls with flexible LED displays, and using virtual or augmented reality helmets.

In the early stages of the Skylab development, Raymond Loewy argued for a window, due to its psychological impact on the crew, and subsequently to the mission. Having a strong psychological connection with the outside requires a window. (Prior to Skylab and Loewy's involvement with NASA, where he provided significant input to the sleep station and hygienic facility (Loewy, 1979, p.205), habitability was not a concern in spacecraft design.) Fast forwarding to the ISS, the European Space Agency (ESA) built the Cupola—an observation module with seven large windows—which represents a delight element for astronauts (shown in Figure 6.13). It predominantly addresses the human behavioral side without a real engineering need or cost justification. The astronauts often spend their personal time looking at Earth or taking pictures. However, the impact of the Cupola on ISS is not limited to the astronauts. It also inspires people on Earth, as can be seen through an Internet search for images on the subject, thus it works as an outreach element in a conversation between NASA and the public. From an engineering perspective, all of the functions from ISS could have been achieved without the additional engineering complexity and cost of the Cupola. Remote sensing observations can be done without it, and a small window could suffice to look outside. As a reflection on NASA's engineering and cost focused paradigm, the NASA-Boeing co-designed Cupola was initially canceled due to budget cuts, but the development continued and completed by ESA through an international agreement between the two space agencies. Now it is a defining feature.

Figure 6.13: Cupola on the ISS.

Correspondingly, a transit habitat to Mars will need a solution with a similar functionality and rationale. During the transfer, for the longest time period, the spacecraft will be between planets, and space will looks star filled at best or black at the worst. As an alternative to real windows, virtual windows or so called Magic Windows (Whitmore, 2015) can be installed, by coating the inside of the hull with digital screens, for example with flexible LED screens. They can display the outside environment, enhanced star maps, or background that will make the habitat feel bigger than it actually is. Showing images from earth, and interacting with family members on a human scale will provide strong emotional support on the journey. These digital solutions will also create the illusion of larger habitat volumes, and may provide an element of discovery, feeding to the delight element of the mission. Yet, even having virtual windows on a habitat may still necessitate having a real window for an emotion connection between the astronauts and their broader space environment.

Without a natural diurnal cycle, the crew's sleep and wake cycles, circadian lock and rhythm has to be maintained through lighting configurations inside the habitat. For this, the wavelength of the lighting system can mimic terrestrial conditions throughout the day, and it can also cause rapid environmental shift (Connors et al., 1985, p.99). Beyond these basic needs, lighting can also change the astronauts' spatial and temporal perceptions, as demonstrated by the Light and Space artistic movement in the 60s and 70s (KPBS, 2011). Further information on this is provided in Appendix C, related to Artistic Attributes. Lighting can be designed as interactive installations, controlled by humans, while enhancing the astronauts' experiences and contribute to their psychological wellbeing.

6.3.5. Exercise and Health on ISS and Beyond

Crew health related research is a significant part of NASA's Human Research Program. Exercise on the ISS takes 2.5 hours per day. It is similar to that for a Mars mission. The microgravity environment impacts bone density, muscle mass, cardiovascular capacity,

Figure 6.14: Exercise equipment on the ISS.

which are countered by on-board exercise routines. The exercise equipment on the ISS is specially designed for a required biomechanics load. However, the exercise equipment on the ISS weights three metric tons (see Figure 6.14), which is unaffordable on a Mars Transfer Vehicle. Therefore, a major design challenge is then to redesign the exercise equipment to be significantly smaller and lighter to fit within the volume and mass allocations, yet provide the same countermeasures for bone loss (spaceflight related osteopenia) and muscle atrophy. Besides addressing physiological needs, exercise also has a positive psychological impact, which is addressed through the behavioral health and performance research elements of HRP, including team interaction. It has been noted that people in confinement adopt extreme work routines, and show limited interest towards leisure activities (Connors et al., 1985, p.100), but this may balance itself over time.

Finding ways to motivate astronauts to perform tasks, like exercising, is an important element of research for long-duration spaceflight. The monotony of the exercise routines can be mitigated in support of emotional wellbeing, by using visual or augmented reality immersive environments. For example, we may simulate skiing on a mountainside or cycling on a country road. Modeling and simulation of VR environments is an ongoing activity, which are being tested during field analog activities, and very recently on the ISS, using a Microsoft Hololens under Project Sidekick (see Figure 6.15). This project is expected to benefit scientific research on the ISS. It also helps mission control to interact directly with the crew in space. Again, these goals are more mission driven than in support of higher-level needs.

HRP studies health risks, related to the most likely medical events and identify what resources needs to be included and taken on a long-duration mission, given the volume and mass limitations. A long-duration human mission to deep space changes the paradigm from today's missions on the International Space Station. The ISS was built over years in a modular way; therefore, it has a significant habitable volume. The Mars Transfer Habitat and the Surface Habitat will be significantly more limiting over a 1,100-day mission duration. This brings up a set of medical, behavioral, performance related, psychological, and physiological issues, which are measured against workload and scheduling of the crewmembers. In this context, HRP also assesses team composition and cohesion, biometrical and mental health aspects, circadian rhythms, and sleep deprivation. Some psychological conditioning can be addressed with straightforward solutions, like long lasting food supply, and exercise equipment. HRP's space radiation risk area focuses on the effect of space radiation and design aspects of a habitat to shield the crew from the radiation effects. Space radiation introduces cancer risks, impacts

Figure 6.15: *Microsoft Hololens tested on a zero-g flight under Project Sidekick.*

the central nervous system, and can have cardiovascular effects. Thus radiation mitigation is human centric. These basic needs need to be addressed regardless of the limited volume.

6.3.6. Robotic Interactions and On-board Making

Robotic exploration has significant scientific benefits, but sending humans is part of our fabric to explore the world. Just like the Moon landing in 1969, a future Mars landing with humans will be more than inspirational. Within NASA, the Human Robotic Systems project is developing robotic technologies to support the crew. As human space exploration is still very expensive and risky, therefore, there is a strong case for robot helpers or assisting robotic systems on these missions. This augmentation can reduce risk, costs, and resource requirements, and reduce the workload for the astronauts. For example, Robonaut 2 (or R2– see Figure 6.16) on the ISS currently performs repetitive and monotonous tasks, including air sampling and cleaning.

The biggest challenge for humans and robots working together in close proximity within a space environment is safety. NASA's robotics group has been successful in developing the strongest and safest robots for these collaborative operations. Robonaut 2 has gone through rigorous safety reviews before using it on the ISS. With built in redundancies, R2 is not only responsible for its own safety and autonomy, responding to potentially damaging actions, but it also monitors safe interactions with the crew and the environment. R2 achieves safety through force-sensing in each joint. When it encounters an obstacle, it stops immediately, and then can re-engage upon a subsequent touch from a human (Ambrose, 2015). Being a humanoid robot, R2 is designed to perform the same actions as humans, with similarly high dexterity. Its behavior is based on first-order cybernetic controls.

The advantages of humanoid robots are the outcomes of being designed to work in a human environment with human interfaces, in collaboration with the crew. From the designer's perspective, they can be programmed for the same actions and movements as humans, and the interfaces with the environment, which will not require any modifications. For example, they can grip the same handle, or go through the same door. In the past, we had to design different

Figure 6.16: Robonaut 2 on the ISS.

interfaces for humans and robots, making the objects unnecessarily complicated. On a human mission we already have to design the habitat around the human crew. Therefore, having a commonality between the interfaces makes logistical and economical sense, and can lead to design simplifications (Ambrose, 2015). Designers only have to think about humans, and this will simplify robotic developments and human centeredness. They can have the same form factor, the same interfaces, and the same functional capabilities. We don't have to redesign the habitat around the robots, instead we can focus on the crew, and add the desired humanly functionality to the robots.

Today's humanoid robots at NASA, like R2 and Valkyrie, have soft outer covers, a material similar to that used on space suits. They are designed this way, because the designers wanted them to work safely around humans in a closed environment. In comparison, hard metallic robot exteriors make the interactions with the crew and the environment risky. Just like the sensory organs of humans, the outer skins of these robots can include various sensors, to provide information on bumping into humans or objects. Skins can also separate contaminated external environments from clean internal ones. Soft surfaces can grip hard objects without crushing or damaging them. These design considerations represent the state of practice, and address basic and safety needs related to the crew. To develop these capabilities on the Valkyrie robot, which participated in the DARPA robotic challenge in 2014, JSC's robotics group employed a fashion designer with an engineering background to design the fabric covering and outer panels on the robot's skeleton. The design had to comply with strict safety, and function-based engineering requirements. The robot was developed through circular iteration cycles between the designer and the engineering team.

The software being used defines robotics, as building mechanisms is a routine engineering challenge (Wilcox, 2015). Software allows the components to work together, and also provide the human interface. This information exchange is bi-directional. A robot receives information through its sensors, and communicates back to humans, in an analogous cybernetic circularity as conversations between humans. For example, the Sojourner rover had a symbolic command line interface, which was incomprehensible to people not directly involved with the operations. In comparison, analogic interfaces through visuals—such as head mounted displays—combined with gesture inputs are on their way to revolutionize human-robot interfaces and interactions. Soon robots will be able to interpret human gestures and voice in real time, with high accuracy. They can learn from the user but can also function as a teaching system, and support the self-actualization and creativity needs of the astronauts. Having a robot assistant will require these characteristics. Verbal interactions might take some time to advance to a point where the robot can differentiate between the truth condition (i.e., literal interpretation) or the use condition (i.e., contextual interpretation) of the language. Thus interpreting jokes and sarcasm might need some time to evolve.

By design, the roles of humans in the interactions with robots will always be supervisory, acting as regulators. At the same time, robots, in line with Asimov's three laws, should not harm humans. Yet, these expectations from today's robots are far from reality. These robots don't even have a conception about what a human is, and do not have the cognition to interpret a human (Wilcox, 2015). But, with the rapid improvement of computing power that still matches Moor's Law, and focused research into cognitive computing, these interactions will be vastly different a decade from now, and can greatly benefit a Paskian interaction between humans and robots on future missions.

Humanoid robots have no higher-level needs. They can be sent to extreme or unsafe environments, wait for weeks or even years to be reactivated, can be kept permanently outside of the habitat, do not use valuable consumables needed for the human crew, do not get lonely, nor need to self-actualize to have a balanced existence. They are different types of members of the crew, giving the mission planners options to use them for the best benefits of the crew and the mission. They don't have good or bad days. However, their human counterparts do. As they work in close proximity with humans on long-duration spaceflight missions, they have to respond to astronaut needs, for example, on a "bad day" it can change the schedule upon recognizing stress, slow down at times, offer suggestions (Ambrose, 2015). This focus on human behavior related needs presents an opportunity for developers to develop selfless human assistant robots, in the footsteps of pioneering work by researchers, like Guy Hoffman (Hoffman, 2014), and robots which are enhanced through emotional design (Ortíz Nicolás, 2014). In today's robotics at NASA these higher-level considerations are not addressed. Therefore, collaboration with external research groups on this topic is highly beneficial.

A different path to robotics is robotic humans, where robotic technology is applied to people, for example through wearable systems that augments human sensory perception (Ambrose, 2015). Finding applications for this augmentation requires designers, who can guide the developments into yet unknown directions. It changes the paradigm the same way as miniaturization changed the way we listened to music, watch television, and make calls on the move. We can have gloves that control robotic hands, allowing the wearer to feel the same as the touch and grip of the robotic hand. Shoes can help to balance and record forces. Bodily sensors can provide dynamic monitoring of astronaut-health, while shortening the time on the feedback and accuracy from regular checkups to instant feedback. Combining these measurements with Big Data can support preventative health care for the crewmembers. Sensory feedback loops from the environment to the astronauts can amplify their variety, while enhancing their experiences, learning, and delight. Thus, enabling circular interactivity between

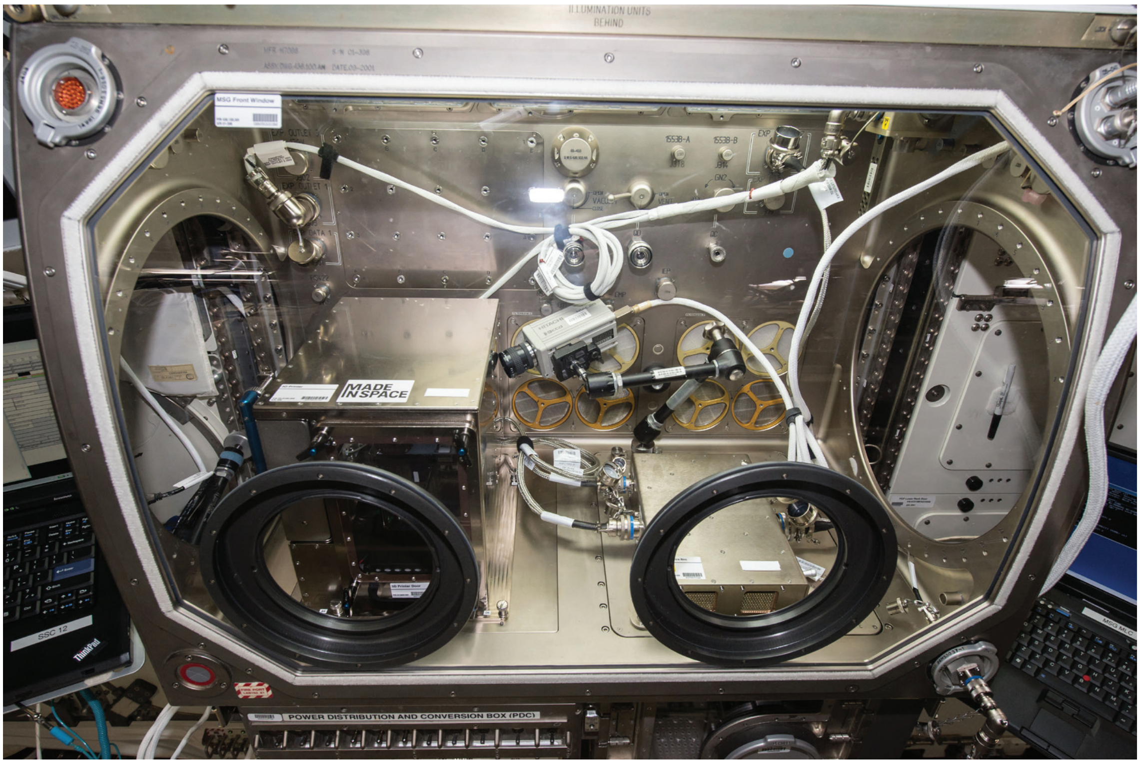


Figure 6.17: 3D printer on the ISS by Made In Space.

the environment and the user through delegated autonomy and amplified variety caters to discovery, and self-actualization.

3D printing has been demonstrated on the ISS in 2015 (see Figure 6.17). A 3D printer was developed in collaboration between NASA and the commercial additive manufacturing company, MadeInSpace (Moore, 2015). It was installed on the ISS last year, and used for public challenges to design parts, which were subsequently printed in orbit. The first printed object was a back scratcher, because one of the astronauts had an itch in his back and didn't have any way to reach it, so he quickly printed a back scratcher with satisfactory results. Additive manufacturing technology can help reduce logistics requirements on a Mars mission, where Instead of taking spares for all eventuality, the crew can print, recycle, and reprint needed parts. Besides functional making, the crew can use 3D printers for self-expression, creativity, and co-creating artifacts with crewmembers and family members from Earth.

6.4. Making a Case for Broadening Humanly Guidelines and Requirements

Today's human centeredness for human spaceflight is bound by the scope of the human-system Integration (HSI) domain standards and requirements, which focus on mission specific aspects of basic, physiological, and psychological needs. These are:

- *NASA-STD-3001, NASA Space Flight Human Systems Standard, Volume 1: Crew Health* (NASA, 2015a). This standard focuses on the human requirements, including the levels of medical care, human performance, fitness for duty, medical screening, exposure limits to space radiation, health screening and medical diagnostics, intervention, treatment and care during training, pre-flight, in-flight and post-flight.
- *NASA-STD-3001, NASA Space Flight Human Systems Standard: Volume 2: Human Factors, Habitability, and Environmental Health* (NASA, 2015b). This standard targets the crew's

interactions with the environment, their physical characteristics and capabilities, perception and cognition processes, environmental factors, habitability functions, architecture, hardware requirements that impact the crew, crew interfaces, spacesuits, operations, and ground support.

- *NASA/SP-2010-3407: Human Integration Design Handbook (HIDH)* (NASA, 2010a). This document provides additional details on the topics presented in the two volumes of NASA-STD-3001.

These considerations evolved over decades from earlier internal and external research findings and recommendations, before becoming actionable standards and requirements. For example, a NASA report (Connors et al., 1985) summarized the state of knowledge related to all considered aspects of extended duration human spaceflight. Some of the stated requirements listed in this report became parts of these above standards, while some remain unaddressed, including the topic I am addressing in my research.

Space habitats are designed for diverse solar system destinations. These include Earth orbit; transfer orbit; and the surfaces of the moon, Mars, and its moon Phobos. This results in configuration differences, which requires a systematic way to compare and assess them. To assess technologies and mission concepts NASA uses the Technology Readiness Levels (Mankins, 1995) and Concept Maturity Levels (Wessen, 2013). For habitats, a similar scale was introduced in (Connolly et al., 2006), called the Habitation Readiness Level (HRL) with a scale from HRL1 for basic technology research, to HRL9 corresponding to a flight proven configuration on an actual mission. HRL is beneficial to assess and compare habitat designs and configurations, even if they are relatively incompatible. (See the Glossary for further information on the HRL, TRL, and CML scales.) This scale is predominantly technology and human factors oriented, in line with existing requirements. Current assessment metrics do not include higher-level needs, as these are not part of the set of requirements considered by habitat designers. However, the HML framework is flexible and sufficiently accommodating to seamlessly integrate new requirements with existing ones as they become available.

In 2015, NASA's Office of the Inspector General performed an audit on the efforts to manage health and human performance risks for space exploration (NASA, 2015c), which listed HRP's human risks and mapped it into an exploration outline, from today's near Earth missions to a long-duration mission to Mars. Out of the 32 listed human health and performance risks, only one risk had a potential—yet remote—link to higher-level needs. It is risk number 18, on inadequate human-system interaction design. (For example, there is a risk that the current human-computer interaction and information architecture design does not support crew tasks effectively, which can lead to errors in flight and on the ground, and lead to failed mission objectives on long-duration missions. Another risk relates to the interactions between the crew and the automated or robotic systems on board.) The proposed path to risk reduction identified this risk "uncontrolled" until 2019, "partially controlled" until 2027, and controlled after 2027. The timeline didn't go far enough to the future to show when this risk gets to the "optimized" stage. Cross-referencing this with NASA's latest budget for Fiscal Year 2016, we can conclude that the mandate to build a habitat by 2018 mismatch the required state of human-system interaction design. Furthermore, none of these risks address the "delight" element of the human spaceflight, the human focus, and human centeredness from the level of higher-level needs, including self-actualization. In contrast, Connors stated over 30 years ago that: *"the overall goal for long-duration spaceflight will be to foster the kind of leisure activities, which will contribute to the general health of the individual…"* and *"…Individuals who actively engaged in their free time are psychologically healthier then more passive individuals. Yet when confined subjects engage in recreational pursuits, they opt for the passive or noninteractive variety."* Understanding this trend can lead to approaches, where "alternative activities can be encouraged" (Connors et al., 1985, p.100). I believe we need to revisit these early recommendations, and include higher-level needs in the overall design considerations. Starting with a conversation that guides these efforts, we can then derive the appropriate guidelines and requirements for long-duration spaceflight.

Up to this point I was setting the stage by discussing the state of practice related to human spaceflight, and the scope of human centeredness within the processes and accumulated knowledge base. From the conducted semi-structured interviews with practitioners and managers—listed in Appendix F—it became clear that one of the barriers to conduct advanced human centered habitat design studies is the lack of good requirements for it. Current studies typically focus on overall mission architectures, technological feasibilities, resource requirements, collaborations with international partners to share both the achievements and the high cost of deep space human exploration missions. As these studies and related research act within NASA's existing mode of operation, primarily focusing on function driven approaches. Human centeredness only comes in at a physiological level, and mission risk related psychological level, in support of the activities.

There is also a question about how requirements are derived in an engineering mode of operation. Relying predominantly on engineering requirements and basic needs considerations have they shortcomings for human spaceflight. Reducing them to engineering requirements and basic physiological needs may make sense within a technology driven paradigm, as these metrics are well defined and measurable. Engineers consider them "hard" requirements. But at the same time they leave out key human centered "soft" considerations. As described by Rittel: *"A related doctrine demands the belief in the existence of a list of basic human needs, common to all people at all times. The designer has just to identify them objectively and to design accordingly. There are numerous attempts to list basic needs, one and for all and for everybody. Unfortunately, in this list 'food' becomes 'protein,' 'carbohydrates,' and 'fat,' breathing requires 'oxygen,' a house becomes a 'shelter,' measured in terms of square feet. Because of their generality, such lists tend to oversimplify the problem: it is easier to provide protein than beef. Such lists wipe out the enormous diversity between people and cultures (even if they list 'privacy as a basic need!') thus erasing the unique and specific constellation of values in which every design project takes place and leading to solutions which cannot be implemented because people want beef not algae. It takes a long and difficult argument to convince people that they should better have algae"* (Rittel, 1971, p.7). Currently NASA does not have guidelines, let alone requirements for higher-level human needs. I believe designerly and artistic modes of operations could overcome the shortcomings of the approach described by Rittel and broaden NASA's engineering driven paradigm.

The job of the design team is how to incorporate human centered design elements into the architecture without significantly increasing the cost of the mission. The role of senior leadership is to recognize the need for human centered design, and through a second-order cybernetic approach, include and enforce guidelines and requirements for human centered design for future human space missions. However, the challenge is to establish meaningful requirements, which addresses these requirements. Novel requirements that address higher-level needs in Maslow's hierarchy are already subjective. Furthermore, these needs have to be translated to a unique environment, which falls beyond the experience base of most designers. In line with co-design, deriving meaningful guidelines for human centered design must be developed through conversations between various disciplines, from engineering to design, and with strong participation by astronauts who are the ultimate users of these environments and also have the cognitive model and experience to live and operate in space. These conversations need to be circular and iterative, through prototypes and analogs. While these approaches are already used within NASA, they still predominantly focus on human performance, human integration for mission related functions, and physiological and psychological needs of the crew, behavioral science, and ergonomics. This may ensure a functional space flight, mitigates risks, improves safety, but still ignores self-actualization, which is an important part of a broadened view where "the whole is greater than the sum of the parts." The third HI-SEAS analog mission ended on June 13, 2016. After emerging from isolation, crewmembers stated that: *"monotony was the hardest part of a yearlong NASA experiment about the mental and psychological rigors of long-term spaceflight."* Tristan Bassingthwaighte, a member of the crew added that: *"If you can work on something self-developmental…you will not go crazy."* Christiane Heinicke said that having *"something meaningful to work on"* was key to helping her endure the yearlong mission (Phys.org, 2016). While the goals of this analog mission were not targeting higher-level astronaut needs, crewmember accounts pointed at the need to study them further, and subsequently incorporate the findings into future long duration missions.

When casting today's space habitat design into the human body analogy, shown in Figure 3.10, we can come to a conclusion that not all systems are addressed. We can map basic functions and physiological needs under System 1, or Operations. This corresponds to body parts. Between Systems 1 and 2, or coordination we address security, safety, and psychological needs. These systems are covered by today's technology dominated paradigm. Between Systems 3 and 1, or audit, we can include love, belonging, connections with others and the environment, and psychological needs. These are partially addressed, especially on short-duration near-Earth flights. On long-duration flights this connection is becoming more decoupled and discontinuous. Planning is part of Systems 4 and 3, where self-esteem (one's place in society and the environment) plays a role. This is valid on short spaceflight, but long-duration spaceflight will start to introduce psychological challenges. Systems 4 and 5 involve direction, which is accounted for through crew training, but more can be done through human centered design, beyond the current state of practice. For example delegating autonomy to the crew to define their environment, schedule, interactions, and allowing for spare time but with sufficiently broad variety to enable the crew members to self-actualize. These are currently not part of the mission design trade space. Finally System 5 covers identity, with higher-level goals, self-fulfillment, being needs, learning, creativity, and aesthetic needs. Today we only have a vague recognition for these needs, but without identified guidelines, requirements, and forcing function to include them in future long-duration human mission architectures.

The inclusion of more human centered requirements is an important first step, but not sufficient. An example is the Resupply Stowage Rack on the ISS that NASA contracted out to Boeing. On delivery it fulfilled all the functional requirements, and NASA had to accept it. However, crew evaluation of the rack demonstrated that the habitat wall curvature and diameter made it impossible for a small-framed crewmember to operate the middle drawers out to a certain distance (Whitmore, 2015). So having internal habitation standards in a handbook is not sufficient. It requires added attention on how each element interfaces with the crew and with other objects inside the habitat, which makes the perspectives of designers and architects essential.

My goal in this example is to describe a perspective and approach that builds on second-order cybernetics and links it to human centered design considerations. These examples can be used by practitioners to implement guidelines and translate them to requirements, which in turn can flow into future point designs. This also introduces a challenge. Identifying novel concepts, or "thinking outside the box," are not part of the prevailing paradigm. Identifying them relates to second-order cybernetics, as well as applying a forcing function to implement them. Once these guidelines and requirements become part of the evolved paradigm, it introduces new options with a broadened boundary. Within this new boundary the broadened variety allows for new options. The implementation and resulting preferable outcome becomes first-order cybernetics, where practitioners interpret the requirements. Engineers, who dominate NASA, are trained to interpret well-defined requirements. For them, "soft" metrics (Palinkas, 2001, p.25)—which are based on psychology, psychiatry, and human centered requirements—are harder to measure. To address these aspects, NASA will need designers and space architects—serving as subject matter experts—to be involved throughout the mission development processes, not limited to the formulation phase only.

Furthermore, the iterative co-design process—e.g., concept design, graphic and physical prototyping, and user experience through analogs—must be followed and coupled with user evaluation of the design objects as it matures through the formulation and feasibility assessment phases into development. The subjective user experiences have to be translated into objective data on usability. This is a regulatory way of approaching design, where the variety of the object is contained to expected and intended outcomes during their use.

6.4.1. Selected Attributes for Humanly Space Habitat and Object Designs

Human centered architecture that builds on cybernetic considerations was strongly advocated by Gordon Pask (Haque, 2007, pp.58-61). His ideas are also applicable to humanly space habitats, making the environment dynamic and interactive. In today's habitat design interactivity is only implemented in an engineering sense, where astronauts spend years to learn operational procedures, set in place by engineers, based on initial requirements to support humans as one of the elements of the overall system. This proved to be sufficient on short-duration near-Earth spaceflight. Looking at Abraham Maslow's Hierarchy of Needs (HoN) in Figure 6.1, as related to astronauts and space systems, we can state that today's technology driven habitat designs only address basic physiological and safety needs, and account for some of the higher-level psychological needs through astronaut pre-selection, and astronaut training.

In my view, today's space habitat designs predominantly cater towards basic needs, do not place high priority on human center design, and subsequently, not sufficiently equipped to support long-duration spaceflight. In current designs, the limited habitat volume and pure functionality, combined with human physiological and psychological factors, will likely make the experience similar to a multi-years long solitary confinement. To make a habitat design more human centered, Maslow's Hierarchy of Needs should be turned around, with a primary focus on the astronauts' higher-level needs. The mandatory basic needs would be designed into the system through a subsequent step, and wrapped around the higher-level needs. In effect, habitat designers would account for dynamic interactions between the astronauts and the environment, handing over control to the astronauts and to the habitat when possible, while removing as many of the predetermined control restrictions as practical. By providing conversation-based creative interactions with the environment across perceptional boundaries of the astronauts, the habitat can mitigate monotony during these long isolation-inducing spaceflight. In this approach, system responses is not be pre-defined by engineers prior to the mission, but instead, the system is designed to construct its own input to the conversation in order to engage the astronauts, and foster harmonious relationships with other crew-members and the habitat environment.

As a consequence, space habitats will become architectural systems instead of passive protective shells. Of course, this should be designed with care, and with the astronauts' safety in mind. It should be also noted that this approach will not negate the need to satisfy basic needs through technological means. But it will improve operational efficiency and psychological wellbeing, once the design is turned around and initiated with higher-level needs, and better conversations.

This "Paskian architecture approach" will allow architects and designers to move beyond the current practice of providing architectural forms and nicer packaging, in line with basic functionality to address engineering and physiological needs. This can also involve artists to create artifacts for these long-duration space missions, and provide a conversation between their objects and the astronauts, while catering to their higher-level needs of love, belonging, esteem and self-actualization.

Beyond the protective shell, space habitats consist of artifacts, which interact with the crew. These humanly objects and artifacts on any space mission need to operate in the extreme environments of space, including vacuum or the Martian atmosphere, extreme temperatures, radiation, and low or reduced gravity. Using objects in a closed habitat requires safety considerations as well. Beyond the strictly physiological and safety needs, they should also provide support for higher-level psychological needs, such as love and belonging. These humanly objects can be designed and created on Earth or in space, and may target one or multiple senses from our sensory perception. Depending on the intended use or designed impact on the observer or user, the sensory stimuli can be coherent or not. Furthermore, on long-duration spaceflight resources are limited, therefore the object can be designed with multiple functions for diverse habitation scenarios, such as working, resting, exercising, and socializing.

The level of interactions between the astronauts and the artifacts may vary from passive observation to full interactivity. The types and levels of interactions with the objects are designed into them in the form of affordances (Gibson, 1986, p.127), and highlighted using signifiers (Norman, 2013, p.18/499). Since the variety of the environment is broader than that of the designer (regulator), the user of the object may find new unintended uses for the object, beyond the affordances conceived by the designer. This can be explained through cybernetic conversations, and cross-referenced with my three-actor model (Balint & Hall, 2015b)—which is further discussed in Appendix C. The first conversation happens between the designer and

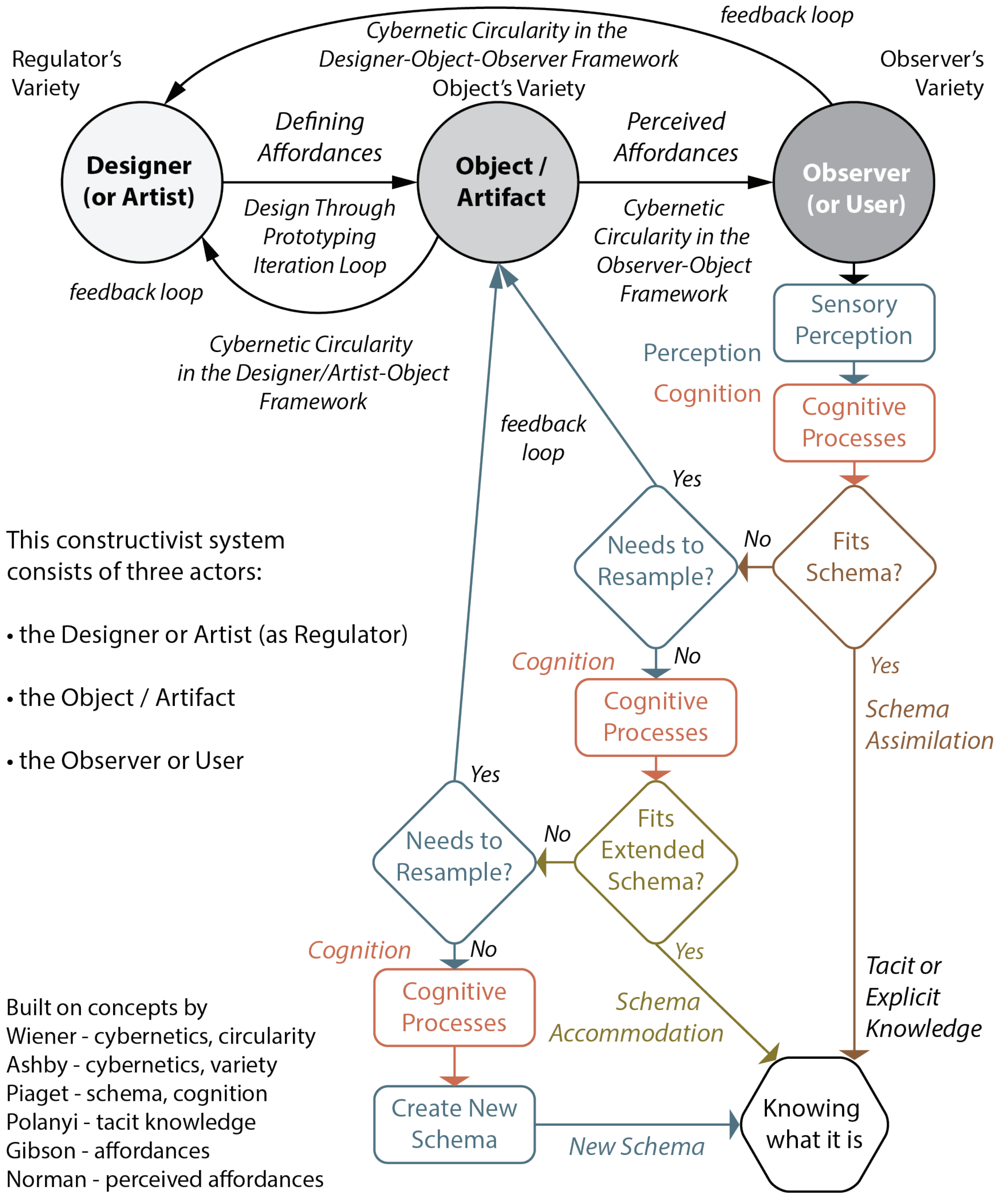


Figure 6.18: A constructivist system with 3 actors: Designer & Object & Observer. The model also includes two sub-systems with 2 actors: the Designer & Object system, and the Observer & Object system. Through the Object, the Designer & Observer are also linked.

the object or artifact, as shown in Figure 6.18. Here the designer or artist (regulator) balances variety across the whole system through prototyping cycles. Such personal conversations with the artifact may create new ideas that advance the design towards a final outcome. For example, when we create a prototype, it represents our cognitive output at that given time. It becomes a representation of our ideas, translated into a real world object. Through the prototyping steps the artifact also contains additional information, which may come from manufacturing or material imperfections, and its interactions with the environment. When we revisit this artifact in a subsequent iteration step, we may see it in a different light, which can provoke new ideas, thus broadening our own variety. This broadened variety from the perceptional feedback through subsequent iterations allows us to create new ideas and solutions, and reformulate our cognitive models or schema about the object. (It should be noted that the external noise from the environment has a cognitive internal counterpart, called cognitive bias (Kahneman, 2013), which may find its roots in culture, or in the person's cognitive inherent models, e.g., rigid ways of linear thinking. Cognitive dissonance (Festinger, 1957) and cognitive bias (Kahneman, 2013, p.1059/1307) can lead to an epistemological obstacle or block (Idlas, 2011, p.8), making changes difficult or at times impossible without new information—or in a cybernetic sense, without increasing the regulator's variety.) The circular conversation between the artist or designer and the artifact or object continues until a stopping rule is applied during this convergence phase of the creative process. At this point the artifact/object is finalized. In a cybernetic sense, with the concluding artifact the artist, acting as a regulator, successfully balanced the variety and reached a perceived equilibrium between all elements of the system. These iterative conversations are essential in the creative process. The second cybernetic design conversation takes place between the object or artifact and the observer or user, who now becomes the regulator of this system that includes also the environment in which they reside.

There can be a broad set of considerations when designing for the space environment. The list of considerations can be grouped into categories, related to design aspects; arts; architecture; and engineering and technology. These span across Maslow's HoN, and may also overlap between multiple categories. While these aspects have been understood and broadly explored through artistic movements and designs for terrestrial applications, transposing them into humanly space objects may require special attention. After all, these objects and artifacts will interact with the users and observers in the extreme environments of space, and impact the unique physiological and psychological conditions they experience during the spaceflight. Furthermore, these artifacts also need to comply with stringent requirements during the development process in order to bring these artifacts to space. The human centered considerations for designers can include—but are not limited to—design attributes listed in Table 6.1. Detailed discussions on design, artistic, architectural, engineering, and combined attributes, wither relevant examples from their disciplines, are given in Appendix C.

Design attributes:

- Affordances and signifiers;
- Interactions (peer-to-peer; regulator versus environment; three-actor model);
- Emotional design and empathy with the object;
- Human centered; human connections (emotional, physical);
- Temporal and spatial dimensions;
- Immersive awareness;
- Cultural aspects;
- Multi-level storytelling (knowledge transfer; emotional);
- Scaled multi-level experiences;
- Cybernetic learning/teaching cycles;
- Relativistic interactions (changing roles);
- Physical and virtual interactions.

Combined attributes:

- These above attributes can be combined into a multi-functional object.

Artistic attributes:

- Abstraction;
- Changing the meaning;
- Certainty versus uncertainty (predictability);
- Movement versus stillness
- Visual impacts of light and dark.

Architecture:

- Space habitats (scale, immersion, interaction).

Engineering and Technology:

- Mass and volume considerations;
- Safety considerations;
- Spaceflight environment / extreme environment.

Table 6.1: Examples for human centered design attributes.

6.5. Epilogue to Humanly Space Habitats

In this section I have discussed considerations for designers, architects and artists, planning to design humanly space objects for long-duration spaceflight. These are objects that can be observed or used in a space habitat, and designed with a primary focus on higher-level self-actualization needs of the users. Cybernetics played a significant role in the formulation of this discourse. Building on interviews from practitioners and senior managers at NASA, background research and personal experiences from project to strategic levels, my synthesized findings through cybernetics provided a perspective on NASA's worldview related to human centeredness within its engineering and technology driven paradigm. I have also included contemporary examples from the fields of design and art to illustrate underlying concepts in Appendix C, thus providing the basis for detailed discussions on the human centered design attributes.

Assessing the state of practice on human centered design at NASA helped to demonstrate that there is a level of human centeredness present, but it is limited NASA's focus to crew health, human factors, habitability and environmental health. In NASA's engineering and technology driven paradigm a mission is built up from subsystems, systems, and system of systems. In this modular system hierarchy each element is developed by a team who takes ownership over it. This controlling oversight of projects and project elements are different from a synthesis-based big picture view of designers and architects. Thus, human centeredness takes a secondary position among the priorities. On today's short-duration spaceflight the activities revolve around work, and supported by basic human needs, such as sleep, food, hygiene and leisure, in the form of exercise. A notional breakdown of these activities is shown in Figure 6.19. On future long-duration spaceflight there will be extended time periods where the weighting on these activity elements have to be adjusted to cater to the crew's self-actualization needs.

Through my research I have concluded that NASA's habitat paradigm for long-duration missions to Mars does not sufficiently address higher-level needs, including self-actualization needs from Maslow's hierarchy. Without addressing this need, the crew will lack some of the necessary functions that are required to make a system viable.

The NASA Space Flight Human Systems Standards (NASA, 2015a) (NASA, 2015b), the Human Integration Handbook (NASA, 2010a), Connors (Connors et al., 1985), Palinkas (Palinkas, 2001), Morphew (Morphey, 2001) and others discussed various physiological and

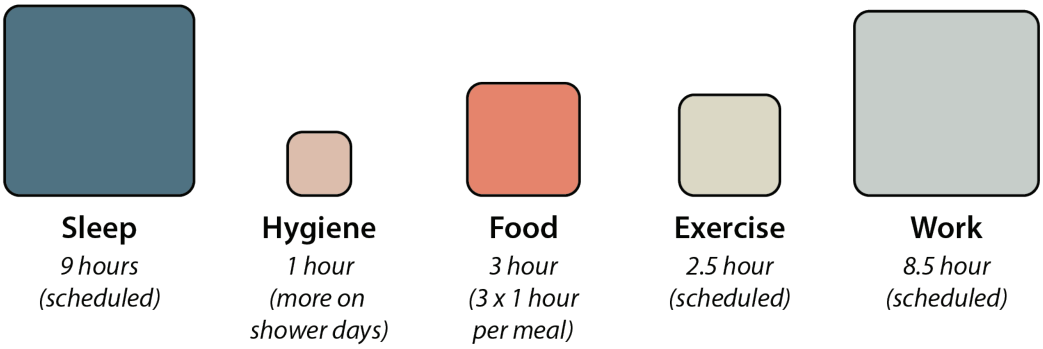


Figure 6.19: Notional activity schedule on a short-duration spaceflight.

psychological aspects impacting the individual, the interpersonal, and the organizational domains, related to long-duration space missions. These examinations also included cross-cutting aspects from engineering, through medial, and biological, to organizational cultures. With future plans to go to Mars, and increasing the mission duration to 1,100 days, there are stressors (acting individually or in combination) that impact the lives of the astronauts. Addressing the human centered aspects can benefit from other modes of operations, including designedly and artistic modes. Specifically, improved conversations between the crew members, the crew and ground control, and the individuals and their environments at various scales from an object to the habitat, can promote discovery, exploration, and provide motivation to perform both work and recreational tasks. The recreational aspects are particularly important on long-duration spaceflight, as they can eliminate monotony, and improve crew dynamics. Artistic modes can help the crewmembers with their performative activities, creating artifacts, and supporting cognitive, aesthetic and self-actualizing needs. Boundary objects can be created for the astronauts or by the astronauts using design attributes, which are detailed in Appendix C. These boundary objects support conversations, and can be designed for higher-level needs, and can be unchanging or evolving - as will be further discussed in Section 7. Including these designedly and artistic modes, however, would required an augmentation or modification to the current NASA paradigm.

Self-actualization related activities have to be supported by the environment that consists of the crew, the habitat and its object content. Designing an environment that provides sufficient variety for discovery and delight should be primarily done by designers and architects, and subsequently supported by engineers. The design principles fall under second-order cybernetics, where the broadened variety of the system accounts for new human centered needs. For engineering systems today’s requirements address functionality towards mission goals and in support of basic human needs, in line with first-order cybernetics. Retrofitting a completed system for human centeredness requires redesigns, which is prohibitive due to cost and schedule constraints. For engineering systems, once the requirements are set, the projects are developed in a linear fashion. For human centered systems the requirements evolve through iterative processes, including the user. The process gradually converges to a constructivist outcome that incorporates experiences throughout the development process. From a typical engineering perspective, evolving requirements lead to requirement creep, which impacts both cost and schedule. Thus in an engineering paradigm with cost constraints, iterative design methods are not embraced. This provides a barrier to include higher-level human centered considerations for future habitat designs.

My gained insights through this research on human centeredness pointed to implementation challenges on multiple levels within the organizational hierarchy. Expectedly, changing NASA’s engineering focused paradigm introduces challenges to designers, space architects—who work with engineers to envision these future habitats. Therefore, the challenge for designers is two-fold. First, their designs have to enhance autonomy and self-actualization of an astronaut in a space habitat environment, and promote conversations between them. They have to broaden the variety of the astronauts and their environments that facilitates discovery and delight. Second, the designs must comply with requirements imposed by health, safety, engineering and performance constraints. Designers also must develop a common shared language with engineers and senior leadership in order to facilitate a shared understanding between the disciplines.

A potential approach to include topic-focused human centeredness to NASA's paradigm involves three stages. In the first stage, and interdisciplinary team of designers, astronauts, engineers and scientist would conduct a series of human centered analog studies and exercises, with a focus on higher-level self-actualization needs of the crew. This would be performed through iterative analog studies, where a broad range of design approaches can be tried out. As the meaning of the used boundary objects are determined by the users and not the designers, an important part of the exercise is to collect feedback from the users and incorporate the findings into subsequent design updates. These iterations continue until the variety between the designer and the user is in equilibrium, and the desired shared and agreed understanding and outcome are achieved. From these analog studies, in the second stage, the team would derive guidelines then requirements, based on user experiences, which would become part of the full set of combined existing and new requirements. This approach is not new. It is similar to the one use by HRP towards addressing the crew's lower-level physiological and psychological needs. In the third development stage, the multi-disciplinary team would develop the habitat through a process that includes close participations by the designers and space architects, and involve the notional crewmembers to test and provide feedback on the progress and the achieved level of user centeredness. Beside terrestrial validations, the designed objects could be also tested on the ISS and in cislunar space, as a stepping-stone towards a long-duration mission to Mars. This described design and development process with the three stages is neither unique, nor novel. In fact it is the standard mode of operation when designing habitats. The new element is the inclusion of higher level needs in the analog studies, and the acknowledgment that all participants are explicitly incorporated into the system, making the analog study an observing paradigm, in line with second-order cybernetics. During these analogs the study goals can evolve over the course of the mission. As an outcome, it can bring self-actualization connected human centered design into NASA's paradigm, which can be achieved by augmenting the current requirements in NASA-STD-3001, to include higher-level needs.

The findings and recommendations in this section on NASA's human space habitation paradigm belongs to speculative research, where I have highlighted the importance of addressing higher-level needs, which is currently unaccounted for. Thus, this research element is only a point of departure towards establishing relevant guidelines and requirements. Further work is needed to develop, advance and substantiate these long-duration human space habitat designs that may provide a fully immersive environment with circularly interacting artifacts in support of the higher-level needs of the crew, including self-actualization.

It is also important to emphasize that without a forcing function from a strategic level (to mandate these added requirements), and delegating decision authority to designers at the implementation level, NASA's operational paradigm will remain unchanged. Furthermore, without addressing self-actualization needs, human centeredness will have an incomplete role in long-duration human exploration missions, which will likely impact mission success.

Finally, in support of this discourse, I have identified a number of design, art, architecture, and engineering related attributes related to designerly and artistic modes of operation, and incorporated them into boundary objects, including the cybernetic astronaut chair, which will be discussed in Section 7.

Section 7. Boundary Objects— Categorizations & Examples

Venus Watch 1.0 (3D Printed Titanium–Sapphire–Parachute Nylon–Woven Carbon / 2016)

7.1. Prologue to Boundary Objects

For over half a century space exploration has been dominated by engineering and technology driven practices. Within this paradigm, technology and resource needs are coupled with scientific and exploration goals. The disciplines became highly specialized, supported by a language that facilitates effective communications between subject matter experts (SME) in the form of a short hand. While this aspect of communicating is beneficial, it also introduces barriers for the SMEs to think outside of their own domains. Subsequently, a bounding language constrains the operating modes and the options space, and may limit innovation to incremental advancements from the current state of practice. Furthermore, this paradigm leaves only limited room for designerly and artistic modes of operation. It is contrasted by other parts of our everyday lives, where creative disciplines, such as art and design, play important roles. They stimulate new ideas and connect people to each other at deeper levels. They are affecting our worldview as we evolve our cognitive models. We construct personal cognitive models through circular conversations with our environment, through perception and making sense through our sensory systems and responding back through language, gestures, actions, and interactions. Designers and artists create artifacts through conversation cycles of sense-giving and sense-making (see Figure 3.8), thus adding variety to the phenomenal world in the form of evolving messages and distinctions. Each message becomes information when the observer decodes it, through multiple sense-making and re-sampling cycles. Simply put, the observer is taking another look, in case the initial cognitive interpretation feels incomplete, or does not make sense. The messages form triggers to the cognitive state of the observer. Having a shared key between the designer/artist and the observer is fundamental to encode and decode the information in conversations. (However, as the observer decides the meaning of the message and not the sender, this may result in a mismatch even if the encoding-decoding key is shared between them.) Art, design, science, and engineering, are all creative practices. Yet, they often speak different languages, where some parts may correspond, while others address a different variety in a cybernetic sense. Thus introducing new modes of operations to existing paradigms—e.g., designerly and artistic modes to NASA's engineering mode—using conversations to construct novel shared languages is key to broaden paradigms, and to develop an environment that supports transformational or disruptive changes. For example, the X-Hab project was funded by NASA and performed at the Pratt Institute. Using an art and design driven approach, the project yielded a novel space habitat configuration, which was not previously envisioned at NASA (Pratt, 2016). Finding coherence and constructing shared and agreed meaning between disciplines enriches the practitioners and their fields, and may pave the way towards new possibilities, which can reach beyond the bounds of each discipline-based paradigm. These specialized languages within disciplines streamline communications, but limit variety. Discipline-specific specialized languages may introduce communication blocks in the intersections of various fields. But, bridging across discipline boundaries can be beneficial, as it can introduce new variety into the discipline, which could lead to novel discourses and options. We may dissolve communication blocks through the introduction of boundary objects in the intersection of multiple disciplines. Boundary objects can ground ideas and bridge language diversity between disciplines. These artifacts are created to facilitate circular cybernetic conversations, supporting convergence towards accepted shared meanings between the actors. A shared language can also create new variety that evolves through conversations between the participants. Misunderstandings through conversations can also lead to new ideas, as they stimulate questions and add unexpected variety to the discourse, which may suggest novel solutions.

In this section I am proposing new categorizations for boundary objects, by drawing from design and cybernetic analogies. I am evidencing these categories with a number of space-related object examples, which were mostly created or co-created by me, unless stated differently. These include the Galileo Flow Field artifact (Balint, 2016), medals (Balint, 2016), the Venus Concept Watch (Balint & Melchiorri, 2014), the Cybernetic Astronaut Chair (Balint & Hall, 2015a), posters, mockups, keystone graphics. I also briefly address space habitats. Making these boundary objects allowed me to slow down, reflect on ideas, and objectify abstract concepts related to my research. The making process helped to convert research findings into communicable and abstracted knowledge. I have used these boundary objects to facilitate conversations with diverse audiences, ranging from scientists, and engineers, to artists, designers, and the general public. In essence, boundary objects and conversations provided a "connective tissue" across my research examples, discussed in previous sections and in the appendix. The making of these artifacts—these boundary objects—also added a vitruvian delight element to my research. In Appendix E, I have provided a complete list of these artifacts, including details on their making processes.

7.2. Expanding the Definition of Boundary Objects

To create an artifact we need to have, at a minimum, a perspective about

- A distinction—by defining how an object fits into the environment,
- A purpose—an idea of its role, and
- A process—a means of creating the artifact.

Making artifacts is an iterative process that requires guiding choices towards a preferable outcome. I have discussed this process through a three-actor model (see Figure 6.18) (Balint & Hall, 2015b). This model consists of circular conversations between the designer/artist, the observer/user, and the artifact/object. In the making and also the interpreting circles converge towards an agreed shared meaning through conversations between an actor (the designer/artist and/or the observer/user) and the environment where the artifact/object is situated. (It should be noted that technically speaking from the perspective of Conversation Theory (Pask, 1976, p.27), a conversation between a person and some type of environment is possible, when the environment is also capable of a conversation. Some of Pask's machines belong to this category, while other environments, like a stone, are not capable of a conversation. However, an observer/user may conjure an internal conversation that is the consequence of the presence of the stone, but in which the stone is not an active agent.)

Artifacts and objects can be created at the boundary of disciplines. Boundary objects were introduced by Leigh Star and Griesemer (Leigh Star & Griesemer, 1989, p.388), discussed in Section 3.4. Based on my research findings, I am proposing to expand Leigh Star and Griesemer's boundary object types through an approach that is similar to Christopher Frayling's categorization of design (Frayling, 1993, p.5). Frayling discussed design research activities under three categories (see also Section 2.2):

- *ABOUT*-design or *INTO*-design,
- *FOR*-design, and
- *THROUGH*-design.

I am proposing to apply this approach and cross-pollinate the concept of boundary objects from social sciences to design in support of effective communications and conversations. The three categories can be described as:

- Communications *ABOUT* boundary objects;
- Boundary objects *FOR* communications; and
- Design conversations *THROUGH* boundary objects.

In the following subsections I am discussing these proposed categories, and include examples to substantiate them. I am also grounding them through their relevance to the three NASA examples in Sections 5 and 6, and Appendix D.

7.3. Communications ABOUT Boundary Objects

Conference papers, journal articles, books, and other media, including films, can be used to communicate blue-sky ideas, low maturity concepts, and theories about real and virtual artifacts. Communications about boundary objects are reflective practices, where the authors of the articles present their theories based on their research. The goal is to disseminate related findings to an interested audience. In this form the conversation loops between the researchers and the audience are spatially and temporally decoupled. Feedback from the audience could help the researchers to refine their presented proposals and arguments about the boundary objects, but the updates can only be addressed through subsequent revisions of the articles.

7.3.1. Boundary Object Example 1—Articles

In this first example, I propose to consider my thesis, and boundary objects related journal articles and conference papers as examples of communicating contextually ABOUT boundary objects through printed and published media. For example, I have presented a boundary objects related paper to an attending audience at the “E.5.3—Contemporary Arts Practice and Outer Space: A Multi-Disciplinary Approach” session of the 67th International Astronautical Congress (Balint & Pangaro, 2016). The audience consisted of space artists, designers, architects, engineers and scientists, who operate within the aerospace enterprise. They came from diverse organizations, from government agencies to private industry. Hence, I have communicated the contextual information from the paper across multiple discipline boundaries. As this material is presented directly to a conference audience, the venue allowed for real-time conversations between me, as the presenter, and the attendees. This subsequently facilitated feedback from the audience, allowing for convergence towards an agreed shared understanding and meaning of the presented concepts and examples. Consequently, the article in its printed form represents communications *ABOUT* boundary objects, while the presentation material acts as a boundary object *ABOUT* and *FOR* communications. That is, the context is *ABOUT*, while the presentation used in conversations is *FOR*. Thus, I am using the articles (Balint & Pangaro, 2016) and (Balint, 2016) as substantiations for these, as boundary objects.

7.3.2. Boundary Object Example 2—Films

In September 2015, I have conducted 32 semi-structured interviews with practitioners from strategic management levels at NASA HQ, to project level subject matter experts at NASA JSC and JPL. These centers were selected for their strategic relevance for Human Centered Design (HCD) inside NASA’s technology and management-driven paradigm. Through these

Figure 7.1: Notional film poster for the documentary film under development.

conversations I have collected and synthesized up-to-date information for my research on NASA's HCD activities related to human and robotic space exploration.

With my collaborator, Oliver Lehtonen (an RCA IDE graduate), we filmed these interviews, and we are currently developing it into an independent documentary film. While this film is decoupled from my research, I am including it for discussion purposes to exemplify a virtual boundary object in this category. The film explores the roles of HCD at NASA. The storytelling approach of the film targets general audiences, as well as subject matter experts from the aerospace enterprise. The film tells stories about boundary objects, including space habitats and humanoid robots, which are in the intersections of HCD, architecture, art, engineering, and science. It also shows how keystone graphics can help to communicate between the proposing science and engineering teams, and proposal evaluators who recommend mission concepts for funding. (Keystone graphics, which will be discussed below, are visual representations of complex concepts that are captured in a single image, and can convey the intended message better than long text-based descriptions.) The film tells a largely unexplored story to the general public about the design and art side of NASA. (The notion teaser poster of the upcoming documentary film is shown in Figure 7.1, which itself is a boundary object, connecting the filmmakers and the audience.) Due to the nature of this medium, initial feedback is collected from selected test viewers. Their comments are subsequently incorporated into the film. The film is positioned in the intersection of art, design, engineering, technology, science, and general interest. Further information on the interviews, including the people, logistics, and topics are presented in Appendix F.

I have also created a second short film about designing and making a boundary object in the intersection of art, design, science, and engineering. It is titled "Making of the Galileo Flow Field Artifact." I have posted this video on Vimeo (Balint, 2016a), with a goal to inform general audiences about the interdisciplinary nature of this sculpture, and the delight of making it. As of October 2016, the film has been viewed 52 times. I have also played the film at the 13th International Planetary Probe workshop (Balint, 2016) to the attending 150+ experts, which initiated conversations about my research, and the object. These Internet views to the public, then the screening and subsequent conversations with engineers and scientists substantiated the short film's viability as a virtual boundary object, bridging multiple disciplines.

7.4. Boundary Objects FOR Communications

This category describes physical boundary objects which are used to cross-pollinate concepts and ideas between disciplines. The purpose of this category is different from the previous one related to *"ABOUT,"* as the subject matter is not related to the explanation of boundary object theories. Instead, these boundary objects are created within one or multiple disciplines, and used in conversations to conceptualize ideas and to provide a common focal point to advance the discourse towards an agreed shared understanding. Research FOR design and art involves practice based objects, where thinking is contained in abstracted artifacts, and implicit knowledge is communicated using them. In this section I am substantiating the proposed categorization using my own boundary objects, created for this research. Other examples include artifacts and posters created by designers and artists at JPL's Studio (see Appendix D.2.4). Members of the Studio coined the term "sneaking up on learning," where they use the objects to provoke conversations about a given topic. This approach is also valid for the examples presented below.

7.4.1. Boundary Object Example 3—Cybernetic Astronaut Chair

In support of the discourse for space habitat related designs, I have designed and built this boundary object to test—in practice—the human-centered design considerations for space objects. I call this artifact a "cybernetic astronaut chair." The object encapsulates and grounds a subset of the design attributes listed in Table 6.1, and in Appendix C.

The artifact's tensegrity structure was inspired by the tensegrity robotics work at the Intelligent Robotics Group at NASA's Ames Research Center (Caluwaerts et al., 2014, p.2). The tensegrity structure—held together by wire tension alone—is light, with a total chair mass under 2kg, including all of its components. These components included five 1m long metal tubes with a 20mm external diameter; two folded canvas seats with 10 eyelets each; 25m of parachute cords, ten wooden and PVC end-caps; and 20 turn buckles. While the assembled chair had a bounding geometry of 1m by 0.7m by 0.7m, the disassembled parts could be stowed as a small volume during the flight to space. As an additional design feature, the parts can be reused and repurposed to change the meaning of the object. The assembly/disassembly also changed the temporal and spatial dimensions of this artifact. This is relevant, as during launch to space the stowed components would occupy a small volume, while in space the habitat can accommodate the larger deployed volumes. Safety considerations are addressed through smooth surfaces, round edges, soft textiles, and light parachute cords. The "IKEA-like" assembly and disassembly activity of the chair can provide a (hopefully) enjoyable activity for astronauts addressing their higher-level needs, and break the monotony of long-duration spaceflight.

The chair—shown in Figure 7.2—demonstrated the circular design conversations of the designer with the self and the environment during the sense-giving and sense making cycles, through the object (see Figure 3.8). My design goals with this boundary object was to evidence design considerations in a physical form, and to initiate a conversation with other space designers, artists, engineers, and the general public. As an outcome, I have exhibited the chair at the RCA Work In Progress Show in 2015; and presented it at the "E5.4—Contemporary Arts Practice and Outer Space: A Multi-Disciplinary Approach" session of the IAC15 conference (Balint & Hall, 2015a), where it stimulated conversations among the audience of artists, designers, engineers and scientists. The paper was also republished in the peer-reviewed journal, Acta Astronautica (Balint & Hall, 2016).

In this example I am also discussing my design process, including divergence and convergence cycles; sense-giving and sense-making circularity; and my circular conversations

Figure 7.2: Front view of the cybernetic astronaut chair.

with the self through the boundary object. Throughout the iterative design flow, I was immersed into the making process, became part of the system, and within a given iterative cycle converged the design to a predetermined goal. It is in line with a first-order observing system (see Figure 3.1). However, between iterations steps I had an opportunity to step back, reassess the design, and modify the design goals for the next iteration. Self-critical assessments from my sense-making observations, and comments from colleagues influenced my thinking about the design, and explicitly incorporated me into the system, resulting in a second-order observing paradigm. Through this process description I am also highlighting the non-linear nature of designing, including dead ends, compromises, concept evolution, and a “creative leap” (Cross, 2007, p.65).

The design process was initiated through an exploration of the following general question: “What type of artifact can be designed that addresses a significant number of design considerations listed in Table 6.1?” My creative design strategy followed a similar process to the one described by Cross (Cross, 2007, p.96). It included:

- ↳ A problem goal of designing a chair for space, highlighting design considerations for a space habitat-based object and the affordances to use it;
  - ↳ A problem frame that addressed the extreme conditions in space;
    - ↳ Addressing relevant first principles, by primarily including and highlighting zero-gravity utilization, but also addressing mass, volume, safety, modularity, and other considerations;
  - ↵ A solution concept with a tensegrity structure for a chair with two astronauts sitting on it, simultaneously, back-to-back; and
- ↵ Solution criteria about evoking space aesthetics and zero gravity functionality for the chair.

Through an initial set of divergence—convergence cycle (see Figure 3.13), I have answered the general design question by identifying a number of potential ideas, then narrowing it down to a single specific question. The set of options ranged from static, dynamic, and interactive objects at different scales, up to a full habitat, from which a chair was chosen as a design object for its simplicity compared to others. In the second convergence—divergence cycle I have explored various options for the chair design, which included sketching and computer modeling. Sketching is an important element of the design process, because *"sketches enable designers to handle different levels of abstractions simultaneously"* (Cross, 2007, p.57). Computer models help to refine proportions, scale, and generate photorealistic representations of the concepts. From these options I have chosen and build a final point design. In this discussion I focus on the second design cycle, limiting the design goal to a chair.

I have designed and developed the chair as a form of abstraction and discussion focal point to highlight a subset of concepts and ideas that designers may consider when designing objects for space use, with attention to human centeredness or interactions. Although there is no functional need for chairs in space, they can provide the familiar cultural and emotional experiences of home, while far away from home. One of the key aspects of the design was the utilization of zero-gravity, where up or down has no meaning or relevance. Consequently, the overarching theme between the various concepts was the use of two seating surfaces, attached back-to-back, which can accommodate two astronauts simultaneously, also symbolizing the circularity of cybernetics.

The first concept, shown in Figure 7.3 (a) to (c), was a relatively traditional looking chair with two seats back-to-back, on the top of each other. I have imagined this compact design with wooden or wired seats and a slightly tilted seating angle for comfort. (I rendered it with the software Blender3D.) With simple and familiar forms it evoked the feeling of comfort, but beside the implied cybernetic circularity of the seating arrangement and the need for zero-gravity to use it by two people simultaneously, it did not provide additional connections to space. One of my research colleagues called the design boring and traditional, the kind that one could purchase from IKEA. These feedbacks on the significant shortcomings made me reassess and modify the design goal for the next iteration.

The second family of the chair designs is shown in Figures 8.3 (d) to (f). Here I have abstracted the form to the two seating and back support areas only. Refinements from Figure 7.3 (d) included further simplifications by taking out the middle truss of the back seats, thus reducing the mass, as shown in Figure 7.3 (e), and adding a seating angle for better support in Figure 7.3 (f). These designs were more compact and lighter than the ones shown in the first set, which is an important consideration when designing for space. I have "painted" the seating and back support areas red on one side and white on the other, acting as signifiers for the two users. However, it was still a large and rigid construction, and the seating angle in (f) provided more of an aesthetic appeal than a real functionality, as in zero-gravity such angles have no relevance or meaning. My conclusions corresponded to the feedback from other RCA IDE researchers and tutors.

This iterative conversation between the self, as the designer, through the object continued in the third iteration, shown in Figure 7.4, where I have carried forward the abstraction and signifiers from the second set, with an added foldability feature and further simplifications. The unfolding process is shown in Figures 8.4 (a) to (e), while (f) and (g) provide information

Figure 7.3: Chair concepts from the first iteration cycle (a) to (c); and the second iteration cycle (d) to (f).

on how the chair can be used by two people or one person. This design satisfied a number of attributes from the list in Table 6.1. These included: compact stowage (relevant during launch, and storage and use inside a space habitat); light weight; safe use; size compatibility with a space habitat, physical connection with the user; abstraction; implied affordances for sitting (as in zero-gravity it is not a real affordance); signifiers; and change in spatial dimensions during deployment. However, even from the designer's perspective it did not provide comfort for the intended users. Also, the form was abstracted too far, resulting in a dead end, and prompting the search for a new design direction, while building on the insights from these three iteration cycles.

The final design emerged through what Nigel Cross called a "creative leap" (Cross, 2007, p.65), when I asked myself: *"what chair configuration can combine the 2-user zero-gravity function with an aesthetic yet robust aerospace structure design style?"* From my prior iterations, sketches, research, and experiences I recalled the NIAC-funded tensegrity

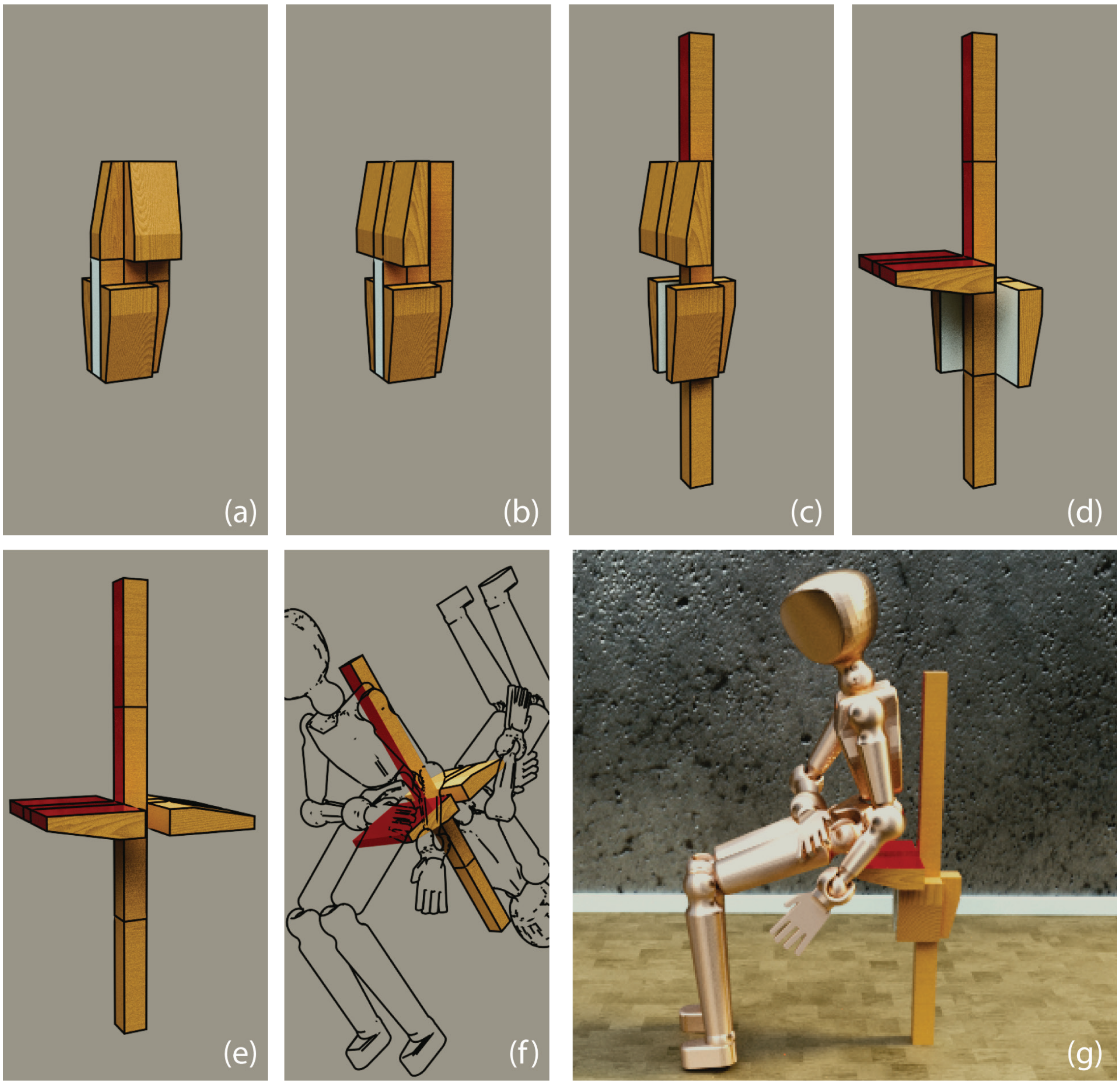


Figure 7.4: Chair concepts from the third iteration cycle.

robotics project, which seemed to match these goals. (Tensegrity robotics is developed at the Intelligent Robotics Group at NASA's Ames Research Center, in collaboration with a number of international universities (Caluwaerts, et al., 2014, p.4).) The term tensegrity refers to tensional–integrity, where the components, such as trusses, are isolated and under constant compression, provided by continuous tension from connecting cables. These are jointless structures, resulting in light yet sturdy and rigid frames. The referenced potential application for space robotics provided a connection between a space theme and the cybernetic astronaut chair.

To experiment with feasible tensegrity configurations, I have created a rudimentary tensegrity toolkit using wooden bars with holes, hooks and rubber bands. From circular sense-giving and sense-making cycles, the experimentation led to a proto-tensegrity chair design, which is shown in Figure 7.5 (a).

The intended affordances for two simultaneous users in zero-gravity are shown as a rendered sketch in Figure 7.5 (b). The two seats provide affordances for sitting, while the cross below each seat—in the form of tensioned wires under the feet—remove affordances, making that segment of the structure non-supportive for seating. (These wires were also needed for

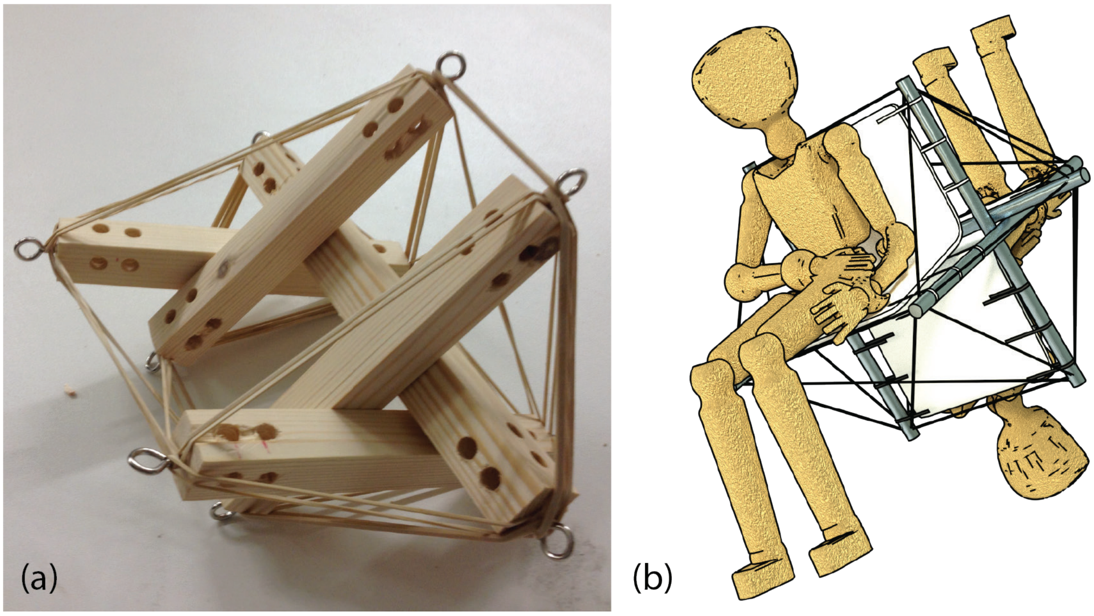


Figure 7.5 Final design iteration: (a) Tensegrity toolkit to experiment with the feasibility of various configurations. (b) 3D rendering of the intended use of the chair by two people in zero gravity.

structural integrity.) In a cybernetic sense, the canvas seats added variety to the object, while the cross–wires removed variety and enforced the intended seating orientations.

The next step was to build a full-size mockup and to create the seating surfaces out of canvas (see Figure 7.6 (a) and (b)). For the frame, I have used five 1-meter long chrome plated metal tubes, and tensioned the temporary wooden end caps with nylon strings. For the final end caps I used customized wood-dowel filled black PVC tubes, with the same diameter as the metal tubes. This was based on aesthetic considerations. The canvas for the seating area provided comfort, a familiar connection with the user, and easy stowage when folded up. The canvas sheets included several signifiers. The seating areas had three eyelets on each side of the sitting surface section, while only two per side on the back support section. To differentiate between the two user sides, the eyelets on one canvas were black, connecting to the frame trusses with black parachute cords, and silver on the other, connected with white parachute cords. The parachute cords, called paracords, were chosen for their high tension-strength and low elasticity, both of which are important for tensegrity structures.

The final chair design is shown in Figure 7.2 for a front view, Figure 7.7 for a side view, and Figure 7.8 for a close-up. Figure 7.9 (a) provides a perspective view of the chair, and Figure

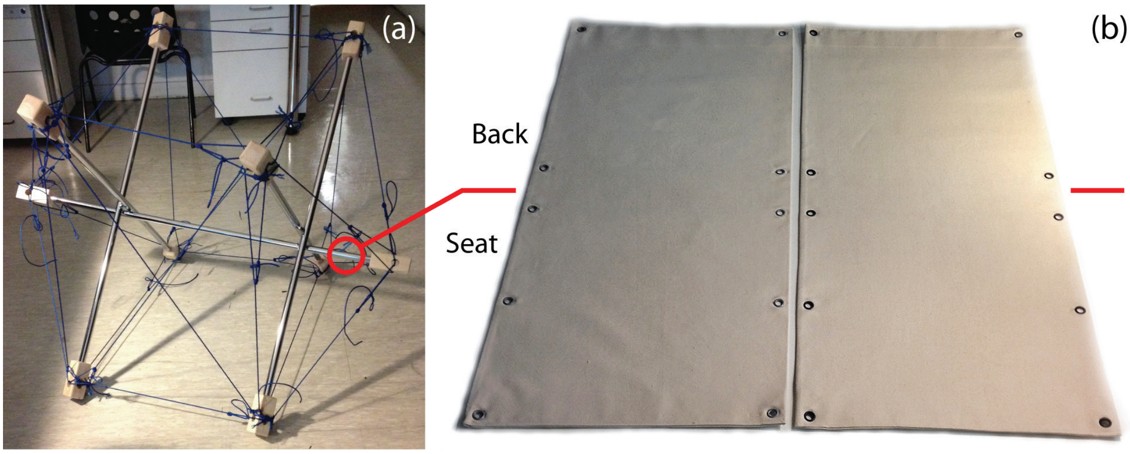


Figure 7.6: (a) Full size chair mockup with wooden end caps and nylon strings. (b) Two canvas seats.

Figure 7.7: Side view of the chair, highlighting its lightness and the expected small volume requirement when disassembled.

Figure 7.8: Close-up of the frame, seating area, eyelets, and the connecting cords.

7.9 (b) an angled view with me holding it for scale. For demonstration, Figure 7.10 shows the artifact exhibited at the WIP-15 show.

I also used this design exercise to highlight four circularly interconnected activities, aligned with co-evolutionary design, shown in Figure 3.14 (Pangaro, 2010). The first was a conversation to agree on the goal, that is, to design a humanly space object. The second was a conversation to agree on the means, which included sketching, computer modeling and prototyping until a

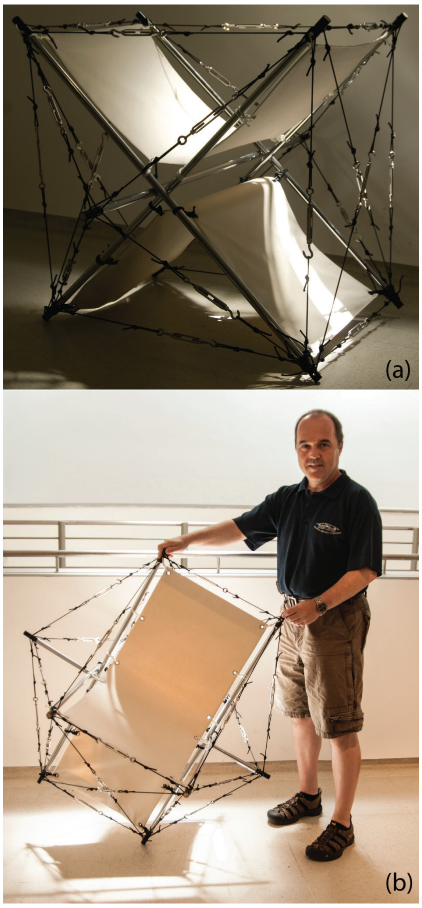


Figure 7.9: (a) Perspective view of the chair. (b) The chair with the designer for scale.

Figure 7.10: RCA Work In Progress 2015 (WIP-2015) show.

final design emerged. The third was a conversation on designing the design process, which included cybernetic circularity for the perspective, and design conversations for the iteration cycles. The forth conversation involved the creation of a novel visual language that translated into the final boundary object with simple and clean forms and aesthetics. Describing this design process, through multiple circular iterations, provides an example for the circular creative process. The resulting boundary object highlights and grounds unique space-specific aspects of my design considerations. This object can also facilitate conversations between design and engineering disciplines. Furthermore, the tensegrity toolkit helped me to evolve the concept through subsequent iterative cycles, where both the concept and the object evolved throughout the design process. This will be discussed further in Section 7.5.

I should point out that the chair could benefit from further improvements, before it could be considered for space demonstration and use. For example, the rods could be replaced with lighter carbon-fiber rods, the seating surfaces could be made out of a thinner material than canvas, and the wires could be custom fitted with a redesigned fastening system to achieve the proper wire tension, instead of using the 24 bulky turnbuckles. These steps would require additional iterations and resources, and would only be carried out if a designer wanted to advance the design from the present demonstration phase towards an actual humanly space object on a spaceflight. As the functionality of this object is non-essential, NASA would likely consider it only as an object for educational outreach, rather than an integral element in support of today’s space exploration environment.

For designers and artists a significant part of the creative process involves a circular conversation through the artifacts they create. While the process of sketching, and 3D computer modeling is suitable to experiment with initial ideas, building physical prototypes are necessary to gain deeper new insights. These range from—using a Glanville term—“slowing down” the process and allowing for reflections, through refining feasibility by trial and error, to learning from constraints, barriers, and mishaps. Through this circular process, having a physical object (and to a lesser extend the drawn graphics by having an external representation) separates the making/knowing part of cognition and the viewing/experiencing part of cognition (see Figure 3.8). Drawing an analogy to design conversations, the making part can be equated with language, where the cognitive thought is expressed externally. In a connected way, looking at the object is equivalent to the sensing and interpreting part of perception and cognition. Consequently, a design activity is a conversation between the designer’s cognition and the phenomenal world through creating (sense-giving) and observing (sense-making), while the designer is explicitly embedded in the system. The process is negotiated or iterated towards a constructivist stage where the designer is satisfied with the object. In a cybernetic sense, at that point the designer/regulator and the environment has a negotiated and balanced system variety, at that specific temporal and spatial junction.

In designing and making these chairs I had to build on my past experiences related to space environments and technologies, and utilize I research in design knowledge and making.

In future work, this approach can be broadened from a single object to an interactive space habitat that supports self-actualization needs of the crewmembers, thus promote exploration, conversations, interactions, and learning, among other considerations.

7.4.2. Boundary Object Example 4—Venus Watch 1.0 concept

Planetary exploration started in 1962 with the launch of Mariner-2, which flew by Venus. The Pioneer-Venus multi-probe mission, in 1978, descended to the surface of Venus with one large and three small probes. The probes encountered extreme environmental conditions, including temperatures about 460°C, pressure up to 92 bars, with a highly corrosive super-critical carbon-dioxide atmosphere at the surface. Mitigating this environment requires special considerations, and the use of specific materials. Yet, at least the pressure environment is similar to that encountered by deep-sea explorers, who employ similar technical solutions and use the same materials for their diver watches. Both designs can tolerate about 100 bars of pressure; housed in titanium shells; with sapphire for the probe’s window or watch glass; carbon fiber; and nylon. From a functional perspective, both planetary probes and diver watches have timekeeping functionalities.

The focal point of this project was storytelling, related to space exploration, extreme environments and the evolution of manufacturing innovation over the past five decades. I have created this boundary object with my collaborator, Julian Melchiorri (Balint & Melchiorri, 2014). This practice-based artifact involved developmental background research on the topic, design (including form giving by Melchiorri), artifact creation using 3D printing, contextualization, and communication of the results to an audience. During the making, the process involved conversations between us, the designers, and the artifact. The sense-giving and sense-making cycles—see Figure 3.8—facilitated the emergence of communicable knowledge. As for scale, the housing of the watch—see Figure 7.11—was designed around a 32mm diameter, 2mm thick sapphire watch glass, with a bounding bezel diameter of 36mm and a height of 11mm.

Figure 7.11: "Venus Watch 1.0", 3D printed titanium, sapphire, woven carbon, parachute nylon, by T. Balint & J. Melchiorri, 2013 (Balint & Melchiorri, 2013) (Balint & Melchiorri, 2014).

This 3D printed Venus Watch 1.0 concept, as a boundary object, was created in the intersection of design, art, engineering, and science. To substantiate the effectiveness of this boundary object, the project was presented at the IAC-13 conference where it was discussed at the "E.5.4—Space as an Artistic Medium" session; published in its proceedings (Balint & Melchiorri, 2013); and republished in the Acta Astronautica journal (Balint & Melchiorri, 2014). It was also discussed on several 3D printing related websites, initiating a discourse on the topic and reaching a broad audience, from designers and artists, to engineers and the general public.

I have provided further information on the design considerations, product development, object making, and cross-disciplinary aspects of the Venus Watch in Appendix E.5. I have also discussed how the various aspects of this project map into Frayling's categorization of design (Frayling, 1993, p.5).

7.4.3. Boundary Object Example 5—"Alvin Seiff Memorial Award" Medal

I have designed and made a dozen of these boundary objects as a commemorative award medal, to be handed out each year at the International Planetary Probe Workshop (IPPW). The award is akin to a lifetime achievement award, and each year it is given to a member of the planetary probe community. As an Award Committee member, and also a designer/artist, I have decided to create a medal to elevate the Award beyond a paper certificate, which was the practice until this years IPPW-13 workshop. Its design is shown in Figure 7.12. On the obverse side it depicts four types of aeroshells—Hayabusa, Galileo, ARD, and Phoenix—representing the international exploration efforts of our solar system. On the reverse side it shows the award title, workshop name, and logo (which I have also designed several years ago). This Alvin Seiff Memorial Award medal was created through methods of computer-based modeling, CNC machining and laser engraving for the master copy, and investment casting for the final patinated bronze medals. The dimensions for each medal are H7cm x W5.1cm x D1.4cm, with a weight of 0.2kg. The target audience for the medals is the probe community with scientific and engineering backgrounds. The medal cross-pollinates object representations from the disciplines of art and design, to engineering and science, and creates opportunities for conversations. The first medal was handed out in June 2016 at the IPPW-13 workshop, and documented in (Balint, 2016). It was well received by the awardee, the organizers, and the attendees of IPPW-13. This boundary object stimulated enthusiastic conversations at the workshop, especially with Rob Manning (see Figure E.65), this year's winner of the award. After starting this new tradition, these medals will be handed out to future awardees until 2027, when the stock runs out. I have provided further details on the making of this medal in Appendix E.4.

Figure 7.12: "Alvin Seiff Memorial Award", bronze, limited ed., H7cm x W5.1cm x D1.4cm, by T. Balint, 2016.

7.4.4. Boundary Object Example 6—"Expanding Boundaries" Medal

In 1610, Galileo declared his discovery of the Jovian moons. His findings, documented in Sidereus Nuncius, changed our view about the solar system. In 1995, more than three centuries later a planetary probe, named after Galileo, entered Jupiter's atmosphere and measured its composition. Its carrier spacecraft, also named after Galileo, mapped the Jovian system for 8 years, providing further knowledge about the Galilean moons, Io, Europa, Ganymede, and Callisto. These scientific measurements were enabled by incredible engineering feats. The Galileo probe had to survive the atmospheric entry-heating at hypersonic velocities, the highest ever attempted, at about 46km/s. The heat shield that protected the Galileo probe was tested inside NASA's Giant Planets Facility at the Ames Research Center. The testing for the extreme entry heating conditions was supported by computational analysis.

The theme of these boundary objects was inspired by the human desire to explore the world around us. Through circular constructivist conversations with our environment, we observe and act in the world, then create and refine our cognitive models about it. In the process, we expand our boundaries both cognitively and physically.

I have created a limited edition of medals, titled "Expanding Boundaries," depicting the story of humanity's expanding boundaries from initial observations to in-situ exploration (see Figure 7.13).

The obverse side of the medal is showing the flow field around the Galileo probe entering the atmosphere of Jupiter. It also pays tribute to computational simulations, and wind tunnel experiments, represented by the column-like bounding edges. The reverse side of the medals depicts a polar view of Jupiter, including the Great Red Spot, the year of Galileo's discovery through his—then revolutionary, now rudimentary—telescope; notes from his diary of the observed moons; the Galileo spacecraft and probe; and the year when the probe entered Jupiter's atmosphere.

The design process included: flow field simulation, 3D modeling, CNC machining of the obverse side; image manipulations of NASA and 3D rendered spacecraft/probe images, using Adobe Photoshop and Illustrator, laser engraving for the reverse side; and foundry processes, including silicone mold making, wax modeling, lost wax casting, chasing, and patination. While the CNC machined master model with a laser etched back resulted in a perfect geometry, the casting process introduced imperfections into the final medal. These are evident along the edges. While these can be corrected during chasing, at the sense-making phase I have

Figure 7.13: "Expanding Boundaries", bronze, limited ed. (6), H7cm x W5.1cm x D1.4cm, by T. Balint, 2016.

decided to keep them uncorrected. Instead, these imperfections represent the uncertainties when exploring the unknown (see the environment noise source in Figure 3.8).

The dimensions of these 0.2kg patinated bronze medals are H7cm x W5.1cm x D1.4cm.

To substantiate the impact of this medal, it was submitted to the British Art Medal Society's (BAMS) Student Medal Project 2015-2016 competition, targeting the community of art medal collectors and the general public. It was selected for an exhibition of the medals in September 2016, hosted by the Carmarthen School of Art in Wales. The exhibition provided an opportunity for conversations with the general public, including artists and designers. The medals link together artistic vitruvian delight, exploration and epistemology, while bridging between art, design, science, and engineering.

I have provided further details on the making of this medal in Appendix E.3.

7.4.5. Boundary Object Example 7—"Galileo Flow Field" Sculpture

The model of the Galileo probe with the flow field around it was also made into a scaled up patinated bronze sculpture, using the investment casting process (see Figure 7.14). A detailed account of the making is given in (Balint, 2016), and in a video (Balint, 2016a).

The key steps of making this boundary object—shown in Figure 7.14—involved four distinct disciplines. Science to understand fluid flow; engineering for the simulation and flow visualization; and engineering, and design for the CNC-machined object creation. For the bronze version the process continued with silicone mold making, wax modeling, lost wax casting, chasing, and patination. These foundry process steps linked design and art to the previous disciplines (see Figure 7.15).

Figure 3.8 illustrates the circular iterative design process between the artifact and designer / artist, who balances variety across the system through prototyping cycles. These personal conversations through the artifact may create new ideas that advance the design towards a final outcome. For example, when we create a prototype, in a sense-giving step, it represents our cognitive output at that given time. It becomes a representation of our ideas, translated into a real world object. Through the prototyping steps the artifact also contains additional information, which may come from manufacturing or material imperfections, and its interactions with the environment. When we revisit this artifact in a subsequent sense-making iteration step, we may see it in a different light, which can provoke new ideas, thus broadening our own variety. This broadened variety from the perceptual feedback through subsequent iterations allows us to create new ideas and solutions, and reformulate our cognitive models or schema about the object. The circular conversation between the designer and the object continues until a stopping rule is applied during this convergence phase of the creative process. At this point the artifact/object is considered finalized. In a cybernetic sense, with the concluding artifact the artist, acting as a regulator, successfully balanced the variety and reached a perceived equilibrium between all elements of the system. These iterative conversations are essential in the creative process. A second cybernetic conversation takes place between the object or artifact and the observer/user (see Figure 7.15), who now becomes the regulator of this system that includes also the environment in which they reside. The two cycles can be coupled when the designer and the observer or user carry out design conversations through this boundary object, and use it to aid the discourse towards a commonly constructed understanding between the designer of the object and the observer/user.

Figure 7.14: "Galileo Flow Field," patinated bronze, limited ed. (4), H16cm x W11.5cm x D4.5cm, by T. Balint, 2015.

To substantiate the impact of this boundary object the bronze model was exhibited at RCA's 2016 Work In Progress Show (WIP-2016), where the audience included designers, artists and the general public. This artifact was also selected as the winner of the 2016 Remet Casting Price (see Figure E.45), where the judges commented on the innovative multi-disciplinary use of flow science; engineering modeling; design making; and artistic processes. (Note: one of the four artifacts is now in the permanent collection of Remet UK Ltd (REMET, 2016).) Depending on the audience, the conversation can be framed to cross-pollinate ideas from one discipline

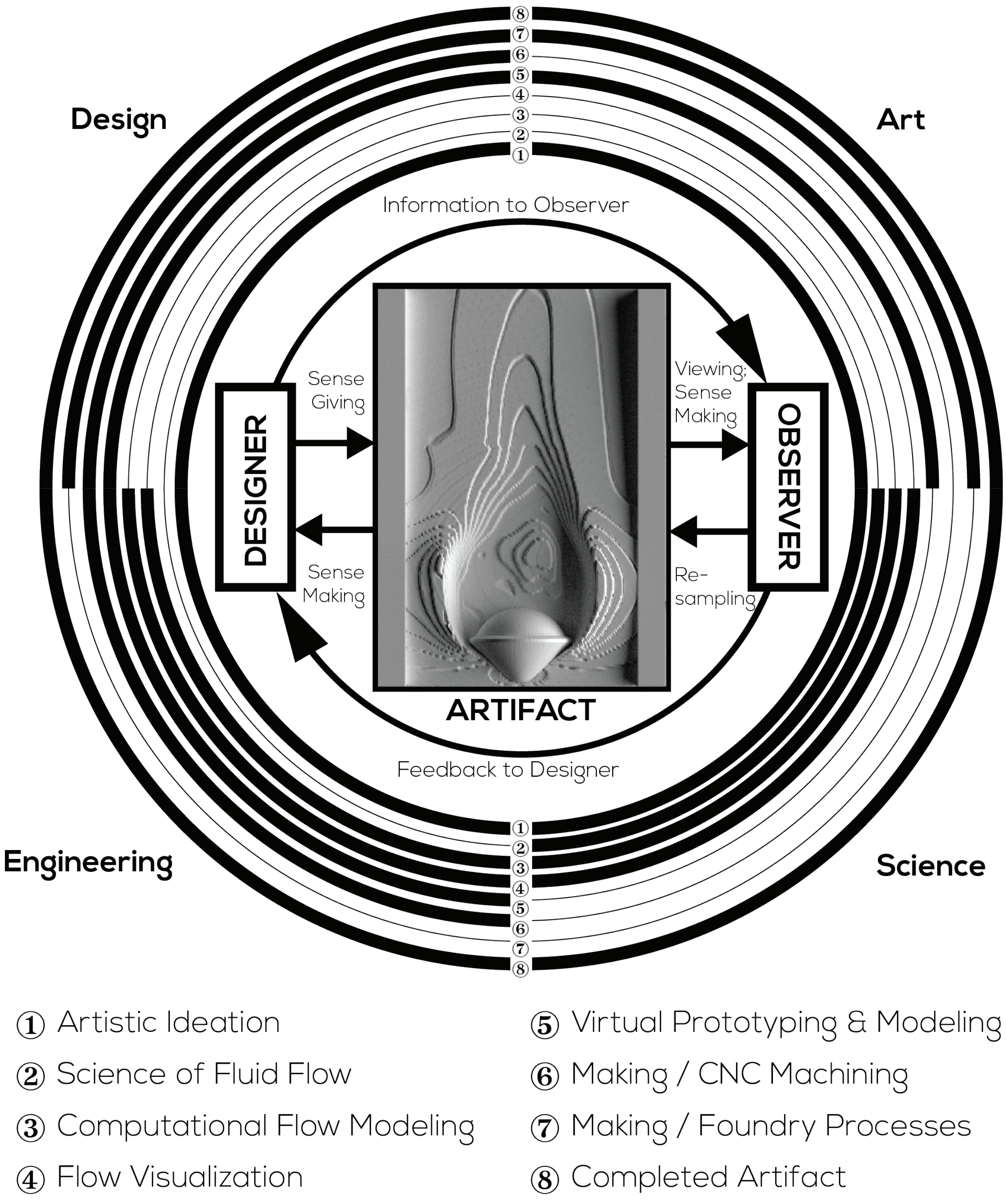


Figure 7.15: Intersections and cybernetic conversations through a boundary object (Balint, 2016).

to another. Being the designer and maker of this artifact, with understanding all of the relevant aspects of the involved disciplines, I can use "modal shift" (Cross, 2007, p. 111), when discussing this boundary object with diverse audiences. I can talk to engineers as a designer and artist; to artists as a space expert; to designers as a scientist; and so on. In this capacity I facilitate conversations across any of these disciplines using the artifact as a boundary object. The dimensions for the four completed bronze artifacts are H16cm x W11.5cm x D4.5cm. Their weights varied between 2.5kg and 3kg, depending on the wall thickness.

I have provided further details on the making of this artifact in Appendix E.2.

7.4.6. Boundary Object Example 8—Visual communications with posters

The design brief for posters is simple. It has to address the topic of the venue (which in this example is the IPPW workshop); it has to be eye-catching; and include key information about the event (e.g., the date, location, the title of the linked short course, and logos from the organizers and sponsors). It may also include pictures of the hosting location. The goal for the organizers is to engage the community and the public with these boundary objects, which may lead to much needed advocacy, and can stimulate the imagination of young people by expanding their horizons—broadening their variety—allowing them to dream, and choose from more career possibilities, when deciding on their professional futures. Posters can also facilitate conversations between the various interest groups and disciplines. As the workshop participants are already familiar with the poster image through the advertising campaign, the image is also used to brand the venue, by reusing the image for program covers, badges, projected slides, among others. The posters are often displayed around town for the public to see. For example, during the IPPW-12 workshop in Cologne, Germany, the poster was incorporated into all handouts to the participants, and a flag with the poster's image was flying outside the hotel throughout the workshop, advertising it to the public (see Figure E.11).

These posters have been typically developed over several months, in multiple iteration stages. In this process, the first conversation occurs between the designer and the image. This stage involves ideation on the topic and imagery, sense-giving through sketching and 3D computer modeling and rendering, then sense-making to assess the outcomes. This typically leads to multiple iterations and two or three draft versions. In the next stage these draft posters are presented to the workshop organizing committee for conversations with the designer. The feedback is then incorporated in future revisions. Knowledge about the IPPW probe community and on the subject matter are important considerations to select iconic imagery that resonates with this expert group, with members strongly routed in their science and engineering driven paradigm. In this environment the artistic license is confronted by literal interpretations of scientific phenomena and engineering perspectives. For example, in the IPPW-12 poster the representation of the flow field was brought into question, as it seemed to show a lower velocity flow regime than it happens during atmospheric entry events. These various types of feedback are either incorporated into the final poster or resolved through conversations. The official IPPW poster examples, created by me, are shown in Figure 7.16. This set includes the latest poster for IPPW-13, which incorporated a walnut version of the Galileo Flow Field artifact. This artistic take on iconic imagery helped to introduce art and design to a technology and science focused community. Conversations about the artifact in the intersection of these disciplines helped to introduce new variety to the discourse, which can stimulate new ideas beyond the bounds of the existing paradigm. I used these posters to substantiate my argument that posters can be used to communicate between discipline boundaries, and can be considered as boundary objects. (The dimensions of the walnut sculpture, shown in Figure 7.16, are H16cm x W11.5cm x D7cm.)

7.5. Design Conversations THROUGH Boundary Objects

To this point I have discussed boundary objects, which were created within existing paradigms, where they can be used to guide, focus, and facilitate conversations. Borrowing a term from cybernetics, we can call these *first-order boundary objects*. They advance the discourse, but they are unchanged throughout the conversations or reflections. Leigh Star

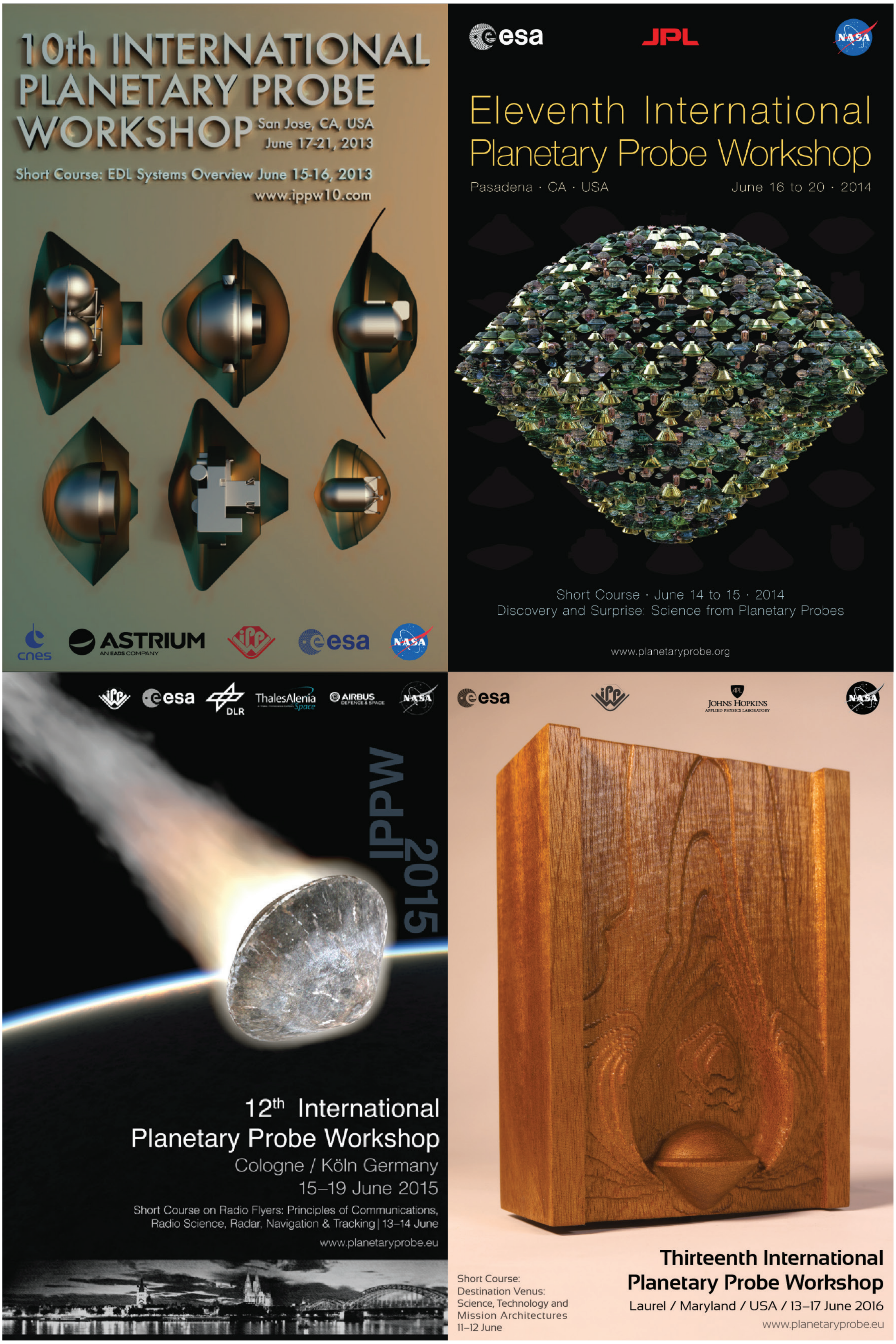


Figure 7.16: Official IPPW posters by T. Balint, from 2013 to 2016. Bottom right poster includes the "Galileo Flow Field," artifact, walnut version, H16cm x W11.5cm x D7cm.

& Griesemer's example of museum-curated boundary objects, and the first two categories introduced above—*ABOUT* and *FOR*—can be considered as *first-order boundary objects*.

However, boundary objects can change and evolve during the conversations, where the new interpreted meaning that is developed through these conversations and concurrent modifications are used to advance the discourse. During a co-evolutionary design process, differences in variety among the cognitive models of the team members from diverse disciplines cause design tension. Boundary objects in the intersections of these disciplines can help to resolve or mitigate this tension. In effect, the conversation loops involve consecutive cycles of co-creation, with sense-giving and sense-making cycles of a shared object. This can also be called an observing environment. Here the conversation participants can modify the goals, the representative meaning, and the form of the object. These design explorations with boundary objects are performative, as they create and offer novel options from a shared agreement on the schemata that is broadened through conversations and object interactions. (It should be noted that knowledge is personal and not transferable (von Glasersfeld, 1984, pp.17-40), thus sharing meaning or schemata, are akin to sharing a glass of wine and not like sharing a flat.) This also works on a personal level. It is a forward search as exemplified through the design process using my tensegrity toolkit, where both my concept and the object evolved through the process, as shown in (Figure 7.17). On one hand the process reflects individually evolving and broadened cognitive models through conversations, while on the other hand at each sense-giving step the contributor broadens the variety of the object for others to interpret. At this point the evolved object becomes a key contributor to advancing and broadening the paradigm, as it reflects the newly agreed shared meaning. I propose to call these *second-order boundary objects*, which are exemplified in this category of design *THROUGH* boundary

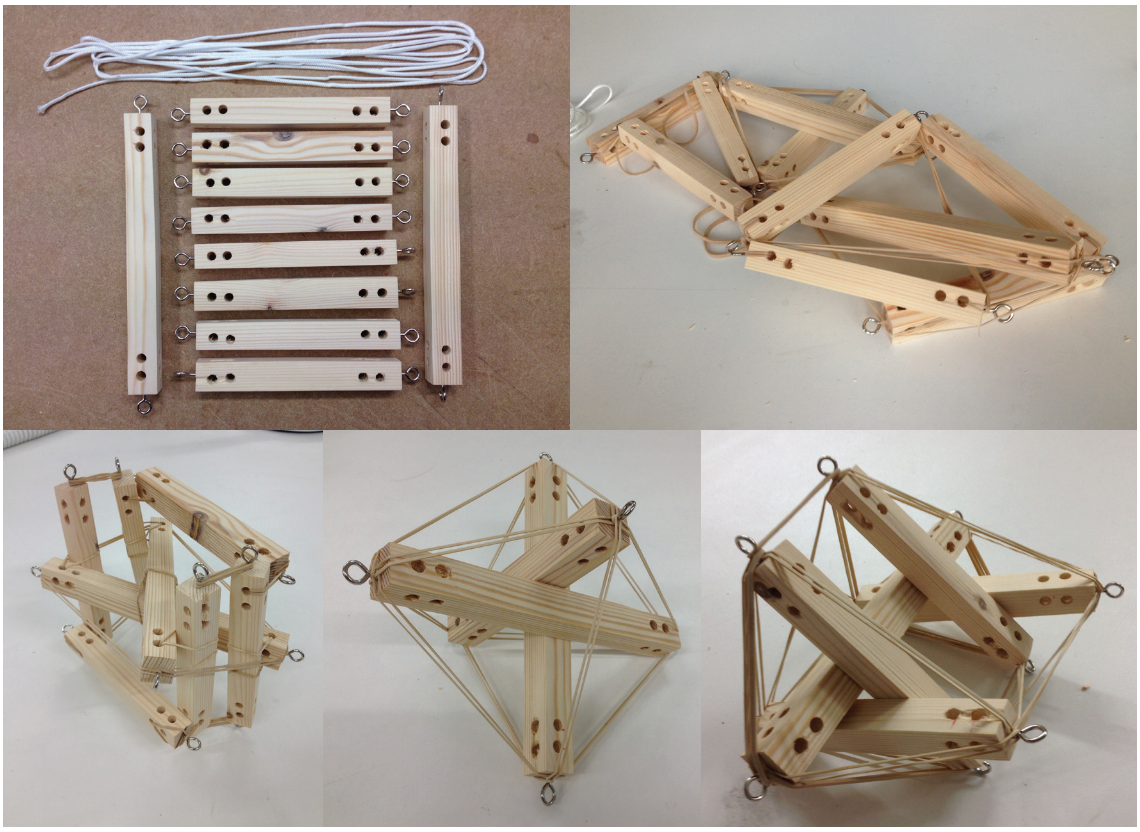


Figure 7.17: Evolution of the tensegrity chair concept; showing my tensegrity toolkit; first failed attempt; overly complex model; overly simple model; and the chosen final configuration for the prototype.

objects. While first-order boundary objects can be cast under today's information paradigm, second-order boundary objects are part of the emerging experience paradigm.

7.5.1. Boundary Object Example 9—Mockups and Models

At JPL's Innovation Foundry, and at JSC's Habitability Design Center (HDC) multidisciplinary design teams come up with novel ideas in support of NASA's robotic and human space exploration plans. These teams often use props to create models and mockups using ad hoc components. For example, creative design environments, such as JPL's Left Field room, includes a great variety of LEGO pieces (see Figure 7.18) to aid the design conversations during the A-Team design sessions. The developed mockups belong to the "ideal type" boundary objects, as they are abstracted with meanings to multiple user disciplines.

Designers at JPL's Studio used 3D printing and then cardboard tubes to create various scaled physically representative versions of RoboSimian in support of the engineering teams (see Figure 7.19). This led to the final robot that competed in the 2014 DARPA Robotic Challenge. Designers and engineers at JSC's HDC also used boundary objects from sketches and scaled models of mobile surface habitats (see Figure 7.20), to a scaled mockup of the Orion Capsule's hygiene bay (see Figure 6.4).

All of these boundary object examples were used to facilitate dynamic conversations among team members, where team dynamics, and team makeup played important roles in developing, evolving, trying out, and accepting new ideas. Bringing scientists, subject matter experts, technologists, engineers, designers, and artists together could provide sufficient discipline and knowledge diversity among the team members, which could lead to conversation-based emergence of an agreed shared new language with new options and potential outcomes, if the team is given the proper guidance. In their design environments the teams should be encouraged to move beyond verbal concept assessments, and instead build prototypes, as new ideas may evolve through building, iterations, and discussions. Mistakes and misunderstandings through the discussions or rapid prototyping can also lead to new ideas, as they can stimulate new questions and could point to new solutions.

7.5.2. Boundary Object Example 10—Object Communications with Keystone Graphics

Boundary objects can help design team members to communicate with others across their own specialized disciplines, and divergent perspectives. For example, at a JPL A-Team

Figure 7.18: Modeling toy boxes to create boundary objects at the JPL Innovation Foundry's Left Field room, home of the A-Team, conducting low-CML concept studies.

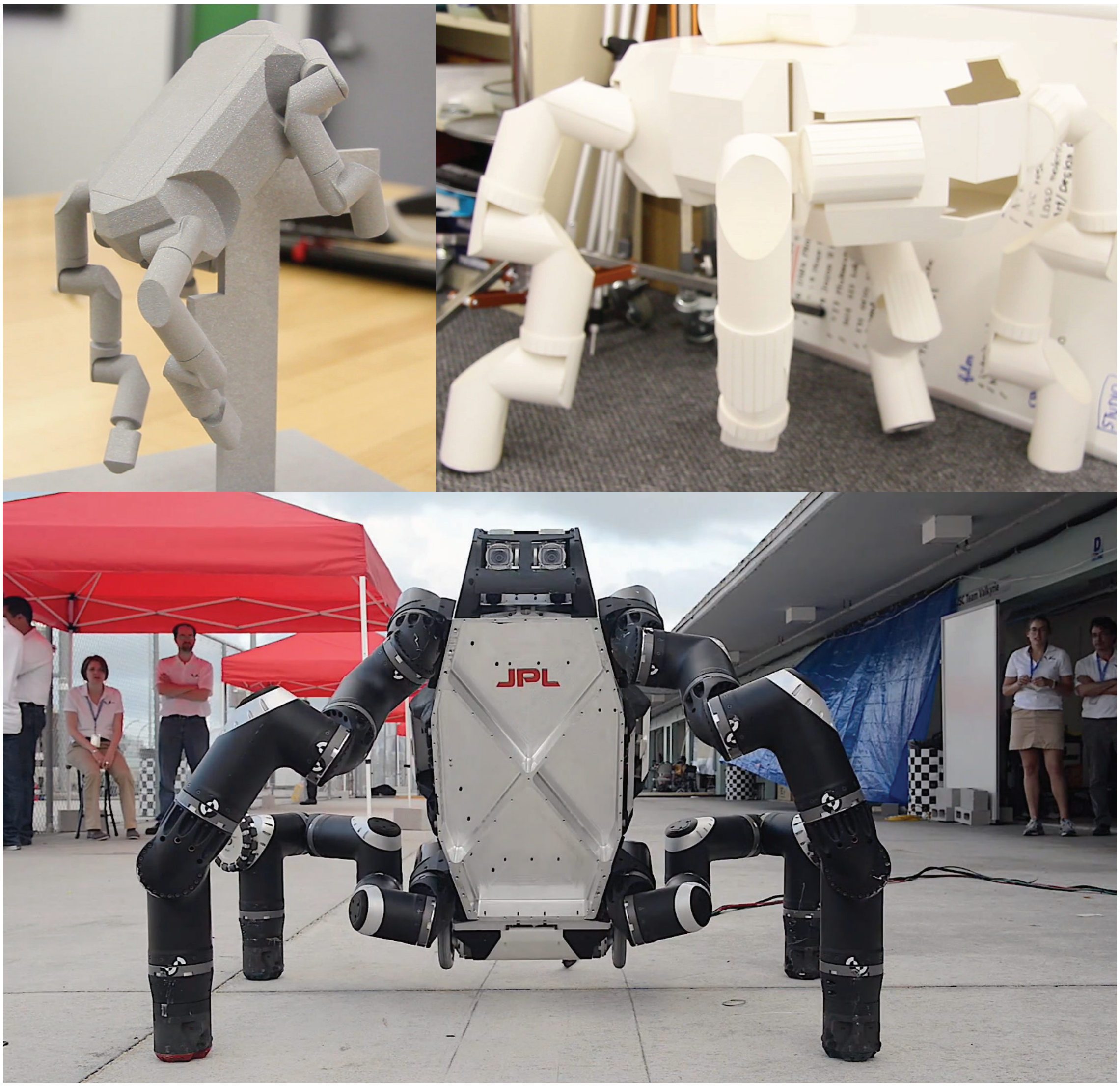


Figure 7.19: From 3D printed model, through mockup, to final build; RoboSimian, JPL's entry to the DARPA robotic challenge in 2014.

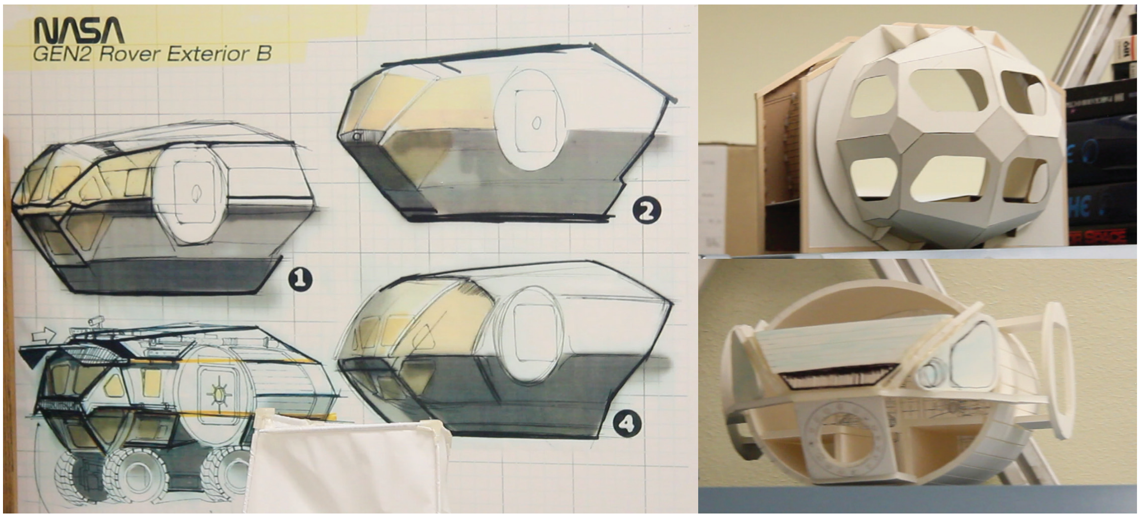


Figure 7.20: Sketches and small mockups of mobile habitats at NASA JSC's Habitability Design Center.

design session during early-stage concept developments, there is a shared commonly agreed exploration goal among team members, while the scientists focus on the science relevance or desirability; the engineers address feasibility; while cost analysts assess the resource requirements.

During the design process a boundary object may evolve through collaborative divergence and/or convergence. Specifically, boundary objects can be used to support conversations during the ideation phase, where they can be a vague representation of ideas. Initially creating, then subsequently changing, modifying and co-evolving the object represents the sense-giving part of a conversation. In the sense-making feedback loop each team member interprets it in consecutive iteration steps, which might provoke ideas beyond the envisioned initial concept from the person who created it. The vagueness of the boundary object, combined with the broadened variety of the environment—which consists of the team members—can increase the variety available to the discourse. In this divergence phase the observer's perception or framing of the object changes, and so it triggers different aspects of the participants' variety. This in turn may provoke multiple ideas from the participants. Some may call this a brainstorming phase. This could be followed by a convergence phase when the variety of the system is attenuated, which helps to refine the concept and direct the conversation towards a preferable outcome. Conversely, boundary objects can be also used with an intention to demonstrate concepts and to communicate a desired meaning to external audiences. In this use the variety of the object is attenuated to limit possible ambiguity. However, as knowledge is personal, it is not guaranteed that the interpretation by the audience is limited to a single intended one.

Boundary objects can aid creative leaps in design. As they objectify concepts, and evolve during the design sessions, they can evoke new ideas and bring concepts to novel directions. For example, a creative leap occurred during the Venus Flagship Mission study, when our multi-disciplinary design team discussed methods for the lander to take panoramic pictures on the surface of Venus. Our brainstorming yielded an unusual and novel concept for rotating the entire pressure vessel on its landing base (JPL, 2009). Traditional approaches included a rotating camera, or multiple windows penetrating through the pressure vessel. All of these were less favorable under the extreme temperature and pressure conditions, coupled with a mission goal to extend operational lifetime on the surface. Rosenman and Gero identified five procedures which can supports creative design: combination, mutilation, analogy, design from first principles, and emergence. Nigel Cross provided detailed accounts on these in (Cross, 2007, pp.72-79).

In this use, keystone graphics can be considered boundary objects. They are useful to communicate the meaning of complex concepts without ambiguity to stakeholders, sponsors, and the public. Communicating to outside audiences requires clarity, while providing an intersection between disciplines, where the variety of the object is attenuated, while allowing for conversations to refine its meaning and the message. A keystone graphics example is shown in Figure 7.21. This approach is successfully used in NASA and JPL proposals to sponsors. (Further information on JPL's Innovation Foundry and the Studio, including their processes, is provided in Appendix D.)

7.5.3. Boundary Object Example 11—Future Space Habitats

As we move from today's information paradigm to an experience paradigm, the objects around us become increasingly more interactive. These objects are not only enhancing our

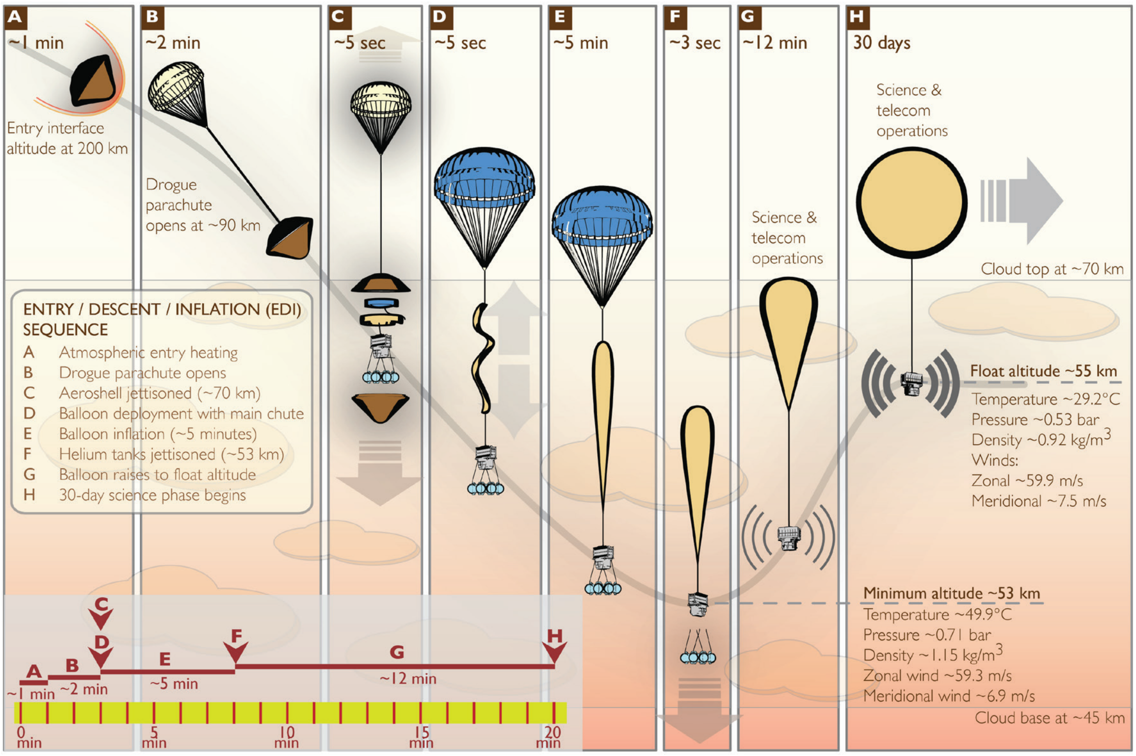


Figure 7.21: Keystone graphics depicting atmospheric entry, descent, and balloon inflation for a Venus mission concept study, by T. Balint.

experiences, but also facilitate exploration. Looking at future space habitats, we will find boundary objects, which cater not only to utility, but also to user needs, by providing object autonomy, learning, discovery, and adaptability. In today's mode of operation, space habitats predominantly address physiological, psychological, and safety needs, with systems providing the required functionalities. A better understanding of higher-level user needs is required to derive guidelines, requirements, and incorporate them into future designs, as proposed in Section 6. Once these new human centered requirements become part of the existing set of requirements, designers and artists will be able to respond with solutions that reflect designerly and artistic modes of operations, and cater to conversations between astronauts and their environments. Designing these types of objects is briefly discussed in (Balint & Hall, 2016), and will be further explored in future research, which can build on conversations with the HI-SEAS analog team, by including these habitat design goals in future astronaut isolation experiments.

7.6. Epilogue to Boundary Objects

In this section I have proposed new categorizations of boundary objects, drawing on analogies from design and cybernetics. These categories introduce distinction and hierarchy to boundary objects, which is a point of departure to purposefully utilize them in the future. I have also provided NASA relevant examples to substantiate the proposed categories. Related to design, I have differentiated between three boundary object categories, based on their use case. These were: boundary objects about and for communications; and design conversations through boundary objects. Through a cybernetic perspective I also differentiated between first-order and second-order boundary objects.

I have found that boundary objects can support spatially and temporally coupled or decoupled conversation flow to refine meaning and converge the discourse towards a constructivist agreed upon shared meaning. Typically, various disciplines can have common aspects, but also have their differences. As boundary objects are created in the intersection of disciplines, they can provide information to all of them. In this sense, their meaning must overlap sufficiently between disciplines. Based on the use case, boundary object-facilitated conversations can broaden the variety of the system, but they can also help to reduce variety and converge towards a common and agreed upon shared meaning. In a design environment, such as JPL's Innovation Foundry, boundary objects represent agreed shared goals between disciplines, which can benefit from method standardization to aid collaborations and conversations.

I believe that boundary objects provide additional means to support effective conversations across disciplines to exchange and cross-pollinate information. In design environments, where during design sessions the team members can modify the goals of the system, co-evolutionary second-order boundary objects can facilitate the emergence of novel ideas and the evolution of shared commonly agreed languages between team members from different disciplines. Boundary objects can also help to broaden the paradigm of an environment, which may lead to a second-order change of the system, with novel preferable outcomes.

Second-order boundary objects promote discovery, and build novel variety into the system. However, it should be recognized that boundary objects are not stand-alone items. Instead, they have a focal, unifying, yet supporting function in the conversations surrounding them.

Through these examples I have substantiated how designerly and artistic modes of operations, specifically design conversations, and facilitated conversations using boundary objects, can offer demonstrable value to enhance NASA's capability to introduce novel ideas and to innovate.

Section 8.
Conclusions and Future Directions

Expanding Boundaries, BAMS Competition Medal (Patinated bronze / 2016)

8.1. Conclusions

Looking at our world from a technological perspective, we may conclude that it is driven by innovation. For over five decades now, space exploration required and benefited from novel technologies and processes to expand human and robotic presence into near and far destinations, while also broadening our scientific understanding of the universe. This was aided by technological innovations, which scaled from incremental through radical to disruptive or transformational, where form is driven by function, addressed via engineering, processes, system complexities, and integrated systems. The high development costs and shrinking resources since the Apollo era, combined with budgetary uncertainties, led to risk averseness, focus on near term stakeholder needs, ever changing priorities, projects guided by government-driven earmarks, rigid policies, solidified processes, often rigid management approaches, and many other factors. In this worldview, design became equated with predominantly engineering design, driven by engineers and technologists through their linear hard requirements-guided disciplines, while design in a Vitruvian sense—blending purpose, construction, and delight in a human centered way—was considered nice to have and largely ignored. Many are still hoping to recreate NASA's old glory for human exploration, with large and expensive flight projects and crash programs on an Apollo Program scale. It is evident from the persistence of large projects, including the Space Launch System (SLS), the Orion Capsule, and large proposed missions, including the Asteroid Redirect Mission (ARM), and a subsequent human mission to Mars, for which SLS and Orion would be enabling technology systems. Similarly, on the science exploration side, the budget of the James Webb Space Telescope (JWST) grew several times beyond previous multi-billion dollars flagship class robotic space missions. One can argue that space exploration is expensive, all the low-hanging fruits are already taken, thus to push exploration boundaries we need larger and more capable missions. A counter argument can point to the cost of brute force approaches, which worked during the Apollo era, when resources were not limited to current levels. To make a space program viable, we need to adjust to the realities of today and retire the dreams of recreating the glorious past. These of course are simplified and cherry picked arguments, and the extent of contributing factors—both within NASA and outside—form a wicked problem with no obvious and clearly implementable solution within the existing paradigm.

Addressing these within NASA's existing worldview is not sufficient, as we would simply rearrange the existing option trades. We need novel and creative approaches to overcome the listed barriers. To exemplify this, we can turn to mythology and cybernetics, where the Apollonian and Dionysian dichotomy provides a good representation on contrasting an implementing both control and creativity. In Greek mythology Apollo, son of Zeus, represented reason and rationale. His brother, Dionysus was the god of irrational and chaos. In a cybernetic sense Apollo acted as a regulator towards convergence thus attenuating variety, while Dionysus did the same towards divergence by amplifying variety. In today's government and corporate environments, control, risk averseness, bureaucracy is prevalent, in line with Apollonian philosophy. Disruption comes from the inclusion of new variety within the system. As the cybernetician, Gregory Bateson stated, *"creative thought must always contain a random component"* (Bateson, 1978, p.182). To innovate, to change the discourse, to introduce novel ideas, to add variety to the system, we have to include a Dionysian element in order to succeed. This may lead to progress, preferable outcomes, and potential disruptions.

Given this background, my research question evolved to ask the following: *“Do modes of operation beyond those predominantly applied at NASA, such as designerly and artistic modes, offer demonstrable value to enhance NASA’s capability to innovate?”*

I can answer this question in two parts. First, addressing how this research contributed to my personal knowledge, and second, how it contributed to address the posed question itself.

To advance my personal knowledge, I have leveraged my past experiences at NASA, related to space technology and management, and augmented it with newly developed perspectives through cybernetics, which provided an opportunity for a forward-looking search. Over the years, it allowed me to systematically evolve my research goals, and develop new cognitive models and modes of operation through designerly and artistic approaches. Why was this important? Because on a personal level, creative thoughts are built on individual worldviews, defined by our cognitive models and personal perspectives. We develop ever-changing, dynamic, and evolving cognitive models through circular constructivist cybernetic conversations with our phenomenal world. We perceive information through our sensory system and respond back through language and gestures. These circular conversations are performed across our perceptional boundary. Cybernetic perspectives and design driven goals, supported by conversations can lead to novel, and broadened variety of the system. Second-order cybernetics is particularly important for this, as in this case the observer, who is explicitly coupled with the observing paradigm, can change the goals of the observed system. Designers create artifacts through conversation cycles of sense-giving and sense-making. These artifacts add distinction, variety and entropy to the environment in a form of a message. The message becomes information when the observer decodes it, through multiple sense-making and re-sampling cycles, as needed. Having a shared key between the actors is fundamental to encode and decode the information (although it is not given that there will be a coherence between the intended and interpreted message, due the personal nature of knowledge.) This key is the language, which may vary from spoken words and gestures to design styles. A specialized language within a discipline streamlines communications, but limits variety. Between disciplines, different languages may introduce communication blocks. Yet, these differences are desired as they add variety to the interactions, and can lead to novel discourses and options. They can become the creative thought with a random component through design conversations. We can resolve blocked communications through conversations, and construct agreed upon shared meanings between the actors. We can also aid these conversations by introducing boundary objects, which may intersect between multiple disciplines and facilitate a convergence towards a shared understanding. Thus, performing this research required me to rethink, customize, and re-design my research process, away from an engineering perspective and towards a forward-looking cybernetic search, using a performative approach. This allowed me to rethink and adjust the goals and means of my research, and apply my performative cognitive model to real world cases at NASA.

Second, I have contributed to design research by applying my performative ontology to four case examples at NASA, and to an overarching case related to design research, showing that human centeredness, and designerly and artistic approaches, coupled with cybernetic considerations can advance today’s state of practice, which is based on typically function-driven engineering systems. I have shown that the use of design conversations, and boundary objects can enhance NASA’s capability to innovate. The five example domains were:

- *Strategic level decision making processes,* aligned with NASA's Space Technology Mission Directorate (STMD);
- *Space habitats on long-duration spaceflight,* aligned with NASA's Human Exploration and Operations Mission Directorate (HEOMD);
- *Design environments*, aligned with NASA's Jet Propulsion Laboratory (JPL) and the Science Mission Directorate (SMD);
- Changing NASA's organizational culture through *design education*, which can benefit the Agency as a whole; and
- *Boundary objects,* in support of design environment and design conversations.

The first example (see Section 5) relates to NASA's strategic decision-making process for technology portfolios and reporting processes. This research element was accomplished by assessing existing processes through organizational cybernetics, specifically by mapping NASA STMD's organizational structure into the Viable System Model. Innovation-focused technology organizations fund and manage their technology portfolios throughout their projects' lifecycles. These projects are influenced by both internal and external factors. Project performance is monitored through well-established procedures from implementation to strategic levels. This is a linear reporting structure in an environment where strategic level events can influence not only the project, but also the broad technology portfolio, with considerations that form a wicked problem. These wicked problems are not understood until a solution is formulated. Decision-making benefits from attenuated information from both linear and strategic levels to the strategic level decision makers. The Project Assessment Framework Through Design (PAFTD) tool was developed to address this need. It is a strategic level tool that utilizes conversations with project-affiliated stakeholders. Subsequently a PAFTD analyst synthesizes the information and this attenuated variety is presented to the strategic decision makers in support of their governing processes. Once briefed on the findings, the senior managers' broadened variety may lead to better strategic insights and support a transparent and traceable governing process. With its appropriate customization of the questionnaires, PAFTD was used on six mid- and high-TRL projects within the STMD technology portfolio and implemented outside of NASA, as substantiated through testimonials from the Director of STMD's Resource Management Office and the Director of Space and Missile Systems at Meggitt PLC (see Appendix B.7). The PAFTD tool (Balint, Depenbrock & Stevens, 2015) (Depenbrock, Balint & Sheehy, 2015) and related topics on innovation (Balint, 2013) and wicked problems (Balint & Stevens, 2016) (Balint & Stevens, 2014) have been documented in conference papers and a peer reviewed journal paper, thus substantiating communicable knowledge.

My second example (see Section 6) addressed design considerations for long-duration deep space habitats, discussing the state of practice and identifying the need to support the higher-level human centered needs of the astronauts. While today's requirements for space habitats include considerations for the crew, these are predominantly focusing on basic physiological, psychological, and safety needs. The crew's psychological and physiological needs are addressed through risk mitigation and engineering approaches, as related to mission goals and objectives. On short-duration spaceflight this is a reasonable approach. However, on a 3-year long mission to Mars, self-actualization needs will also play a significant role for the crew. At present, there are no requirements for self-actualization within NASA's Procedural

Requirements, although it has been acknowledged that at one point, steps should be taken to address them. Through my research I have made a case for having these considerations integrated into habitat designs in the very near future, instead of trying to retrofit a future long-duration habitat point design at the end of the development process. It should be noted that human centered considerations for space habitats is not new. But a focus on higher-level needs, achieved through second-order cybernetic considerations is. Designing such a habitat and related objects with sufficient variety for the crew to discover and explore, needs appropriate requirements. Identifying them cannot be done from the top down; they have to be developed through conversations, and with the involvement of stakeholders (e.g., astronauts, space architects, designers, and engineers). For this, the process can start with a terrestrial analog mission—for example a dedicated HI-SEAS analog with a study goal related to higher-level needs—that would lead to guidelines, then requirements and subsequent implementation in future habitat designs. For this example my research didn't provide a substantiated habitat focused outcome, aside from making a supporting case for the importance and inclusion of these guidelines, requirements, and a strategic level forcing function that makes the codified requirements a mandatory part of future design considerations. However, on an object scale, I have identified design considerations for human centered space objects, drawn from various disciplines. To evidence these design considerations, I have designed and built a boundary object, which I called the cybernetic astronaut chair. My designerly process was performative and circular, and it differed from NASA's requirement-driven engineering design mode. Through this design process I have highlighted the challenges designers face when addressing soft and subjective requirements. I have generated communicable knowledge by exhibiting this boundary object at the RCA WIP-2015 show, and presented my findings about this research element in conference papers (Balint & Hall, 2015a) (Balint & Hall, 2014) and peer reviewed journal papers (Balint & Hall, 2016) (Balint & Hall, 2015b). During the WIP show and the conference presentations I also had an opportunity to discuss my design process and findings, with a target audience of designers, scientists, engineers, artists, and the general public.

In the third example (see Appendix D.2) I have reflected on the state of practice of design environments, specifically looking at JPL's Innovation Foundry, its structure and processes. I have chosen the Innovation Foundry for this assessment, as this organization represents the state of the art not only within NASA, but also for the broad national and international aerospace field. My incoming assumption was that the environment uses somewhat outdated processes, where designerly processes do not play a role. Instead, I have found this environment to be dynamic, progressive, and forward looking. The leadership of the innovation Foundry is actively involved with designing the design environment, designing the means in support of mission concepts and strategic goals, and facilitating conversations in design sessions. For these, they employ designers from JPL's Studio in support of storytelling, creating keystone graphics, including them in design studies and proposal preparations. This provides a clear strategic advantage for JPL to compete for funding from NASA sponsors. Based on semi-structured interviews with members of the Innovation Foundry and the Studio, and mapping the organization into VSM's organizational hierarchy, helped to uncover a misalignment related to organizational roles to advance and maintain development tools for mission concept studies. My recommendation provided to JPL points to a preferable mode of operation and may help to advance computational model and tool developments, if supported by a forcing function from the strategic level to implement it. Making this new alignment—that is, modifying the goals of the system from a strategic level, related to roles and responsibilities within the Innovation Foundry and connected offices—is in line with second-order cybernetics. For this research segment I have generated communicable knowledge through a conference paper, discussing the structure, functions, and processes of JPL's Innovation Foundry and Studio, in support of JPL and NASA (Balint & Freeman, 2016). The conference presentation provided an opportunity for conversations with a target audience of aerospace professionals.

The fourth example (see Appendix D.3) is focused on gradually and systematically changing NASA's organizational culture. A potential way to do this is from the ground up, which can be achieved by educating the next generation of non-linear design thinkers and to bring them into the workforce, opposed to indoctrinating the new hires into existing linear process-driven methods. An appropriate space focused graduate-level university program can be fashioned after RCA's Innovation Design Engineering (IDE) and Global Innovation and Design (GID) programs. It can train a new generation of non-linear thinkers with trans-disciplinary expertise in space related human centered design, engineering, cybernetics, and management. Introducing these educational approaches to NASA from an entry level can gradually evolve the organizational culture and foster new conversations and activities through designerly modes of operations, which includes making, prototyping, and co-evolutionary circular design processes. In this research I have made a case for setting up a graduate-level academic program, but the discussions between JPL and neighboring universities were unsuccessful at this time. Setting up a new program can take years. It requires strategic level support and significant resource allocation from NASA and the universities involved, who would ultimately host this academic program. This example mirrors the produced white paper, advocating for a design focused educational program.

The fifth example (see Section 7) provides a "connective tissue" between the first three examples (Sections 5, 6, and Appendix D.2) and is dedicated to boundary objects in support of conversations. The designerly and artistic modes of making them afforded me to slow down, reflect on my research, and subsequently propose new categorizations for them. These categories are building on the original definition by Susan Leigh Star and James Griesemer (Leigh Star & Griesemer, 1989) from social sciences, and borrowing categorization themes from design through Christopher Frayling (Frayling, 1993) and cybernetics (Glanville, 2004) (Dubberly & Pangaro, 2010). My proposed categorization included: a) communications ABOUT boundary objects; b) boundary objects FOR communications; and c) design conversations THROUGH boundary objects. I have also proposed a distinction between first-order boundary objects, which were created within an existing paradigm, and used to guide, focus, and facilitate conversations; and second-order boundary objects, which can change and evolve during the conversations through a co-evolutionary process, which can help to mitigate or resolve design tension between team members and disciplines during the design process. To substantiate my proposed categorizations of boundary objects, in this thesis I have presented over a dozen artifacts, which I have designed and made over the course of this research. These were developed by me or in collaboration with research colleagues. The categorizations co-evolved with the making process, and generated communicable knowledge through exhibitions, art competitions, journal and conference papers, and conference presentations, leading to conversations with target groups representing diverse disciplines and interests. I am providing a number of examples in this conclusion, and a complete account in Section 7 and in Appendix E. The official IPPW conference posters (see Figure 7.16) informed subject matter experts and the public about the workshop. The Galileo Flow Field sculpture was made in two versions. The walnut version, that is shown on the IPPW-13 poster, became the first physical artifact ever used in these posters over the 13 years history of the workshop. It introduced and abstracted artistic representation to a predominantly engineering audience. A bronze version of the same design (see Figure 7.14) was exhibited at the WIP-2016 show in the context of my research, and won the Remet Casting Prize 2016. Remet UK Ltd acquired the sculpture for their in-house collection. I have also presented conference papers on this and other sculpted artistic boundary objects in (Balint, 2016) and (Balint & Pangaro, 2016). These sculptures were created to highlight the intersection between science, engineering, design and art, and generated conversations among members of these disciplines. A small bronze medal version of this design, titled Expanding Boundaries, was submitted to the British Art Medal Society's 2016 student competition, targeting medal collectors and the artistic community. It was selected for special exhibition at the Carmarthen School of Art, Wales, in September 2016. I have created the IPPW's Alvin Seiff Memorial Award medal as a commemorative artifact presented for life time contributions to the planetary probe community. The first award was handed out to Rob Manning at the IPPW-13 workshop. The Venus Watch 1.0 concept was designed for outreach, educating the audience about the advancements in manufacturing innovation, the extreme environments of space, and the history of Venus Exploration, while linking these stories to a functional designerly artifact. The Venus Watch 1.0 project was documented in a conference paper (Balint & Melchiorri, 2013), a peer reviewed journal paper (Balint & Melchiorri, 2014), and discussed in a number of online articles dedicated to 3D printing. I have used these examples to substantiate the proposed first-order category, while also representing conversations *about* and *for* boundary objects. The cybernetic astronaut chair example is discussed in the conclusions on habitats. It exemplified design conversations between the designer and the environment through a second-order boundary object, which evolved throughout the making process and involved a creative leap. These making experiences oriented me towards creating future second-order boundary objects through designerly and artistic modes, and to refine my proposed categorization in the process.

In reflection, NASA's processes are complex, mature, complicated, and framed within its paradigm. It is slow to respond to internal and external influences. It is predominantly driven by rigid engineering, technology, and project management practices. It utilizes systems approaches (e.g., related to systems thinking, integrated design, and control systems), which align with first-order cybernetics that describes an observed paradigm. In contrast, second-order cybernetics defines an observing paradigm, where the designer can modify the goals of the observed system, while being explicitly embedded in that system. Adding new disciplines to the discourse, such as design, art, or social sciences, would introduce new modes of operations, and broaden NASA's paradigm.

However, such multi-disciplinary design conversations towards changes can be challenging, as there are fundamental differences between the approaches of design engineers and designers. Design engineers typically operate under first-order cybernetics. Their design processes place an emphasis on analysis, working towards operative outcomes. The system goals and requirements are well defined and set within their paradigm and they innovate and design within these requirements. This typically results in incremental innovations and developments. On the other hand, the processes of designers—and also architects—are more aligned with synthesis, which can lead to new requirements outside of the operating paradigm. This makes it harder to get accepted within a rigid and established worldview.

Consequently, under today's dominant engineering paradigm at NASA, a strategic level forcing function is required to introduce new disciplines into the discourse. While this sounds logical, its implementation might be less straightforward. Organizations are dynamic systems, where paradigm changes go in leaps and bounds. A viable system is stable when its variety is balance between its components. Introducing new variety to the system causes imbalance, which can be balanced through conversations. When designers introduce new requirements it can lead to new options. These requirements can be introduced to the system through a forcing function from the strategic level. These outside-the-box steps correspond to second-order cybernetics. Once the new requirements become part of the paradigm, the observed system can leverage the benefits, and advance the system incrementally, until all the benefits of the added variety are exploited. At this stage the system operates under first-order cybernetics. The nature of guidelines and requirements is that once they are codified and enforced, they become parts of a new broadened, yet limiting boundary for the system. This can introduce resistance from the system to change, and it may take some time before new requirements can be introduced again. In an environment where the culture is solidified and the decision makers ascended through its hierarchy as part of this culture, they often resist changes that are outside of their familiar disciplines.

From my research I can conclude that organizations, including government run and academic institutions, need to implement new ideas to grow and lead. This requires designing its design processes. To overcome innovation barriers, at times, new modes of operation is needed to interrupt existing ways of thinking and doing things, and through it changing the organizational culture. Such a new organizational culture has to be adopted at all levels within the organizational hierarchy, starting with strategic level management then filtering down subsequently to lower levels. While the grassroots enthusiasm is present, middle management represents a challenge, which can be explained through first- and second-order cybernetics. Middle management oversees an observed system, in line with first-order cybernetics. They have they rules well established to perform a task. They are first-order regulators, keeping projects on track according to well-defined objectives and requirements. Introducing new goals to their observed system has to be initiated, enforced and supported from a strategic level, which is an observing paradigm. Senior leadership has the authority to modify the goals of the observed system, led by middle management, and provide a forcing function to include new goals—for example human centered requirements—from the top down. Including new modes of operation requires a paradigm shift in NASA's organizational culture, but it is the only way to change the worldview within the system.

Throughout my research I have found that design conversations and the use of boundary objects provided demonstrable value to enhance NASA's capacity to innovate. They can reduce innovation barriers by improving communications across discipline boundaries; between team members; with sponsors; and with the public. Improved conversations support transparency, traceability and openness, which can reduce innovation barriers within NASA's paradigm. Specifically, it can mitigate risk averseness and communication overload.

Finally, let's address the question posed to me by my supervisor, Ranulph Glanville, halfway through my research: *"Where is the delight?"* The answer to this question depends on who was asked. From semi-structured interviews I have found that at NASA, vitruvian delight and human centeredness manifests themselves in multiple ways. On long-duration spaceflight, it might be the inclusion of self-actualization that can bring delight to the astronauts. In an engineering environment it can be the satisfaction of working together in a team towards a goal. For an engineer, it might be finding an elegant and closing solution to a complex technical problem. On a personal level, knowing to be part of a greater common purpose by contributing to the exploration of our solar system. These are all human centered considerations, with different scopes and cybernetic interactions with the self and the environment. For me, this question on delight help to refine my research question and allowed me to explore new disciplines, broaden my cognitive model and apply it back to NASA's paradigm, showing how new modes of operation can enhance NASA's capability to innovate.

8.2. Future Directions

Future directions consist of two distinct yet connected elements. On a personal level, I am planning to advance my cognitive model related to cybernetics and human centered design. In parallel, I will look for opportunities to identify and apply my performative ontology to other cases and domains, both inside and outside of NASA. In addition, my research led to a number of new questions, which can be addressed in future research.

Specifically, for the habitat topic, I have identified the need for guidelines to address higher-level astronaut needs through second-order interactions with the environment. This could be addressed through a dedicated analog mission with a focus on such higher-level needs. For example, HI-SEAS (the Hawai'i Space Exploration Analog & Simulation, a long-duration Mars exploration terrestrial analog program by the University of Hawaii) could set its study goals for one of the upcoming missions to focus on these needs and approaches. This would help to generate relevant empirical data through a performative and designerly mode of operation. Synthesized findings from it could help to derive guidelines, which could be developed into future requirements. Subsequently, working with strategic level decision makers would provide a forcing function to include these requirements in NASA's Procedural Requirements (e.g., in NASA-STD-3001). Including higher-level human centered design requirements for long-duration space habitats through these steps would be a demonstrable way to broaden NASA's paradigm.

Without a champion, the future of PAFTD is uncertain. However, I believe that this is a valuable strategic level project assessment tool that can benefit various organizations in the future. Advancements from its current state may include: incorporating data science, machine learning, and development of dynamic performance metrics for performance trend forecasting. These can improve the accuracy and the speed of the feedback loops about changes at both project and strategic levels. As I have shown it through testimonials, PAFTD is not specific to NASA, and its approach based on cybernetics and design conversations has been adopted by at least two external companies. With the right advocacy, this adoption can be extended to other organizations within the government and commercial sectors, in support of their strategic decision making processes.

For JPL's Innovation Foundry, the recommended change on resource allocation for software tool and model developments can lead to the development of more advanced human centered tools. It can result in improved interfaces between subject matter experts and their application interfaces, and between team members through these interfaces. Furthermore, amplifying the roles and influences of human centered designers within its design environments can lead to further strategic advantages for JPL.

Related to space focused design education, seeking support from NASA at the strategic level, and looking for partnerships with appropriate universities can eventually lead to setting up a graduate level program. Subsequent hiring of these graduates, who are trained in designerly and artistic modes of operation would help to change NASA's culture and paradigm over time.

Boundary objects can become the focus of dedicated research. The proposed second-order category with evolving boundary objects can play ever-increasing roles in ideation, concept developments, and habitat designs, where the artifacts would evolve on long-duration space missions. These artifacts could stimulate discovery, learning, autonomy, emotional interactions, and other designerly and artistic modes of operation. Within NASA, an improved emphasis on first-order boundary objects—e.g., keystone graphics, data visualizations, and art installations—could improve conversations across disciplines and between diverse groups of stakeholders, and mitigate communication barriers.

The challenge for this research is that NASA's culture—with its assumptions and beliefs—became so rigid that it is difficult to influence, let alone change. NASA needs visionary leaders who introduce change. Therefore, the follow-on goal for this research is to find these strategic leaders and through conversations influence them to include these considerations in their future goal-setting activities for the Agency.

This research showed that today, designers and space architects are not in strategic positions, where they can modify the goals of an observed system, and with that broaden NASA's variety and its paradigm. While NASA has a Chief Scientists for science matters, a Chief Technologist to oversee Agency-wide technology developments, and a Chief Engineer for enforcing the processes and requirements, it does not have a Chief Designer who can champion and coordinate human centered approaches, and advocate for designerly and artistic modes of operation across the Agency. Thus creating a strategic level Chief Designer position would be an important step towards broadening NASA's modes of operation, which would subsequently benefit NASA's strategic mission, culture, and core processes through second-order change.

Appendices

Galileo Flow Field (Walnut wood / 2015)

Appendix A: What is Innovation? (Supporting Material)

In my research the purpose of introducing cybernetic perspectives and human centered design is an intended application to NASA's current worldview, driven by engineering, technological innovation, and related management practices. This necessitates the inclusion of NASA-relevant topics, such as the definition of innovation, which is discussed here, and NASA specific innovation barriers, and the concept of wicked problems, which are discussed in Section 3.5.

A.2.1. What is Innovation?

Organizations need to successfully implement new ideas to progress, to develop and grow, to become more profitable, efficient and sustainable. Innovation can be categorized in different ways, and the discussion presented here is just one of the possible approaches. In general, innovation can sustain or interrupt existing ways of doing things for the whole system or for its components.

The *extent* or levels of innovation can vary significantly, and can be categorized as:

- *Incremental & sustaining innovation:* which provides improvements to existing products, processes, or services. For example, increasing the performance or a product by a small percent.
- *Radical innovation:* changes the nature of products, services, and/or processes. For example, using additive manufacturing to produce rocket nozzles, or breaking the battery recharge cycle limit can have a significant impact on the aerospace industry.
- *Transformational and disruptive innovations:* are revolutionary in their impact, and may affect the whole sector or even the economy. For example, deep space optical communications and inflatable aeroshells can enable future human exploration missions to Mars by providing high data rates to communicate with the crew, and by enabling an order of magnitude larger landed mass on the surface of Mars, which is needed for a future human habitat.

Temporal characteristics of innovation:

- Innovation can occur at different *times*, on different *time scales*, and their *infusion* to stakeholders can also vary.
- Innovation can occur *before or ahead of its time*. For example, Apple's Newton set the stage for the Palm Pilot and for other personal assistants until the iPhone became highly successful. Google Glass was recently under development, but its success is far from guaranteed. Such products may not gain momentum for wide diffusion and growth, which may mean no chance for infusion for even decades. This brings up the question: "why invest now?"
- Innovative products may take *too long to develop*: during that time other ideas may come forward and succeed. For example, a new product might be superior or cheaper. This can be leveraged with parallel investments in the same topic area, where other solutions may emerge faster with nearer-term infusion potentials.

Markets and technologies can also *shift*:

- Some ideas may have looked good at the time, but opinions and options may have changed under a new outlook. For example, recently the Mars program selected a mission architecture for 2020, which will result in the re-flight of technologies from the previous Mars rover mission. This removed the need to advance some of the new technologies that initially targeted this mission opportunity. Under such circumstances a programmatic response is needed to reassess the technology portfolio and use these markers to justify redirection to a new and relevant technology development content.
- In other cases the idea may have looked good at the time of initial conception and may have had initial successes, but with changes to the infusion potential and stakeholder needs, the "why invest now" questions can no longer be satisfied.
- Short development time scales may point to incremental developments, while radical innovations may need long development and infusion time scales.

The *diffusion* of innovation can also range from short to long time scales. For example, Internet-based services can infuse services within months or shorter, while pharmaceutical products, such as new drugs, may need many years to introduce to the market.

The innovation framework includes *first movers* and *fast followers*. First movers are the initial innovators who take and assume the risk of being first on the market. This may provide an edge if managed well. Fast followers "jump on the bandwagon" and try to capitalize on the emerging market. This is often enabled by venture capitalists.

Customers or stakeholders are key elements to innovation, since an innovation is not successful unless they use it. Infusion paths are established with stakeholders in mind, but this by itself may pose challenges. In some fields, such as space and medicine, the innovators are also the users of the innovation. Furthermore, stakeholders can inhibit innovation, by being conservative in their approach to infuse them. They can be complacent, locked into ways of doing things, and risk averse (Dodgson & Dunn, 2010, p.56). Consequently, a potential problem of listening to customers too closely may result in catering to their immediate and incremental needs, without supporting truly innovative ideas. Thus, responding to customers too closely may result in being left behind when changes occur in technologies and markets.

A.2.2. Risks and Failures

Technology development and innovation, especially transformational and disruptive innovation, inherently carry risks (Kolko, 2015, pp.66-71). There are various types of risks that one needs to address:

- *Technology risks:* are often encountered by technology developers, but a good risk posture allows accepting informed risks. New innovative technologies may fail, but it is expected when the developers push the boundaries. The relationship between informed risks and failures during the technology development process is further discussed under the sections on guiding principles for space technology programs and implementing new projects.
- *Organizational risks:* are often overlooked. Setting up an organization in a certain way allows operating in that mode. Consequently, the products it produces will align with the operational mode. Trying to get a different outcome than allowed by the setup

can be challenging. (In *“Chapter 1: The Medium is the Message”* of his book, entitled *“Understanding Media,”* Marshall McLuhan explored the circular relationship between people and the environment (McLuhan, 1964, pp.7-21). McLuhan’s discourse is captured by John Culkin when he wrote: *“We shaped the alphabet and it shaped us”* (Culkin 1967, p.70). A more commonly referenced version of this was included in the recorded version of McLuhan’s book, the *“Medium is the Message,”* stating: *“We shape our tools and thereafter our tools shape us”* (McLuhan et.al, 1967, time:15:34).)

- *Network risks:* can impact operations when working with other stakeholders. For example when a project is co-founded and fiscal constraints cause a partner to withdraw, it can have a significant impact on the project and its elements. Recent example is the US Sequestration decision, impacting a large number of projects within NASA’s portfolio. Many of these were executed in collaboration between multiple Mission Directorate partners. The resolution required negotiations.
- *Contextual risk:* is related to ambiguity and can occur when poor communications between various stakeholders are present.
- *Wicked problems:* describe problems that are difficult or impossible to solve to the full satisfaction of all parties involved, due to contradictory or partial information, or impacted by requirement creep. These can be also hard to recognize (Rittel & Webber, 1973, p.160). The complexities can also be driven by cross dependencies between various fields, and solving one element or an over-constrained problem may introduce new problems at other areas. This can be illustrated by looking at NASA’s management of technology programs with multiple contributing factors. The first uncertainty is the overall budget for the Mission Directorate with its dependence on the Agency’s budget, which in turn is provided by the government. Not passing the national budget on time results in a so-called continuing resolution and imposes constraints to programs and projects. The second uncertainty is the funding allocation to each program and projects within, which can be impacted by overruns. The third is the work force allocation at NASA Centers and center politics, which influences some of the project decisions. The fourth is the availability of procurement—namely the funds available for purchases of products and services. The fifth is the time dimension with potential fluctuations in the phasing and spending. There are a number of other constraints as well, making programmatic balance and execution an often over constrained wicked problem, where program managers are challenged to find the best possible outcomes. The solutions to wicked problems are not true or false, but good or bad. NASA’s wicked problems are bound by the annual budget cycle, and typically don’t perpetuate. Instead they repeat piecewise, year after year, while introducing new and unique challenges (Balint & Stevens, 2016). This topic is further detailed in Section 3.5.3, and in Section 5 for the NASA specific examples.
- *Business risk:* is typically not applicable to the government sector, although there are project risks related to funding instabilities, changing priorities, and other factors.
- *Demand risk:* is typically not applicable to NASA, but collaborated projects may require deliverables to stakeholders, where the risk is related to meeting schedule, budget, and milestones.

A.2.3. Learning

Organizations learn by doing familiar things. However, radical and disruptive innovations—those that include significant breakthroughs and break with traditional ways of doing things—can introduce significant challenges to organizations and the way they learn. Organizational responses are a function of the pressure to change.

- *Status quo:* is often considered by management as positive, since it does not require change.
- *Novel:* is perceived as uncertain, hard to control, distant, often due to the unfamiliarity towards oversight, and it can be seen as negative.
- *Radical innovation:* goes another step further, and these technologies can destabilize existing capabilities or an organization, if not handled appropriately.
- *Disruptive innovation:* often results in disconnects with current stakeholders. In industry it can impact business and cash flow, and within NASA's technology program it may prevent infusion and may result in the cancellation of the whole program if it is no longer considered beneficial to the Agency.

Consequently, senior leadership has a significant role to play by providing strategy, encouragement, resources, reviews, and performing post-project assessments. It is also important to strike the right balance between the various segments of the portfolio investments. It has been suggested that portfolios for innovative organizations should be balanced by including core, adjacent and transformational content, using the golden ratio of 70%, 20% and 10%, respectively (Nagji & Tuff, 2012, p.8).

A.2.4. Workplaces, Creative People and Teams

Edison showed that organizational vision, understanding and accepting educated risk postures and potential failures, and diversity at the workplace are all key contributors to innovation (Dodgson & Gann, 2010, p.94). Furthermore, fun and enjoyable work environments are preferred to impersonal and bureaucratized workplaces. Open conversations and opinions contribute to generating and implementing new ideas. Allowing constructive criticisms to surface is welcomed, instead of complaining against already made decisions Edison also found that people work harder when involved with interesting and rewarding work, and given meaningful rewards to foster individual ambitions and needs (Dodgson & Gann, 2008, p.112).

Innovations typically occur through team efforts, combining various ideas and experiences. There are many contributing factors to success, including the core knowledge of the individuals and the organization, coherence of the team, and a suitable team structure that facilitates the project goals. Incremental innovation can be approached in a structured way, but radical and disruptive innovation ideas need more creative people on the team, and more flexibility and freedom to experiment. Of course, this does not remove the need for due diligence.

Consequently, everybody in an organization has a role to make innovation happen. Management needs to champion innovation in an organization by creating an environment where innovation is encouraged, supported by organizational culture, and where people are allowed to push the boundaries without the fear of being reprimanded in the case of failure. An organizational structure needs to support team and technical coordination, portfolio management, implementation of the projects, while communicating the message of innovation to all stakeholders. In addition to management and the workforce another group, called "boundary spanners," can greatly benefit an organization. Such people provide links between their own organizations and cross-pollinate with external entities. For example, at NASA they interact with mission directorates, other government agencies, industry, academia, attend conferences and meet with stakeholders. Within STMD the Senior Technical Officer, the Senior Technical Advisor, and the Director for Strategic Integration fulfill these functions.

In general, everyone inside an organization has equally significant roles to promote innovation, but in turn the organization must recognize and reward talents and utilize them to the highest degree. The rewards can manifest in training and incentives. As a result, these organizations will attract the best people, thus perpetuating the cycle of innovation.

A.2.5. NASA's Collaboration with Universities

The primary product of universities is knowledge, which is transmitted to the stakeholders. Over the years the roles and functions of universities have extended towards economic activities, while teaching took a second seat. Through economic activities universities generate growth both regionally and nationally, benefiting industries and government agencies. They are well suited for early stage technology development through grants and other types of awards. For example, NASA's Space Technology Research Grants Program under STMD works closely with both university graduates and faculty researchers, through fellowships and grants, leveraging the knowledge base of the universities and the dynamic enthusiasm of their researchers. These researchers and early career faculty members are considered problem solvers who provide a bridge between the knowledge base of their institutions and the outside technologists they are working with. In turn these real world experiences help the university researchers as well. For example, many researchers who participated in NASA's Planetary Science Summer School, or had internships at NASA (e.g., from the International Space University), completed their advanced degrees and became NASA researchers or technologists. Thus, ensuring funding continuation through budget uncertainties may represent challenges for NASA, which needs to be addressed in order to maintain the continuity of these university connections.

A.2.6. Regions and Cities

Innovation is often regional and it can cluster for numerous reasons (e.g., social and cultural). For example, the government played a key role in establishing and encouraging Silicon Valley by donating lands to universities, while also stimulating industry development. The government created policies that encouraged interactions between academia and businesses. Currently NASA's Manufacturing Innovation Project under STMD's Game Changing Development Program (GCDP) is involved with the Strong Cities, Strong Communities (SC2) national initiative, launched by the Obama Administration in 2011. Such initiatives can attract excellent people and create a buzz that feeds further developments.

Many cities around the world are considered major innovation hubs, each with a different focal point. Some cities are renowned learning centers (e.g., Oxford, Cambridge); engineering centers (Birmingham); finance centers (London, New York); or design centers (London, Milan). These innovation hubs developed over the years and through the various economies, which started with the industrial economy, through the experience economy, to today's knowledge economy (Brand & Rocchi, 2011, pp.7-11). Regardless of the change of ways businesses connect or people interact, there will always be a need for these innovation hubs leveraging a critical mass of core expertise.

A.2.7. Governmental Roles

Governments are well positioned to establish an overall national innovation system and influence it. For example, in the US there are a number of National Initiatives to encourage innovation, and through various projects NASA's STMD is involved with several of them, including the National Robotic Initiative, Manufacturing Innovation, Nanotechnology and the National Materials Genome Initiative.

Another key role for governments is to create suitable policies that support, impact, and stimulate innovation. These policies may include:

- Effective monetary and financial policies to provide confidence in the future.
- Good education policies to mature well educated people who then can innovate.
- Competition policies to prevent monopolies.
- Trade policies to increase the size of the market.
- Intellectual Properties (IP) laws to provide innovation incentives.
- Environmental protection laws that lead to innovation.
- Free and open access to information.
- Information access through high-speed digital connections.
- Immigration laws to allow hiring of talents.
- Industrial relation laws to provide a secure work environment.
- Governmental resources (finance) to purchase innovation.

It should be noted that there is a difference between the government providing functions and regulations in support of innovation (as discussed above), and a government agency like NASA, which receives funding from the government and operates as a research and development environment.

Just like NASA, all government agencies receive funding from the federal government on an annual basis. Over the years, funding for most agencies was stagnant, stimulating collaborations on various projects, when the core competences and project goals sufficiently aligned. In a shrinking budgetary environment these consolidations can provide short-term success, but gradually it makes them not viable. *"You can't shrink your way to greatness"* (Peters, 1997, p.592/624).

A.2.8. NASA's Links with Industry

Looking at Industry from NASA's perspective, NASA works closely with the industrial base, ranging from small to large companies with strong funding dependencies from the government. Aerospace companies, focusing on space related technology development can be impacted by limited and uncertain budget appropriations. Maintaining core competence at these companies can be important for the future of the Agency, but decreasing or stagnant budgets can reduce the number of solicitations for new technologies, and the number of awards to be handed out. Further complications for NASA can rise when dissatisfied companies attempt to force alternative approaches, by appealing to their congressional representatives in support of leveraging a more favorable response from the Agency.

From this long list it is clear that the number of influencing factors impacting technology development at NASA range well beyond a purely technological feasibility, resource related viability, and Agency or national needs.

Appendix B: NASA's Budget and PAFTD Supporting Material

B.1. NASA in the Government Framework

To demonstrate why I consider technology development at NASA a wicked problem, I also need to discuss the budgetary process, and influencing drivers within this broader framework.

B.1.1. NASA's Budget

NASA's annual budget is part of the United States federal budget, which funds government operations for a given fiscal year. The US Government Budget begins as the President's Budget Request (PBR) from the Executive Branch, to the US Congress under the Legislative Branch. In the PBR, the President recommends funding levels for the next fiscal year. The fiscal year begins on October 1, and ends on September 30 of the following year. The PBR is not the final budget for the government agencies. By law, the budget is appropriated by Congress on an annual basis. Congressional decisions are set by budget committees, identifying spending limits, which are subsequently approved by appropriation subcommittees to allocate funding to the various federal agencies and programs. The funding bill is then passed by both the House of Senate and the House of Representatives of the Congress, and sent to the President of the United States (POTUS) for signature.

To understand the budgetary environment at NASA, I am providing here a notional and simplified explanation of the process. It is simplified, because in practice the appropriation bill may come in other formats, including an omnibus spending bill, a Continuing Resolution (CR), or a supplemental appropriation bill. It can also be impacted by other spending measures, such as the sequestration process. Further details on the NASA relevant budgeting process is discussed in the following sub-section, describing the Programing, Planning, Budgeting and Execution (PPBE) process.

It is important to relate the size of NASA's budget to the overall federal budget, as it provides an indication on the perceived importance and relevance of this government agency, compared to other entities. I am demonstrating this through the US Federal Budget breakdown from the Fiscal Year (FY) 2013 (HoR, 2014), shown in Figure B.1.

The total spending amounted to $3.45 trillion, which included mandatory and discretionary spending elements. Spending for mandatory programs cannot be reduced. It includes paying the interest on the national deficit, and covers the major entitlement programs,

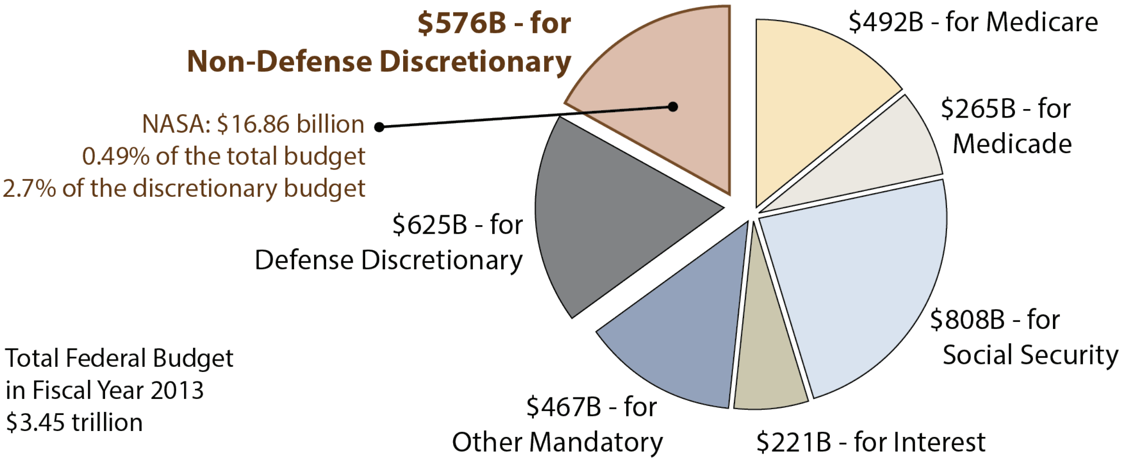


Figure B.1: Federal budget breakdown for Fiscal Year 2013 (HoR, 2014).

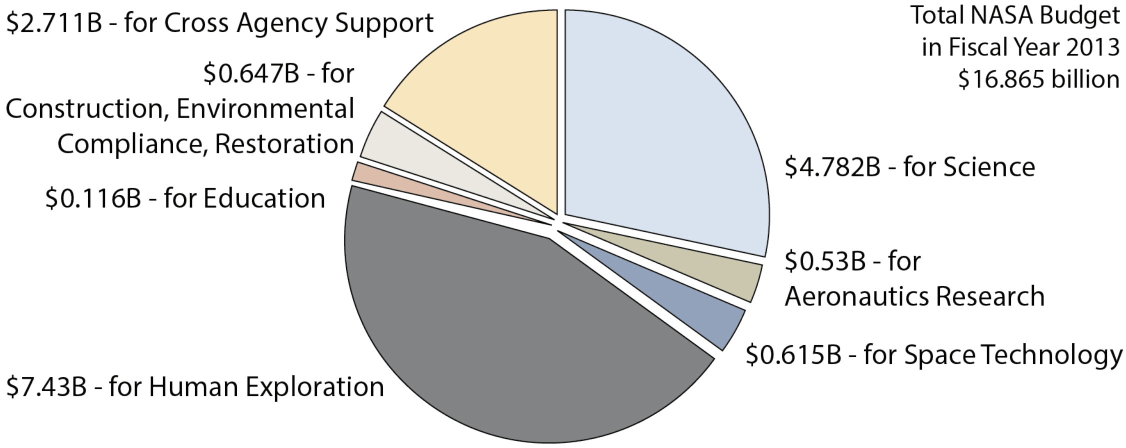


Figure B.2: NASA internal budget breakdown for Fiscal Year 2013 (NASA, 2014).

such as medicare, medicaid, and social security. In comparison, discretionary spending can theoretically be reduced to zero by Congress, based on Constitutional law. It includes both defense and non-defense related spending. NASA falls under the non-defense related discretionary spending category and its budget can fluctuate year after year. In FY2013 NASA's appropriated budget was $16.865 billion, which is 2.7% of the non-defense based discretionary funding, and 0.49% of the total federal budget. In comparison, during the peak of the Apollo era in 1966, NASA's budget amounted to 4.41% of the national budget, which ratio was about 9 times higher than the current level.

Further breakdown of NASA's FY2013 budget shows a mixed distribution between the 4 Mission Directorates (NASA, 2014)—see Figure B.2. The enacted budget for Science was $4.782B; for Aeronautics Research $530M; for Space Technology $615M; for Human Exploration $7.43B; with further allocation for Education ($116M); Construction and Environmental Compliance and Restoration ($647M); and Cross Agency Support for NASA-wide management and operations support ($2.711B). While these numbers may look reasonably large compared to other national space agencies, the allocations are further divided by Mission Directorate Divisions, Programs and Projects. The appropriated budget includes a large number of mandatory ("earmarked") spending allocations as well. For example, it covers the continuing development of the Orion Multi-Purpose Crew Vehicle, the Space Launch System (SLS), and the Exploration Ground Systems (EGS) under Human Exploration, or the James Webb Space Telescope under Science. Additional details on the budget breakdown are provided in (NASA, 2014). Note that this analysis is based on NASA's FY2013 budget. (The Fiscal Year 2016 budget for NASA was appropriated in December 2015, and over the past three years it increased to $19.285B. This includes $5.5894B for Science; $640M for Aeronautics; $686.5M for Space Technology; $4.03B for Exploration and $5.0292B for Space Operations (that is, $9.0592B for Human Exploration); $1.2438B for Commercial Crew; $115M for Education; $2.7686B for Safety, Security and Missions Services; $388.9M for Construction, Environmental Compliance and Restoration, and $37.4M for the Office of the Inspector General. I am providing this information for completeness, but it does not impact the findings and conclusions, which are based on the FY2013 budget.)

The main purpose of the above discussion was to demonstrate the complexities and constraints associated with NASA's budget, and to illustrate how budget uncertainties can have a significant impact on the initial science, exploration and technology development plans.

B.1.2. PPBE Process

NASA's annual budget is part of the US Federal budget and negotiated through the Planning, Programing, Budgeting and Execution (PPBE) process, which focuses on financial management and resource allocation for current and future acquisition programs. While the budget is set for a given fiscal year, the PPBE process bridges an approximately 3-year fiscal time period.

The PPBE process consists of four distinct phases, which are carried out in parallel. These are:

Planning: this phase is designed to define content and examine alternative strategies, analyze trends and changing conditions, needs for new technologies, threats, and to provide an economic assessment of potential outcomes from new options, and projected long-term outcomes of current choices. If not done correctly, it may revert to a simple forward projection of current activities, leaving out the strategic assessment of alternatives. While on a short-term this latter approach may indicate a firm direction, on the longer term it can harm the organization.

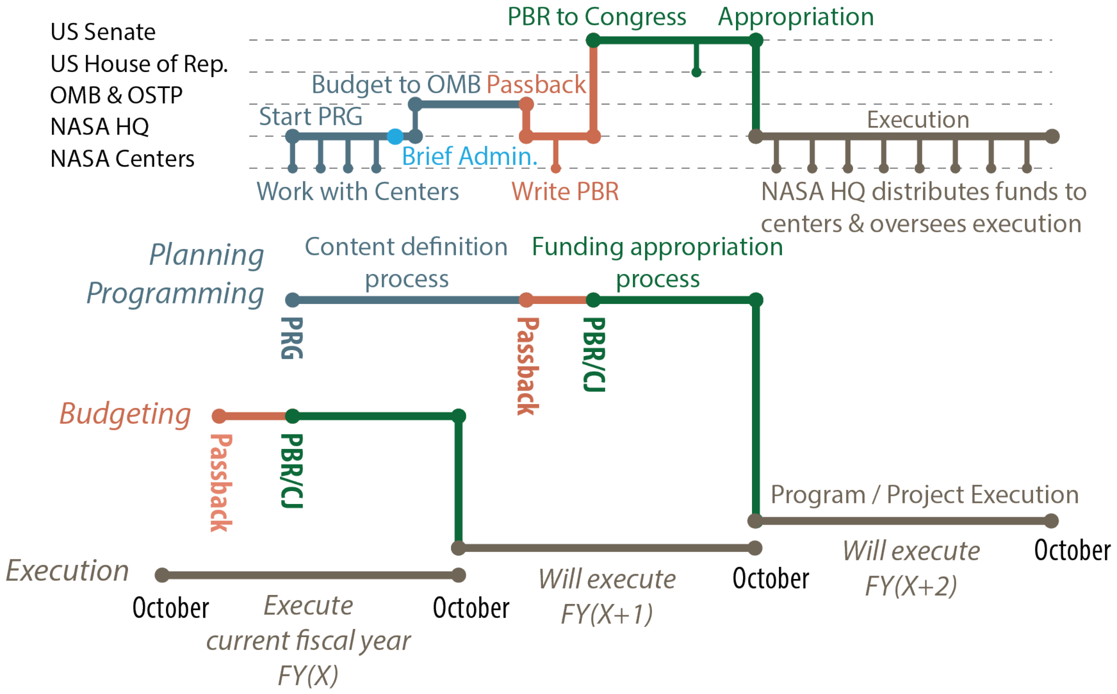
Programming: this phase connects the planning elements with their multi-year resource implications, and evaluates various tradeoff options. When planning and programming are performed concurrently, with a focus on forward planning only, there is a danger of describing a broader yet linearly projected future, instead of providing trades and alternatives.

Budgeting: this phase addresses the formulation, justification, execution, and control of the budget for the following year. It is formulated to align with both national and NASA needs and requirements to achieve the set out plans.

Execution: this phase represents the actual implementation of the process, where the budget is spent in the current fiscal year, according to plans defined through the previous phases. In a typical PPBE cycle, the budget is appropriated on time at the beginning of the fiscal year, and the program is executed accordingly. However, appropriation delays and other factors may result in resource allocation changes throughout the year, which can introduce budget uncertainties, focus creep, and may negatively impact the initially planned execution.

The idealized PPBE process is shown in Figure B.3. Idealized, because it assumes a predictable theoretical cadence of the steps and actions. In practice a number of uncertainties can have significant impacts on carrying out this plan. For example, reoccurring delays related to annual budget appropriations result in so called Continuing Resolutions (CR), which may take from months to even a full fiscal year to resolve. In turn, CR has an impact on funding and resource allocation, project execution, descopes, delays, and even new content initiation in a given fiscal year.

Planning and programming is performed through interfaces between three key stakeholders. These are: NASA HQ, the NASA Centers, and the US Government's Executive Branch. The activity is led by NASA HQ as a focal point, first interacting with NASA Centers regarding resource allocation plans and needs in support of the planned content. Next, following a briefing to the NASA Administrator, the budget and related content plans are sent to the Government's Executive Branch for assessment against national funding plans, strategies and policy alignments. This process starts about a year and a half in advance of budget



NASA HQ - NASA Headquarters
OMB - Office of Management & Budget (Executive Branch)
OSTP - Office of Science & Technology Policy (Executive Branch)
US Congress - House of Representatives & Senate (Legistlative Branch)

FY - Fiscal Year
PPBE - Planning, Programming, Budgeting, & Execution
PBR - President's Budget Request
CJ - Congressional Justification
PRG - Program and Resrouce Guidance

Figure B.3. Notional PPBE process for NASA.

appropriation. This phase completes with the "Passback" step, where the Office of Management and Budget (OMB) under the Executive Branch provides actionable feedback on the submitted plans. It occurs less than a year before budget appropriation. In addition to OMB, NASA is also coordinating with the Office of Science and Technology Policy (OSTP) under the Executive Branch, to align with national strategies and policies.

The *budgeting* phase involves three stakeholders. NASA, and both the Executive and Legislative Branches of the US Government. After receiving the "Passback" from OMB, NASA HQ makes the necessary adjustments to the plan, and compiles the President's Budget Request (PBR) document, which is also called Congressional Justification (CJ). The updates are made after discussions with the NASA Centers, in order to optimize—within constraints identified in the "Passback"—for common goals and targeted outcomes. The PBR document is sent to Congress in the middle of the fiscal year. Within Congress, four entities are set to assess the PBR document, namely the authorization and appropriation sides of the Senate and the House of Representatives. The budget—to be appropriated—requires an agreement between the Senate and the House of Representatives before signed by the President and passed into law.

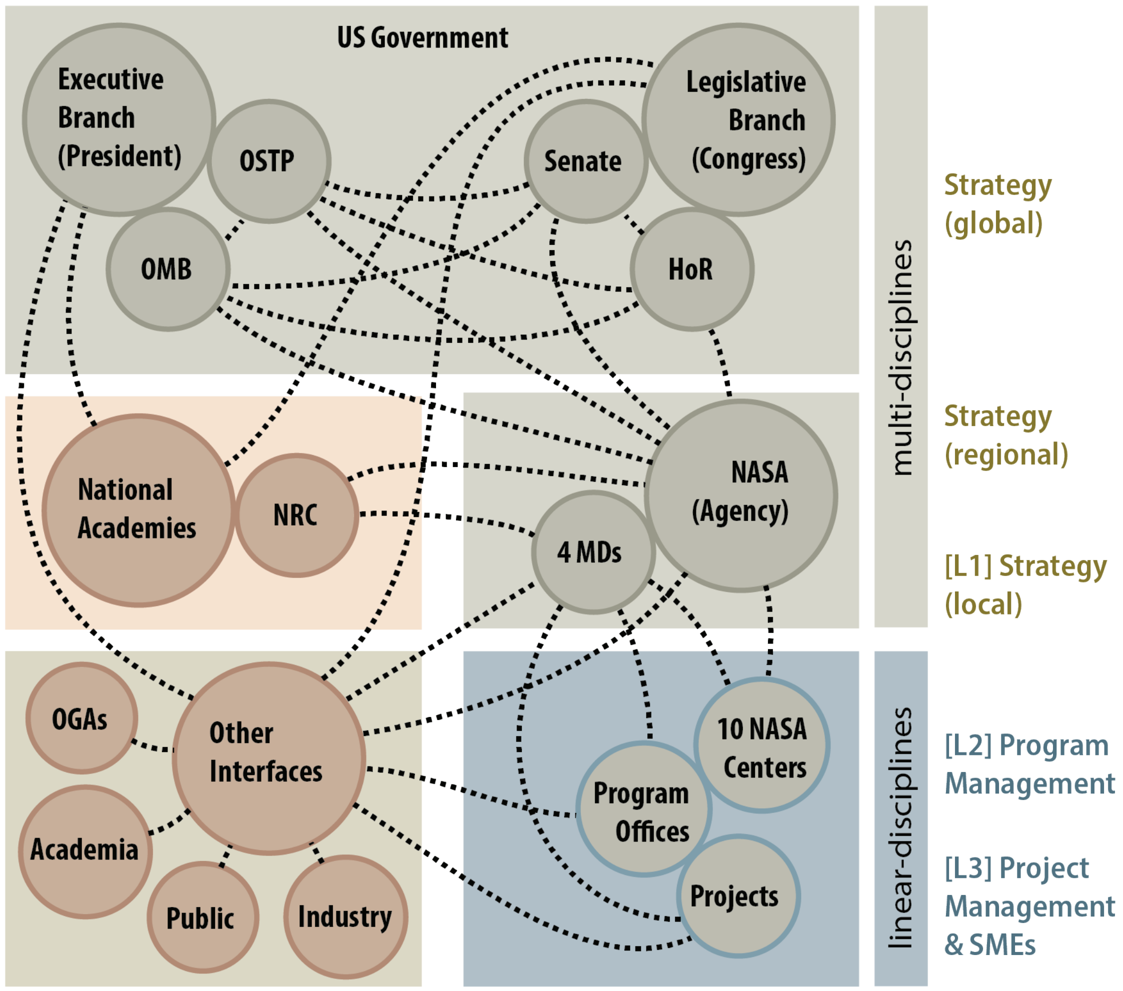
Once appropriated, NASA receives the budget with markups from the Congress, and proceeds with the *execution*. This markup often includes earmarks and other changes, in addition to modifications to the final budget, which is often lower than recommended in the PBR. This can result in a flurry of re-planning activities within NASA, including the assessment of the impacts on various projects, and modifications to the milestones and deliverables. The mismatch between the PBR plans and the appropriated budget plans translates to changes to the programs and projects, which may vary from minor impacts to significant or complete redirections. If the budget is not appropriated on time, which has been the case for most years over the past decade, then the projects are forced to execute under the assumption of the previous year's budget allocation. If the subsequent appropriated budget is lower than that for the previous year, projects can be significantly impacted and often harmed for the rest of the fiscal year and beyond. From NASA's perspective the appropriated budget at the end of the budgeting step of the PPBE process is highly important, as it sets the funding level for the execution step. It allows programs and projects to plan and refine their internal implementation steps during the execution year, which then completes the PPBE process for that given cycle. Complications resulting from higher government level budgeting delays, such as unfinished budgeting by the Legislative Branch at the beginning of a given fiscal year can lead to an administrative stop gap measure, called Continuing Resolution (CR), which propagates budget uncertainty for the execution step of the process. (Continuing Resolution and other processes impacting standard flow of the PPBE cycle can be complex with special rules and considerations, and therefore, these are not discussed further in this thesis.) The PPBE cycle then repeats year after year, as each execution year overlaps with future programming, planning, and budgeting steps for subsequent years.

The PPBE process is cyclical, with annual cycles and associated uncertainties. Consequently, planning and execution is often becomes a challenging exercise, putting significant pressure on all of the parties involved, from the Mission Directorate level at NASA HQ down to the project execution level. In this domino effect, project resource changes can also propagate to external contractors, thus impacting space related industries, small companies, and academic institutions.

B.1.3. Influencing Drivers

Technology development and related innovation at NASA are influenced by both direct and indirect drivers. These include the highest branches of the US Federal Government, NASA's organizational structure from Headquarters to NASA Centers, and external entities from the National Research Council, to academia, industry, and Other Government Agencies (OGA). I am discussing these influencing elements from a top down hierarchy, shown in Figure B.4. Other factors influencing innovation are detailed in Appendix A and (Balint, 2013).

US Federal Government: At the highest level, two branches of the US government are involved, namely the Executive and Legislative Branches. The third, Judicial branch, does not have an active role on the day to day activities of NASA. The Executive Branch under the President of the United States has two offices, which are working with NASA on the budgetary process and setting strategic directions. The former is the Office of Management and Budget (OMB), where the Science and Space Branch is embedded in the fourth level under the Resource Management Offices, the National Resource Programs, and the Energy Science and Water Division. Similarly, for the latter one, the Space and Aeronautics Branch is positioned under the Advisors of Policy, then the Office of Science and Technology Policy (OSTP), and Technology and Innovation Division. OMB is concerned with the planning of the overall annual national budget, where NASA's budget is below 0.5% (compared to the 4.41% during the peak of the Apollo era). Its perceived importance at this level is often aligned with the allocated budget. OSTP is driven by national level interests, where STEM (Science, Technology, Engineering and Mathematics) education, national and international prestige and leadership are important factors. One possible way to achieve some of the national goals are through space



OSTP........Office of Science and Technology Policy
OMB........Office of Management and Budget
HoR.........House of Representatives
OGAs......Other Government Agencies

NRC...........National Research Council
MDs...........Mission Directorates at NASA
[L1]-[L3]...NASA Organizational levels 1 to 3
SMEs.........Subject Matter Experts

Figure B.4. Connections between NASA and its stakeholders (Balint & Stevens, 2016).

exploration, but it is not the only path. NASA's alignment with national initiatives, for example with the National Robotic Initiative, Material Genomes Initiative, National Nanotechnology Initiative, and Manufacturing Innovation are also important drivers. Consequently, the considerations about NASA's importance within the overall national level strategic and political framework and related resource allocation portion from the national budget are weighted accordingly. The 4-year presidential election cycle also influences presidential priorities and related decision making, primarily focusing on other higher priority national interest from health care to national security, thus keeping decisions related to NASA on a flat and continuous trajectory. Regularly pointing to the fact that NASA's budget is still higher than that of the combined budget of other national space agencies, and the politically driven space race is over, the drivers to increase the budget are not strong. Still, the annual President's Budget Request shows an increasing budget trend, which typically does not materialize to the proposed PBR level during the appropriation process by Congress. The Legislative Branch is represented by the Congress, and includes the Senate, with two senators per state, and the House of Representatives with one representative for every 13,000 people. Both has their authorization and appropriation committees, responsible for advancing the PPBE process, and appropriating the budget. Within the Congress the drivers are often different from those for OMB and OSTP. Priorities include resource allocation to specific states, championed by state representatives on appropriation committees. Related earmarks in the appropriated budget often identify specific high budget projects, linked to specific states, thus creating jobs and stimulating local economies. Earmarks, combined with budget cuts, frequently overwrite the set directions described in the President's Budget Request, and constrain NASA's ability to allocate resources and start new projects recommended by the nation's leading scientists and technologists. At times the Executive and Legislative Branches, and within the Congress the Senate and the House of Representatives align, and at other times seem to act as obstructionists. These dynamics can also have an impact on the budget appropriation outcomes. Furthermore, NASA's annual budget is affected by multiple overlapping temporal and spatial cycles, related to elections and the regional impact of changing representatives on committees, influencing budget appropriation.

National Research Council: The National Academies of Science, Engineering and Medicine is the collective entity of four distinguished organizations. These are: the National Academy of Sciences (NAS), the National Academy of Engineering (NAE), the Institute of Medicine (IOM), and the National Research Council (NRC). These honorary membership organizations have over 6,300 members, with new members elected annually based on their distinguished careers and research achievements. As a result, the National Academies bring together the nation's most respected scientists, engineers, technologists and researchers. The members carry out their activities for these organizations *pro bono*, and act as advisors to the nation in the respective fields. The data collection, assessment and studies are documented in independent and unbiased reports, which are subsequently used by stakeholders as expert reviews, recommendations, and advice. The primary sponsorship for the activities by the Academies are provided by federal agencies, but additional studies are funded by the National Academies endowment, foundations, state agencies, and other entities from the private sector. In the case of NASA, recommendations for exploration targets through either human or robotic exploration are supported by studies under the National Research Council. Subsequently, NASA uses the NRC provided study reports as guiding documents. Through decadal surveys, technology roadmap studies, and targeted reports, the NRC provides advice and guidance to NASA on priorities about future missions and technology development needs. These are used by NASA during the PPBE phases, when discussing future strategic content both within the Agency and with the government. The NRC also provides independent direct input to the government's side during these budgetary negotiations. It should be noted that the advice and guidance from the NRC is non-binding, however, it is used as weighted input to a broader set of considerations involving other opportunities and constraints faced by NASA or the government.

NASA—Processes: Agency level strategic and programmatic coordination and oversight at the ten NASA Centers are performed from NASA Headquarters. In effect, the role of NASA HQ is to provide the primary interface between the Government and the Centers, plan, prepare, and negotiate NASA's annual budget (with inputs from the Centers on workforce and resource allocation needs), and subsequently distribute appropriate resources to the performers. HQ is also responsible for Agency and Mission Directorate level (Level 1) strategic decision making, execution oversight, setting and enforcing procedural requirements, portfolio assessment, balancing and planning based on strategic considerations, oversight of roadmapping and design reference mission planning activities, communications, and interfacing with stakeholders inside and outside of NASA. Collaboration and alignment between the four

Mission Directorates is coordinated at the HQ level. External stakeholders, from industry, academia, and other government agencies are approached to discuss strategic collaborations and future project ideas. (International collaboration is desired, but ITAR regulations can make the arrangement non-trivial. ITAR is short for International Traffic in Arms Regulations, which controls the export and import of defense-related articles, information, and services. Space technologies are considered dual-use, that is, they can be potentially used for both civilian and military applications. Thus, technologies, information, and experts working with them, also fall under ITAR regulations. Typically, anything under ITAR control can only be shared between US Persons, unless authorization is given by the Department of State, or a special exemption is made.) HQ runs solicitations for future projects through a competitive process, or authoritatively directs projects to performers. These projects can range from a simple instrument or component technology, through system of systems, to full space missions.

Typically NASA Centers house the Level 2 (L2) Program Offices. These L2 offices provide the interfaces between Level 1 (L1) and the Projects at Level 3 (L3). Centers work within their own organizational structures, managing their workforce and active projects, which is often challenging due to budget uncertainties. Re-planning at the program and project level is a frequent activity, with impacts to project execution and deliverables. Budget uncertainties and reduction can introduce stress points between the various centers with somewhat overlapping capabilities, competing for the same funding. The geographic distribution of the ten NASA Centers can introduce complexities to collaborations on distributed projects.

NASA—Structures: Beside the procedural influences, organizational structures can impact operating modes and outcomes, and we can't expect different results and efficiencies from organizations if the setups are identical. For example, we can create a sub-organization, such as NASA's STMD, with a specific goal of operating differently from the rest of the organization in order to achieve specific goals. This sub-organization then needs to have a new structure that facilitates a new way of thinking and operating. Otherwise the outcomes will be predictably similar to outcomes from other parts of the organization and bound by the same constraints that may prevent them to cut through innovation barriers.

NASA—People: While not specific to NASA, another contributing factor to maximize the potential of an organization is related to its people. Personalities at every level play important roles at workplaces. Leadership styles vary from collaborative to authoritative, while professional and interpersonal skills can differ greatly, influencing workplace dynamics, conversations, program and project outcomes, and the overall success of the organization. Appropriately delegated roles and responsibilities, and targeted rewards can greatly influence workspace morale, and effectiveness.

External Entities and Affiliates: NASA routinely works with other government agencies, academia, and the aerospace industry, where NASA leverages the expertise of these organizations, funds research and technology development activities, or collaborates with them. The roles of these entities are discussed in Appendix A.

B.2. PAFTD Through the Language of Business & Management

PAFTD is a management decision tool that facilitates the testing of different managerial hypotheses. The intent for developing it was to help solve the persistent challenge of selecting and managing technology investments within a resource constrained portfolio. It leverages a set of design thinking principles, which include: empathy with customers, a discipline of continuous managerial inquiry, and a tolerance for prototyping concepts and encountering possible failure (Kolko, 2015, p.66).

The consistency and repeatability of the PAFTD process is maintained through a qualitatively balanced scorecard that leverages management insights collected from primary and secondary sources, such as interviews, meetings, reports, and other forms of collected data. PAFTD enables a more enhanced definition of the considerations that influence the achievement of utility functions that an organization has identified. In the public sector utility functions of a technology organization may include innovative technology transfer, national security, commercial business development, and ultimately GDP creation. In the private sector a need also exists to continually identify and evaluate the appropriate means to achieve desired utility functions of value creation and maximized profit. PAFTD's methodology can help public and private sector entities sift through causality hypotheses, and provoke strategic analysis related to how and why decisions are made.

PAFTD is a decision maker's aid at the strategic leadership level, and it is composed of a number of strategic questions designed to help managers optimally evaluate and calibrate their portfolios. Selected reply differentiators provide senior management with quick and diverse insight into both exhibited technical and cost performance and surrounding strategic level system dynamics. PAFTD was developed through thinking that a need for a quick, integrated and objective "read" (feedback in a cybernetic sense) on a technology investment is necessary to diagnose more effective management techniques at the project execution level, combined with relevant information from the strategic level. The use of PAFTD is meant to foster a more responsive, flexible, and innovative culture within NASA's Space Technology Mission Directorate. Within the NASA environment, STMD has diverse interests and goals, and anticipate stakeholder needs. The PAFTD evaluation process allows NASA STMD senior leadership to drive out deeper and more difficult analysis in order to compare the strengths and weaknesses of various mid- to high-TRL technology elements that compose the technology portfolio. At NASA, insights gained from applying PAFTD to projects can be leveraged for more informed portfolio investment analysis, but most importantly it can facilitate essential discussions about the identification and implementation of the effectiveness of NASA STMD's strategy. PAFTD helps leadership design a way of coordinating and focusing actions to deal with change as it occurs over the course of technology development lifecycles (Depenbrock, Balint, & Sheehy, 2015).

NASA STMD's investment choices are generally influenced by the Strategic Space Technology Investment Plan (SSTIP) (NASA, 2013) and the National Research Council's Space Technology Roadmaps (NASA, 2010). PAFTD was developed to respond to outlined assumptions in these documents, and to help STMD management prioritize and to direct focus towards identifying and directing resources that align with achievable goals. Management of a fluid technology portfolio pushes managers towards three simultaneous actions:

1. Conduct the exercise of realistically assessing current technical and cost performance of invested content;
2. Monitor the external environment for elements that may affect currently executed content (e.g., identify risks and opportunities); and
3. Identify new ideas and investment areas for future content.

Balancing the efforts to both adequately evaluate and create is difficult. It is very easy for managers at NASA HQ to focus on just linear execution, as key decision makers tend to possess highly developed technical expertise in specific areas. This is largely a good thing for the agency as groups of experts contribute to the development of concentrated talent pools, recognized centers of functional excellence, and enhanced knowledge capture. However, technology development leaders within the organization need to realistically scrutinize and calibrate their investment portfolios to optimize defined utility objectives. Because of the array of technical expertise that exists across NASA, technology development managers tend to possess varying notions about benefits and costs associated with types of system level technologies.

NASA STMD has many stakeholders, and possesses a limited budget to make an impact. Simply adhering to a varying set of stakeholder interests and needs creates a disparate focus and a lack of a cohesive narrative to describe a portfolio of technology content. Thus, mechanisms need to be in place at NASA HQ to not only robustly assess programs and projects, but also to justify decision making that enhances the success of the organization. PAFTD's thorough approach using strategic level questions empowers managers to understand how the past, present, and future content affects the development of the organization's brand and the achievement of desired utility functions. PAFTD packages controllable information in order to influence the achievement of desired outcomes.

B.3. PAFTD Assessment Categories and Questions

A PAFTD assessment consists of semi-structured multi-nodal interviews with internal and external stakeholders from strategic and project levels, who are connected to the project being evaluated. Brett Depenprock, my collaborator on PAFTD and a Booz Allen analyst working at the STMD Resource Management Office, compiled the standardized question sets for these conversations. The questions are derived from discussions with NASA STMD Senior Technical Advisors (including me at the time) and mid- and high-TRL Program Executives (Depenbrock, Balint, & Sheehy, 2015). The PAFTD categories addressed the design thinking categories of usability, feasibility, and viability. Subsequently, Deperbrock cross-mapped these categories to IPAO criteria, as it demonstrated alignment with existing NASA assessment processes, instead of creating yet another new evaluation process. (IPAO is NASA's Independent Program Assessment Office.)

PAFTD's underlying foundation and strength are the formulated questions that comprise the model. The questions used in PAFTD were compiled by Brett Depenbrock—a Booz Allen Hamilton analysts at the time, under contract at STMD—from interviews with NASA STMD Senior Technical Advisors (including me at the time) and mid- and high-TRL Program Executives (Depenbrock, Balint, & Sheehy, 2015). The STMD differentiators and question-specific analysis included extensive intelligence gathered from research, meetings, and semi-structured interviews with stakeholders. The PAFTD process included multi-nodal conversations with internal and external stakeholders from both strategic and linear project execution levels. Mid- and high-TRL projects are those that develop, demonstrate, and then attempt to infuse technology elements into other mission directorate efforts. Mid- and high-TRL investments also compose the most expensive and most highly visible parts of the STMD portfolio.

During the development of PAFTD, the created questions were mapped into one of the NASA IPAO (Independent Program Assessment Office) six review criteria—numbered here for clarity and traceability from (i) to (vi). IPAO is the Agency's independent body within the Office of Evaluation that provides impartial and comprehensive assessments, free from the management or advocacy chain of programs and projects. IPAO's purpose is to determine whether the program's or project's planned budget and schedule are adequate to accomplish the proposed technical work. These IPAO criteria were mapped into related PAFTD design thinking categories as follows:

- *IPAO's "(i) Agency Strategic Goals" criterion mapped into PAFTD's "Usability" category:* Usability addresses the issues of "why invest now," user needs, infusion points, technology push, and mission pull and needs. It introduces strategic discussion as it seeks to consider customer needs, emerging trends, technology differentiation, and obsolescence.
- *IPAO's "(ii) Technical Approach" & "(iii) Resources other than Budget" criteria mapped into PAFTD's "Feasibility" category:* Feasibility is related to the technical, engineering, and science soundness of an innovative concept. It also concerns the team and its relevant core knowledge, and the availability of suitable facilities to carry out the development.
- *IPAO's "(iv) Management Approach" & "(v) Budget and Schedule" & "(vi) Risk Management" criteria mapped into PAFTD's "Viability" category:* Viability relates to cost, other funding sources, and schedule, risk, and management techniques.

This mapping of PAFTD categories into IPAO criteria was important, as it demonstrated alignment with existing NASA assessment processes.

B.4. PAFTD's Usability Category

In the latest iteration of PAFTD, the Usability category was expanded to enhance the fidelity and clarity of strategic level factor assessments. During the divergence phase of PAFTD-based project assessments, the analysts leverage the developed line of questions, in order to gain a more robust understanding of the relationship between:

- The performance of the technology;
- The management's desired level of technology risk tolerance; and
- The projected health and extracted benefits of advancement, as the project moves through its lifecycle.

The following discussion details a series of key questions, related sub-questions, and justifications that shine the spotlight on the Usability category of PAFTD. The Usability category includes four questions, which are mapped into IPAO's "(i) Agency Strategic Goals" criterion. These are:

1. *To what extent is the technology development effort still programmatically relevant?*

- Have there been any recent NASA policy changes that might have affected the relevancy of the technology? Agency policy is dictated by the Office of Science and Technology Policy

(OSTP) and the Office of Management and Budget (OMB) of the White House (referring to the Executive Branch), and can change. (See Appendix B.1.2.)

- Has a contribution from a defined end-user diminished? STMD's partnerships with defined stakeholders and/or customers help to ensure that STMD's technology contributions are focused and specific.
- Do additional investment costs—e.g., to infrastructure, workforce—in this technology development now outweigh extracted benefits, referred to as Return on Investment (ROI)? ROI measures the degree to which performance benefit exceeds the cost to develop the technology to the point of infusion.
- Is there an increased level of political risk? Political risk can influence an investment if international partners do not support the effort or if the technology has a defense application that might create geopolitical tensions.

2. *To what extent is concurrent investment within industry or other organizations in the given technology a threat to the relevancy of the technology investment?*

- Do significant external investments exist (e.g., at other government agencies (OGAs), international partners, commercial sector)? Significant external investments have the ability to render NASA's contribution in a particular topic area less valuable, because NASA would not be recognized by stakeholders/customers as the dominant provider of an investment. (I.e. NASA would not have a competitive advantage in that topic area.)
- Have other state of the art (SoA) capabilities—either inside of outside of NASA—advanced to a point to diminish the significance of this particular NASA investment? NASA needs to demonstrate tangible return to congressional stakeholders who appropriate the budget, and if an opportunity to demonstrate a short-term return is made obsolete by advancing capabilities from industry or OGAs, NASA may need to consider another architecture/mission application to invest into.

3. *To what extent has the project succeeded in avoiding delays—as delays might drive future interested/infusion partners away from this effort?*

- Is the technology considered "push" or "pull"? (Simply put, if the technology is advocated by the developing technology organization (push), or requested by a stakeholder to address its existing need (pull).) To assess this, we need to address the question: "Why invest now?" If the technology is considered "pull", have the customer's demands for Design Reference Missions (DRM) or Design Reference Architectures (DRA) shifted towards a significantly delayed implementation date? This would draw out the infusion date for STMD's more near term technology delivery, thus negatively impacting investment resource needs. (In STMD's case, the primary customers are from NASA's Human Exploration and Operations Mission directorate (HEOMD) or from the Science Mission Directorate (SMD).) If the technology is considered "push," then STMD, as the technology development organization, has established that it is necessary to advance a given technology to an infusion ready state. In some instances, infusion potential—the ability to directly utilize the technology on a future space mission—is affected by changing DRMs/DRAs that may affect STMD's decision to invest. It may negate the need for a given technology, but it can also open the mission trades to infuse these push technologies, and enable new capabilities for a specific mission or for the Agency.
- Have cost/schedule/technical issues affected the ability for STMD to meet its previously forecasted infusion delivery schedule, such that other missions or architectures have

developed that negated STMD's ability to provide more near term return? In some cases, the desire for a particular capability fluctuates between the start and completion of a technology development effort. A compelling reason to invest "now" may shift based on external demand and because of STMD's inability to meet a previous delivery schedule.

4. *To what extent is there a differentiating element/value proposition for NASA's investment in this technology?*

- Have other Mission Directorates (MDs) invested resources into this technology area at a level that renders STMD's contribution as less valuable? Other MDs serve as both competitors for NASA funding, as well as customers of STMD developed technologies. STMD has to find technology areas where their MDs/customers not only advocate for STMD's role in technology development, but they also do not make parallel internal investments, making STMD's contribution less valuable.
- If NASA did not invest, would another entity fill the need (e.g., OGA, international, commercial)? Also, could the technology be commercialized and then purchased by NASA? STMD needs to monitor ongoing investment trends within the aerospace technology environment as opportunities may emerge that enable the MD to deliver products to its customers with less development cost by procuring them commercially off the shelf. However, it may be the case that NASA invests in a technology to maintain its core competency/workforce and to enable ongoing development in an area.

B.5. PAFTD's Feasibility Category

Questions in the Feasibility category serve to gather more project specific insight, and attempt to identify primary areas of technical concerns for HQ. STMD needs to be cognizant of the risk that the appropriated budget from Congress may differ and often is less than what is asked in the President's Budget Request, as discussed in Appendix B.1.1 (Balint & Stevens, 2016). A reduced STMD budget that needs to sustain a technology portfolio with the same number of high-TRL investment commitments requires greater emphasis on cost and schedule, and can lead to less willingness to take risk that may result in overruns. If STMD wishes to push boundaries, it must develop expectations regarding the types of outcomes it may be willing to accept should it select certain types of technologies to invest in. (This consideration ties in with the barrier on NASA's risk-averse culture.)

The Feasibility category includes seven questions. Five of them are mapped into IPAO's "(ii) Technical Approach" criterion. These are:

1. *To what extent have project requirements been appropriately tailored?*

- This question addresses the effectiveness of project management and execution tailoring. In developing a lean and agile set of investments STMD tailors project requirements to reduce process, reporting, and test requirements that do not contribute to the effectiveness of technology development. This is particularly challenging given the high level of operational and engineering complexities that STMD Project Managers encounter. In addition, a mission-oriented agency geared toward human exploration tends to reward proven technologies with lower risk postures. Tailoring system development efforts implies an increased risk tolerance. As such, reaching a consensus on what constitute appropriate levels of tailoring can be difficult because mission failures within NASA are not acceptable.

(This aligns with process streamlining to resolve innovation barriers, as discussed in Section 3.5.1.)

2. *To what extent were the component based technology readiness levels (TRLs) for this project initiated at the appropriate levels to advance the system level TRL against Level 1 requirements?*
3. *To what extent have heritage hardware/complexity assumptions been built into the bases of estimates, and how accurate were the assumptions surrounding work with hardware/software?*

- The second and third questions probe into technical assumptions. Component based pieces of a subsystem technology at lower than anticipated TRLs as well as heritage must be investigated as part of system developments for high-TRL efforts. The optimistic culture at NASA may lead managers to overestimate their ability to overcome risks inherent in delivering projects within available funding constraints (NASA, 2012a). The additional rework that comes from having to advance a previously unforeseen technology as well as fixing inaccurate assumptions about uniqueness and the design of the hardware provide clear challenges to project managers within STMD.

4. *To what extent have project descopes either affected Level 1 requirements or altered the technology value capability associated with interests from stakeholders?*
5. *To what extent has the project made technical progress and how effective have developed technical solutions dealt with challenges that have occurred?*

- The fourth and fifth questions examine the origin and necessity of project descopes. When funding constraints are too tight, project managers face difficult decisions regarding descopes and continuing previously outlined technical progress. Project managers are able to adjust the dates of different reviews to mitigate risks, but the experience of a project manager is vital in the ability to diagnose the balance between technical progress and either cost or descopes mitigation practices.

Two questions are mapped into IPAO's "(iii) Resources Other than Budget" criterion:

1. *To what extent was the workforce planning and skill mix appropriate given the outlined technical content to be accomplished?*
2. *To what extent do participating NASA Centers and/or lead contractors possess adequate manufacturing and test facilities to complete the outlined scope?*

- These questions are concerned with the design of the business. It is a challenge for NASA to attract and to distribute top tier talent. Given the complexity of the technology issues within NASA, a continued evaluation of resources and facilities contributes to an intelligent design of the organization.

B.6. PAFTD's Viability Category

The Viability category questions are oriented toward identifying levels of accountability and corresponding management strategies. Hierarchical organizations like NASA need to continue to make roles and responsibilities clear, and to acknowledge the difficulties of communication gaps that inevitably occur.

The Viability category includes twelve questions divided between three IPAO criteria. Five are related to IPAO's criterion on "(iv) Management Approach." These are:

1. *How well do primary calculations, rationales, and sources of data exist to explicitly identify how work breakdown structure (WBS) elements—as part of project bases of estimates (BOEs)—were created?*
2. *To what extent has the project employed financial management best practices to assess results and performance?*
3. *To what extent has the project effectively coupled and coordinated technical and financial efforts?*
4. *To what extent has the reporting/communication process from the project to the program office included the appropriate level of detail of planning, tracking, and analysis results?*
5. *To what extent have external influences—e.g., the Office of Management and Budget (OMB); Government Accountability Office (GAO); Office of Science and Technology Policy (OSTP); and the Congress—played a role in creating budget and schedule stability?*

- These questions probe effective cost estimation and financial management techniques of the project and the program office. To some extent, it is necessary to acknowledge that for budget and schedule related issues projects with the most knowns would tend to have the best cost-performance (Balint, 2009)(Peterson, et al., 2008)(Peterson, et al., 2009). STMD is an organization with ambitious goals. Project with excellent cost performance are expected to produce a reliable outcome.

Four questions are mapped into the “(v) Budget and Schedule” criterion. These are:

1. *To what extent has the project delivered robust cost performance, i.e., quality phasing plans, justified variances between obligations and cost, timely budget execution, and risk mitigation strategies?*
2. *To what extent is the project funded with the resources of a willing and vested partner(s)?*
3. *To what extent has HQ coordinated the budget with the schedule plan to ensure that funds were available when needed for the project?*
4. *To what extent is the current resource level sufficient to complete the work by the target date in the current NASA budget environment?*

- In an effort to create reliable outcomes, two qualities are identified within the “(v) Budget and Schedule” category in relation to successful high-TRL projects, namely a committed and willing partner and a clear buy in from senior leadership. The ability for NASA HQ to allocate funding to a project is often determined by fluctuating resource levels, driven by external influences (e.g., from Congress for budget appropriation, and OMB, OSTP for budget requests, see Appendix B.2). It is important to consider these factors as they play a vital role for enabling stability.

And three questions are mapped into the “(vi) Risk Management” criterion. These are:

1. *To what extent were project reserves applied based on risk analysis findings?*
2. *To what extent have encumbrances, liens, and threats been adequately and clearly reported and explained by the project?*
3. *To what extent have project risk diagnoses accurately forecast future encumbered cost and schedule growth?*

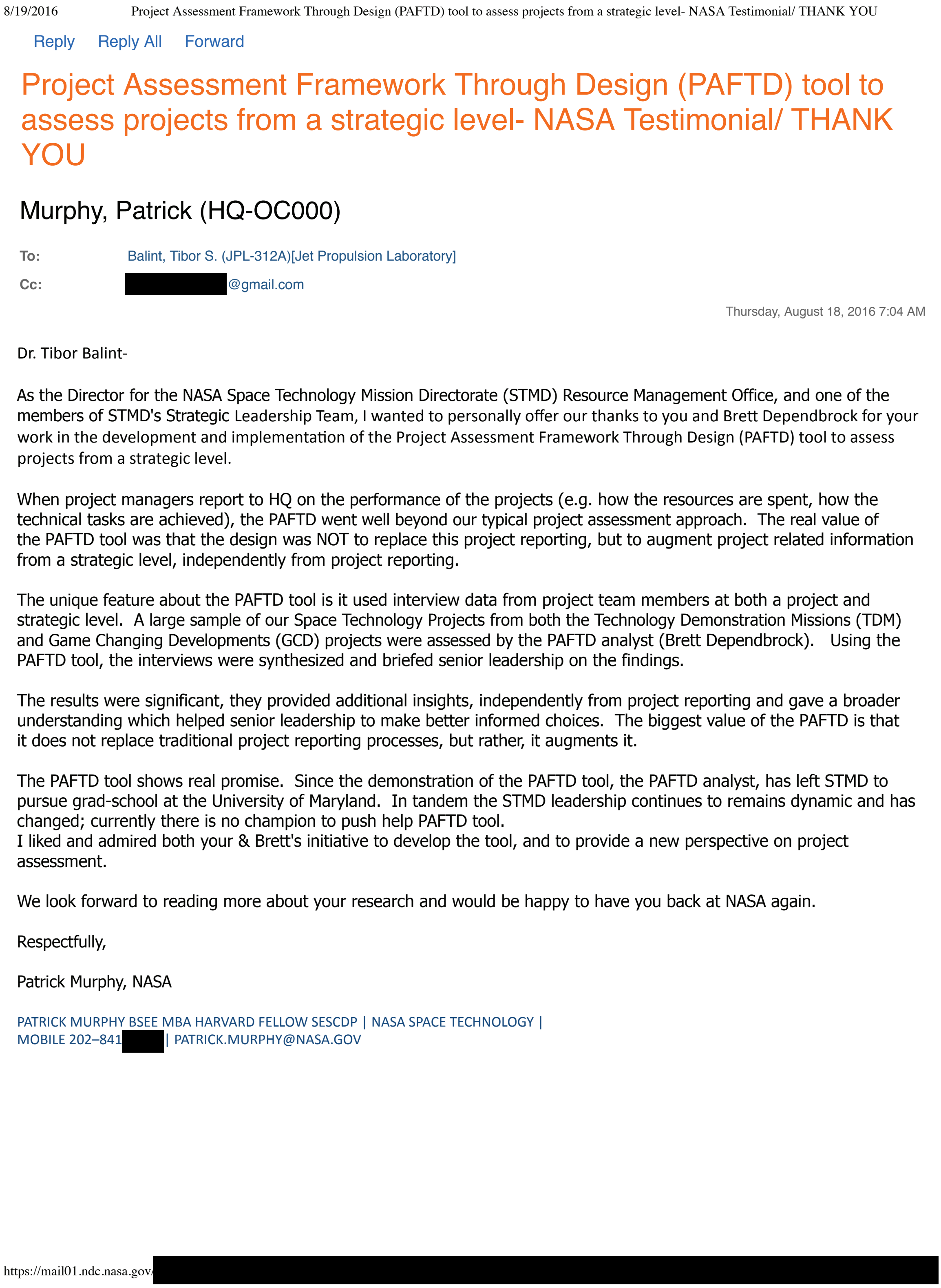
- These questions were constructed around outcomes that might involve clarity for HQ. As there are different factors incentivizing performance across NASA Centers, HQ sometimes may encounter challenges with extracting clear traces of cost and schedule growth from the projects. “Risk Management” identifies the effectiveness with which a project applied risk, how adequately they were reported, and if they could easily be traced to burdening cost and schedule growths.

B.7. PAFTD Testimonials

To substantiate the utility and benefits of PAFTD, I am including three unedited versions of the testimonials provided by people closely associated with this project assessment tool. They are:

- **Patrick Murphy**—Director of the Project Management Office, NASA HQ Space Technology Mission Directorate;
- **Frederic C. Baker**—Director of Space and Missile Systems, Meggitt PLC;
- **Brett Depenbrock**—former Booz Allen contractor working at the Resource Management Office of the Space Technology Mission Directorate at NASA HQ.

B.8. Testimonial from Patrick Murphy



8/19/2016 Project Assessment Framework Through Design (PAFTD) tool to assess projects from a strategic level- NASA Testimonial/ THANK YOU

Project Assessment Framework Through Design (PAFTD) tool to assess projects from a strategic level- NASA Testimonial/ THANK YOU

Murphy, Patrick (HQ-OC000)

To: Balint, Tibor S. (JPL-312A)[Jet Propulsion Laboratory]

Cc: [redacted]@gmail.com

Thursday, August 18, 2016 7:04 AM

Dr. Tibor Balint-

As the Director for the NASA Space Technology Mission Directorate (STMD) Resource Management Office, and one of the members of STMD's Strategic Leadership Team, I wanted to personally offer our thanks to you and Brett Dependbrock for your work in the development and implementation of the Project Assessment Framework Through Design (PAFTD) tool to assess projects from a strategic level.

When project managers report to HQ on the performance of the projects (e.g. how the resources are spent, how the technical tasks are achieved), the PAFTD went well beyond our typical project assessment approach. The real value of the PAFTD tool was that the design was NOT to replace this project reporting, but to augment project related information from a strategic level, independently from project reporting.

The unique feature about the PAFTD tool is it used interview data from project team members at both a project and strategic level. A large sample of our Space Technology Projects from both the Technology Demonstration Missions (TDM) and Game Changing Developments (GCD) projects were assessed by the PAFTD analyst (Brett Dependbrock). Using the PAFTD tool, the interviews were synthesized and briefed senior leadership on the findings.

The results were significant, they provided additional insights, independently from project reporting and gave a broader understanding which helped senior leadership to make better informed choices. The biggest value of the PAFTD is that it does not replace traditional project reporting processes, but rather, it augments it.

The PAFTD tool shows real promise. Since the demonstration of the PAFTD tool, the PAFTD analyst, has left STMD to pursue grad-school at the University of Maryland. In tandem the STMD leadership continues to remains dynamic and has changed; currently there is no champion to push help PAFTD tool.
I liked and admired both your & Brett's initiative to develop the tool, and to provide a new perspective on project assessment.

We look forward to reading more about your research and would be happy to have you back at NASA again.

Respectfully,

Patrick Murphy, NASA

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B.9. Testimonial from Frederic Baker

24 July 2016

Project Assessment Framework Through Design (PAFTD) Tool:
Pertinent references cited supporting my testimonial to and evidence for its implementation:

1. 2015 IEEE Aerospace / Big Sky, MT, USA: "Leveraging Design Principles to Optimize Technology Portfolio Prioritization" (Presenter: Brett Depenbrock)
2. 2015 International Astronautical Congress / Jerusalem, Israel: IAC-15-D1.6.1: "Design Driven Approach to Optimize the Research and Development Portfolio of a Technology Organization" (Presenter: Tibor Balint)

Dear Tibor,

With respect to my interest in the PAFTD tool and my experience with its focus and intention, its implementation and integration, its execution, its effectiveness and its success within a strategic framework, please allow me to provide some of my insights as an interested party or "user" (as best as I was able to within my specific corporate context) and supporter of the tool for future applications.

My introduction to the PAFTD tool was at the 2015 IEEE Aerospace conference in Big Sky, Montana, when I attended Brett Depenbrock's presentation of your co-authored academic paper. The context of interest directly related to leveraging our corporation's competencies and capabilities across diverse business units (5, in my case) to optimize growth, performance, market capture and portfolio prioritization within the sector under my responsibility as Director – Space and Missile Systems and I was fortuitous enough to have noticed this paper within the proceedings.

My attention was drawn to the potential of the tool to support my intention as a Swiss-based subsidiary of a FTSE-100 corporation to drive our Space sector strategy and vision and I immediately organized an informal discussion with the presenter, Brett Depenbrock (Booz Allen Hamilton) subsequent to his presentation as he was the only author present at the conference. We spent close to an hour's time together and committed to further engage on the subject once we both returned to our mutual offices (he in D.C. and me in Switzerland).

Upon my return, we organized two separate one-hour teleconferences, together with two of BAH's upper management team members (Vice Presidents), to discuss the tool in more depth. Subsequent to my realization that BAH's intention was to leverage their professional consulting services to take this to the next level and having no current funding vehicle to finance this during the current reporting cycle until 2016 (the ubiquitous 'temporally cyclical' problem faced by highly rigid organizations), I was obliged to terminate our discussions and apply this from my own best understanding of the tool.

The 'usability', 'feasibility' and 'viability' focus category questions provided an excellent place to start for holding this inter- and intra-SBU conversation and for communicating its importance to upper management. Where necessary, I replaced the TRL-relevant and US government offices (i.e., OMB, GAO, OSTP) questions applied to the NASA context with related technical maturity level and governance driver questions based upon our product heritage and development approaches. This was necessary due to the fact that we're a publicly-traded corporation and not a government agency.

Personally, the ‘viability’ questions were the most important part of the tool for me (pertaining, particularly, to the multiple ‘wicked problems’ I was facing) related to my corporate strategic needs since the management, budget, schedule and risk topics/areas would be the most challenging toward growing the sector for the corporation as the execution mastery of the answers arrived at would prove to be the ‘nexus’ of success of the health and performance of our future Space projects’ and products’ ecosystem. The prioritization success of our Space project and product executions were greatly reliant upon the effective communication, management strategies and subsequent ‘buy-in’ of the diverse decision makers across the management hierarchy within the five different SBUs of the corporation, ergo, successfully addressing the ‘viability’ topics provided the highest-weighted arguments to move this into the realm of development priority.

As my employer was in the middle of a 10-year strategy and future growth ‘search and deploy’ frenzy, beginning in March of 2015 and extending through June of the same year, the contents presented within this paper were fortuitously of direct value to me and I began implementing its approach.

During my initial discussions with Brett, I was made aware of your future work, Tibor, anticipated to be presented at the IAC 2015 in Jerusalem, and it was at this time that I contacted you for additional information related to the PAFTD tool. At the IAC and following your Chaired session and paper presentation entitled “Design Driven Approach to Optimize the Research and Development Portfolio of a Technology Organization” (IAC-15-D1.6.1), I became further intrigued by the potential value of harnessing your presented approach applied to my strategic prioritization focus for driving my company’s Space sector forward.

As any endeavor we set out to accomplish and execute within a corporate or agency ecosystem depends, primarily, upon human-centric decision and relational data points, I was particularly intrigued by your notion of integrating a cybernetic approach within the process. This is what you call, if I’ve understood it correctly, the ‘cybernetic circularity and design dialog’ process of the PAFTD tool. I had not yet been aware of this unique approach to successfully establishing a more focused and coherent process toward developing a company’s strategic technology and market-driven portfolio and believed it had great merit to explore.

The dialog aspect of the tool was of particular interest containing great value as the majority of strategic directions embarked upon by many corporations are based on but a few human interactions from within their ecosystem and, generally, by those with “quantified” heritage, i.e., years of service, while by extension not always necessarily the most “qualified” sources nor those with the most to gain from the strategy to be eventually entertained. This approach supported the conversations I had already begun across the SBUs with a coherence, focus and practicality to which I could point for credibility and consistency. Thank you!

Since the company’s greatest challenges were/are to prioritize, select and manage technology and internal R&D investments within an annually-constrained financial system, I was excited to leverage the insights gained from the PAFTD tool to facilitate this selection and decision-making process. More specifically, my goal was to “onboard” upper management to my strategic vision by balancing the insights from each of the stakeholders (President; Strategy VP; CTO; …) toward the objective of proactively evaluating, calibrating, mitigating the associated risks and, eventually, choosing various paths of execution. In the end, as we all know, it still comes down to humans placed higher in the corporate food chain deciding ‘yea’ or ‘nay’ to suggestions from those in the trenches. The ‘subset’ questions (relative to the initial PAFTD paper from the 2015 IEEE Aerospace conference in Big Sky/MT) within the ‘usability’ category served to support my positions and further expand my focus within the company’s resource-constrained ecosystem.

My results within the company at executing successful strategic technologies and programs has been supported by the approaches provided within both of these academic references (2015 IEEE Aerospace/Big Sky, MT and 2015 IAC/Jerusalem). I’m grateful to have had the opportunity to discuss the PAFTD tool with you, Tibor, at great lengths during our several meetings and conversations (2015 IAC and in London during the London Space Week in November 2015) and look forward to continuing its application within my future professional endeavors.

With respect to having ‘validated’ the tool, I can unequivocally state that I, through the best of my abilities within a resource-constrained and limited “big-picture” ecosystem within which the Space sector is not the company’s primary focus, effectively applied and implemented the PAFTD tool and its relevant questions from the three different categories, ‘usability’, ‘feasibility’ and ‘viability’ with successful results.

The importance to applying this new ‘technology’ of incorporating both a design dialog and cybernetic approach is invaluable as it addresses a comprehensive environment of human relational, resource-driven, management and externally-driven data points, imperative for the successful prioritization of strategically-driven technology investments.

My experience over the years has demonstrated that, for the vast majority, such data points are arrived at by but a few individuals within a corporate or agency environment typically ill-equipped (i.e., purely linear-based thinkers) to provide this executive-level decision. The PAFTD tool, as presented within the references cited, opens the door for a new process while empowering all team members with a participatory, contributory, effective and, dare I say, ‘holistic’ perspective to improving the overall chances of success of this engagement and its end results. The tool’s implementation provides for a successful path away from the simply linear and often ineffective prioritization approach toward incorporating a cybernetic, multi-faceted, relational, empowering, conscious, dynamic and optimized approach enhancing the overall chances of success of the stated objectives.

Given the fact that I had just, single-handedly, begun the process for effectively defining and prioritizing the Space sector’s future directions across the next 10-15 years, both internally and in conjunction with our external partners, I can also state that we were off to a great start. Among the successes is a multi-national, multi-stakeholder, cross-SBU program for an external client which would not have been materially possible without my having come across this new approach of a design dialog and cybernetic ‘technology’.

Thanks for having brought this new, dynamic and exciting tool to my attention and for having made the time to explain its implementation during our several meetings.

Kind regards and all the best with your future endeavors (particularly with the PAFTD tool!),

Frederic C. Baker
Director – Space and Missile Systems

B.10. Testimonial from Brett Depenbrock

PAFTD Validation from Brett Depenbrock

(Analyst for Booz Allen at NASA 2014-2016)

As part of two different work streams for Booz Allen that each spanned one-year (June 2014-July 2015 and July 2015-July 2016), Brett Depenbrock supported NASA with the assessment of various technology projects within the NASA STMD portfolio, using the Project Assessment Framework through Design (PAFTD) methodology. Booz Allen and NASA endorsed the use of the framework, and its name was formally utilized on Statement of Work (SOW) documents. These SOWs required the use of PAFTD as part of specified deliverables on two different task orders.

In late 2014 at the suggestion of senior leadership from NASA Depenbrock and Balint further advanced the conceptual underpinnings of the framework, with the creation of the 2015 IEEE paper submission, titled “Leveraging Design Principles to Optimize Portfolio Prioritization.” NASA STMD was impressed with the utility and the breadth of the PAFTD related work Depenbrock had delivered by early 2015, and endorsed and paid for Depenbrock to formally present the submitted paper externally in Big Sky, Montana, at the “Management, Systems Engineering, and Cost” panel of the 2015 IEEE Aerospace conference. The presentation was well received, and Depenbrock and Frederic Baker (a program director from a European aerospace company) had a lengthy discussion after Depenbrock’s presentation. This conversation subsequently resulted in Baker’s adoption of certain tenants of PAFTD for his commercial organization.

As a technology and strategy consultant for NASA at Booz Allen, Depenbrock was asked to provide recurring project assessments and recommendations as part of formalized deliverables. These included PAFTD-based project assessments. Depenbrock conducted interviews, analyzed and synthesized the collected information, and presented it to senior leadership. It is apparent that the work was valued, because Depenbrock was asked to return for a second task order from July 2015-July 2016, to continue providing a similar value stream.

It is important to note that within NASA a number of factors drove decision-making surrounding technology investment projects. Although Depenbrock’s deliverables provided substantial influence, the insights gained from PAFTD assessments could not control the ultimate decisions leaders might make regarding a certain project. Those final project-related management decisions were made as a result of multiple inputs, including project reporting, PAFTD analysis, organizational strategies, and others.

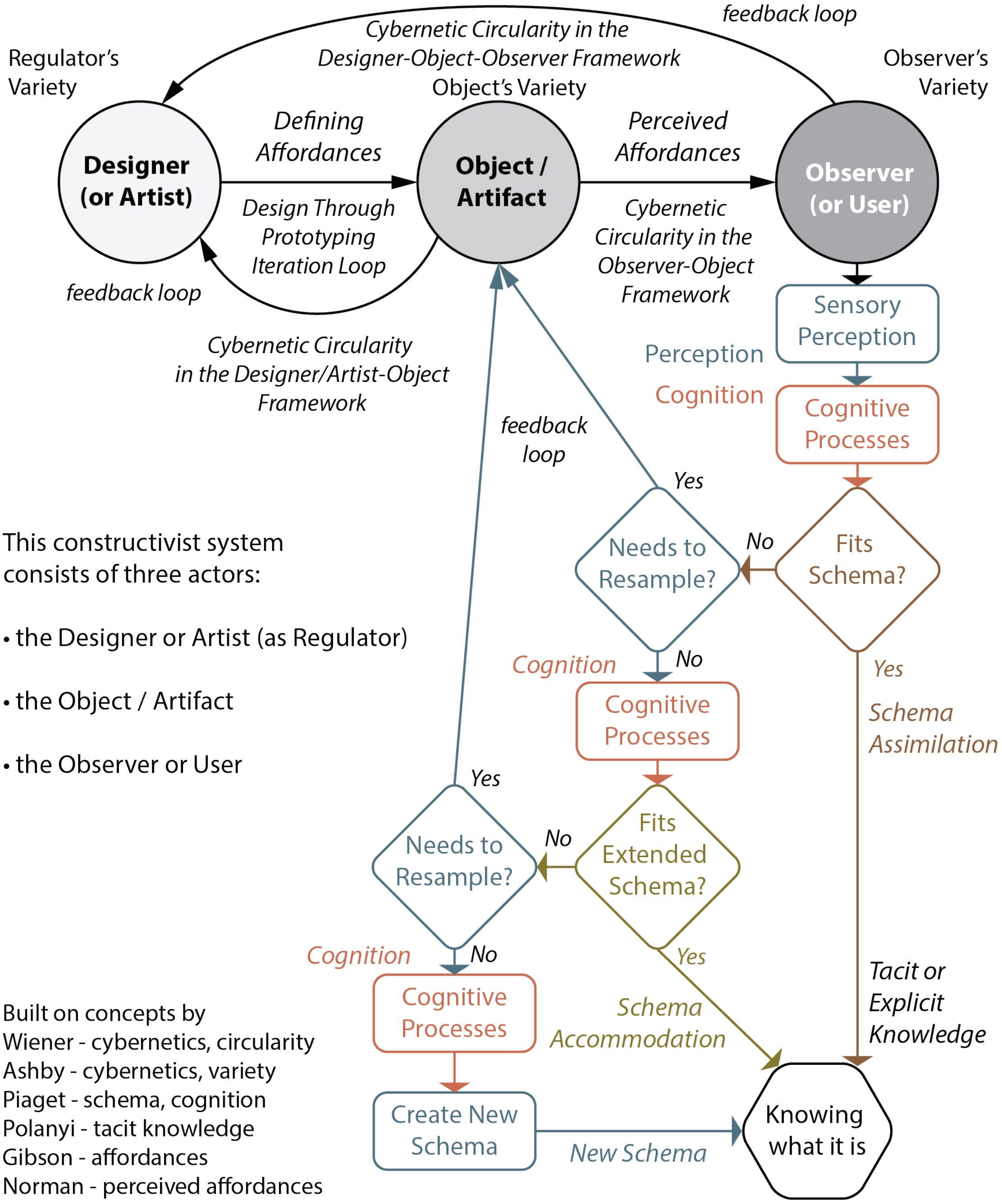
Depenbrock left NASA and Booz Allen in the summer of 2016, to pursue graduate studies in business management. Without a champion, the future of PAFTD is currently uncertain at these organizations.

Prepared by Brett Depenbrock, September 2, 2016.

Appendix C: Selected Attributes for Humanly Space Habitat and Object Designs

C.1. Design Attributes

To illustrate the link between the designer, the object, and the observer (for example an astronaut), I have created a *simple constructivist system with 3 actors* (see Figure C.1). The model also includes two sub-systems with two actors each, specifically the designer–object system, and the observer–object system. From the designer's perspective, the designer acts as a regulator, and through a process interacts with the environment, which consists of both the object and the observer. From the observer's perspective, the observer is the regulator and the object and the designer are the environment. Once the object is created by the designer, the observer interrogates it through sensory perception and relates the experience (e.g., the object's movements and other characteristics) to his/her schemata, which is built on *a priori* sense observation and other cognitive processes. The information sampling consists of picking out clues from the object (e.g., via affordances, signifiers, movements, colors). When a new experience from the interaction either fits into an existing schema or relates to the observer's tacit knowledge, an instantaneous connection may form. The longer and more sequentially or persistently the observer's schema aligns with the object's performance, the stronger the connection is. Furthermore an expectation or desire may build in the observer to perpetuate this connection and anticipate the subsequent actions through inference. At the same time the perception gap widens between the surprise element of the continuing connection with the object and the knowledge that the object's behavior is unpredictable—e.g., a leaf blown by the wind on the ground. If, however, the observer is interacting with a designed object, it may allow to inquire into the mind of the designer by trying to resolve the puzzle that awaits, set up by the designer through the affordances of the object. This decoupled system represents two loosely coupled connections. One between the designer and the object and another between the object and the observer. The clarity of the transferred information is also dependent on the shared knowledge base between the designer and the observer. Higher clarity may translate the designer's intention to the observer through the performance of the object. That is, the designer acts as a regulator, and the variety and—real or perceived—affordances and signifiers (as guidance) built into the object define the interactions and outcomes to be interpreted by the observer. The observer only sees the object's performance and not the designer, as the designer is very likely both spatially and temporally decoupled from the observer and the performing object. A looser connection with the designer, or less restricting variety, may provide hints to the observer about the designer's cognition, but it doesn't over-control the object, and allows for interpretation differences experienced from the observer. This adjustment of the object's perceived variety could change throughout the performance or interaction. For example, starting with strong guidance, then transitioning into vagueness, or vice versa. From the designer's point of view, the processes of regulation of an object, that is modifying its variety, translates to the shaping of the observer's perception. From the observer's perspective, the recognition of the person (designer) in the performance (of the object) is a skill. One needs to recognize that a performance is being witnessed before trying to interpret it (see Figure C.1). The interaction between the designer and the observer can be fully or loosely coupled, or decoupled. For example, during the prototyping iteration phase—consisting of divergence and convergence cycles—the designer may test the observer's response to the object, making the connection closely coupled. (This aligns with co-design.) This allows the designer to identify



This constructivist system consists of three actors:

- the Designer or Artist (as Regulator)
- the Object / Artifact
- the Observer or User

Built on concepts by
Wiener - cybernetics, circularity
Ashby - cybernetics, variety
Piaget - schema, cognition
Polanyi - tacit knowledge
Gibson - affordances
Norman - perceived affordances

Figure C.1: Simple constructivist system with 3 actors: Designer & Object & Observer.

various options and alternatives, and modify the object iteratively. The prototyping circularity helps to align the schema of the designer with that of the observer. The designer acts as a regulator, and the variety and affordances infused into the object are expected to result in the desired interpretation by the observer. In another case, the observer may provide feedback after the use of the object, which can give after-the-fact feedback to the designer, in a spatially and temporally decoupled manner. Here the designer is physically separated from the observer by large distances and time. The third option involves a fully decoupled connection, where the designer does not have any feedback from the observer at any point. This is the least desirable mode, as it does not transfer knowledge from the observer back to the designer that could be incorporated into future designs.

On long-duration spaceflight we need to go beyond engineering and technology solutions and cater to the psychological and emotional needs of the astronauts. This provides a fertile field for designers and artists targeting astronauts on long-duration space missions. However, we first need to gain acceptance from the engineering and technology community regarding the importance of these fields, and subsequently broaden our approach to include emotional designs in future space exploration plans and developments. There are terrestrial examples for human centered emotional connections between a user and an interacting object, including the collaborative robotic designs of Guy Hoffman (Hoffman, 2014). His pioneering work on a human-robot joint theater performance, and improvising real-time human-robot jazz duet was combining technology with human-robotic interactions. For the theater performance (Hoffman, 2007) he used a robotic desk lamp (see Figure C.2a), that served as a non-anthropomorphic, collaborative robotic platform. With 5 DOF (degrees of freedom) a robotic arm mounted lamp evoked a personal relationship with the human partner, without resorting to human-like features. Similarly, working with Gil Wainbert at the GeorgiaTech Center for Music Technology, another non-anthropomorphic robot, Shimon, was performing collaboratively with a human in an improvisational jazz performance (see Figure C.2b), and in another case the robot collaborated with a rap artist (TEDTalks, 2013). The movements, timing, and gestures of the lamp and the robot as they interacted with the human companion evoked compassion, empathy, and the feeling of collaboration, which would be important considerations on long-duration spaceflight.

Emotional design relates to the hierarchy of user needs, from functionality, through usability, to pleasure (Jordan, 2000). Connecting to the pleasure element of this hierarchy, Ortíz Nicolás (from Imperial College, London) reported a foundational investigation on pleasant user experiences through human-object interactions (Ortíz Nicolás, 2014). Through four empirical studies, he characterized the observer's pleasant experiences with an object. He identified 25 positive emotions and ranked them through the perspectives of both observers/users and designers, and four relevant connected issues for product design. The four issues were: frequency and preference of the experience (from the side of the observer/user), and preference and difficulty of elicitation (from the side of the designer). Designers highly ranked the emotions of: curiosity, joy, surprise, confidence, inspiration, fascination, satisfaction and pride. Observers/users ranking of emotions included: satisfaction, inspiration, joy, amusement, and relaxation. Infrequent emotions that affected only one side were: lust and worship. He found that there is limited knowledge in the field about the difficulty of eliciting positive emotions through durable objects. Ortíz categorized three levels for arousal and for pleasantness of emotions. For arousal these were: exciting, neutral and calm emotions. For

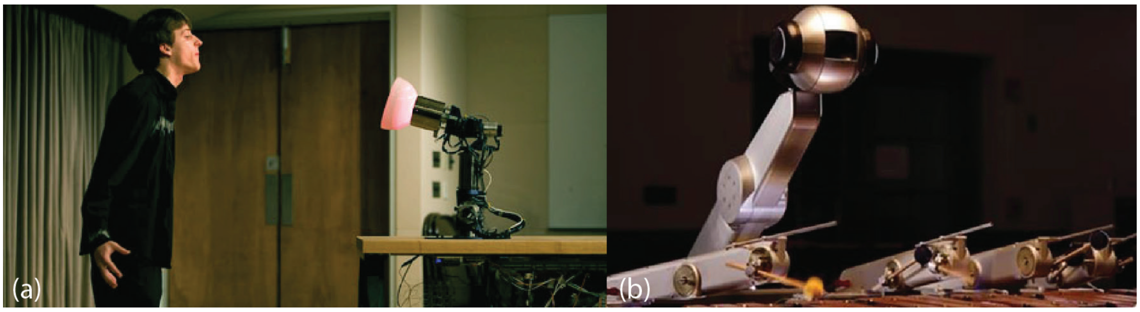


Figure C.2: Guy Hoffman's non-anthropomorphic robots. (a) The "Confessor" theater performance with the AUR lamp (Hoffman, 2007). (b) Collaborative performance with the robot "Shimon" (Hoffman, 2014).

pleasantness he included pleasant, quite pleasant and very pleasant emotions. In addition, he addressed triggers, appraisal structures, thought-action tendencies, and thematic appraisals of the emotions. These findings are also reported in (Ortíz Nicolás, Aurisicchio, & Desmet, 2013). The knowledge gained from this research could inform and help designers and artists to improve tools and processes to better convey positive emotions and experiences through their designs, from smaller scale objects/artifacts to full habitats. Due to the constrained resources on long-duration spaceflight, the object could be multi-functional and multi-purpose, when used in various habitability scenarios (e.g., during work, rest, entertainment, exercise). From the observer's point of view the interaction can be passive, where the object performs for the observer, or fully interactive. The affordances of the object could be highlighted using signifiers, or can be hidden, waiting for discovery by the observer during use. The object may interact with the environment and coded for certain behaviors. These behaviors and interactions with the observer and the environment are coded into the object by the designer. The built in level of variety and control propagates from the designer through the object to the observer, driving certainty or uncertainty in the perceived behavior of the object. For example, a robot—either humanoid or non-anthropomorphic—could mimic the actions and gestures of the observer in sync, store the movements in its memory then at a certain point start to move out of sync using these stored actions. This would initially create an expected, followed by unexpected interactions with the observer, and likely trigger emotional responses of amusement and surprise, and can result in some unpredictability and inconsistency of the object's behavior as perceived by the observer. Emotional design could play an increasingly important role on long-duration spaceflight, where astronauts experience isolation, monotony, stress, and fatigue. This approach can benefit from utilizing best practices from existing designs (Hoffman, 2014).

Beside the temporal and spatial connectivity of the 3-actor system from a constructivist perspective (as discussed above), the designer can also consider the temporality and spatial dimensions of the object. This could include the duration and the rhythm of the experience, while the physical dimensions of the object can remain static or change dynamically, as shown by Hideki Yoshimoto (Yoshimoto, 2015) (see Figure C.3). Furthermore, the scale can vary from a single small object/artifact to the full size complex and integrated space habitat. On long-duration spaceflight during the rest and relaxation periods a dynamically changing and emotionally connected immersive environment could be highly beneficial to the psychological wellbeing of the astronauts.

During interactions with the object, the observer's focus could narrow to particular details, while blocking out the surroundings. In other cases the observer can be fully and panoramically immersed into the environment, not worrying about particular details. Shifting between focused and immersive experiences can enhance the evoked emotions in the observer. Artists, like Olafur Eliasson, use this approach in their designs. Eliasson's large-scale installations, employing—often in combination—natural agents (e.g., light), elemental materials (e.g., water), and environmental conditions (e.g., temperature) to stimulate and enhance the viewer's experience. For example, his "Weather Project" was installed at the Turbine Hall of the Tate Modern, London, in 2003 (see Figure C.4). In this project, Eliasson created a fine mist in the air, installed a large circular sun-like disc on the interior wall, made up of hundreds of monochromatic lamps, radiating a yellow-orange light. Furthermore, the ceiling of the hall was covered with a huge mirror, allowing the visitors to see themselves from afar through the mist and in the orange light. This panoramically immersive experience included an abstractionist

Figure C.3: Kihou (rhythm and pulse), by Hideki Yoshimoto (Yoshimoto, 2015).

Figure C.4: "Weather Project" (2003) by Olafur Eliasson, installed at Tate Modern's Turbine Hall, London.

translation of the schema of a sunset. The mist provided a measure to sense the immense volume, while the mirror helped the observer to interact with the environment (Eliasson, 2016). As the deep-space habitat volume is constrained, changing the perception about volume and mood could benefit the physiological and psychological wellbeing of the astronauts. As discussed above, these approaches could complement virtual and augmented reality applications, and display walls.

Figure C.5: "Space Musical Instruments—Cosmic Seeds" project (2009–12) by So Negishi and Ayako Ono. A pair of musical instruments flown on the ISS.

On a spaceflight the crew might be international, where cultural conventions could play an important role. Some of these can be bridged through training and team building prior to the mission, but not all. This may result in perception differences between the various observers. Clear signifiers and perceived affordances, where the cultural and social conventions are overlapping are important for the communication between the observers and their interactions with objects. Suggesting that certain actions are possible is not an affordance (real or perceived), but a symbolic communication, which only works if the observer is familiar with the convention and understands it. This can be driven by the observer's schemata, and influenced by physical, logical and cultural constraints (Norman, 1999).

Storytelling—which will be explored further in Appendix D.2.3—is a key element of dialogs between the crew members, with their environments and with family and colleagues on Earth. An example for artistic collaboration is Ayako Ono's project, titled "Space Musical Instruments—Cosmical Seeds," which was co-designed with a metal artist, So Negishi, in 2009 (Ono, 2014). It consisted of a pair of musical instruments suitable for weightlessness. The instruments were called "Ellipsoid Bell" and "Fractal Bell" (see Figure C.5). The project was selected by the Japan Aerospace Exploration Agency (JAXA) under the Cultural and Artistic Utilization of the International Space Station (ISS/Kibo) theme. This pair of musical instruments were played on the ISS by Daniel C. Burbank, the Expedition 30 commander, on February 10, 2012. One of the two pieces of music was composed by Jaakkoo Saari, called "Dream Starts," and the other by Akira Takahashi, titled "Kiyoraka na sora." The astronaut played the music multiple times for 15 minutes and improved his skills beyond the procedure manual. The performance included both procedural play and improvisations. The project combined a physical artifact, which was both an artistic object and an interactive instrument. It provided textural and auditory interaction with the observer. The object and the sound linked the observer to both the designers and the composers, who were spatially and temporally disconnected. Through the performance the astronaut had a direct connection with Earth and its culture. Similar objects could provide entertainment and creative self-actualization on long-duration spaceflight.

For self-actualization giving astronauts paper and pencil to draw is the same as treating highly trained and educated experts as little children. Technology can play an important role to create meaningful experiences. For example, using interactive virtual reality where an astronauts may create something either alone or in groups with other crew members or with family members on Earth (Bannova, 2015). Sense giving and sense making through a shared virtual object, that can subsequently 3D printed in the habitat can provide personal connections and emotional support. Having dialogs between the astronaut and crew members, where the roles of the designer or artist and the observer or user can change throughout the artifact generation and use adds variety to both the astronaut and the habitat, which can be utilized subsequently. It would also contribute to self-determination, decision making, and autonomy for the participant inside the habitat.

Self-expression through VR is only one example, but designers should think about how to increase variety inside a habitat that could be utilized to achieve it through other means, which may include computer based interactive entertainment, materials for multimedia creations, composing or playing music. Many of these options could be developed through conversations with astronauts, and cater to their interests.

Autonomy will also drive the interaction inside the habitat and can help with training activities on the way to Mars. A conversation-based artificial intelligence system could learn the behavioral patterns of each astronaut and customize interactions to optimize the learning/teaching experience. These systems could be designed to provide emotional support to the astronauts. As demonstrated by Guy Hoffman, even non-anthropomorphic robots can make this connection. Therefore, including this interactive capability in humanoid robots could further benefit these circular conversations, and could be either real with an object or virtual through an avatar.

C.2. Artistic Attributes

Abstraction could be used in multiple ways. It may mean the level of definition of a physical object, ranging from a highly detailed artifact to a non-anthropomorphic robot, or lights and shadows implying forms without actual materials, yet could be interpreted by the observer. Through interactions the meaning is negotiated, where part of the knowledge is carried by the artifact and part by the cognitive interpretation by the observer, which is also influenced by sensory perception.

In a multi-functional space environment—habitat— where resources are scarce and resupply is not an option, object might be designed for multiple uses and for various operational phases, such as work, relaxation, and entertainment. Consequently, objects could be designed with this in mind, and change their functions and meaning depending on when and how they are used. However, multiple uses, and different functions of an object using the same interactive connections (e.g., buttons, screens) could lead to mistakes as ambiguous and unclear information is transmitted to the observer. It can also result in slips and mistakes, when the interactions with certain functionalities become automatic, and the observer does not pay appropriate attention to the function change (Norman, 2013).

The mind interprets the information, and creates a perception based on explicit or tacit knowledge formed around a schema. For example, as the observer looks at an object, he/she develops a mental construct about it. As a first impression, the observer relates the sensory information (visual, tactile, etc.) to previous knowledge (shape, color, texture, material etc.), then to other characteristics (e.g., behavior, movement). Is the collected information coherent? (E.g., an object is inanimate, while a living thing is animate.) When there is a mismatch, it causes the observer to feel an emotional or mental imbalance or non-equilibrium. This evokes

Figure C.6: A "Strandbeest" by Theo Jansen.

uncertainty unbalances the already established and rigid schema for the object, which may not fit for the full framework, the schemata. In case of a mismatch, the observer may resample the object multiple times, or uses internal cognitive processes, until the experience fits to either an extended schema or a new schema (see Figure C.1). For example, Theo Jansen's large self-animated truss mechanical creations, known as "Strandbeest" (see Figure C.6), have built in artificial intelligence to avoid obstacles by course adjustment upon detection. These Strandbeests, while clearly machines, resonate with the observer as their movements, hesitations evoke recognition within the observer's schema of animals. The perception chain may sweep through multiple phases. At first it captures the familiar movement within an existing schema, followed by an attempted accommodation within a schema. Once recognized as an outlier, a new schema is created for this multi-legged, moving, still lifeless, but animal-like animated object, which falsely projects self-awareness (Jansen, 2014). Blurring reality between what is alive and what is not may provide exciting stimuli to astronauts, and exemplifies the process of creating a new schema.

Clear communication is an important aspect of good design. If the method to use an object/artifact is not obvious, and the users can't use it, it will be quickly ignored or even rejected. Thus the designer needs to include appropriate information about the usability and understandability of an object/artifact. Using a suitable schema (or conceptual model), the observer/user can be guided through the usage by providing clues about correct usage. Good communication by the designer to the observer through the object is important where the goal is knowledge transfer. For this, affordances and signifiers can play an important role. An object can have both real and perceived affordances and these do not need to be the same. The designer/artist can design an object that either guides or misguides the observer. For example, visual clues (signifiers) in the form of arrows on the road can indicate an affordance to the observer, while the real road is not turning, thus misguiding the observer. This misguidance also builds on cultural references, related to the acceptance of road signs. As the object/

artifact interacts with the observer, certainty or uncertainty may or may not be desired. For example, for a functional object uncertainty becomes a distraction. For an entertainment purposed object, uncertainty might be desirable, especially on long-duration spaceflight, where predictable repetition my decrease the desirability of the continuing interaction with the object.

Movement and stillness can be best described through Guy Hoffman's robots and their interactions with the observer. With the right movement, timing, rhythm or stillness the perceived connection between the observer and the object/artifact can be heightened and evoke strong emotions. It is considered separate from static and dynamic dimensions.

Inside a deep space habitat, extreme dark and light could be used to enhance space, volume and time perceptions. This can be localized to a small object/artifact, or the full environment. Light, colors, darkness, and shadows can have a deep emotional impact, evoking emotions in the observer from calmness to excitement. The terrestrial knowledge base on this topic is vast, and could be easily transferable to space related designs. For example, the Light and Space movement, which started in the 1960s, focused on the perception of light, large volume, and scale. To highlight these goals, it typically used a combination of glass, fluorescent light, neon, and reflective surfaces with resin and cast acrylic. The artists played with light directionality, shadows, combination or natural and artificial lights, transparency, translucency and reflectivity. They often incorporated the latest technologies from the aerospace industry, engineering and technology, and benefited from the proximity of these industries in Southern California. The movement consisted of a large group of artists, including James Turrell, Robert Irwin and Doug Wheeler (see Figure C.7). Through their works, the artists investigated sensory deprivation or overload, which resulted in extreme retinal responses by the observer. They used light to create abstract shapes, without using actual materials. In turn this allowed the observer to perceive the light and shapes without overemphasizing the physical aspects of an actual object. This representation highlighted the idea that the world around us is a mental image, perceived and interpreted by the human mind (KPBS, 2011). On long-duration spaceflight we could employ similar effects and approaches inside a multi-functional habitat to interact with the astronauts and create diverse moods between various modes, including work, rest, and exercise.

C.2.1. Architectural Attributes

On a large systems scale, space habitats represent key mission architecture elements for future human missions to Mars. These include habitable spaces during the flights to-and-from Mars, and also on the surface of Mars.

Habitats are highly integrated multifunctional spaces combining engineering systems, with incorporated advanced elements from the fields of Information and Communication Technologies (ICT). Throughout the mission these habitable volumes serve as shared multi-functional spaces for working, resting, exercising, socializing, playing, communicating.

While it may seem that these space habitat related technologies are unique to space exploration missions, they are deeply rooted in the human experience related to terrestrial habitats. On Earth, significant ongoing research effort is dedicated to cross-cutting and multi-disciplinary fields, such as architecture design; city design; design theory; design conflict management; generative and parametric design; hybrid spaces design; process and product modeling; ergonomic human interfaces; and from ICT, augmented, virtual and mixed reality; information design; information design and modeling; multi-agent decision-support systems;

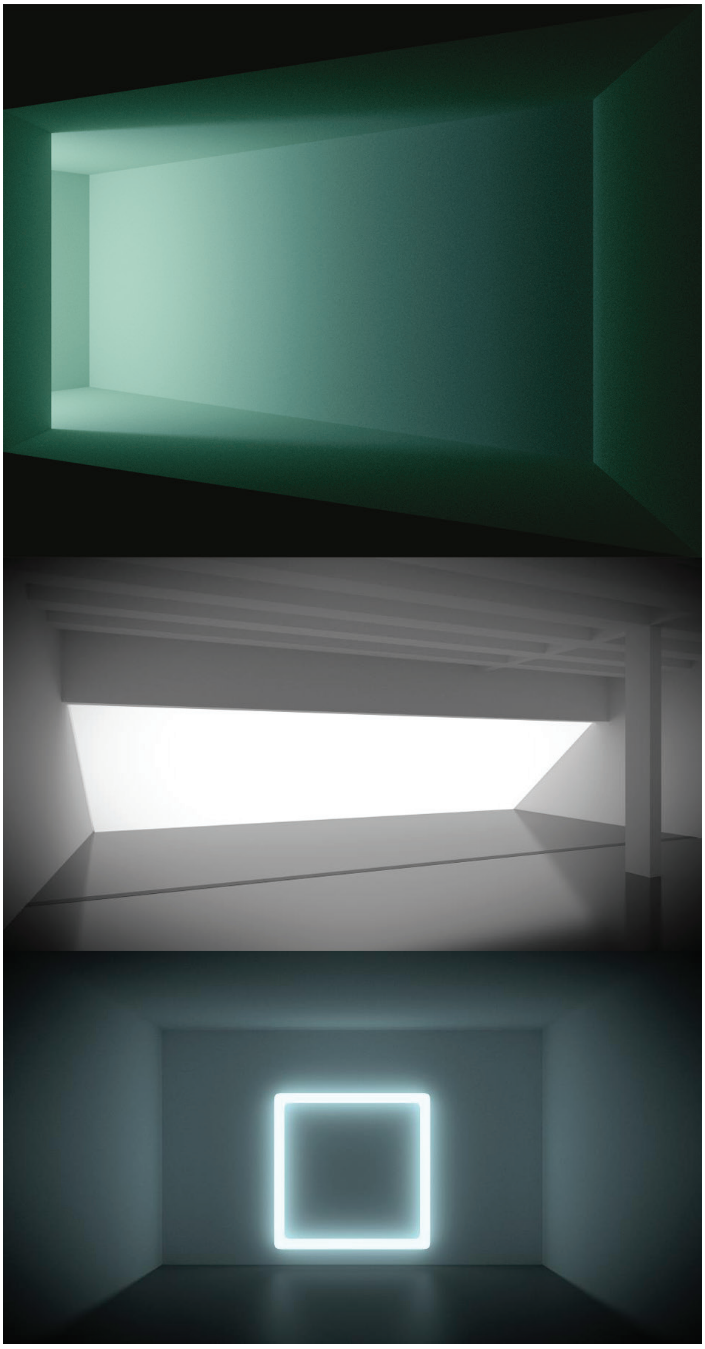


Figure C.7: Artistic recreations, using Blender3D, by T. Balint after:

(top) James Turrell, "Wedgework" (1969);

(middle) Robert Irwin, "Slant/Light/Volume" (1971);

and
(bottom) Doug Wheeler, "M669" (1969).

sustainable green design systems; and user participation in design. Building Information Modeling (BIM) and Industry Foundation Classes (IFC) provide a bridge between these fields.

Many of these terrestrial research findings and advances could be explored and translated into human centered space exploration environments. For example, approach similarities can be found between human centered building architectures and space habitats; sustainable green design systems and Environmental Control and Life Support Systems (ECLSS). On long-duration space flights multi-functional hybrid space designs could play a significant role, due to habitable volume limitations.

There is also a complex and interdependent relationship between the astronauts and their environments. Information and communication technologies are vital to make the multi-year journey successful, and enjoyable. This is where new thoughts on the use of virtual, augmented and mixed reality designs, and emotional designs can make an impact beyond NASA's current approaches, which are driven by engineering and technology solutions to address functionality and support human biology. Thus, novel human centered approaches and applications can have terrestrial spinoffs to benefit the elderly and the disabled, and enhance the human experience, and augment functions and operations. ICT could also include smart objects and communicative objects. Current examples include automated inventory tracking, but with the rapidly improving terrestrial technologies and design interaction concepts many of these could be translated to space use. Future examples could include interactive objects for entertainment, ranging from small scale to an interactive habitat.

Consequently, new insights could be gained through research by allowing experimentation around the parallels between terrestrial architectures; city designs; and information & communication technologies. These could be projected into space habitat designs and connected human centered interactions. The findings would be the results of the researcher's exploration, and may yield high impact transformational approaches. This approach to a habitat design would be a departure from the current state of practice, which is still focusing primarily on technology solutions with modest advancement in the state of knowledge. The current approach has a lower risk, but lower impact, while only notionally addressing the human element, and mostly neglecting the higher level needs.

C.2.2. Engineering Attributes

Engineering constraints related to available volume and mass provide an initial bounding condition for designers and engineers. Furthermore, any object designed by or for NASA, and to be used in space, has to adhere to the highest safety requirements. As defined in (NASA-JSC, 2014a): *"Safety is NASA's highest priority. Safety is the freedom from those conditions that can cause death, injury, occupational illness, damage to or loss of equipment or property, or damage to the environment. NASA's safety priority is to protect the following: (1) the public, (2) astronauts and pilots, (3) the NASA workforce (including employees working under NASA award instruments), and (4) high-value equipment and property. All research conducted under NASA auspices shall conform to this philosophy."* These objects/artifacts need to operate in the extreme environment of space and in close proximity with the astronauts. Thus, the strong safety requirements introduce additional constraints for designers, which may result in more complex and costly objects/artifacts, as they go through the required testing process in relevant environments.

As discussed above, during long-duration spaceflight the crew encounters extreme space environments (e.g., temperature extremes, microgravity, solar and galactic cosmic radiation, vacuum, zero gravity, and high-velocity micrometeorites), which in turn impact crew health, performance, psychology, and biological responses. Biological sciences, including psychology, psycho-sociology, human factors, and habitability, can play important roles to mitigate these environmental effects. Designers and artists also need to be aware of these circumstances when designing artifacts or habitable environments at any scale for human-object interactions. They could address stressors related to isolation, monotony, emotional conditions, cognitive effects, privacy, confinement, sensory and perceptional stimuli from various sources, multi-cultural and recreational aspects, microgravity, absence of natural time parameters, altered circadian rhythms, and physical effects on the crew. (A more exhaustive list of stressors is provided in (Morphew, 2001).)

C.2.3. Combined Attributes

The attributes listed above can be combined to achieve a more complex experience for the observer. The attributes can be coherent, where the behavior is predictable, or not, which introduces uncertainty to the experience. For a working environment a predictable behavior is beneficial, while for entertainment purposes an unpredictable object behavior can heighten the experience.

The examples from this Appendix illustrate a range of examples of how we can account for affordances, tacit knowledge, perception and linked schema, and the circularity of cybernetics to achieve a constructivist middle ground between the physical world and its interpretation by the observer. Consequently, when designing a new artifact the designer should consider one, multiple, or all of the principles discussed above, may it relate to a small object or the whole environment or habitat. (Note: throughout the discussions I am referring to an object not as an inanimate artifact, but a system capable of advanced performance and interactions via digital and other systems.)

Appendix D: Examples 3 & 4: Designing the Design at NASA

D.1. Prologue to Designing the Design

Within government organizations, such as NASA, programmatic and project management practices are often rigidly linear. To help with understanding the complexities, we can look at the structures and operations of such organizations through the perspective of management cybernetics (Beer, 1974)(Beer, 1981). Accordingly, we can characterize these practices through first-order cybernetics, where the organizational paradigm, mission, and culture are bound by well-established rules and requirements. This does not readily accommodate flexibility and change. To achieve change, we need to broaden the organization's paradigm, which can be achieved by the introduction of new perspectives, new disciplines, and novel shared languages through conversations. These can be introduced into the processes and the organizational culture in the early stages of formulating new ideas.

At the Jet Propulsion Laboratory (JPL), early stage concept development is performed at a specially formulated environment, called the Innovation Foundry. Within this environment, re-designing the design processes helps to broaden the variety of the option trades. It is achieved by an added focus on conversations, storytelling, and the inclusion of non-engineering disciplines, such as human centered design (HCD). Communicating the information more effectively through conversations and symbolic means benefits from the skills of human centered designers and artists. Thus, communicating through design environments, design, art, and also design focused education introduce opportunities, which are needed to advance the state of practice and help to broaden JPL's and NASA's operational paradigm. Furthermore, changing the organizational culture by bringing in new graduates with a designerly way of thinking can lead to new ways of thinking. Thus design environments, design and art based communications, and design education introduce additional touch points, where novel perspectives and design conversations can broaden NASA's paradigm, which is needed to advance the state of practice.

D.2. Example-3: Design Environments and Processes

Within NASA, potentially the most successful design environment is JPL's Innovation Foundry, where the next generation of ideas are being developed. From and organizational perspective it is situated between JPL's Program Offices and Line Organizations. It provides a bridge between these sub-organizations. To highlight the structure, hierarchy, and functions of this part of the organization, shown in Figure D.1, I have mapped it into the Viable System Model. The Program Offices, at the System 3 level of VSM, request and fund studies and proposal developments in line with the Agency's space exploration goals. The Line Organizations, at the System 2 level, provide the personnel for the studies (e.g., the engineers and the scientist) and maintain the development tools. The Innovation Foundry, at the System 2 level, is a performing organization. It is considered a strategic asset for JPL, and it is a key part of its business model, as it helps the Center to compete with other NASA Centers and external organizations for funding and resources from NASA HQ. It also supports NASA HQ's goals to study and map development needs and directions. The Innovation Foundry is not only representing the state of practice, but also the state of the art within NASA for developing new mission concepts. This setup is highly successful, but it has also developed barriers due to its institutional and operational paradigm, that can be addressed at specific touch points.

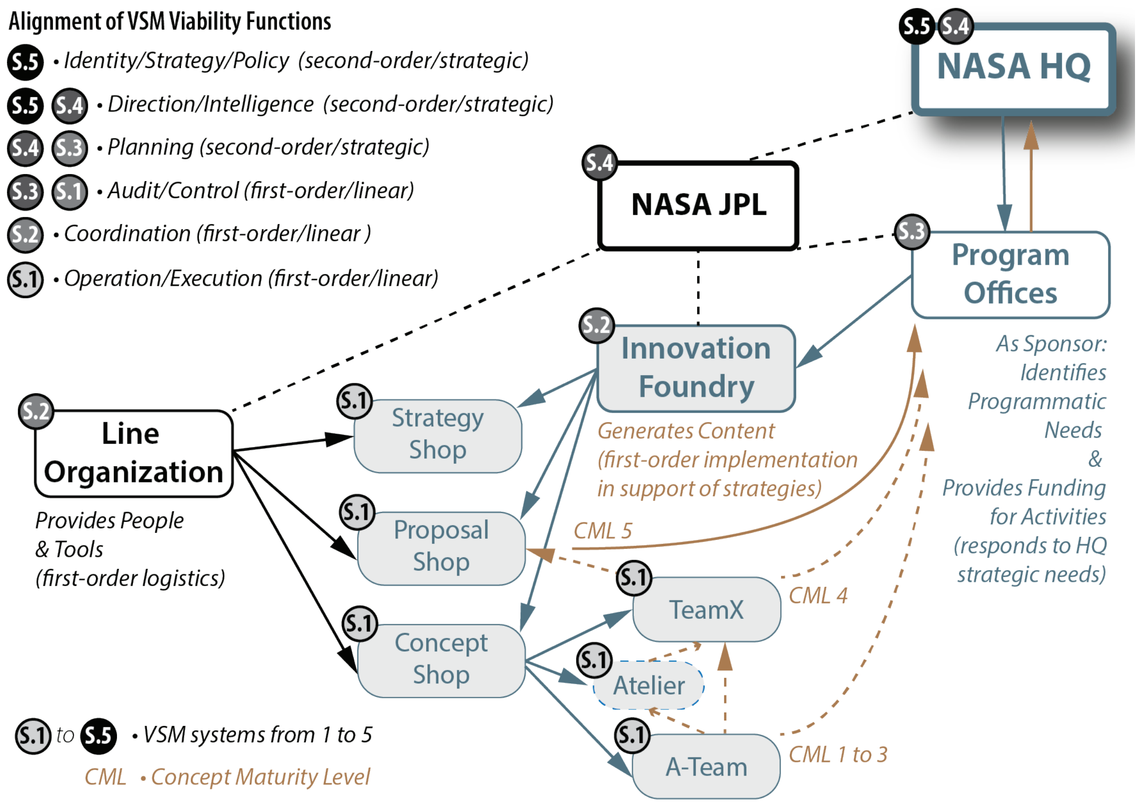


Figure D.1: JPL's Innovation Foundry structure, and connections to other organizational entities as the function of their hierarchy, mapped into the Viable System Model, for this research.

D.2.1. Innovation Foundry Structure

The framework for the activities at JPL's Innovation Foundry is the Concept Maturity Level (CML) scale (Wessen, 2013) for mission formulation concept studies. (The CML scale for such concepts aligns with the well-known Technology Readiness Level (TRL) scale for technologies (Mankins, 1995). CML was discussed in Section 3.3.1.) The CML scale covers the phases of mission concept formulation from "cocktail napkin" to Preliminary Design Review (PDR). It is part of JPL's formulation approach and embraced by NASA SMD's Planetary Science Division (PSD). In simple terms the CML phases are: 1) Cocktail napkin; 2) Initial feasibility; 3) Trades space; 4) Preferred design point within trade space; 5) Concept baseline; 6) Initial design; 7) Preliminary integrated baseline; 8) PDR.)

The Innovation Foundry is divided into three main areas in support of its functions. At the lowest CML—from about CML 1 to 4—the Concept Shop assesses feasibility and matures concepts to a level, where they can be proposed to NASA for funding. Proposals can be both formal—in response to a NASA Announcement of Opportunity (AO)—and informal—as mission concepts that JPL takes to NASA HQ for their consideration. The Proposal Shop is responsible for putting the formal proposals together—at CML 5—signaling to NASA that the concept is now well-defined and ready for implementation, if selected and funded. Finally, the Strategy Shop advises JPL's senior leadership on long–term strategy options for the Center. The options provided by the Strategy Shop inform JPL's leadership (in a cybernetic sense broaden their variety), allowing them to make preferable strategic choices that would help the Center compete, while also benefiting the Agency as a whole. (In effect, this function is similar to that of a PAFTD analyst at the HQ level, illustrating the recursive nature of VSM, discussed in Sections 3.2.12 and 5.3.1.)

The Concept Shop consists of two—and soon three—design environments. At the CML 1 to 3 levels, the activities of the A-Team range from ideation, through initial feasibility studies, to trade space exploration. This is followed by point design mission concept studies within Team X, at CML 4 (Case, 2015).

As an adjunct to the A-Team and Team X, the Innovation Foundry is experimenting with a third environment, a small studio called Atelier, which is modeled after Leonardo's workshop. Its purpose is to fill the gap between the studies done at the other two low-CML design environments, by carrying out very rapid prototyping of ideas. Atelier allows for the infusion of design into system development and integration, thus providing advantages over typical engineering approaches. Atelier design processes can optimize the system configuration for a broader set of requirements, from volume and aesthetics to higher-level needs, if warranted by a given mission concept (Freeman, 2015).

Finally, in the Proposal Shop the study teams prepare for Step 1 and Step 2 proposals. (Note: NASA uses a two-step process to down-select proposals for flight projects. This process ensures that at the final selections only the highest ranked proposals are being funded.)

D.2.2. Innovation Foundry Processes

Team X, is a concurrent and collaborative engineering team environment, which started 20 years ago, and has executed over 1500 mission studies. It focuses on detailed point design developments for mid-CML mission concepts. For these mission studies the feasibility is already established, which puts the emphasis on mission goals and objectives, and evaluating technologies and costs, resulting in an output that can be proposed for funding and implementation. Concurrent design means that the mission elements are developed at the same time, in parallel, during a small number of design sessions, often within a single week. The mission design is performed by subject matter experts (SME). Throughout the concurrent process, partial results are shared periodically among SMEs and with scientists, allowing real-time collaborations between disciplines. In this environment each SME is a regulator of his/her own discipline, and maintains design conversations with the environment, which consists of the other SMEs. At each sharing instant, the SME broadcasts information to the environment with attenuated variety on local design results. At the same time-step the SME receives attenuated information from other SMEs. This feedback broadens the variety of the SME by understanding how different disciplines advanced their own discipline-based designs since the previous broadcasting time-step. This also allows the SME to assess the impacts of the incoming information on his/her discipline and make adjustments until the next iteration step, when the interim results are shared again. This is a first-order cybernetic system with set rules and an environment with attenuated forward and feedback loops. This process facilitates convergence to a point design solution. The SMEs work in real time on their system designs through human-computer interfaces—simply put, on their monitors using their discipline-based models—but can converse with other SMEs in collaboration, as required.

A newer second team, called the A-Team, was established about 3 years ago. It focuses on lower fidelity—low-CML—earlier stage mission concept studies than Team X, but at the same time it explores a broader trades space in search of the most promising feasible outcomes. Under the A-Team, various innovative concepts are being developed, using design tools and methods, starting with brainstorming. During these studies the team has a facilitator, who leads the discussions, advances the discourse, and guides the thinking towards creativity. The facilitator must be concerned with guiding the conversations to agree on the goals, means, and to maintain openness for new shared languages and conversations. At the same time, the design process needs to be designed too. For example, every meeting should be designed with the right attendance membership, and changed depending on the goals of that specific meeting. Then, the meeting needs to be guided to achieve those goals. Compulsory meetings with large invited memberships often result in wasted resources and do not achieve desired outcomes. Customizing team membership for each meeting is an approach that has been used within the Innovation Foundry. For example, the A-Team consists of a core team of 10 to 12 members, but can involve additional SMEs, as required by the study topics. The concepts from these studies are developed to a point, where they can be handed over to Team X for a dedicated point design study, to advance the CML further. The studies often start with an open-sheet architectural setting, which may focus on science questions, mission impacts of technologies, and “out of the box” mission architectures to assess their feasibilities. The study teams rely very heavily on systems engineers, who are often generalists and can communicate across boundaries. In early stage feasibility studies these generalists are called systems architects, who are knowledgeable about many subtopics, and can explore different options and mission architecture trades (Ziemer, 2015).

To date, the Concept Shop has developed over a hundred mission concepts. Several of them led to flight projects.

Both A-Team and Team X have their own design environments. The Left Field, home of the A-Team, is a reconfigurable space with flexible seating, large boards and walls to write on or project to, and physical modeling tools, toys, LEGO pieces to build quick small mockups or even miniature prototypes of spacecraft in support of conversations. These mockups are often used as boundary objects that help team members communicate their ideas between different sub-disciplines, and reach a constructivist middle ground in discussing ideas, concepts, and solutions. Human factors are considered in designing the design environment; including room temperature and layout, in ways that impact mood and team dynamics. It is not a typical conference room, which allows team members to have a different frame of mind. The Team X working environment is structured like a bridge of a “starship,” which is conducive to steering the team towards a common goal from the “Captain’s Chair” at the focal point. One flavor of Team X, known as the Team X CubeSat group, focuses on the design of small shoebox-size spacecraft, utilizes 3D printing based prototyping. This has proven to be successful, because of the modular nature of CubeSat components, which have to fit within well-defined mass and especially volume constraints.

The Proposal Shop holds and maintains the best practices on proposal writing at JPL, regardless of the scope. These can be a large proposal worth billions of dollars or a small research proposal, which represents a major funding source for the researchers. On the larger proposal teams the Principal Investigator (PI)—typically a scientist—is the lead who focuses on the science goals, objectives, and investigations of the concept. If the PI is a newcomer to the process, they may be reinforced with a Project Scientist (PS), who understands formulation at JPL and can guide the PI through it. The Capture Lead is a programmatic thinker, who comes up with winning strategies, while the Proposal Manager is the chief editor of the proposal document. The Lead Systems Engineer guides the engineering team to develop the technical content (Grogan, 2015). Currently, at this CML stage the projects are typically developed to a point where the work is conducted by SMEs, as proposal development follows engineering and management practices. Graphic designers are included on the teams to support visual communications. However, this approach is evolving to allow designers from other sub-disciplines, such as industrial designers, to contribute to the development of proposals.

D.2.3. Novel Shared Languages, Storytelling, Conversations, and Objects

Within the Innovation Foundry it has been recognized that today's engineers are under-skilled in two areas. As stated by Anthony Freeman (Freeman, 2015), *"…one of the problems we've got with the current engineers is that they have two things beaten out of them: one is the ability to write a narrative and the other is the ability to actually draw."* First, they have difficulties in writing a narrative, to tell a story effectively. They often resort to PowerPoint to express their concepts. However, PowerPoint is a presentation software that reduces complex problems to linear bullets and hierarchies. In effect, this weakens communications and may result in the loss of key aspects of the message by misrepresenting complex interconnected aspects in oversimplified linear thoughts. (For example, Tufte states: *"…slideware often reduces the analytical quality of presentations. In particular, the popular PowerPoint templates (ready-made designs) usually weaken verbal and spatial reasoning, and almost always corrupt statistical analysis…"* (Tufte, 2006, p.3).) Second, engineers often lack the ability to draw, and result to plotting their data in chart form with Excel or Matlab. Consequently, their skills to represent concepts visually are not fully developed. Caltech's data visualization course is trying to address this by *"developing iterative visualization tools…(which is providing) a back and forth process, it is not just a figure"* (Mushkin, 2015). Effective communications are therefore a key area that can be improved through shared novel languages, improved storytelling, effective conversations, and boundary objects—including keystone graphics—in support of them.

Specialized Languages: Language represents the code that helps to encode and decode information between the participants in a conversation. Depending on its use, it can advance the discourse, or limit it. For example, within the planetary probe community the following sentence makes perfect sense: *"At IPPW we discuss EDL TPS options, including HIAD/IRVE; LDSD; W-TPS; and ADEPT."* Without the proper code this sentence has no meaning for others outside of the community. Even a fully written out sentence may be too specialized for many people, which is: *"At the International Planetary Probe Workshop we discuss Entry, Descent and Landing Thermal Protection System options, including the Hypersonic Inflatable Aerodynamic Decelerator and Inflatable Reentry Vehicle Experiment; the Low Density Supersonic Decelerators; woven thermal protection systems; and the Adaptable, Deployable Entry Placement Technology."* This shorthand provides familiar and efficient means to exchange discussion points among subject matter experts. This language evolved over decades to address specific topic-relevant questions. Within specialized mission concept studies, or at venues attended by members of the same discipline, it is expected that the meaning of the sentences and abbreviations are understood. But as shown through this example, the language gradually became more and more narrow, accessible only to the indoctrinated few. Beside all the benefits that a specialized language and standardization can represent, there are also potential shortcomings. It focuses on the here and now, with a set near-term event horizon, in order to support ongoing activities. By being too specialized, it can block out new ideas and approaches, thus limiting the potential of the field. In a cybernetic sense, the regulators (the experts in their fields) do not allow feedback from the environment outside of the discipline by filtering the information through the language. It might be done unconsciously and without recognizing the imposed limitations. Thus, the first-order short-term efficiency-gain gets in the way of absorbing new information from the environment, bounding the variety of the regulators at the present state, and eliminating the opportunity for them to find new insights, which would be based on a broadened variety. Language sets the boundaries of the paradigm, and within that it only allows for incremental advancements at best. Therefore, language represents a focus area, where the introduction of new shared languages can open new information channels and add variety to the conversations, leading to new insights and options. These new shared languages may come from the inclusion of new disciplines—e.g., human centered design and human centered space architecture—which need to be added to the conversations between the language of systems engineers, systems architects, scientists, and technology managers. For example, Caltech's data visualization course focuses on broadening the discourse by *"…forcing of the user or the researcher to articulate their concerns, their research concerns, to somebody who is not in their field. And just by doing that, that sometimes is already the first step towards thinking differently and developing a language that is different from the one they are used to"* (Mushkin, 2015).

Storytelling and keystone graphics: Over the past couple of years the Innovation Foundry's senior leadership placed an emphasis on communications, by challenging the A-Team to nurture storytelling skills at every level within the organization, and improve visual thinking by communicating concepts graphically (Freeman, 2015).

Storytelling is beneficial for both internal and external communications. Internally it can be used to enhance conversations within the A-Team and Team X members. Externally it is beneficial to communicate complex concepts clearly, through an appealing narrative to sponsors in the form of proposals and presentations. It can be used to convey information to external stakeholders, including reviewers, evaluation boards, selection officials, and during budget negotiations to higher-level government agencies. Storytelling is typically an "up and out" unidirectional activity, where the message clarity is highly important. Yet it does not have to be dry and boring. The skill to storytelling is finding an angle that resonates with the listeners, the observers. Their interests and understanding can differ; therefore, the story has to be told at multiple levels (Sherwood, 2015). Conversations are not always available to clarify the meaning. For example, in the proposal process, the documentation has to be sufficiently clear and self-contained, knowing that feedback—in the form of a debriefing—will only be provided after selections are made. This negates the possibility of a conversation. The information has to be accessible, with a language that is understood by the target audience. Storytelling is involved with every aspect of the Innovation Foundry operations, from presentations to sponsors, to writing proposals, and interfacing with the public through outreach. But keystone graphics can play another role during the concept development process, which will be discussed below under object communications.

The language and the visuals of a proposal are key to communicate the message to the sponsors who might be familiar with the general topic, but less so about its in-depth finite details. The inclusion of keystone graphics can convey a message better than long discussions in text form. Keystone graphics is a graphical element that tells the whole story about the mission concept. At JPL the people who work on these are called visual strategists (Goods, 2015). They have industrial design or graphic design backgrounds and well versed in visual communications. Still, their place at the table is often limited to graphics and visualizations, although gradually they get more and more involved with mission concept studies as designers

(Kawata, 2015)(Kim, 2015)(Barrios, 2015). Keystone graphics as boundary objects are discussed further in Section 7.

Communicating the findings of a study clearly to external customers, stakeholders, and sponsors requires a regulatory approach, where the variety of the information is attenuated. *“Everything should be made as simple as possible, but not simpler.”* (This quote is accredited to Einstein, although there is no direct evidence of it in his writings.) Informing the observer with clarity and simplicity, combined with aesthetics to peak interest is key to these types of communications.

Data Visualization: Related to storytelling and visual communications, is data visualization. The California Institute of Technology (Caltech), in collaboration with JPL and the Art Center College of Design (ACCD) offers a summer course on this topic. The course is designed to introduce scientists and engineers to art and design based creative practices. Data visualization tells the story about what the data means, and how the information is encapsulated in its presentation, often at a glance. Scientists and engineers who take the course have little formal education in creative exploratory processes, which involve the application of intuition, design thinking and art thinking. Hillary Mushkin (Mushkin, 2015), who leads the course, believes that in a traditional sense design creates artifacts with a purpose, while art is not created for a practical use. Yet, she argues, a lot can be learned from non-purpose based thinking, that can then be applied purpose to. She found that the people who attend the course are self-selecting. They reached the end of their process and wanted to try something new. They have exhausted all existing options within this specific area of their ontology (their personal view on reality through their cognitive model). The course introduces new variety to their schemata, leading to new options. In addition to the creative practice, the activities include conversations, where the students have to explain their work to others, who are often outside of their fields. This forces the students to expand beyond the boundaries of their specialized language, and articulate their research concerns through the conversation, that subsequently evolves into a shared common language with a broadened meaning.

One of the most successful projects that started at the Caltech data visualization course involved a Martian rover connected group from JPL. They wanted to develop a rover path-planning tool, where the operator can visualize the planned traverse by drawing it on the screen. The methodology was based on user-centered design and interaction design, using prototypes and workflow planning. The objective was to reduce the operators’ cognitive load.

Data visualization can have at least two functions, which are on various sides of the storytelling continuum. It can ask the question, while allowing others to explore it. For example, it explores the underlying meaning of information contained in the data, it’s context, and it’s relations to other data. In turn, it can also validate a hypothesis by articulating it visually, which is typically lacking from traditional science and engineering education. Good data visualization can play an important role in storytelling at any level towards any audience. Just by placing a focus on storytelling and visual communications represents a first step towards thinking differently, and broadening the language. These practices benefit from human centered design, by formulating the message with the user in mind.

Conversations and Shared Meaning: Customizing and delivering a coherent message to diverse audiences is the responsibility of an organization. Message clarity is a key strategic activity, where the information provided to stakeholders has a purpose to guide their understanding, and to initiate conversations. If the messages are not at the appropriate cognitive level, unclear, or can be misinterpreted, then the consequences may range from as little as the loss of interest, to potential loss or reduction of funding. Thus, working with visual strategists, graphic designers and visual artists, and relying on their expertise to encapsulate the message into appropriate communication packages is highly relevant and should be expanded from a few local pioneering examples—e.g., at JPL—to the whole Agency.

Subject matter experts typically act within their own disciplines and their own paradigms, where they gradually develop their own specialized languages. Due to overlaps between disciplines, their meanings could correspond partially or fully, while the language representations may differ. Conversations are important because they offer the opportunity of interactions to refine the communicated message to a constructivist, common understanding between the participants. For each discipline, its specialized language carries specific meanings to express concepts within its paradigm. These may introduce a communication barrier, which can be resolved through conversations. Circular exchanges could lead to the emergence of shared common languages and meaning, or by adopting and substituting expressions. For example, within NASA's flight missions the term "operability" has the closely similar meaning as "usability" in the field of design. Recognizing this correspondence, JPL designers improved communications with their flight project counterparts, after substituting the appropriate word. Thus, at times the adoption of terms across disciplines might be simpler than developing novel terms with shared meanings (Davidoff, 2015).

Object Communications and Boundary Objects: Boundary objects help team members to communicate across their disciplines, or support outreach. In these communications the designers and engineers should be aware of the role of aesthetics that contributes to the appeal of space hardware. From an engineering perspective there is no reason to address this, but people can relate to them better if an artifact is designed with this in mind. For example, the Mars rovers with their mast-mounted stereo cameras had an anthropomorphic appeal, which contributed to their popularity and their iconic status. As a further successful example, the outreach team for the Rosetta mission deliberately set out to anthropomorphize their primary "parent" spacecraft and its "plucky" little lander, Philae (Mignone, 2016).

The topic of boundary objects is extensively explored in Section 7.

D.2.4. JPL's Studio

JPL's Studio houses a small, but unique group of creatives with diverse backgrounds, from graphic design and illustration to advertising and product design. They contribute to the laboratory's efforts in diverse ways, from creating art pieces and public places to participating in Innovation Foundry studies, where they help with brainstorming about future mission concepts and creating keystone graphics and illustrations for studies and proposals. The Studio benefits from JPL's entrepreneurial spirit, where scientists, engineers, or study teams can engage in conversations with Studio artists and designers that leads to a diverse set of outcomes for their projects. Dan Goods, the Studio lead, envisioned the roles and functions of his Studio within the organization as *"the office of special projects, supporting people who wanted something out of the ordinary and unique"* (Goods, 2015). With the resulting artifacts the JPL-based customers can convey information to their sponsors, review boards, and the public. Studio designers often utilize their skills to bridge between disciplines, and help them think through their processes faster. From an outsider's perspective on the science and engineering design teams they can reflect on the conversations and make connections and discoveries which might not be obvious to the subject matter experts (Barrios, 2015). In this way, they are integrated into the problem solving process. Another function for the Studio is to improve human centeredness of the laboratory facilities (Kim, 2015). External companies, for example LEGO, or visiting artists, interface with the Studio team, allowing them to converge on common areas for collaborations. In this way the Studio draws work from different types of people, who previously didn't consider working with NASA. Over the years, members of the Studio became strategic partners of their customers from within the science and engineering paradigm, and added value through non-typical design solutions that was unexpected, but highly valuable.

NASA has great and exciting stories to exploit through better storytelling. Graphic artists and designers at the JPL Studio have created artifacts that engaged public imagination. These range from supporting the Concept Shop, giving presentations to sponsors, through designing Laboratory facilities, to creating public posters and installations. The following examples can help to illustrate how human centered design is already being used within NASA's paradigm, where its value is recognized and allowed to happen:

- *Supporting the Concept Shop:* Studio members with industrial design and graphic design backgrounds are routinely embedded into A-Team mission concept developments. They contribute to storytelling, keystone graphics, and provide design related inputs to the studies. In a competitive environment where every year hundreds of proposals are submitted for funding a clear and compelling visual language—using a human centered approach to reach the decision makers—can be an important differentiator (Kawata, 2015) (Freeman, 2015).
- *Influencing Sponsors:* When the concept development started for the JUNO mission, the Principal Investigator approached Dan Goods about creating a proposal cover. It resulted in an abstracted image showing Jupiter's clouds as code, that the mission decodes for our understanding. Dan and his designer colleague, David Delgado, also helped to design the site-visit experience for the selection committee, and branded the experience with posters, presentations, badges, guiding imagery, handouts, and other visual aids. This approach was unique for NASA and opened the door for further collaborations that still happens today (Goods, 2015)(Delgado, 2015).
- *Working with Project Teams:* JPL participated in the DARPA robotics challenge with RoboSimian, a four-limbed disaster relief robot. The engineering team wanted a glamour shot from the Studio (see Figure D.2). As part of the customer support, Studio members started a conversation with the engineering development team, asking about their background research, functions, motivations, and intended users. They have found that the robot was designed from the ground up as a functional engineering system, without considerations for human centered needs. Yet in a disaster relief situation, human centered interactions between the robot, the people to be rescued, and the operators, are key to the success of its operation. It is just as much about how a person feels about the robot as its technical capacity to carry out its relief functions. In response, Jessie Kawata carried out a human centered assessment, which included interviews with JPL's firefighters, who are themselves first responders. Due to time pressure and resource limitations the engineering team didn't incorporate these findings into the RoboSimian design, but it made them think deeper about design considerations (Kawata, 2015). However, there could be another

Figure D.2: Robosimian, JPL's entry to the DARPA robotic challenge in 2014.

explanation that contributed to this choice. Within NASA's paradigm there is no requirement for human centered design, and similarly, it was not part of the DARPA challenge requirements. Without requirements, and a forcing function to include them, human centered design in the NASA paradigm will always be looked at by middle-management as nice to have, that can be addressed at the end of the process, if there is sufficient time and funding available—which of course is seldom the case.

- *Engaging the Public:* Posters with retrofuturistic themes were conceived for imaginary advertisements about traveling to distant habitable planets (see Figure D.3), discovered with the Kepler space observatory. These posters were originally created for JPL's Exploration Office in appreciation of the short-term residency of the famous planetary scientist, Sara Seager, and celebrate the large number of exoplanets discovered by Kepler. The posters went viral overnight (Delgado, 2015). Since then JPL released additional posters related to the exploration of our solar system, including Europa and Mars. It inspired a segment of the population, who are excited about exploring the boundaries between the possible and science fiction. This group is typically not targeted by NASA's outreach activities, as

Figure D.3: Retro-future themed posters about exoplanets discovered by the Kepler space observatory.

Figure D.4: The JPL Studio co-designed NASA installations at the World Science Festival, New York. (a) Comet (2014). (b) NASA Orbital Pavilion (2015).

the focus is on delivering factual science news from existing projects. Nevertheless, sci-fi enthusiasts can contribute new ideas to the discourse and should be considered, as shown by these posters. (Decades before the Studio was established, during the Jupiter and Saturn encounters by the Voyager spacecraft, JPL brought in science fiction writers, which was later reflected in sci-fi book themes over the 80's and 90's (Freeman, 2015). Today these types of engagements are less targeted, although Hollywood often consults with NASA experts on the feasibility of mission concepts (Wessen, 2015). Gravity (2013), Interstellar (2014), and Ridley Scott's Martian (2015) and Prometheus (2012) are just some of the latest examples.) Furthermore, the dynamic installations at the World Science Festival in New York, included the "Comet" (2014), abstracting the Rosetta mission's rendezvous with the comet Churyumov-Gerasimenko, and the "NASA Orbit Pavilion," an immersive sound environment inside a shell shaped structure, representing each of the 20 active NASA Earth satellites passing overhead, with a network of speakers evoking the "movement" of the sounds (see Figure D.4) (Goods, 2015)(Delgado, 2015). These art installations in the intersections of art, design, science and engineering, reached a broad segment of the public, informing and entertaining them about NASA's activities in a non-typical fashion.

- *Adding HCD to Facilities:* JPL accommodates about 5000 people. Over the decades new building were added or demolished, but the laboratory never had a cohesive feel to it. This influences the experiences of both professional and public visitors. The Studio is helping to improve these experiences through configurations and interactive displays on the work done at the Laboratory and about our knowledge about the solar system. Newly built buildings now include VIP places, which are designed to create a utility and impression for official visitors. Shared spaces for scientists and engineers are created for relaxation and to encourage interactions (Kim, 2015). Designers from the Studio are also involved with brainstorming at the Strategy Shop, that influences future center strategies on user experience and human centered work environments.

JPL's Studio develops a broad variety of design and art projects in support of storytelling, communications, outreach, and public engagement. The resulting artifacts are often non-traditional abstractions of science and mission concepts. With these, they reach a broader audience, or a segment of the audience who are not typically interested in space exploration. By starting a conversation with them, they engage new disciplines, which enriches the discourse on the topic. The Studio members call their interactive installations "sneaking up on learning" (Goods, 2015)(Delgado, 2015), where the initial encounter with the artifact brings up further questions from the observer. This leads to conversations with the artists, designers, scientists or engineers present, and in the process the observer learns more about the subject matter than can be done through static exhibits with a unidirectional communication flow. In contrast, graphic artists at other parts of NASA, including NASA HQ, perform excellent, yet more traditional outreach work using graphic designs and static installations (Mottar, 2015). These images and installations can be considered "propaganda art," as they typically conform to literal translations of concepts into artistic representations. Branding at NASA is strictly regulated through guidelines, including the use of the "meatball" logo, its placement, color variations, and font types. It is a constant struggle between nurturing NASA's well-established identity, enforced by the Agency (the regulator), and mission teams who wish to establish their own unique new identities for upcoming spaceflight projects (Sarkisian Wessen, 2015). From this perspective, the Studio practices represent state of the art, while corresponding work at other parts NASA can be seen as state of practice. Efforts to improve storytelling, and setting up Atelier as a prototyping studio pushes the boundaries of Innovation Foundry operations beyond SoA.

It is important to recognize that introducing the Studio into the JPL process happened because the JPL Director at the time, Charles Elachi, and other members from the senior leadership level, including Firouz Naderi, Anthony Freemen, and Brent Sherwood were willing to give it a try, and provided funding and freedom to prove its value to the laboratory. From a cybernetic perspective, the second-order strategic level identified a function, which was not part of the JPL organizational paradigm. By modifying the goals of the first-order implementation level, they enabled new disciplines to become part of the organizational culture, and provided protection until it became self-sustaining. The result is a special group not only within JPL, but also within NASA. The Studio already has substantiated success stories, and it continues to grow its influence with close ties to the Innovation Foundry.

D.2.5. Barriers for the Innovation Foundry

One of the barriers for the Innovation Foundry is related to interactions with the Line Organization. The Line Organization provides the subject matter experts for the Innovation Foundry studies, and maintains the computational tools and models for these studies. Both the personnel and design tools are continuously negotiated between the two organizations. This ensures that the studies are staffed with the appropriate skill-set experts, backup team members are identified in case of logistics complications, and the tools are kept up to date. (Personnel changes and discontinuities during these week-long studies may introduce delays, and communication challenges, which can negatively impact the studies.) While the tools are managed through the Line Organization, a Change Control Board for Team X oversees the model maintenance and development. The Board has representatives from all three organizations—Program Office, Innovation Foundry, and Line Organization—and chaired by the Concept Shop manager. This introduces a challenge, because the Line Organization at the System 2 level—shown in Figure D.1—aligns with a first-order cybernetic system, where linear engineering considerations translate to compliance with requirements within the existing paradigm. From the perspective of the Program Office at the System 3 level, novel solutions may lead to a strategic advantage for the organization, which can be leveraged through the work of the Innovation Foundry at the System 2 level. This hierarchy would necessitate decision authority on tool development through the strategic level Program Office, based on recommendations from the Innovation Foundry, which is the performing organization. This aligns with second-order cybernetics, where the Program Office can modify the goals of the Line Organization, by managing the new tool development. Allocating funding and having decision authority on tool development under the linear discipline creates barriers, as it complies with rigid existing requirements. At this System 2 level the Line Organization is not in a position nor has the incentive to change, modify, or expand its requirements, that is, its system goals. To overcome this barrier, senior leadership at the System 3 level, or above, could restructure the delegated decision authority. This can be achieved by placing new tool development related decisions under the Innovation Foundry, supported through delegated decision authority from the Program Office, and executed by the Line Organization in line with the broadened requirements. This approach would decouple tool development from tool maintenance, thus align the functions with a dynamic organizational structure and hierarchy, described in the Viable System Model.

At the A-Team level, the current Innovation Foundry processes—from ideation, and early-stage concept developments, to feasibility trade studies—are very progressive. The emphasis on storytelling, keystone graphics, facilitated design sessions, study sessions that are designed and customized *a priori*, represent the state of the art at NASA. The interactions and design conversations between team members are reasonably human centered, and the inclusion of a designer among the team members is an important step to include new disciplines in these conversations. They also represent the state of the art for design environments within the aerospace industry. Yet, from the interviews with team members I have found that the activities are still overwhelmingly engineering and technology driven, where the input of the designers are often limited to graphic design and visual communications. This can be improved by further emphasizing a balanced utilization of designers in the design conversations, which can include trial studies, where a designer would act as the facilitator, coordinating between all participating disciplines. This leading-by-design approach can be pioneered through pilot studies under the A-Team, the same way as it is done at commercial companies, where design plays a key differentiating role.

D.3. Example-4: Design Education and Training for Space

Today we witness the growing importance of design within emerging companies and startups. These companies are looking for highly talented designers specializing in product design, user experience design, user interface design, and other design disciplines. A number of companies, including Apple, Dyson, Nest, Pinterest, Google, Facebook, and Philips, consider design as their core business. They benefit greatly from design education and practice.

When NASA wishes to hire new design graduates, their educational background is based on traditional design disciplines, without a space focus. Hiring new design graduates introduces at least two challenges. First, NASA does not have a job category for designers, which highlights the unrecognized value of designers, translated to human resources limitations and regulations, where designers are typically hired under other job categories. Second, even if successful, the graduates have to go through years of training to learn NASA-specific disciplines where they can apply their design backgrounds. By that time they get indoctrinated into the “NASA way of doing things.” This means that, in today’s paradigm designers are expected to conform to linear engineering ways of thinking, instead of utilizing their non-linear processes.

Leveraging design education at NASA can be achieve in three distinct ways, two of which are already part of the state of practice. These three approaches are:

- *Collaborations with design schools:* While NASA’s Space Technology Research Grants (STRG) program predominantly focuses on engineering and science fields (Falker, 2015), there have been a few occasions when projects have been developed at design schools in line with NASA’s human exploration goals. For example, RISD (Rhode Island School of Design) contributed to the SEV mobile habitat concept at NASA JSC (Bluethmann, 2015), while Pratt Institute worked on a human centered habitat design, called X-Hab, for HEOMD AES (Moore, 2015)(Pratt, 2016), both discussed in Section 6.2.3.
- *Short courses in design:* introducing design practices to NASA’s workforce is currently done through self-initiatives. NASA supports continuing education courses, where employees can take design related classes including graphic design, information design and others. Over the past years, Caltech, in collaboration with the ACCD (Art Center College of Design) and JPL offered a data visualization course, where one of the projects focused on a human centered visual interface for mission operators to plan exploration paths for a Mars rover (as discussed above) (Mushkin, 2015)(Davidoff, 2015).
- *Dedicated design degree course with a space focus:* the Sasakawa International Center for Space Architecture (SICSA) at the University of Houston (SICSA, 2016) is a unique interdisciplinary research center that offers degrees in space architecture (Bannova, 2015), but for graduate-level space focused design education there is not an equivalent program in existence.

The skill set and approaches to designing and making, obtained through design schools, are different from those gained at engineering and business schools. The skill set of designers emphasizes the “knowing how” aspects (e.g., swimming) compared to the engineering focus

Rank	University	Country
1	*Royal College of Art (RCA)*	*United Kingdom*
2	*Parsons School of Design at The New School*	*United States*
3	*Rhode Island School of Design (RISD)*	*United States*
4	*Massachusetts Institute of Technology (MIT)*	*United States*
5	*Pratt Institute*	*United States*
6	*School of the Art Institute of Chicago (SAIC)*	*United States*
7	*California Institute of the Arts*	*United States*
8	*University of the Arts London*	*United Kingdom*
9	*Art Center College of Design (ACCD)*	*United States*
10	*The Glasgow School of Art*	*United Kingdom*
11	*Politecnico di Milano*	*Italy*
12	*Goldsmiths, University of London*	*United Kingdom*
13	*University of Oxford*	*United Kingdom*
15	*Aalto University*	*Finland*
15	*Yale University*	*United States*
16	*Carnegie Mellon University*	*United States*
17	*Stanford University*	*United States*
18	*University of California, Los Angeles (UCLA)*	*United States*
19	*Design Academy Eindhoven*	*Netherlands*
20	*Royal Melbourne Institute of Technology (RMIT)*	*Australia*

Table D.1: QS World University Rankings by Subject 2015—Art & Design. (QS, 2015)

on “knowing that” focusing on understanding (Cross, 2007, p.21). NASA typically hires new graduates from engineering and business schools and familiar with their curriculum, which is in line with the Agency’s paradigm. Furthermore, looking at the top 20 design schools in the world in 2015—see Table D.1—it is evident that none of these educational institutions offer a space specific design curriculum. Some of the universities provide links between their design and engineering programs, for example CMU (#16), but they follow more of a traditional curriculum and not focusing on space related education. MIT’s Media Lab (#4) is strongly technology and engineering driven with design related intersections. Stanford’s (#17) d.School offers courses on design thinking, but it is not a stand alone curriculum. Instead, it is an add-on program to other Stanford educational disciplines. Two universities, RISD (#3) and Pratt Institute (#5) worked on NASA projects before, although their curricula are not space focused, as discussed above. ACCD’s (#9) new Drucker Innovation Systems Engineering dual-masters program combines an arts & design curriculum with a business program (Claremont-Drucker, 2015). It focuses on the business aspects of design, and the resulting degree is a combined MS and MBA. Space related graduate programs—not listed in the table—include the International Space University (ISU), Strasbourg, France; and the Singularity University (SU), Moffett Field, CA. The similarities between the two are due to their common founder, Peter Diamandis. ISU is and interdisciplinary, inter-cultural, and international, one year long masters program with five modules, which includes a professional placement. (Note: I was one of the ISU interns at JPL, who was hired after graduation.) The ISU model is similar to that of engineering and business schools, where the curriculum follows an interdisciplinary yet top down approach, and while it promotes systems thinking, it does not develop design thinkers. George Washington University's (GWU) Space Policy Institute takes the approach of a typical management and policy school. Consequently, none of these represent overlaps with a space design curriculum based graduate program, that echoes the educational methodology of RCA (#1) and its Innovation Design Engineering and Global Innovation Design programs.

When reflecting on linear disciplines—which are typical for engineering schools—it can be observed that the curriculum is built on a range of independent core modules, which are expected to be assembled into an interdisciplinary knowledge-base upon graduation. While a number of engineering schools offer a certain level of systems engineering modules that address integrated thinking, the main parts of the curriculum still keeps the students on a linear track. Linear approaches are simpler to implement, due to the imposed control from the educational institution in return to an expected greater predictability of the outcomes. In comparison, a non-linear educational model encourages innovation that is drawn out of the students, rather than imposing the topics through top down control, and the systems level integration is delayed until all of the foundational areas are sufficiently established and understood. Therefore, the typical linear convergent teaching of engineering schools with a systematic building-block approach is different from the non-linear divergent teaching method of RCA's Innovation Design Engineering program, exploring multi-disciplinary ideas in an iterative manner. The former indoctrinates them into the traditional ways of doing things, while in principle, the latter stimulates the creativity of the students. Glanville addresses such co-operative sharing as: *"It is argued that creativity might be amplified through the co-operative sharing of brain power (in contrast to Ashby's amplification of intelligence by restricting attention to the problem)"* (Glanville, 1994, p.1).

An educational program, that brings together scientists, engineers, and designers face methodological challenges, as experienced at both RCA-IDE and ISU. Engineers and scientists typically build on precise technical, scientific, and analytical knowledge, and employ a problem focused-strategy; while designers often deal with fuzzy or gray data and focus on strategies towards a solution through synthesis. An RCA study pointed out that in design education *"there are things to know, ways of knowing them, and ways of finding out about them.… there are designerly ways of knowing, distinct from the more usually-recognized scientific and scholarly ways of knowing."* However, the authors didn't provide examples to define the distinctions between scientific and scholarly inquiries and the designerly inquiry (Cross, 2007, p.22). Perhaps Pickering can provide a perspective, by pointing out that science is concerned with description and prediction, while cybernetics enacts a *"forward-looking search"* (Pickering, 2010, p.18). This temporal process of cybernetics can be related to design processes and approaches. In design education, cross-pollination between students with diverse disciplines through joint problem solving exercises may also require shifts in well-established personal beliefs and approaches, especially when dealing with ill-defined, ill-structured, or "wicked problems" (Rittel & Webber, 1973, p.160).

These design programs are important to develop a new generation of thinkers with a joint experience in both design and engineering, with thinking that is different from those graduating from traditional engineering schools. Building on the adaptation of diverse creative opportunities, divergent attitudes and teaching styles of a novel program, the program can provide a complementary approach to the criticism-based education system of engineering schools. This is key for innovation, which strives on diversity, and works less so in highly regulated environments.

The inclusion of human centered design in an organizational culture requires new ways of thinking, based on former best practices, then broadening them using design based approaches. Thus, if an organization, like NASA, is trying to find new directions and approaches, it can't do it with the current way of thinking and basing it on today's personnel. Instead, a good way to change the culture is to develop a new workforce with a new way of thinking, then foster their talent that they can bring into the organization, instead of indoctrinating them into the old ways of thinking. Consequently, a novel educational program could be established, which could be the key to revolutionary changes in approaches and methods, building on the old, but expanding into yet unseen new possibilities. Establishing such a space focused graduate level program would also align with the innovation related roles of the government, universities, learning, and regions, as discussed in Appendix A.

This program would be considered unique and unparalleled within its space-related field. If modeled on RCA's IDE program, with a dual-masters degree offering, it would leverage the links between design and engineering schools, with connections to NASA. The primary focus of the curriculum would be given to space related design and innovation, technology, design and designerly thinking, prototyping, learning by doing, strategic thinking, human centered design, and emotional design. Similarly to RCA-IDE, the non-linear teaching approach could include modules, workshops, master classes, given by experts in their specialized fields from design and engineering and space technologies, mission architectures and system design processes. Individual and team projects would lead to self-reflections, social networking, collaborations, and interdisciplinary perspectives. The graduates would be employed at NASA Centers, and throughout the broad aerospace sector.

If established, this new space design program would provide benefits to the educational institution hosting it, to the students, and to the employers. The institution would build bridges and collaborations with other universities, both in the US and around the world. It would establish itself as a unique contributor to space focused design education, with a strategic advantage. For the students, the course would help them to develop a unique skill set through the acquired knowledge, differentiating them from the normal employer intake from traditional engineering schools. For the employers, the new graduates would represent a specially trained workforce with a novel way of thinking and problem solving skill set. This could lead to organizational paradigm and culture change.

Setting up such a program would benefit from co-locations of the various disciplines. For example, in Pasadena, Caltech, ACCD, and JPL, or in San Francisco, Stanford University (#17) and NASA Ames Research Center could leverage their regional proximity and work synergistically, the same way as RCA and Imperial College is co-located in London. Many other universities in the US have strong aerospace engineering and design departments, including CMU (#16), where a joint program would be possible. If established at any location, a space design focused graduate degree program would be a highly unique MS/MA program, which would train a novel workforce for the space enterprise and respond to a need. Such a program would be without competition from any of the educational institutions not only in the US, but also in the world. Over time, the graduates hired from this program would impact and broaden NASA's paradigm, by introducing a new discipline to its culture.

D.4. Epilogue to Designing the Design

Design environments, such as JPL's Innovation Foundry, are ideally suited to embrace design conversations and cybernetics, as these are the places where novel ideas and future mission concepts are envisioned. The ongoing attention within JPL's Innovation Foundry to storytelling, keystone graphics, shared meaning for communications within study groups, and the use of boundary objects, align with human centered design approaches. These conversations among team members, team dynamics, and team makeup play pivotal roles in developing and accepting new shared languages. Bringing scientists, subject matter experts, technologists, engineers and designers together would provide sufficient diversity, leading to the emergence of new shared languages with new options and potential outcomes, if the team is given the proper guidance. Even now, members of the Innovation Foundry are encouraged to move beyond concept assessments and build prototypes, as new ideas may evolve through building, iterations, and conversations. Similarly, boundary objects would ground ideas and bridge language diversity between disciplines. Mistakes and misunderstandings through conversations or rapid prototyping can also lead to new ideas, as they can stimulate new questions and point to new solutions. These approaches represent the state of the art within NASA, which is the state of practice at design focused commercial companies. Incorporating these practices into design processes translates to highly competitive proposals and improved communications during concepts studies. It also builds excitement for the public, and helps advocating the work performed at NASA.

Looking ahead, finding solutions to existing barriers at a touch point on computational model and tool developments would benefit from alignment with the Viable System Model, including reassessment of the related roles, responsibilities, and funding allocations. Similarly, design processes during early stage concept studies could be advanced at another touch points by further leveraging the skills and expertise of designers in a predominantly engineering focused environment. Another potential way to introduce change to NASA is by developing a new workforce through a novel design focused non-linear educational program. Setting up a program and hiring graduates would address a need at NASA in connection with changing its paradigm from the ground up, by introducing a new language and non-linear methods to the workforce, that over time, would change NASA's worldview. Such a graduate-level educational program would closely align with the innovation related roles of the government and universities.

Science, engineering, art and design are all creative practices. Yet, they often speak different languages, where some parts may correspond, while others address a different variety in a cybernetic sense. Intersections between these disciplines through conversations and creative projects, including boundary objects, and prototyping, can break communication barriers and result in a shared language that includes the added variety, specific to each discipline. The shared language can also create new variety that evolves through constructivist conversations between the participants. To broaden a paradigm, we have to introduce this new variety, with a forcing function from the strategic level in order to ensure its viability. This requires designing the design.

Appendix E: Details on Boundary Objects and Other Artifacts

E.1. Conference Posters for Communications

The International Planetary Probe Workshop (IPPW) is an annual event. It brings the science and technology community together from space agencies and space related companies. I have been involved with the organization of IPPW since the 2nd workshop, and started to make its official posters from the 4th workshop (Figure E.1). To date, I have created nine official posters out of the 13 workshops. Until last year I have designed and made these posters with Blender3D, Adobe Photoshop and Illustrator. I have started my research at RCA in fall of 2012, thus my research overlapped with the last four posters, shown in Figures E.1, E.2, E.4, and E.5. In 2015 I have also created an official proposal cover, submitted to the European Space Agency. All posters include iconic planetary probe images, from aeroshells to probes and parachutes. These posters are communication devices to attract potential attendees to the workshops, or target agency stakeholders who evaluate submitted proposals for funding.

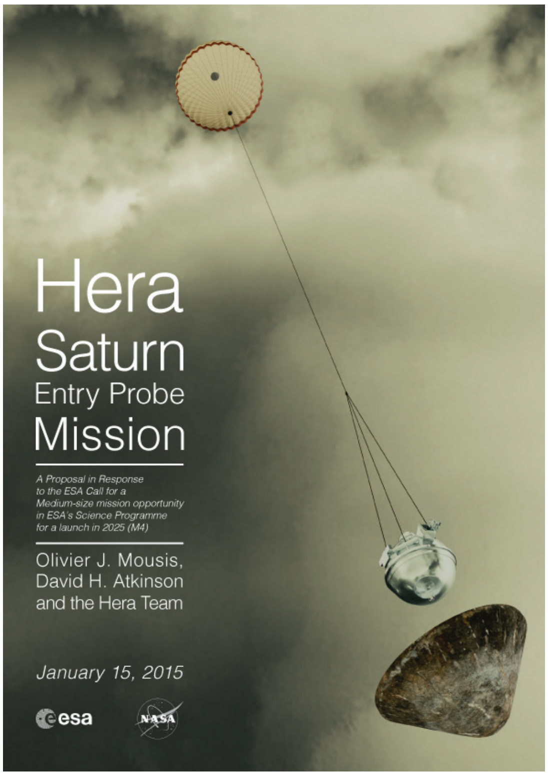
The designing and making of the posters involved an initial design phase by me, and a dialog with the IPPW organizing committee to gather feedback and incorporate them into the design. Once accepted, the communication dialog continued with the probe community via the poster.

These images are not only used during the promotion of the workshop, but also prominently displayed during the conference, on program booklets, conference bags, as projected images between presentations, large scale posters around town and at the workshop, and at times even as flags in front of the conference venue, as shown in Figure E.11.

In addition, I have also created the official workshop logo, shown on the right, which is constantly being used in communications and presentations.

Figure E.1: IPPW13 Poster, 2016.

Figure E.2: IPPW12 Poster, 2015.



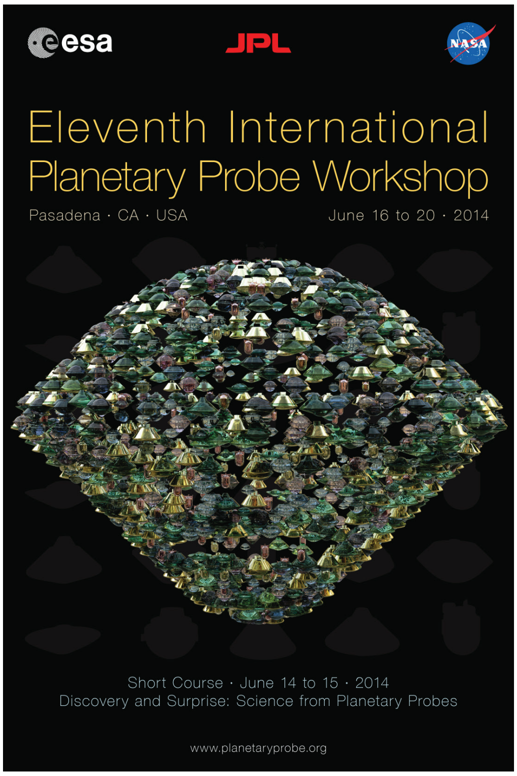
Hera
Saturn
Entry Probe
Mission

A Proposal in Response to the ESA Call for a Medium-size mission opportunity in ESA's Science Programme for a launch in 2025 (M4)

Olivier J. Mousis, David H. Atkinson and the Hera Team

January 15, 2015

Figure E.3: HERA Proposal Cover for ESA, 2015.



Eleventh International Planetary Probe Workshop

Pasadena · CA · USA

June 16 to 20 · 2014

Short Course · June 14 to 15 · 2014
Discovery and Surprise: Science from Planetary Probes

www.planetaryprobe.org

Figure E.4: IPPW11 Poster, 2014.

10th INTERNATIONAL PLANETARY PROBE WORKSHOP

San Jose, CA, USA
June 17-21, 2013

Short Course: EDL Systems Overview June 15-16, 2013

www.ippw10.com

Figure E.5: IPPW10 Poster, 2013.

9th INTERNATIONAL PLANETARY PROBE WORKSHOP

Toulouse, France June 18–22, 2012 www.planetaryprobe.eu

Short Course: Probe Science Instrumentation Technologies June 16–17

Figure E.6: IPPW9 Poster, 2012.

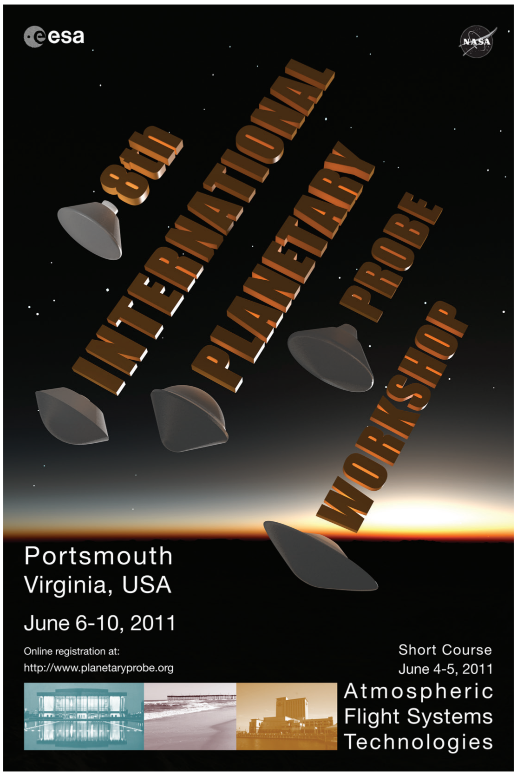


Figure E.7: IPPW8, 2011.

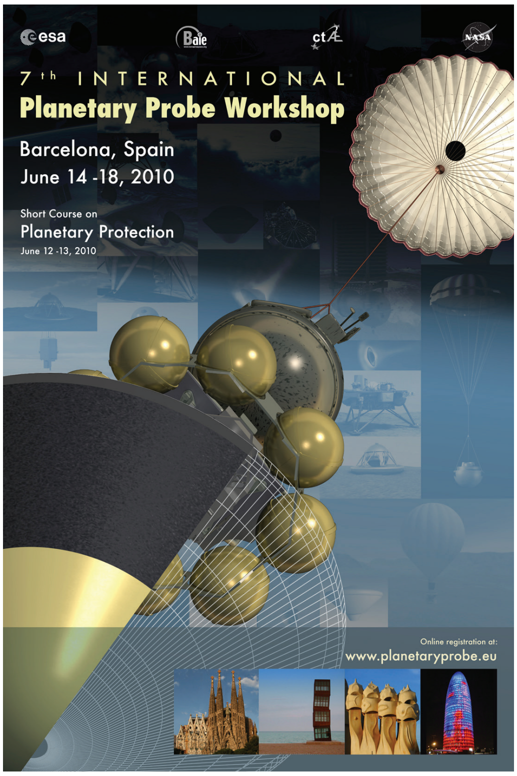


Figure E.8: IPPW7 Poster, 2010.

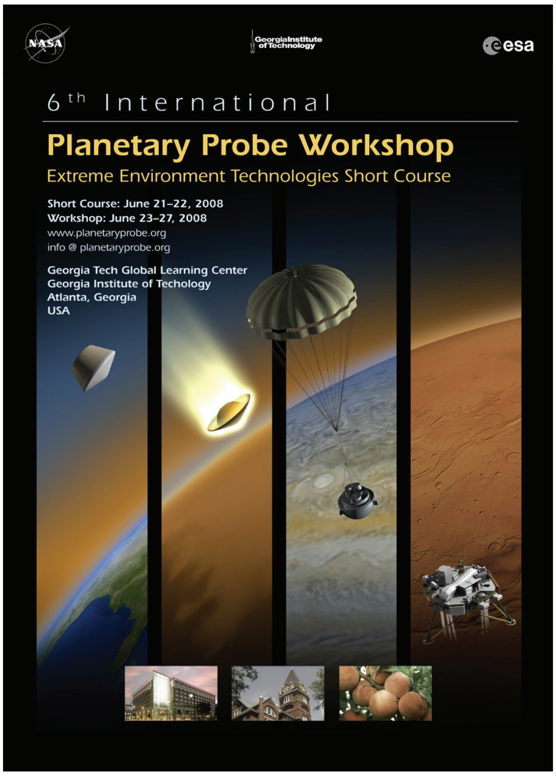
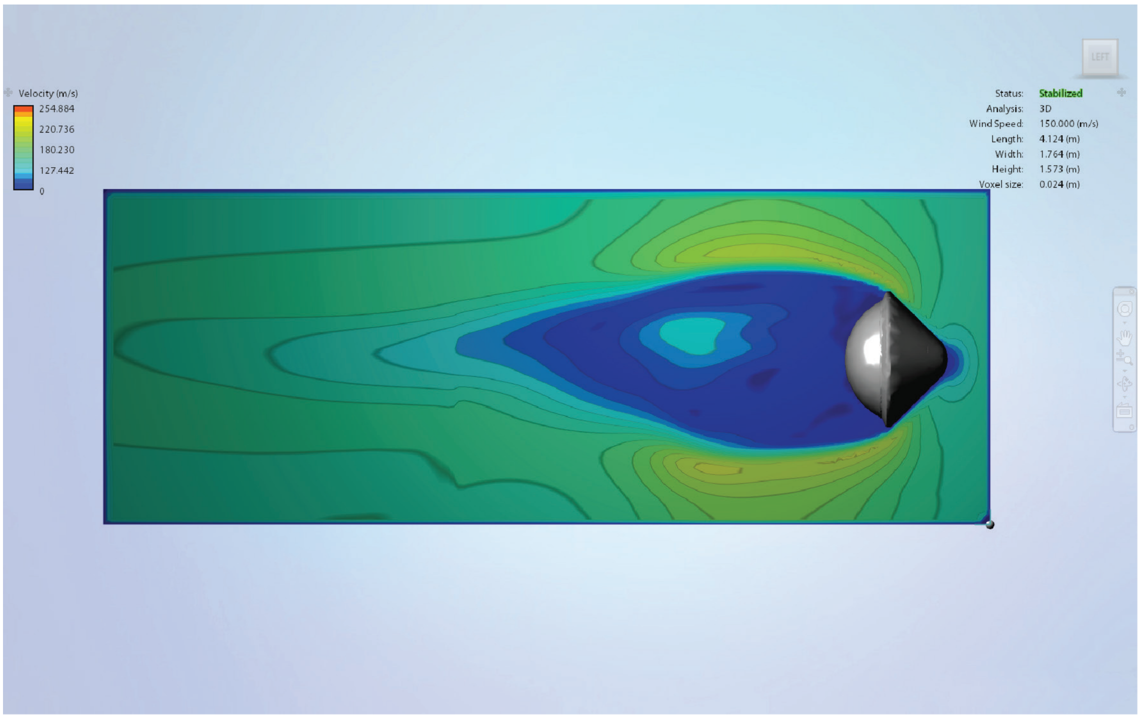


Figure E.9: IPPW6 Poster, 2008.

Figure E.10: IPPW4 Poster, 2006.

Figure E.11: IPPW12 branding: conference poster image on program booklets, bags, name tags, rooms, projections during breaks, and on a flag outside of the venue.

E.2. Making of the “Galileo Flow Field” Artifacts



Status: Stabilized
Analysis: 3D
Wind Speed: 150.000 (m/s)
Length: 4.124 (m)
Width: 1.764 (m)
Height: 1.573 (m)
Voxel size: 0.024 (m)

Figure E.12: Flow field simulation around a Galileo type probe in a virtual wind tunnel, using Autodesk Flow Design. This was the chosen concept from the ideation process.

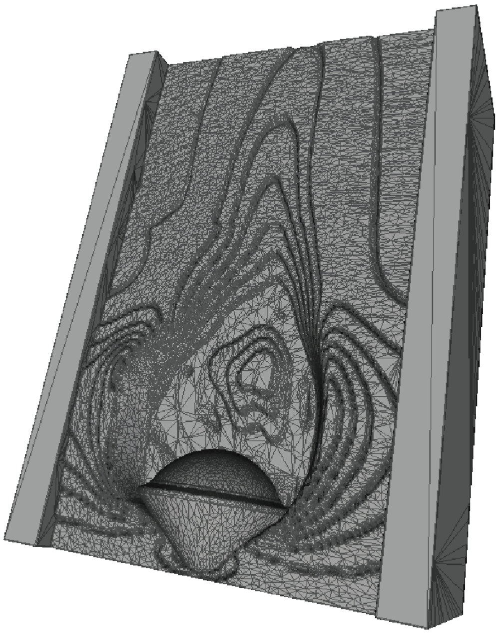


Figure E.13: Mesh generated with Blender3D’s displacement modifier, applied to the flow contour plot.

Figure E.14: 3D rendered image of the model, using Blender3D.

Figure E.15: Visualizing the virtual model through a 3D rendered image of the mesh, using Blender3D. This perspective was chosen for subsequently photographing the actual walnut model for the IPPW13 poster.

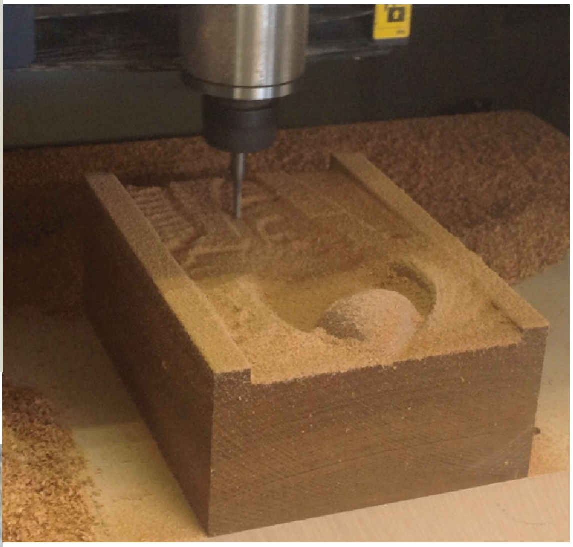


Figure E.16: CNC machining the model out of walnut. This was used in the IPPW poster.

Figure E.17: CNC machined chemiwood version used as the master model for the bronze sculpture project.

Figure E.18: Making the first layer of the silicone mold.

Figure E.19: Second layer of the silicone mold, with keys to fit into the plaster shell.

Figure E.20: Adjusting the edges of the silicone mold.

Figure E.21: Making the plaster shell around the silicone mold.

Figure E.22: Plaster shell showing the locations where the silicone mold keys fit.

Figure E.23: Hollow wax model created using the silicone mold.

Figure E.24: Creating the back plate for the wax model.

Figure E.25: Building up 8 layers of ceramic coating, layer by layer, allowing sufficient time to dry (at least 4-5 days total).

Figure E.26: Melting out the wax from the ceramic shells. (Note, the backs of the models are cut out, and will be poured separately from the front sides.

Figure E.27: Getting ready to melt out the wax.

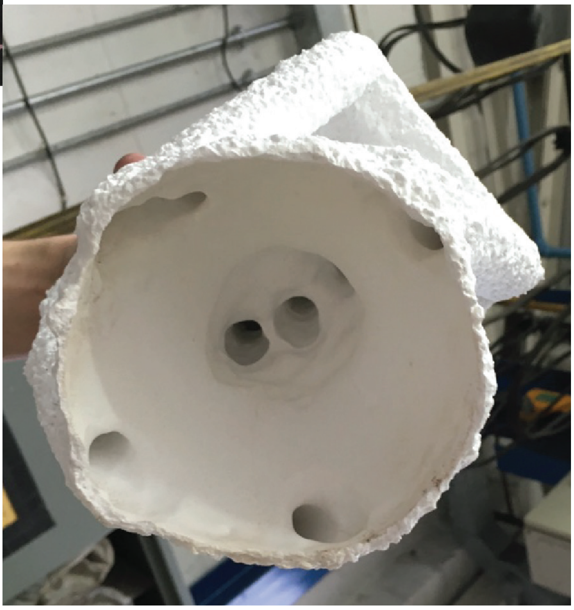


Figure E.28: Wax melted from the ceramic shells.

Figure E.29: Shells preheated before the pour.

Figure E.30: Shells placed is sand for support during the pour.

Figure E.31: Preparation for melting the bronze.

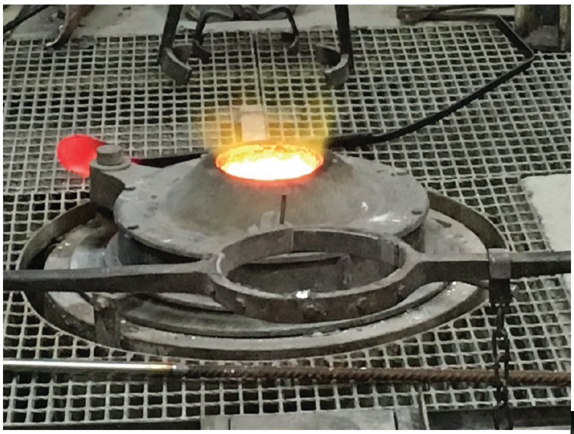


Figure E.32: Bronze being melted.

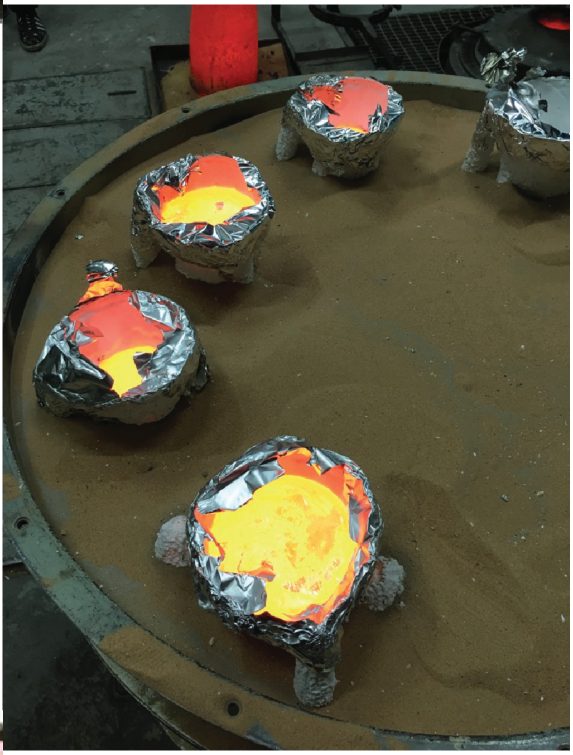


Figure E.33: After the pour (still red hot).

Figure E.34: Ceramic shell fragments removed, artifact sand blasted. Runners and risers still attached.

Figure E.35: Ceramic fragments, runners and risers removed (front sides & back plates).

Figure E.36: Ceramic fragments, runners and risers removed (back sides).

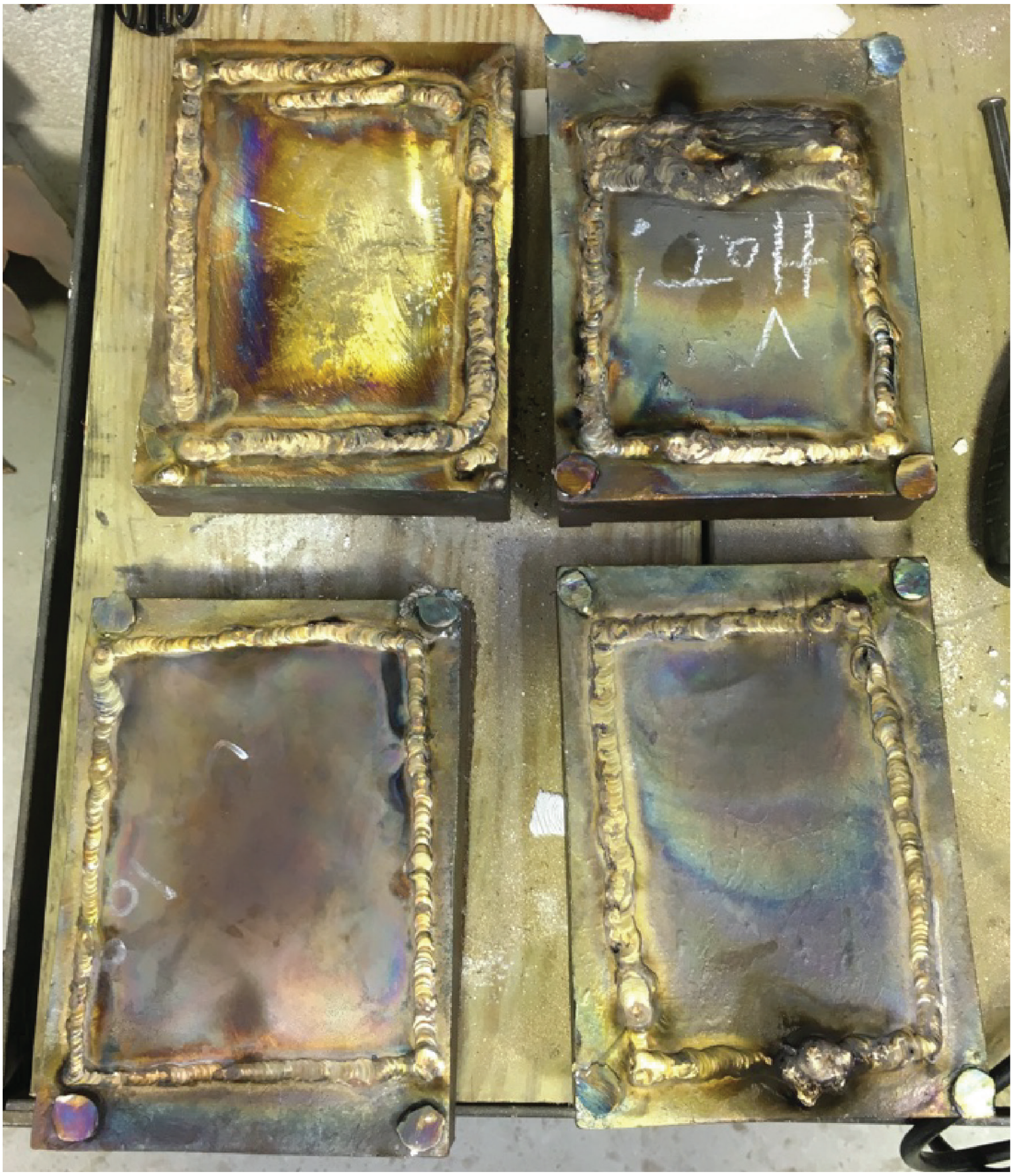


Figure E.37: Back plates welded back. (The artifact is hollow inside, with a wall thickness of about 5mm. Still each artifact is about 2.5kg to 3kg.)

Figure E.38: Next chasing step: grinding the edges and weld marks.

Figure E.39: Final sand blasting.

Figure E.40: Patination in progress.

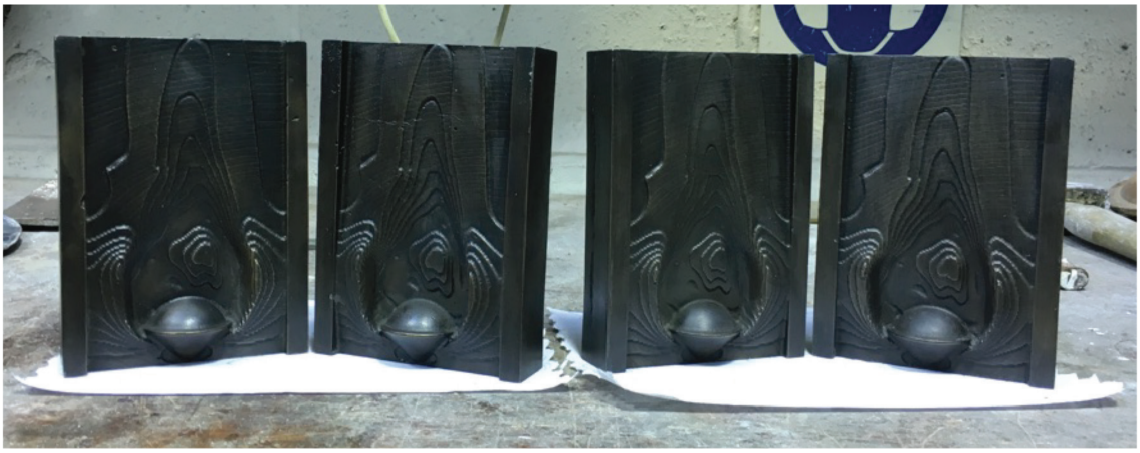


Figure E.41: Patinated artifacts.

Figure E.42: Drew Cole, head of the RCA Foundry, and Tibor Balint pose with the artifacts.

Figure E.43: Bronze and walnut versions shown together on the mantelpiece.

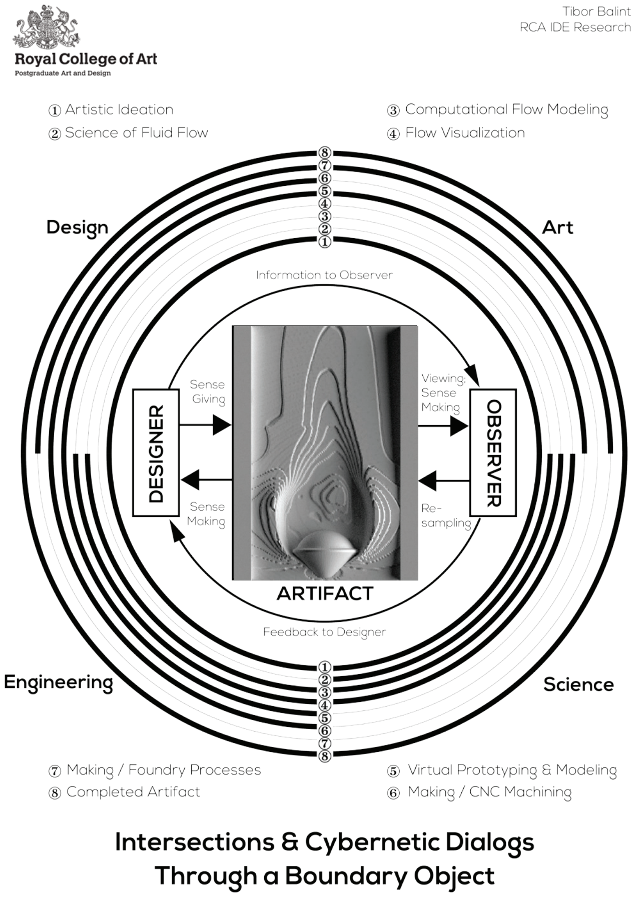
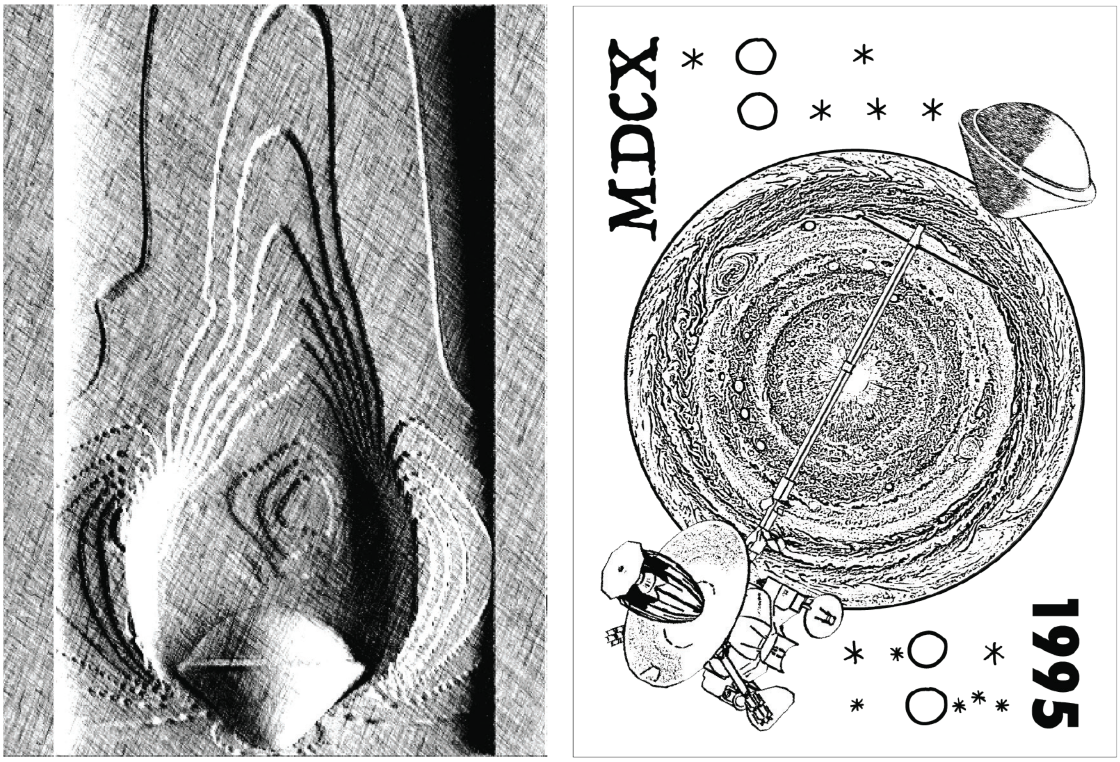


Figure E.44: Graphics used for the WIP-2016 show display.

Figure E.45: WIP-2016 show display front view, with the bronze artifact.

Figure E.46: Winning the 2016 Remet Casting Prize.

E.3. Making of the “Expanding Boundaries” BAMS Competition Medal



Obverse side

Reverse side

Figure E.47: Medal design for the British Art Medal Society (BAMS) Student Competition 2016.

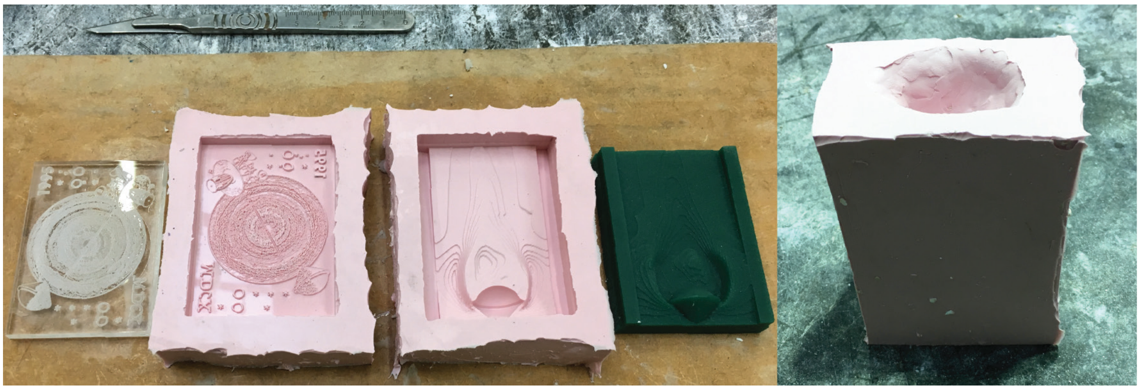


Figure E.48: (left) Front and back BAMS master models and silicone molds. Obverse side CNC machined out of chemiwood. Reverse side laser engraved into acrylic. (right) Silicone mold from the final master model, made out of a single chemiwood piece. Obverse side CNC’d, reverse side laser engraved.

Making a single master model simplified the process. The original idea was to create front and back sides, then join them together to make a new master model. Each steps would have introduced unwanted errors. Thus, having a single master model was a preferred solution.

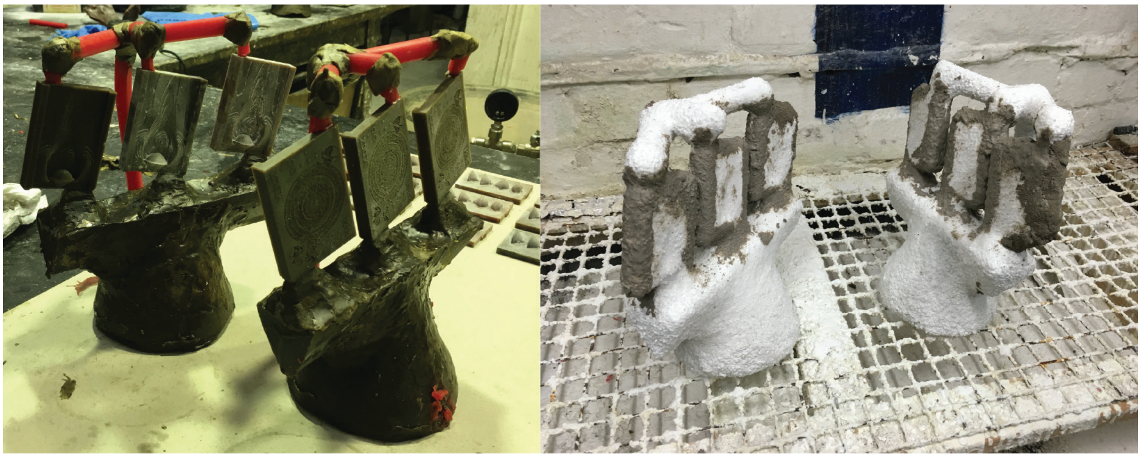


Figure E.49: (left) Building up a tree with runners and risers. (right) Building up the ceramic shell layers.

Figure E.50: (left/middle) Melting out the wax. (right) Preheating before the bronze pour.

Figure E.51: (left) After the pour. (right) The six medals with runners and risers.

Figure E.52: The six medals without runners and risers.

Figure E.53: The six medals after the chasing steps, including griding and sand blasting.

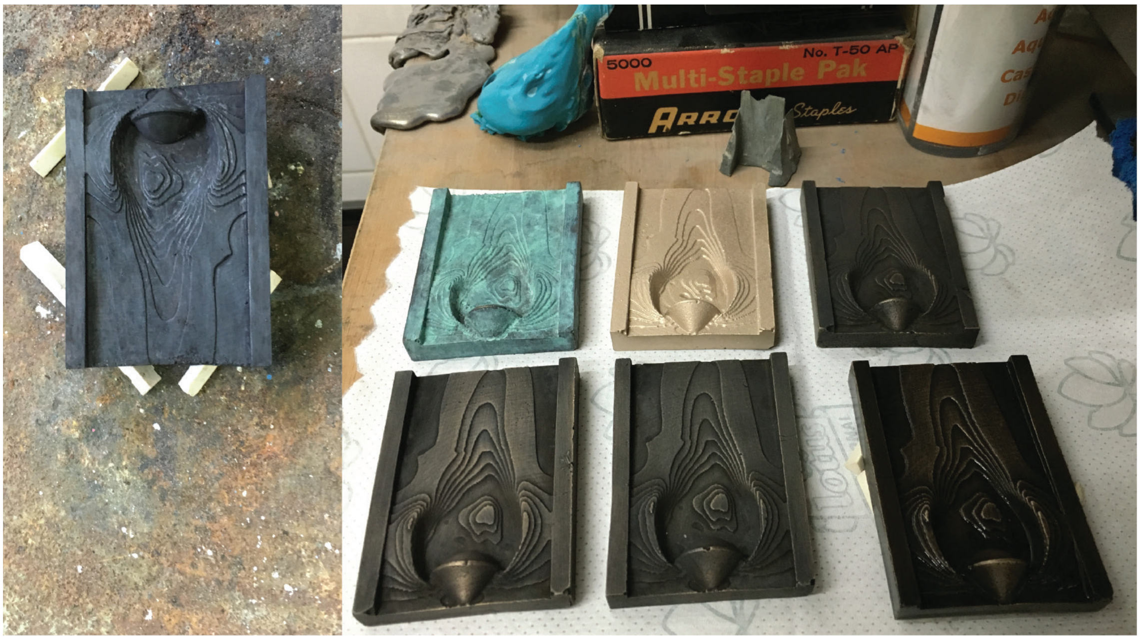


Figure E.54: (left) Ongoing patination process. (right) The six medals during the patination process.

Figure E.55: Final patinated medals. (upper) Obverse sides. (lower) Reverse sides.

E.4. Making of the "Alvin Seiff Memorial Award" Medal for IPPW

Figure E.56: Initial design of the IPPW medal. (left) Obverse side rendered in Blender3D. (right) Reverse side created with Adobe Illustrator.

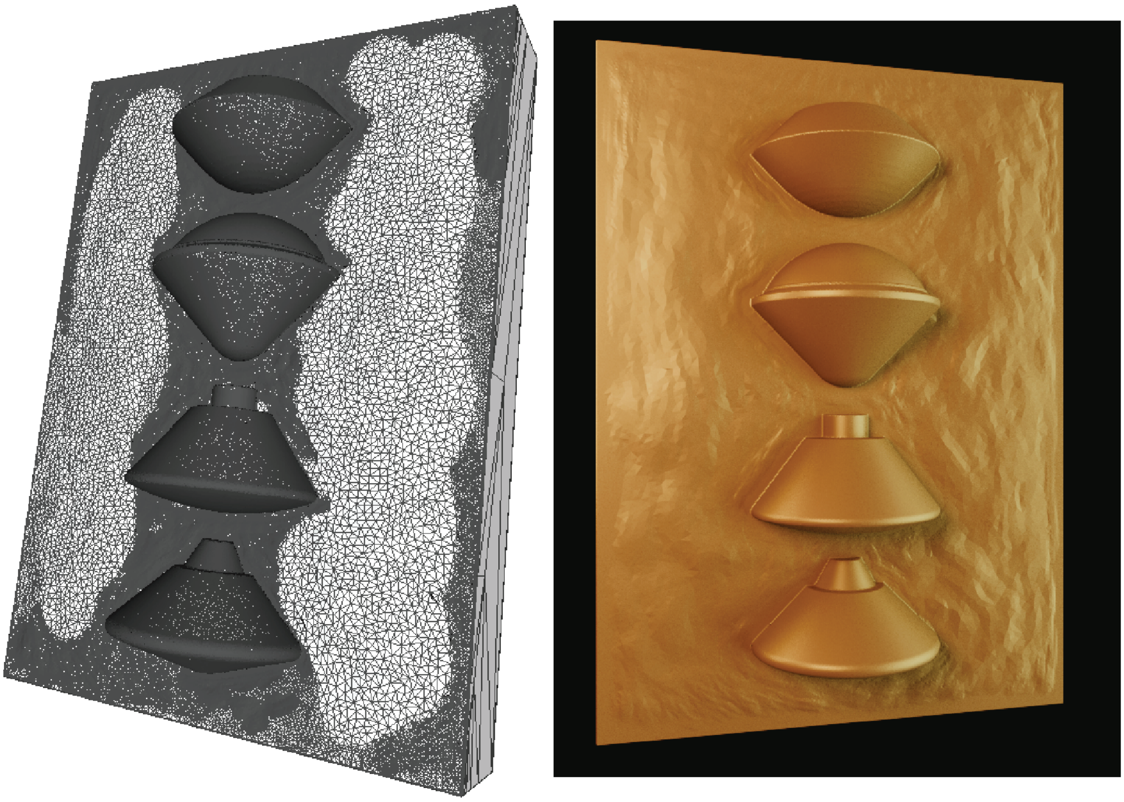


Figure E.57: (left) IPPW medal STL mesh. (right) Perspective view of the obverse side, rendered in Blender 3D.

Figure E.58: IPPW medal master model. (left) Obverse side CNC machined at RCA's Digital Aided Making (DAM) workshop. (right) Reverse side, laser etched at RCA DAM.

Figure E.59: In the process of creating the silicone mold from the master model.

Figure E.60: Creating the silicone mold. (left) Creating the walls. (right) Pouring the silicone around the model.

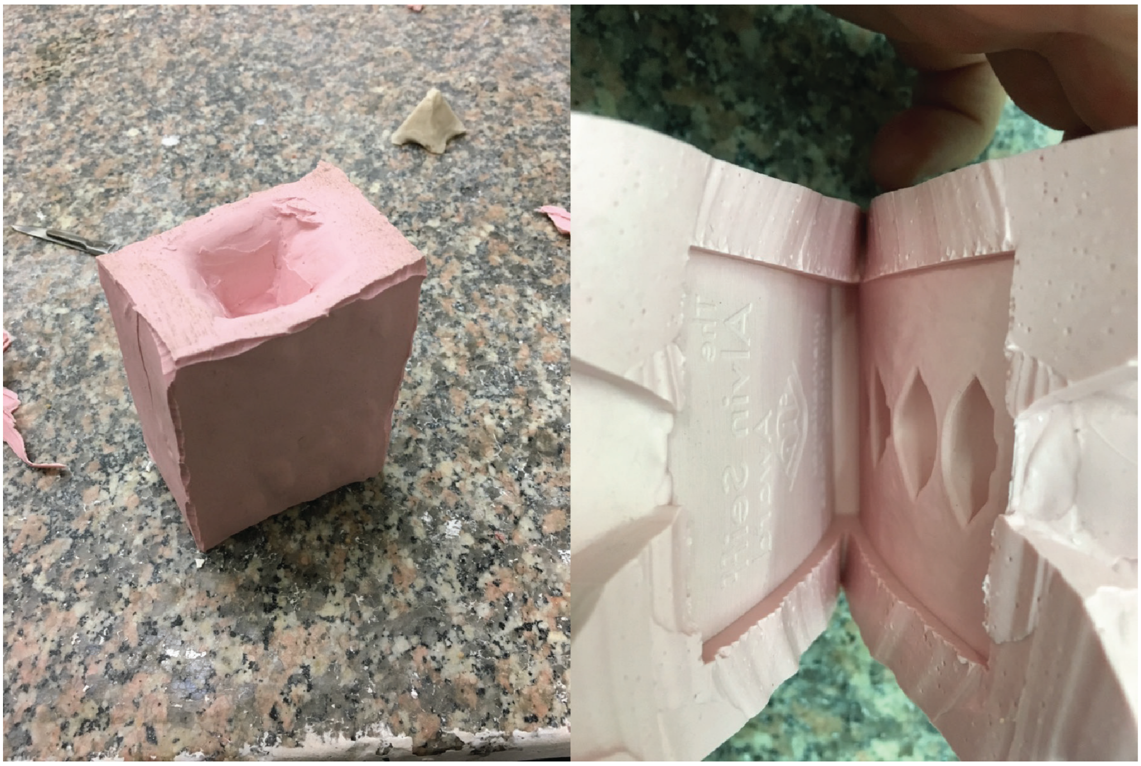


Figure E.61: (left) Silicone mold. (right) The silicone mold is cut open, master model removed, ready to create wax models.

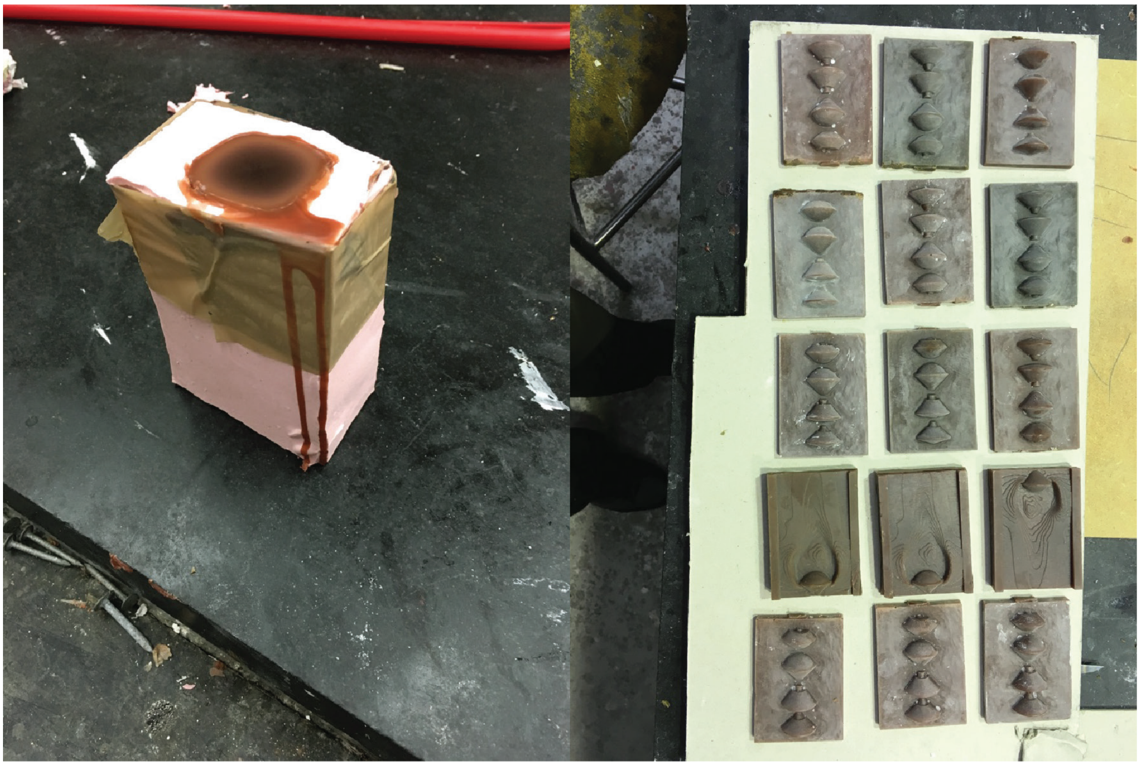


Figure E.62: (left) Wax in the silicone mold. (right) Created wax models.

Note: due to trapped air bubbles, the shoulders on this medal were not formed properly. Cutting risers into the silicone mold mostly fixed the air bubble issues.

Figure E.63: (top) Closeups of the example wax model. (bottom) Final bronze medals, obverse and reverse sides, with two types of patination.

Figure E.64: IPPW-13 presentation on Making the Galileo Flow Field artifact.

Figure E.65: With Rob Manning, recipient of the IPPW-13 Al Seiff Award

Figure E.66: Al Seiff Award Medal (un-boxed)

Figure E.67: Al Seiff Award Medal (boxed)

E.5. Making of the "Venus Watch 1.0" Artifact

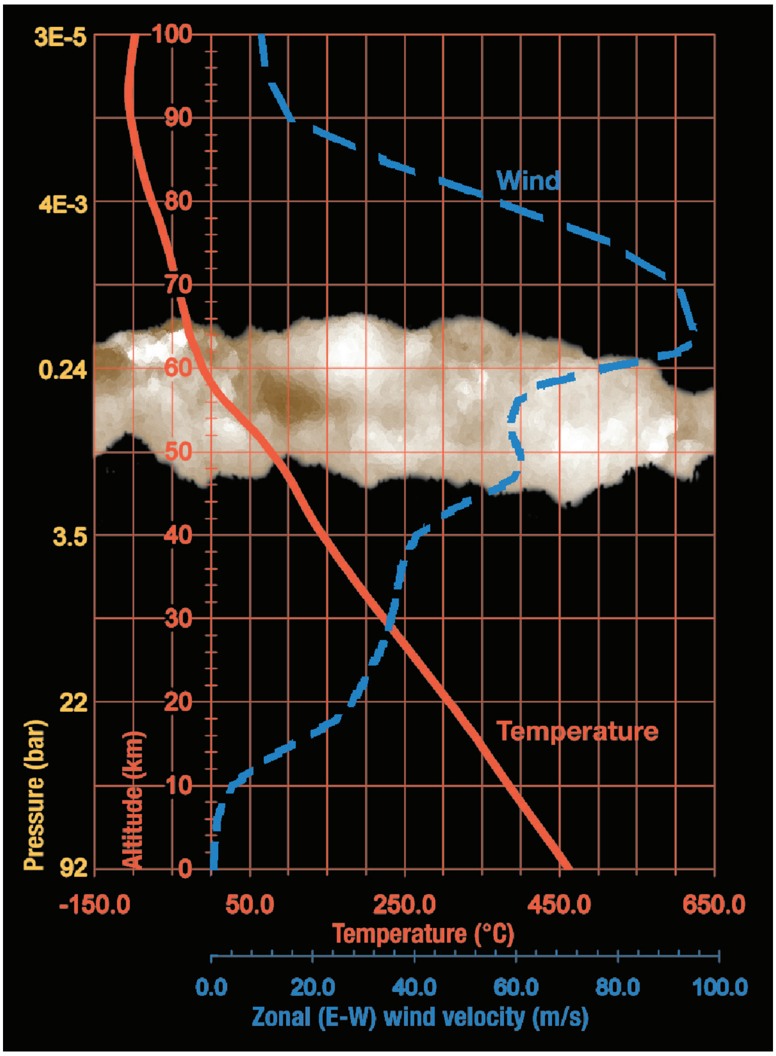


Figure E.68: Extreme environments at Venus.

Note: The surface temperature is about 460°C, the surface pressure is about 92 bar, sulfuric acid droplet in the clouds at about 50km altitude, where the temperatures and pressures are near Earth-like.

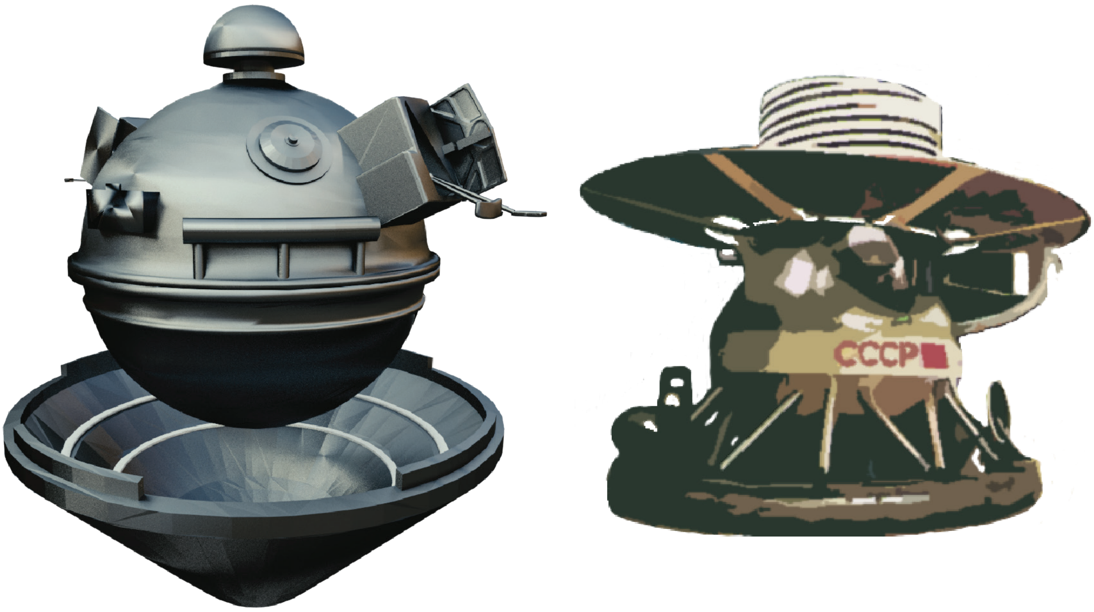


Figure E.69: (left) Artist's impression of the Pioneer-Venus small probe and front aeroshell (by T. Balint). It entered Venus on December 9, 1978. (right) Venera 13, landed on the surface of Venus, on October 30, 1981. It survived for 127 minutes, a record still today.

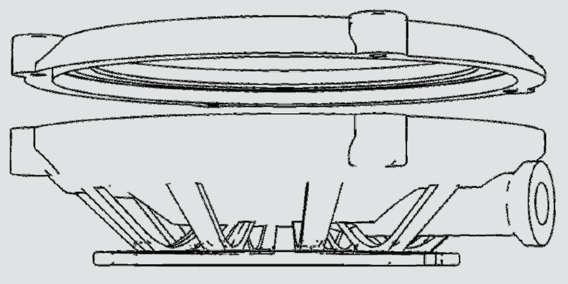


Figure E.70: Venus Watch housing, echoing the Venera lander. (Freestyle sketch rendered in Blender3D from the STL model. The model was designed by J. Melchiorri).

Figure E.71: Venus Watch elements, modeled and rendered in Blender3D.

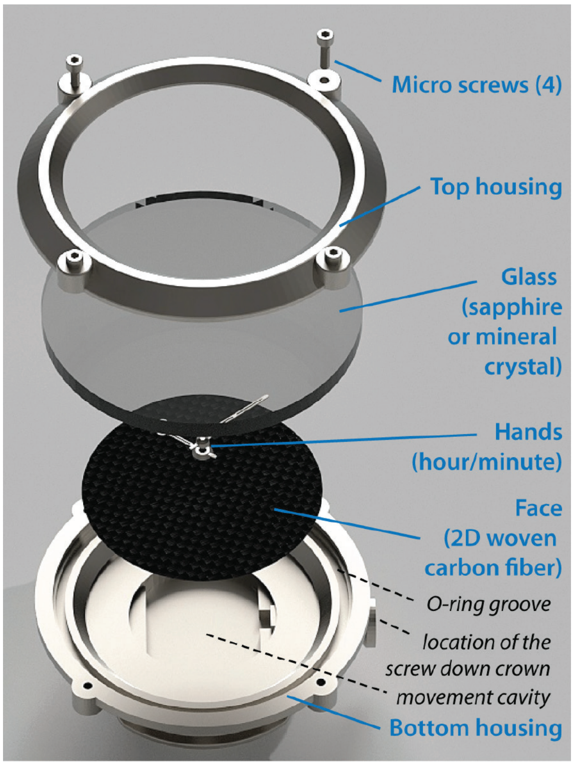


Figure E.72: Artist's impression of the Venus Watch 1.0 concept, showing the top and bottom cases, crystal, woven carbon face sheet, the minute and hour hands, and screws holding the top and bottom cases. Rendered in Blender3D from the CAD models.

Figure E.73: MIL-T-5608 TyII Class E parachute ribbon, used for the watchbands.

Figure E.74: Commercial off the shelf (COTS) parts; top row, from left: magic seal; screw-in crown; digital movements; artificial sapphire crystals; high precision mineral glass. Bottom row from left: more digital movements; O-rings; extra screw-in crowns for water tightness.

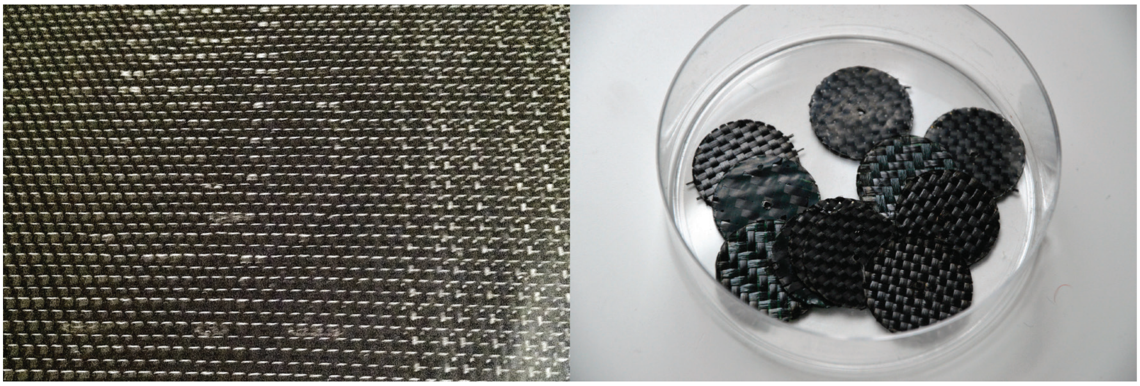


Figure E.75: (left) 3D woven carbon sheet, impregnated with resin.
(right) Laser cut 2D woven carbon sheets.

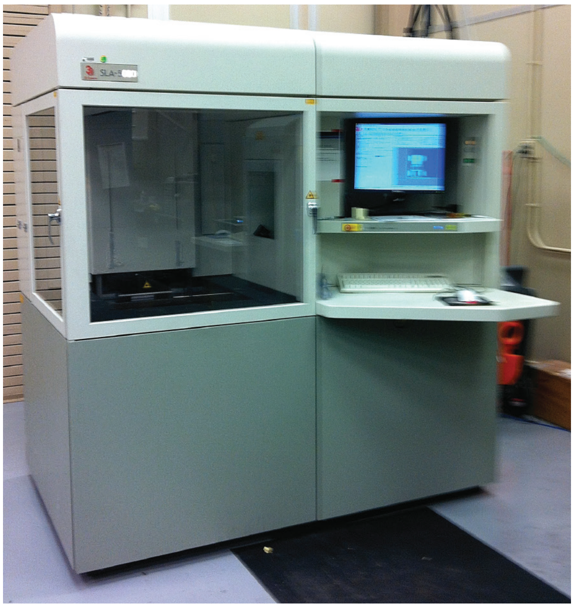


Figure E.76: Stereolithography (SLA) machine.

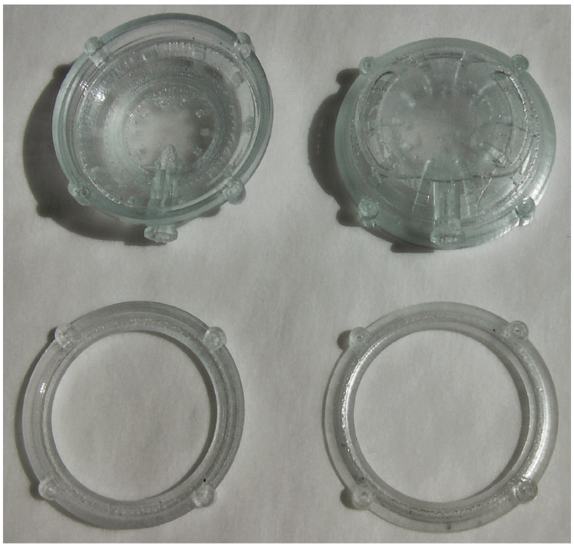


Figure E.77: SLA printed plastic parts.

Figure E.78: ARCAM EBM S400 for Electron Beam Melting.

Figure E.79: 3D printed titanium parts (top and bottom housing / upside and down views). This EBM printing method did not produce the desired parts with the right accuracy.

Figure E.80 M2 Cusing SLM machine, built by Concept Laser, a division of Hoffman Innovation Group of Lichtenfels,Germany.

Figure E.81: SLM printed titanium parts. This sample 3D print did not provide the needed accuracy.

Figure E.82: SLM printed stainless steel parts, used for the assembled Venus Watch 1.0 concept.

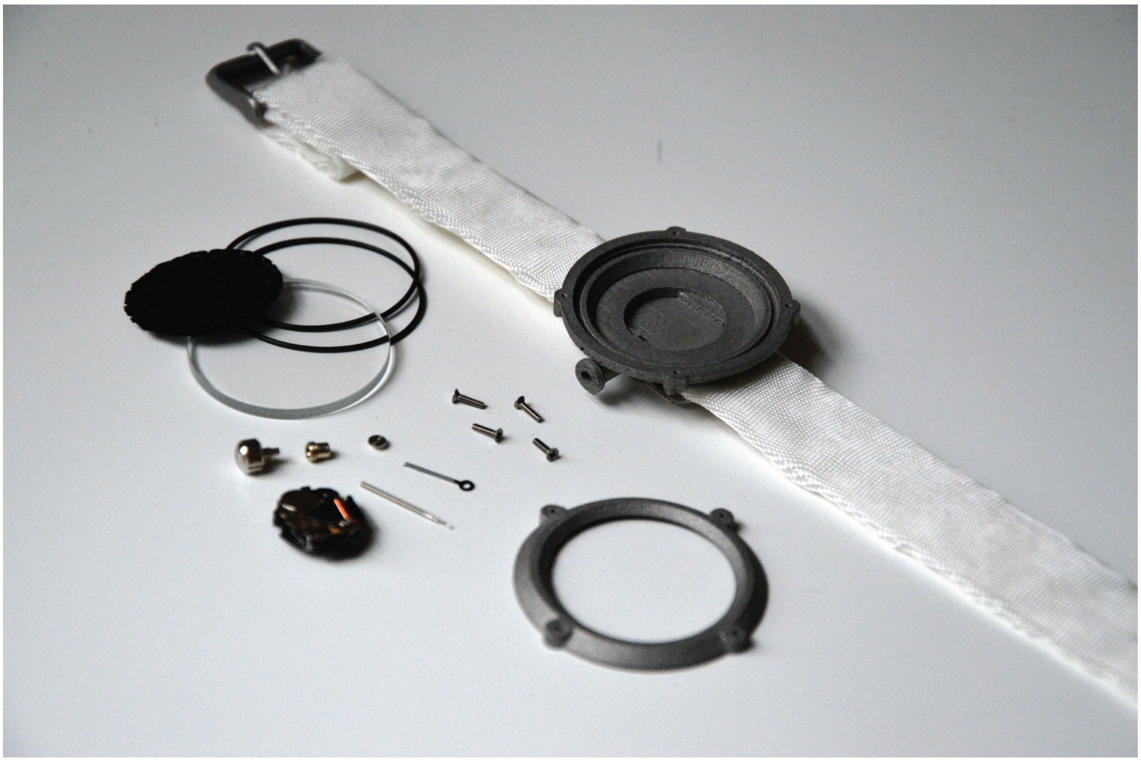


Figure E.83: Pre-assembled prototype with its parts.

Figure E.84: Watch band options. (top) Glued. (bottom) Sewn.

Figure E.85: Watch face, using a laser-cut 2D woven carbon sheet.

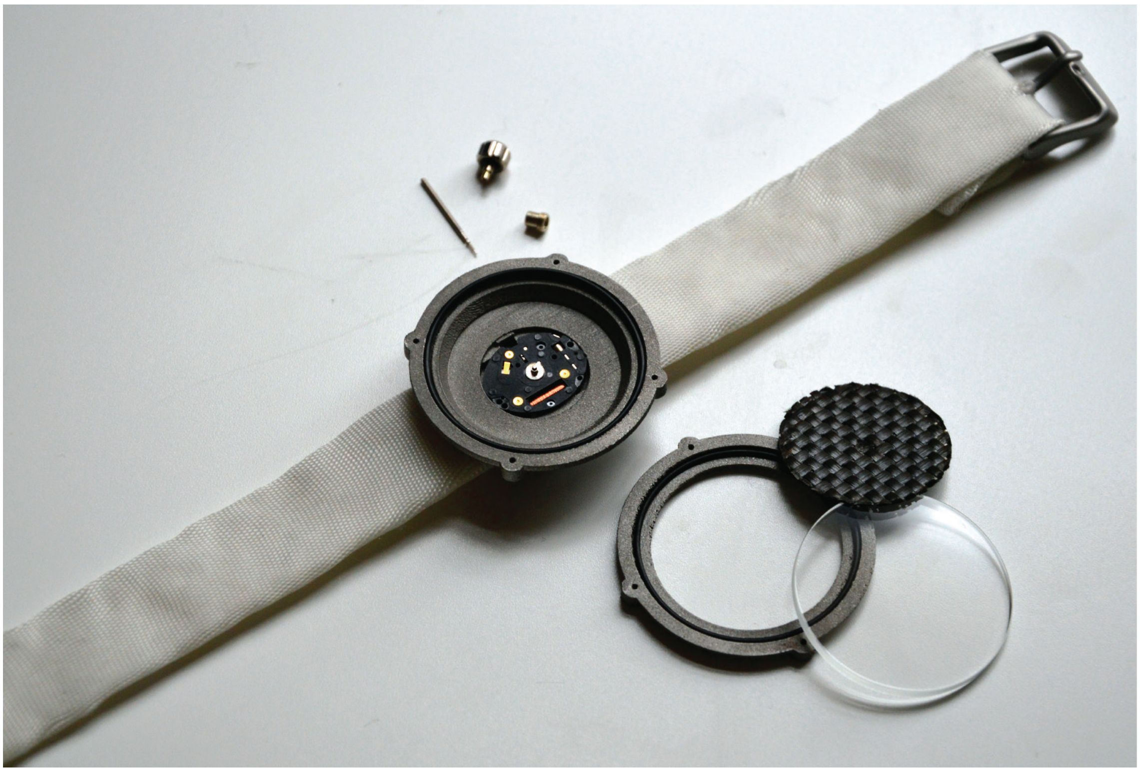


Figure E.86: Movement and O-rings in place.

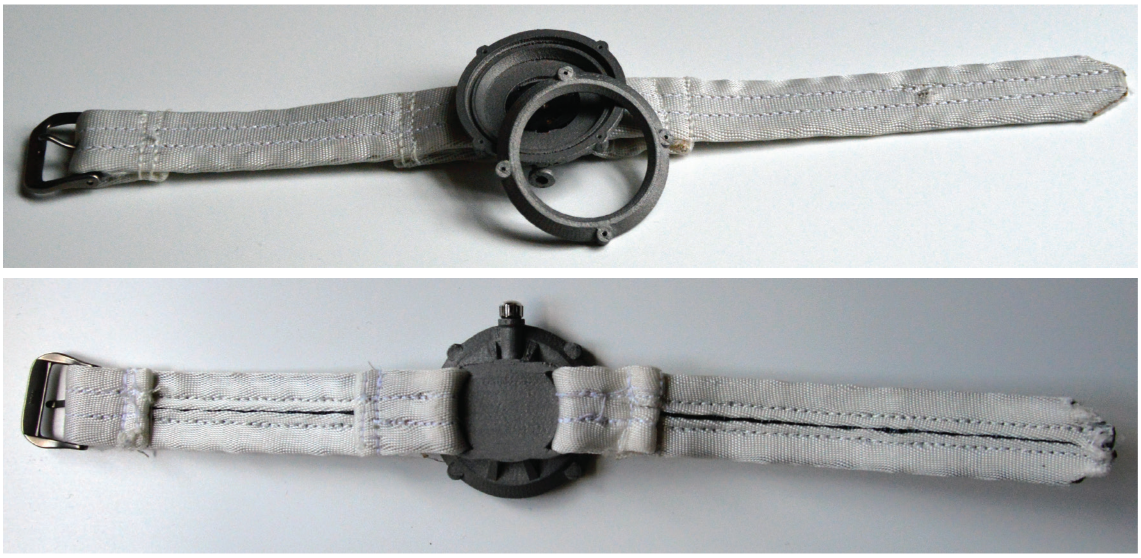


Figure E.87: Second prototype with the sewn band and the movement in place.

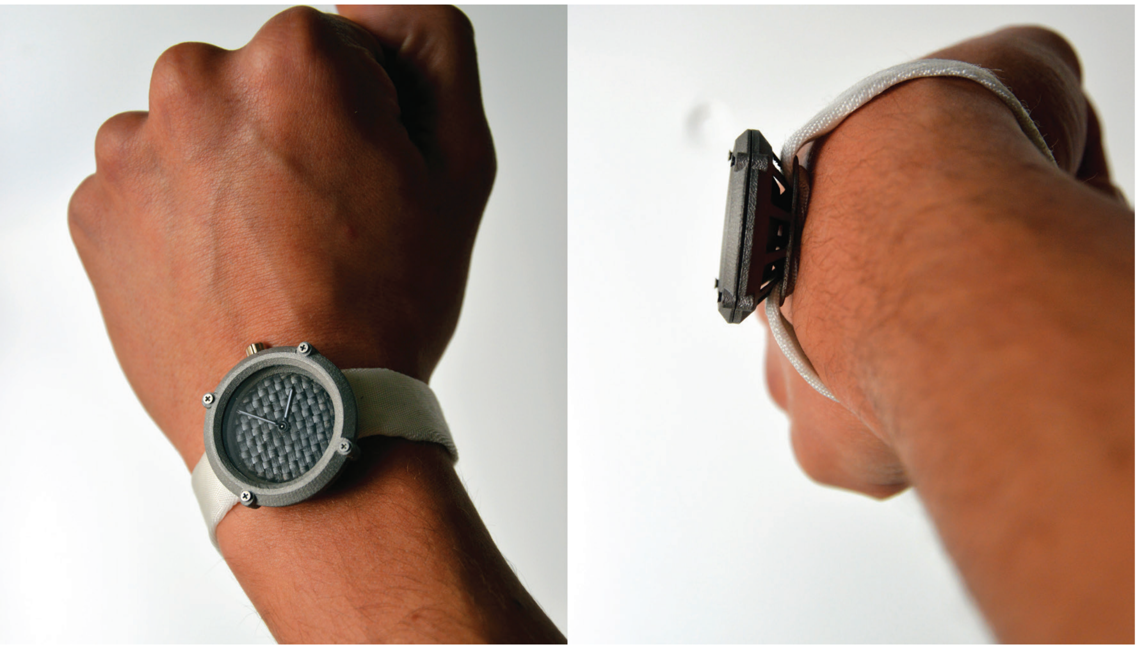


Figure E.88: (left) The watch fits comfortably on the wrist, as tested and reported by Julian. (right) Side view of the watch, elevating from the wrist.

Figure E.89: Finalized assembled prototype watches.

E.6. Additional Artifacts in Support of My Research Experience at RCA

This Appendix sub-section provides examples of additional artifacts, which were inspired by my research. Objectifying research concepts helped with the abstraction of theoretical ideas. Creating them also contributed to my learning and making experiences.

Figure E.90: Collection of artifacts displayed on a mantelpiece.

Figure E.91: "Crossing the Perceptional Boundary" artifact (CNC machined out of walnut wood, 2015).

E.6.1. "Crossing the Perceptional Boundary" Artifact

The top half in Figure E.91 represents the real world with infinite variety. It is symbolized by a perfect circle and a high resolution terrain. The rugged terrain on the lower half, and the heptagon are the cognitive models of the terrain and the circle from the environment, but at lower fidelities. The horizontal line in the middle is the perceptional boundary, where information from the environment enters through the 5 sense organs. The 5 small circles indicate sense-information crossing the boundary from the environment. After cognitive processing, the response is language. It is shown as the small heptagon on the left side, crossing over to the environment side. This also represents a circular dialog between the regulator and the environment.

The model was generated in Blender3D, then CNC machined out of wood (walnut) from the STL file at RCA's Digital Aided Making facility. Post-treated with Danish oil. The artifact is H15cm x W8cm x D3cm.

E.6.2. “Visual Perception Error of Self” Artifact

Our cognition interprets incoming visual information by circular guessing between that and our cognitive model. Visual perception error occurs when our cognitive model misinterprets the incoming signals, as demonstrated through a concave face.

From a 3D scan of myself I have generated a block imprint 3D model (STL) in Blender3D, using a Boolean operator. Subsequently the model was CNC machined out of maple wood at RCA DAM. The face is CNC machined into both sides, with the nose points almost touching. This also represents a circular dialog with the self. The artifact is H13.3cm x W9.5cm x D7.4cm.

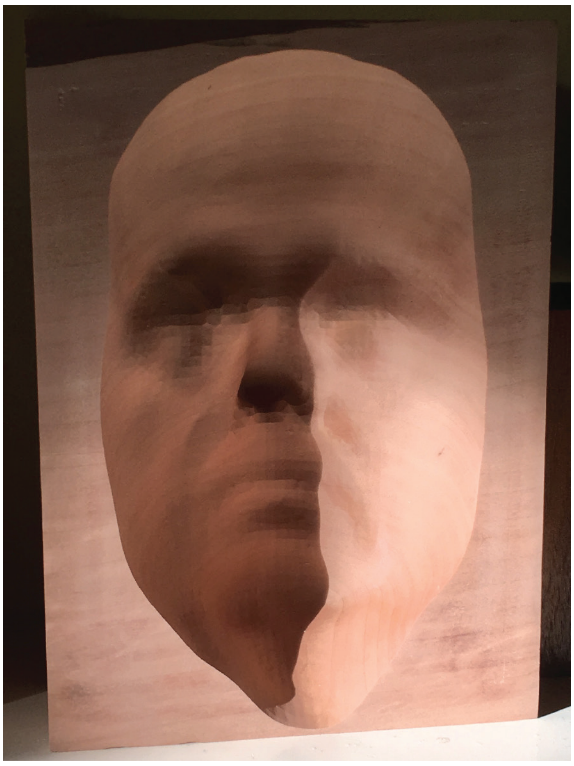


Figure E.92: “Visual Perception Error of Self” artifact (CNC machined out of maple wood, 2015).

E.6.3. “Abstracted Terrain” Artifact

As we observe the environment, we develop our cognitive model of it. The better the coherence between our model and the environment, the better is our understanding of it. The lower refined terrain was recreated in two increasingly coarser versions above it.

I have generated the initial mesh in Blender3D with a wave displacement modifier, the in two subsequent steps re-discretized it with the remesh modifier. The generated STL file was used to CNC machine the artifact out of a recycled mahogany shelf at RCA’s DAM. The artifact is H38cm x W11.5cm x D2cm.

Figure E.93: “Abstracted Terrain” artifact (CNC machined out of recycled mahogany wood, 2015).

E.6.4. “Stacked Aeroshells in Negative Space” Artifact

Aeroshells are used during planetary entries to protect the payload. This artifact is a follow on to the IPPW10 poster image (see Figure E.5), but in a physical form instead of computer graphics I used to make the poster. Beside the visual perception demonstration, it combines engineering precision with artistic expression, and symbolizes the lack of current probe missions due to funding constraints and resource prioritization. The represented aeroshell shapes from the top down are: Hayabusa (JAXA); Galileo and Pioneer-Venus (NASA); a generic aeroshell shape; Phoenix (NASA); ARD—Atmospheric Reentry Demonstrator (ESA); and Huygens (ESA) with missing rim due to machining limitations.

I have generated the initial STL mesh in Blender3D. It was CNC machined out of butternut wood at RCA’s DAM. The artifact is H16cm x W3.5cm x D2.8cm.

Figure E.94: “Stacked Aeroshells in Negative Space” artifact (CNC machined out of butternut wood, 2015).

Figure E.95: “Iroquois War Club” artifact (CNC machined out of rose wood, 2015).

E.6.5. “Iroquois War Club” Artifact

I have made the model of an Iroquois war club in Blender3D, based on a photo I took at the Smithsonian American Art Museum in Washington DC. The scale of my artifact is about 60% of the original.

The model was CNC machined out of rose wood at RCA’s DAM. This exercise allowed me to learn about creating 3D objects through two-sided machining. During the making I have decided to keep the object in this shown artificial frame. To this end, we enlarged the supporting beams to become holding features of the integrated object, which now includes the war club, the frame, and the support beams. The model was angled and tilted relative to its frame. The final artifact was treated with Danish oil. The artifact is H25cm x W7.5cm x D4.4cm.

E.6.6. “Black Hole / Letter Opener” Artifact

The letter opener also started out from my 3D scanned image. After manipulating the 3D model in Blender3D with displacement modifiers, the result was a skewed yet recognizable image. This bust was CNC machined at RCA’s DAM using a 4-axis setup. This recycled oak artifact is H22cm x D5.5cm. The final finish is done with Danish oil. (See Figure E.96.)

Its narrowed chest and shoulder areas gave me the idea to expand the model further into a blade. In effect, converting the model into a letter opener, where becomes head is the handle.

After consultations we have decided to created a 3D printed wax model at RCA Jewelery, then complete the bronze artifact at RCA Sculptures. The making process is discussed below in the related figures.

The final letter opener gives the illusion of being sucked into a black hole, thus providing an alignment with the space theme of my research. It is also both a personal and a usable item. Each final bronze artifact is about 22cm long and weights 0.25kg.

Figure E.96: “Skewed wooden bust of self” artifact (CNC machined out of recycled oak wood, 2015).

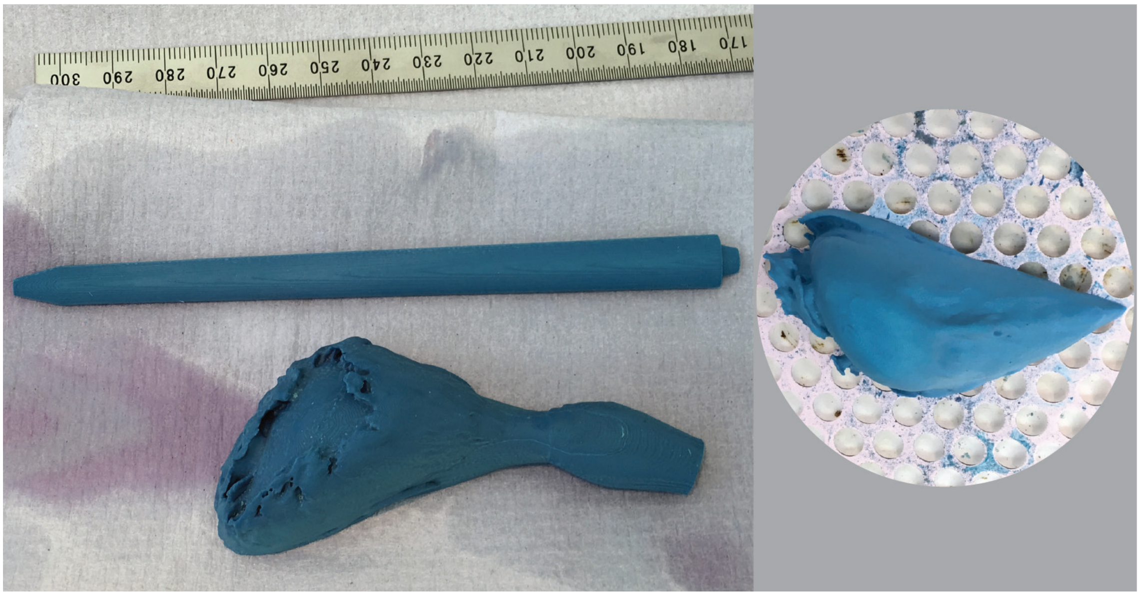


Figure E.97: Wax 3D printed parts of the letter opener.

Figure E.98: The assembled wax master model.

Figure E.99: Silicone mold making steps, creating two halves.

Figure E.100: Final silicone mold, showing the inlet for the liquid wax.

Figure E.101: Ceramic shells with cement fixes of cracks after melting out the wax.

Figure E.102: Illustration of the correspondence between the patinated bronze and oak versions.

Figure E.103: The 8 letter openers after sand blasting, but prior to patination.

Figure E.104: Dark patinated version.

Figure E.105: “Black Hole / Letter Opener” artifact closeup.

Figure E.106: Closeup of dark and green patinated artifacts.

Appendix F: Interviews & Documentary

Approach

To better understand the current state of practice (SoP) at NASA, as related to human centered design for human and robotic space exploration I have conducted semi-structured interviews with practitioners from all levels. These ranged from strategic managerial levels down to project levels, where practitioners implemented these approaches. To conduct the interviews—including filming them—I have collaborated with Oliver Lehtonen, who graduated from the RCA IDE Masters program in 2016.

We sat down with visionary decision makers and practitioners to conduct semi-structured interviews at three locations, namely at NASA Headquarters (HQ) in Washington DC; NASA Johnson Space Center (JSC) in Houston, TX; and at the Jet Propulsion Laboratory (JPL) in Pasadena, CA. These NASA Centers were selected for their strategic relevance for human centered design (HCD). While most of the interviews were prearranged, upon recommendations during these interviews we followed up on opportunities to conduct additional interviews in relevant topic areas. Inversely, due to the limited time spent at each NASA Center, a number of planned interviews had to be canceled, as the experts were on travel.

With an HCD focus, we conducted and documented these interviews around four main themes, related to the current state of practice (SoP) and future possibilities in the areas of:

- HCD for space architectures and habitats, from trans–habs to surface habitats, and mission architectures, including NASA's Human Research Program (HRP);
- HCD approaches for robotic exploration of space;
- HCD approaches for design environments; and
- HCD conversations to communicate NASA's message to stakeholders, including science, engineering, design and art.

Our trip itinerary in 2015 was as follows:

- September 7-9: Washington DC;
- September 10-13: Houston, TX;
- September 14-19: Pasadena, CA.

For the filming of the footage for our self-funded documentary, we purchased and carried two very light hand-held DSLR cameras, a digital audio recorder, three tripods, and a portable LED light. This configuration required minimal equipment setup time, and virtually no baggage volume beyond hand carried bags.

The planned duration of the interviews for the raw footage was about 30-60 minutes per person to be interviewed, dependent on time availability. I have used the synthesized information from the interviews in this thesis.

We are also working on an independent, self-funded documentary, based on these interviews. Additional public domain NASA footage, related to human spaceflight and human activities in space, will be added for B-Rolls. This student documentary will be edited and finalized in 2016. It is primarily targeting the design, architecture and art community, but we are planning to make it broadly accessible, dependent on the approval processes.

NASA Headquarters

At NASA HQ we conducted 30-to-60 minutes semi-structured interviews with:

Doug Craig (HEOMD Manager of Strategic Analyses within the AES Division): about NASA's Evolvable Mars Campaign and human space exploration mission design reference architectures.

Steve Davison (HEOMD Human Research Program (HRP) Manager): on space life– and physical–sciences, specifically related to the Human Research Program.

Jason Derleth (STMD NASA Innovative Advanced Concepts (NIAC) Program Executive (PE)): about his views related to early stage technology project developments, specifically under NIAC.

Brett Depenbrock (STMD Resource Management Office (RMO) Analyst from Booz Allen Hamilton (BAH)): about organizational processes, and strategic level project assessments.

Dr. Jay Falker (Space Technology Mission Directorate (STMD), Early Stage Portfolio Executive): about his views related to early stage technology project developments, including advanced concepts under NIAC, university collaborations under Space Technology Research Grants, and internal feasibility developments under Center Innovation Funds.

John Guidi (HEOMD AES Deputy Program Director): about AES activities related to human centered design, future habitat designs; Deep Space Habitation; Vehicle Systems; Analogs and integrated testing; the AES Z-1; the Bigelow inflatable module demo, leading to commercial spaceflight; and public outreach.

Dr. Chris Moore (Human Exploration and Operations Mission Directorate (HEOMD) Advanced Exploration Systems (AES) Division Deputy Program Director): about AES activities related to human centered design, such as the universities-based X-Hab projects for future habitat designs; Deep Space Habitation; Vehicle Systems; Analogs and integrated testing; Additive Manufacturing; the AES Z-1 Space Suit design considerations, including user perspectives and outreach activities; the Bigelow inflatable module demo, leading to commercial spaceflight; and public involvement through TopCoder.

Jenny Mottar (SMD Graphic Designer): the roles of graphic design, installations, and visual communications at NASA.

Alice Sarkisian Wessen (Science Mission Directorate (SMD) Outreach Manager): on the roles of outreach at NASA.

These interviews at NASA HQ were conducted on September 8 (Tuesday) and 9 (Wednesday), 2015

Additional activity while in Washington DC—on September 7, Monday—included filming at the Air and Space Museum for potential supplementary/B–Roll footage.

NASA Johnson Space Center (JSC)

At NASA JSC we conducted 30–to–60 minutes interviews with:

Dr. Robert Ambrose (NASA JSC Robotics Program Director): talked about human interactions and human robotics, from Robonaut 2 to Valkyrie, and living and working in a close environment between humans and robots.

Dr. Bill Bluethmann (NASA JSC Robotics Deputy Program Director): took a guided tour of the robotics laboratory where we were given explanations about design considerations for humanoid robots and mobile surface space habitats.

Dr. Robert Howard (NASA JSC Habitability Design Center Manager): heard about human centered designs, habitats, ergonomics, and how these are considered today, and in the future.

Kriss Kennedy (NASA JSC Space Architect, Human Health & Performance Directorate): discussed human centered approaches for the commercial crew program; CisLunar Habitat Systems; human health and performance; space habitats; space architecture as a discipline; space vs. terrestrial architecture; human centered design; current state of practice, future possibilities.

Larry Toups (NASA JSC Exploration Missions & Systems Office): discussed human centered approaches for space habitats on long–duration human missions, space architecture as a discipline, analogs, current state of practice, future possibilities.

Dr. Mihriban Whitmore (NASA JSC Manager of the Usability Testing and Analysis Facility; Space Human Factors & Habitability Elements Scientist): heard about the Human Research Program at NASA, and human centered considerations in the past, present and future.

Our dates at NASA JSC for these interviews were September 10 (Thursday) and 11 (Friday), 2015; External interview while in Houston:

Prof. Olga Bannova (Research Associate Professor, Sasakawa International Center for Space Architecture (SICSA), University of Houston): we discussed human centered space architectures and design approaches.

NASA Jet Propulsion Laboratory (JPL)

At JPL we conducted 30-to-60 minutes interviews with:

Liz Barrios (JPL, Studio, Visual Strategist & Graphic Designer at the JPL Studio): described her activities from supporting outreach, visual communications, and the Innovation Foundry's design environment.

Kelley Case (JPL, Innovation Foundry Concept Shop Lead): described the structure of JPL's Innovation Foundry, and its processes; from the A–Team to Team–X.

Dr. Scott Davidoff (JPL, Human Interfaces for Mission Operations Manager): discussed human-machine interfaces, visualization, and human centered design at JPL.

David Delgado (JPL, Studio, Visual Strategist, Designer & Artist): gave examples of his space-theme artwork, including the retro-futuristic travel posters, and other visual communications done through JPL's Design Studio.

Dr. Anthony Freeman (JPL, Manager of the Innovation Foundry): provided his strategic views and implementations related to the roles of design, design dialogs, and communications to advance Foundry activities.

Dan Goods (JPL, Studio Lead, Visual Strategist, Designer & Artist): related to his activities from supporting outreach, visual communications, and the design environment.

Dr. Keith Grogan (JPL, Innovation Foundry Proposal Shop Lead): discussed the proposal development processes and structure under JPL's Innovation Foundry.

Dr. Scott Howe (JPL, Space architect): described human centered considerations and future directions related to human space architectures and habitats.

Jessie Kawata (JPL, Innovation Foundry Creative Strategist and Industrial Design Lead): described her activities from supporting outreach, visual communications, and the Innovation Foundry's design environment (e.g., the A–Team).

Lois Kim (JPL, Studio, Visual Strategist & Graphic Designer at the JPL Studio): discussed her activities from supporting outreach, visual communications, and the Innovation Foundry's design environment.

Brent Sherwood (JPL, Solar System Mission Formulation Manager and space architect): discussed the roles of human centered design from robotic missions to human missions.

Dr. Tom Soderstrom (JPL, Chief Technology Officer (CTO)): described the roles of human centeredness from an information technology point of view.

Dr. Randii Wessen (JPL, A–Team Study Lead): explained his work with the A–Team, and with Hollywood, advising artists and designers on space exploration technologies, concepts and architectures.

Brian Wilcox (JPL, Robotics Manager): discussed human centered robotics, planetary robotics, space habitats and related developments at JPL and NASA.

John Ziemer (JPL, A–Team Lead, Innovation Foundry): outlined the human centered design processes in a technology and engineering focused design environment.

These interviews at JPL were performed between September 14 (Monday) and 18 (Friday), 2015.

An additional outside interview was conducted at the **California Institute of Technology** with:

Prof. Hillary Mushkin (Caltech, Visiting Professor of Art and Design): on the roles and importance of Data Visualization and design.

Coordinating the interviews and navigating through NASA approval processes for Oliver's access to NASA Centers was a logistics challenge. Getting through the forms and approvals benefited greatly from the help of Robin Hood, Rose Gardner, and Kim Butler at NASA HQ; Andre Sylvester, Brittany Kimball, and Davis Moyer at NASA JSC; and Phyllis Zambrano at JPL.

Summary Statistics

We have conducted **32 interviews at 3 NASA Centers**, specifically:

- 9 at NASA Headquarters;
- 6 at NASA Johnson Space Center;
- 1 at the University of Houston, Sasakawa International Center for Space Architecture (SICSA);
- 15 at the Jet Propulsion Laboratory; and
- 1 at the California Institute of Technology.
- The interviews covered activities at all 3 space related Mission Directorates, namely HEOMD, SMD, and STMD, but not included the fourth—Aeronautics—as it has no connection to this research topic.

Table F.1 lists the interview participants, their positions, and how their subject matter expertise maps into the four research topic areas. The mapping demonstrates that all of the topic areas were well covered through multiple interviews.

We have taken additional footage at the Air and Space Museum in Washington DC; the robotics and human factors laboratories at JSC; at JSC's Rocket Park; and at various public sites at the Jet Propulsion Laboratory. We have filmed over 20 hours of high definition video footage with each of the two cameras, and took matching digital sound recordings.

Interview Participants	Positions & Affiliations	Humanly Space Habitats & Architectures	Human Centered Robotics	Humanly Design Environments	Design Dialogs, Communications & Arts
NASA Headquarters (HQ), Washington DC					
Dr Jay Falker	STMD Early Stage Portfolio Manager	X	X		X
Jason Derleth	STMD NIAC Program Executive	X	X		
Brett Depenbrock	STMD Resource Management Office (from BAH)				X
Dr. Chris Moore	HEOMD AES Deputy Manager	X	X		
John Guidi	HEOMD AES Deputy Manager	X	X		
Doug Craig	HEOMD Architectures Manager	X			
Steve Davison	HEOMD Human Research Program Manager	X			
Jenny Mottar	SMD Graphic Design / Outreach				X
Alice Sarkisian Wessen	SMD Outreach				X
NASA Johnson Space Center (JSC), Houston, TX					
Dr. Rob Ambrose	JSC Robotics Program Director		X	X	
Dr. Bill Bluethmann	JSC Robotics Deputy Program Director		X	X	
Robert Howard	JSC Habitability & Human Factors	X		X	
Dr. Mihriban Whitmore	JSC Human Research Program	X			
Larry Toups	JSC Space Architectures	X			X
Kriss J. Kennedy	JSC Space Architect, Human Health & Perf. Directorate	X			X
University of Houston, Sasakawa International Center for Space Architecture (SICSA), Houston, TX					
Prof. Olga Bannova	Space Architect, Research Associate Prof. at SICSA	X			X
NASA Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA					
Dan Goods	NASA Visual Strategist—JPL Design Studio Lead				X
David Delgado	JPL Design Studio—Designer & Artist				X
Liz Barrios	JPL Design Studio—Graphic Designer			X	X
Lois Kim	JPL Design Studio—Graphics & Motion Designer			X	X
Jessie Kawata	JPL Innovation Foundry—Industrial Design Lead			X	X
Dr. Anthony Freeman	JPL Innovation Foundry Manager			X	X
Dr. Keith Grogan	JPL Innovation Foundry—Proposals & Processes			X	X
Kelley Case	JPL Innovation Foundry—Teams & Processes			X	X
John Ziemer	JPL Innovation Foundry—A-Team Lead			X	X
Dr. Randii Wessen	JPL A-Team Study Lead / Systems Engineer	X		X	X
Dr. Scott Howe	JPL Space Architect and Designer	X		X	X
Brent Sherwood	JPL Solar System Exploration Manager & Architect	X			X
Dr. Scott Davidoff	JPL Human Interfaces & Mission Ops. Manager	X		X	X
Brian Wilcox	JPL Robotics Manager		X		
Dr. Tom Soderstrom	JPL Chief Technology Officer			X	X
California Institute of Technology, Pasadena, CA					
Prof. Hillary Mushkin	Caltech, Visiting Professor of Art and Design				X

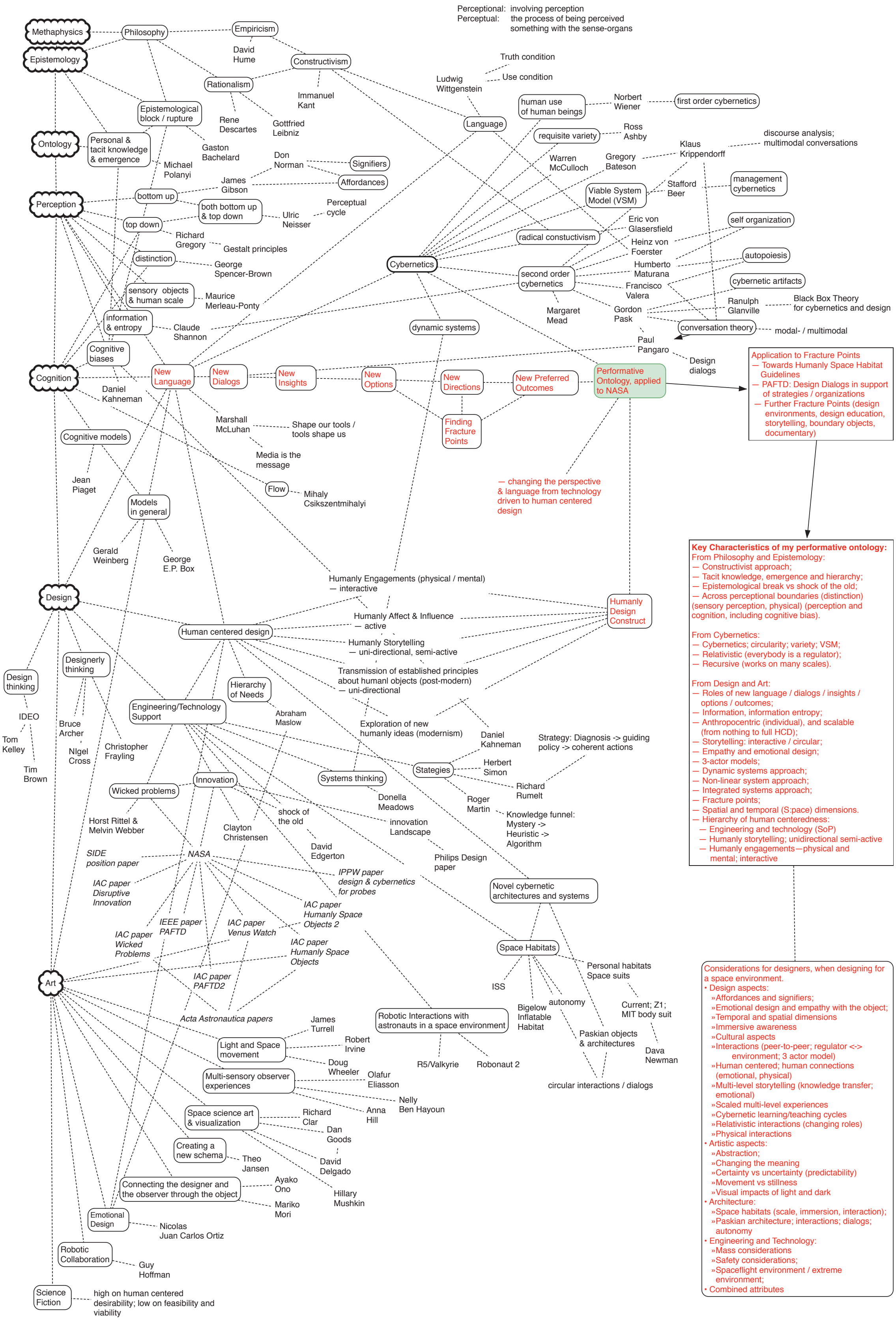
Table F.1: Interview participants, their positions and subject matter expert topic areas.

Appendix G: Mapping of the Research Domain

Design Space for Space Design —
Humanly {S:pace} Constructs Across Perceptional Boundaries

by Tibor Balint, RCA-IDE Research   PhD Research / Model development   Updated: March 2, 2016

— Performative ontological exploration of a cybernetics-based recursive framework in support of novel languages, to reshape discourses, leading to preferred outcomes, as applied at fracture points within NASA's paradigm



Perceptional: involving perception
Perceptual: the process of being perceived
something with the sense-organs

Methaphysics
Epistemology
Ontology
Perception
Cognition
Design
Art

Philosophy
Empiricism
David Hume
Constructivism
Rationalism
Immanuel Kant
Rene Descartes
Gottfried Leibniz
Epistemological block / rupture
Gaston Bachelard
Personal & tacit knowledge & emergence
Michael Polanyi
Don Norman
Signifiers
Affordances
James Gibson
bottom up
both bottom up & top down
top down
Ulric Neisser
Perceptual cycle
Richard Gregory
Gestalt principles
distinction
George Spencer-Brown
sensory objects & human scale
Maurice Merleau-Ponty
information & entropy
Claude Shannon
Cognitive biases
Daniel Kahneman
Cognitive models
Jean Piaget
Models in general
Gerald Weinberg
George E.P. Box

Ludwig Wittgenstein
Truth condition
Use condition
Language
human use of human beings
Norbert Wiener
first order cybernetics
requisite variety
Ross Ashby
Warren McCulloch
Gregory Bateson
Klaus Krippendorff
discourse analysis; multimodal conversations
Viable System Model (VSM)
Stafford Beer
management cybernetics
radical constuctivism
Eric von Glasersfield
self organization
Heinz von Foerster
Cybernetics
second order cybernetics
Humberto Maturana
autopoiesis
Francisco Valera
cybernetic artifacts
Margaret Mead
Gordon Pask
Ranulph Glanville
Black Box Theory for cybernetics and design
conversation theory
modal- / multimodal
Paul Pangaro
Design dialogs
dynamic systems

New Language
New Dialogs
New Insights
New Options
New Directions
New Preferred Outcomes
Finding Fracture Points
Performative Ontology, applied to NASA

Application to Fracture Points
- Towards Humanly Space Habitat Guidelines
- PAFTD: Design Dialogs in support of strategies / organizations
- Further Fracture Points (design environments, design education, storytelling, boundary objects, documentary)

Marshall McLuhan
Shape our tools / tools shape us
Media is the message
Flow
Mihaly Csikszentmihalyi

— changing the perspective & language from technology driven to human centered design

Key Characteristics of my performative ontology:
From Philosophy and Epistemology:
- Constructivist approach;
- Tacit knowledge, emergence and hierarchy;
- Epistemological break vs shock of the old;
- Across perceptional boundaries (distinction) (sensory perception, physical) (perception and cognition, including cognitive bias).

From Cybernetics:
- Cybernetics; circularity; variety; VSM;
- Relativistic (everybody is a regulator);
- Recursive (works on many scales).

From Design and Art:
- Roles of new language / dialogs / insights / options / outcomes;
- Information, information entropy;
- Anthropocentric (individual), and scalable (from nothing to full HCD);
- Storytelling: interactive / circular;
- Empathy and emotional design;
- 3-actor models;
- Dynamic systems approach;
- Non-linear system approach;
- Integrated systems approach;
- Fracture points;
- Spatial and temporal (S:pace) dimensions.
- Hierarchy of human centeredness:
  - Engineering and technology (SoP)
  - Humanly storytelling; unidirectional semi-active
  - Humanly engagements—physical and mental; interactive

Humanly Engagements (physical / mental)
— interactive
Humanly Affect & Influence
— active
Humanly Storytelling
— uni-directional, semi-active
Transmission of established principles about humanl objects (post-modern)
— uni-directional
Exploration of new humanly ideas (modernism)
Humanly Design Construct
Human centered design

Design thinking
IDEO
Tom Kelley
Tim Brown
Designerly thinking
Bruce Archer
NIgel Cross
Christopher Frayling
Engineering/Technology Support
Hierarchy of Needs
Abraham Maslow
Daniel Kahneman
Strategy: Diagnosis -> guiding policy -> coherent actions
Stategies
Herbert Simon
Richard Rumelt
Roger Martin
Knowledge funnel:
Mystery ->
Heuristic ->
Algorithm
Systems thinking
Donella Meadows
Innovation
Wicked problems
Horst Rittel & Melvin Webber
Clayton Christensen
shock of the old
David Edgerton
innovation Landscape
Philips Design paper

NASA
SIDE position paper
IAC paper Disruptive Innovation
IAC paper Wicked Problems
IEEE paper PAFTD
IAC paper Venus Watch
IAC paper PAFTD2
IPPW paper design & cybernetics for probes
IAC paper Humanly Space Objects 2
IAC paper Humanly Space Objects
Acta Astronautica papers

Novel cybernetic architectures and systems
Space Habitats
ISS
Bigelow Inflatable Habitat
autonomy
Personal habitats Space suits
Current; Z1; MIT body suit
Dava Newman
Paskian objects & architectures
circular interactions / dialogs
Robotic Interactions with astronauts in a space environment
R5/Valkyrie
Robonaut 2

Light and Space movement
James Turrell
Robert Irvine
Doug Wheeler
Multi-sensory observer experiences
Olafur Eliasson
Nelly Ben Hayoun
Anna Hill
Space science art & visualization
Richard Clar
Dan Goods
David Delgado
Hillary Mushkin
Creating a new schema
Theo Jansen
Connecting the designer and the observer through the object
Ayako Ono
Mariko Mori
Emotional Design
Nicolas Juan Carlos Ortiz
Robotic Collaboration
Guy Hoffman
Science Fiction
high on human centered desirability; low on feasibility and viability

Considerations for designers, when designing for a space environment.
- Design aspects:
  - »Affordances and signifiers;
  - »Emotional design and empathy with the object;
  - »Temporal and spatial dimensions
  - »Immersive awareness
  - »Cultural aspects
  - »Interactions (peer-to-peer; regulator <-> environment; 3 actor model)
  - »Human centered; human connections (emotional, physical)
  - »Multi-level storytelling (knowledge transfer; emotional)
  - »Scaled multi-level experiences
  - »Cybernetic learning/teaching cycles
  - »Relativistic interactions (changing roles)
  - »Physical interactions
- Artistic aspects:
  - »Abstraction;
  - »Changing the meaning
  - »Certainty vs uncertainty (predictability)
  - »Movement vs stillness
  - »Visual impacts of light and dark
- Architecture:
  - »Space habitats (scale, immersion, interaction);
  - »Paskian architecture; interactions; dialogs; autonomy
- Engineering and Technology:
  - »Mass considerations
  - »Safety considerations;
  - »Spaceflight environment / extreme environment;
- Combined attributes

Glossary

Analogs: During the development cycle, subject matter experts (SME) build mockups and prototypes to demonstrate feasibility. Prototypes become analogs when they are put into simulated operational scenarios. Analogs refer to full systems instead of stand-alone artifacts. Under NASA's HEOMD terrestrial analogs are important to gain experiences for operational scenarios, logistics, group dynamics, and co-habitation, among others. (See also Mockup and Prototype.)

A-Team: Under JPL's Innovation Foundry the Concept Shop consists of two project development teams, the A-Team and Team X. At the lowest Concept Maturity Levels (CML 1 to 3), the activities of the A-Team range from ideation, through initial feasibility studies, to trade space exploration (Ziemer, 2015)(Case, 2015)(Freeman, 2015). (See also Team X.)

Autopoiesis: The term was introduced in 1972 by two Chilean biologists, Humberto Maturana and Francisco Varela (Maturana & Varela, 1980, pp.xvii-xxiv). While their originally used it to define self-maintaining biological systems at the cell level, the concept has been adopted by other disciplines including sociology, systems theory, and cybernetics. They invented the term after stating: *"If indeed the circular organization is sufficient to characterize living systems as unities, then one should be able to put it in more formal terms." "…a formalization can only come after a formal linguistic description… yet we were unhappy with the expression 'circular organization,' and we wanted a word that would by itself convey the central feature of the organization of the living, which is autonomy." "…analyzed Don Quixote's dilemma of whether to follow the path of the arms (praxis, action) or the path of the letters (poiesis, creation, production)…" "I (Maturana) understood for the first time the power of the word 'poiesis' and invented the word that we needed: autopoiesis."* According to Maturana and Varela, unity, organization, structure, structural coupling, and epistemology define an autopietic system. It is an observer-dependent approach to cognition, in line with second-order cybernetics. In connection with design and design education, Dubberly and Pangaro (Dubberly & Pangaro, 2010, p.9) described autopoiesis as: *"One of the great challenges facing the design profession is how it can create sustained learning about design practice. In recent years, several universities have begun to grant PhDs in design, but design research is still young and relatively unformed. The feedback systems necessary to sustain it are not yet in place. Designers need a self-sustaining, learning system whose components make and re-make itself: the curricula must contain 'the practice' while also capturing processes that learn while also sustaining those that already exist. Inherent in the seven cybernetic frameworks are mechanisms to make such activities explicit for the design community and for the institutions (schools, consulting studios, and corporate design offices) that support it."* (See also Cybernetics and Viable System Model.)

Bottom up theory: One of the key considerations of perception and cognition is to identify if perception of our phenomenal world relies on a) information received directly through the bodily sensors, or b) if previous knowledge by the person and expectations also adds to the cognitive interpretation. James J. Gibson, the American psychologist, proposed a direct "bottom up" theory of perception, discussing it under "the optical information for perceiving affordances" in (Gibson, 1986, p.40). His theory of direct visual perception is detailed in Chapters IX to XII related to vision (Gibson, 1966, pp.154-255). This approach

is data driven, and linearly unidirectional through visual processing, and it initiates with the sensory stimulus. For example, when objects are superimposed, one of the observed objects blocks the view of another; or the relative sizes of the same type of objects change as we move them to different distances from the eyes.
(See also "Top down theory.")

Boundary objects: The term was originally introduced under social sciences by Susan Leigh Star and James R. Griesemer (Leigh Star & Griesemer, 1989, p.388). These objects are simultaneously: concrete and abstract; specific and general; conventionalized and customized. Boundary objects are often internally heterogeneous. Leigh Star and Griesemer have identified four types of boundary objects. For the first type, they used the example of a museum curator, who collected objects from a broad set of contributors with different backgrounds. The curator set the rules for the collectable objects, and then derived theories from them. We can look at this as a reflective practice, where the initial set of rules bound the derivable theories. The second type of boundary object is an "ideal type," which consists of an abstracted object, such as a map. It can have meanings to multiple user groups. It can be used by tourists, experts, geologists and others, which all are using the same symbolic representation and abstraction. The third type refers to coincident physical boundary, for example the boundary of California, where the object collectors all operate within its perimeters. The fourth type refers to standardized forms, which helps communications between the participants. For example, this may refer to common interfaces between spacecraft designs, where both NASA and ESA are developing subsystems, which are connected through a standard connection at their interface boundary. Leigh Star and Griesemer were interested in boundary objects, which contained different elements or aspects in different worlds, considered magical to those worlds. They called them boundary objects, where the mismatch, caused by the overlap between worlds (or disciplines) becomes the problem space for negotiations. The conflict resolution could be done by oscillating across the boundaries of the disciplines, and in the process forming a new social world. Subsequently, the object forms a common boundary between the worlds, inhabiting them simultaneously. In a cybernetic sense, a common meaning is constructed through conversations between the disciplines. In this PhD thesis I am proposing to expand Leigh Star and Griesemer's boundary object types through an approach that is similar to Christopher Frayling's categorization of design (Frayling, 1993, p.5). When we apply Frayling's approach to boundary objects, communications, and conversations, we can describe them as: communications ABOUT boundary objects; Boundary objects FOR communications; and design conversations THROUGH boundary objects. I am also proposing a distinction between first-order and second-order boundary objects, referring to static and evolving boundary objects throughout the conversations across disciplines. (See Section 7.)

Co-evolutionary design: Developed by Paul Pangaro (Pangaro, 2010), with influences from Hugh Dubberly, Heinz von Foerster, and Michael Geoghegan, this model discusses design conversations between four conversationally and circularly interconnected elements. These elements are: (a) a conversation to agree on the goals; (b) a conversation to agree on the means; (c) a conversation to design the designing; and (d) a conversation to create a new and shared language with agreed upon meanings.

Cognitive bias: represents a subjective "noise" which influences the interpretation of the received message (Kahneman, 2013, p.1059/1307). According to Wikipedia, it refers to a systematic pattern of deviation from norm or rationality in judgment, whereby inferences about other people and situations may be drawn in an illogical fashion. Individuals create their own "subjective social reality" from their perception of the input.

Cognitive dissonance: represents a state of having inconsistent thoughts, beliefs, or attitudes, especially as relating to behavioral decisions and attitude changes, according to Wikipedia. Cognitive dissonance (Festinger, 1957) and cognitive bias (Kahneman, 2013, p.1059/1307) can lead to an epistemological obstacle or block (Idlas, 2011, p.8), making changes difficult or at times impossible without new information—or in a cybernetic sense, without increasing the regulator's variety.

Concept Maturity Level (CML): The framework for the activities at JPL's Innovation Foundry is the Concept Maturity Level (CML) scale (Wessen, 2013) for mission formulation concept studies. The CML scale covers the phases of mission concept formulation from "cocktail napkin" to Preliminary Design Review (PDR). It is part of JPL's formulation approach and embraced by NASA SMD's Planetary Science Division (PSD). In simple terms the CML phases are: 1) Cocktail napkin; 2) Initial feasibility; 3) Trades space; 4) Preferred design point within trade space; 5) Concept baseline; 6) Initial design; 7) Preliminary integrated baseline; 8) PDR. The CML scale for such concepts aligns with the well-known Technology Readiness Level (TRL) scale for technologies (Mankins, 1995).

Constructivism: represents a position about the nature of knowledge. The theory of cognition and human intelligence development was first constructed by Jean Piaget, a Swiss developmental psychologist (Piaget, 1952, pp.357-417) (Singer & Revenson, 1996, pp.1-11). Through a constructivist approach Piaget theorized that knowledge is developed gradually, in stages, and by constructing and understanding of the world through sensory experiences and interactions. Furthermore, alignments and discrepancies with building blocks of intelligent behavior and knowledge (schemata) influence interpretation and learning. Our cognitive model of the world is personal, in line with von Glasersfeld's radical constructivist model (von Glasersfeld, 1984, pp.17-40) (von Glasersfeld, 2001, pp.31-43). According to von Glasersfeld: *"Constructivism necessarily begins with the (intuitively confirmed) assumption that all cognitive activity takes place within the experiential world of a goal-directed consciousness"* (von Glasersfeld, 1984, p.10). We construct and refine meanings through conversation loops. The conversation may continue until a commonly agreed understanding is constructed.

Conversation Theory: was proposed by Gordon Pask in the 1970s (Pask, 1976, p.27). It is a cybernetic framework that uncovers meaning through conversations. Through this scientific theory knowledge is constructed. As knowledge is personal and evolving, there needs to be a "knower." CT is also a dialectical method, where the conversation is conducted between two or multiple people, holding different points of view about the subject matter they are discussing, and aiming to converge towards a shared meaning through reasoned exchanges regarding their personal beliefs. A conversation between a person and some type of environment is possible, when the environment is also capable of a conversation. Some of Pask's machines belong to this category, while other environments, like a stone, are not capable of a conversation. However, an observer may conjure an internal conversation that is the consequence of the presence of the stone, but in which the stone is not an active agent.

Concept Maturity Levels (CML): Drawing analogy from the Technology Readiness Level (TRL) scale, CML was developed at JPL by Mark Adler to assess mission concept maturity (Wessen et al., 2013). It is beneficial to assess and compare mission concepts, which are relatively incompatible. The scale covers the phases of mission concept formulation from "cocktail napkin" to a NASA Preliminary Design Review (PDR). It is part of JPL's formulation approach and embraced by NASA SMD's Planetary Science Division (PSD). In simple terms the CML phases are: 1) Cocktail napkin; 2) Initial feasibility; 3) Trades space; 4) Preferred design point within trade space; 5) Concept baseline; 6) Initial design; 7) Preliminary integrated baseline; 8) Preliminary Design Review (PDR). (See also Technology Readiness Levels, and Habitation Readiness Levels.)

Cybernetics (first-order and second-order): Cybernetics can be described simply as circularity. It is a trans-disciplinary field, first introduced by Norbert Wiener in 1948, as the "Control and Communication in the Animal and the Machine," in his book with the same title (Wiener, 1948, p.62/549). The origin of the word, cybernetics, traces back to the Greek word Kybernetike (κυβερνητική), in relation to governing, steering a ship, and navigating. The words government and gubernatorial also refer back to this Greek word. Cyberneticians study—among other things—a broad range of fields, including philosophy, epistemology, hierarchy, emergence, perception, cognition, learning, sociology, social interactions and control, communications, connectivity, mathematics, design, psychology, and management. These areas can overlap with other disciplines, such as engineering, computer science, biology, and anthropology, but instead of regulation (that is rapidly converging towards a single solution), cybernetics focuses on an abstracted context to find underlying dynamics and understanding. As described by Ranulph Glanville in a course description for Cybernetics of Cybernetics (Glanville, 2003, p.16), *"first-order cybernetics developed the epistemology for comprehending and simulating biological processes as, e.g., homeostasis, habituation, adaptation, and other first-order regulatory processes. 'Second-order cybernetics' provides a conceptual framework with sufficient richness to address second-order processes as, e.g., cognition, conversation, socio-cultural interactions, etc."* Perspectives of second-order cybernetics could be given by numerous quotes. For example, *"Everything said is said by an observer"* (Maturana & Varela, 1980, p.xxii), for which von Foerster provided a corollary: *"Anything said is said to an observer"* (von Foerster, 2003, p.283). On second-order cybernetics being an observing system, Poerksen explains: *"The dualism of observer and observed is thus eliminated; one has become fully aware that, when observing, one may become one's own or somebody else's object of observation"* (Poerksen, 2011, p.20). Later he follows this by quoting von Foerster as: *"Objectivity is a subject's delusion that observing can be done without him"* (Poerksen, 2011, p.52) (von Glasersfeld, 2001, p.37).

Distinction: is marking a difference, or differentiating between things. George Spencer-Brown defined distinction through a mathematical system in his book, titled the "Laws of Form" (LoF) (Spencer-Brown, 1972, p.1-2). When void is considered in its most primitive form, it is without dimensions. A single distinction, such as a circle leads to the creation of space, where the perimeter of the circle provides a distinction between the inside space and the outside of the circle. Spencer-Brown's arithmetic and algebraic system is based on Boolean logic and Boolean algebra by George Boole (Boole, 1847).

Epistemology: Some consider it as a branch of Metaphysics, concerned with the theory of knowledge. In a narrowly simplified sense, it includes the nature of knowledge, truth, belief, and justification. It asks, "how do we know what we know?" It looks at the distinction between justified true belief (JTB) and opinion.

Epistemological obstacle, Epistemological block, and Epistemological rupture: Cognitive models define paradigms, where new information is used to validate them. Variety that is uncognized or does not fit the model is not seen, as it is not made sense of yet. Gaston Bachelard used a similar construct for the history of science, proposing that science is coupled with the concept of progress (Idlas, 2011, p.10). In this scientific evolution the worldview is converging towards an increasingly better approximation of the world in our cognitive models, which also represents a subjective reality. When the way of thinking encounters limits, these limits manifest as "epistemological obstacles" or "epistemological blocs." Overcoming such obstacles through an "epistemological rupture" requires new knowledge, and new variety in a modified cognitive model, that is, a new worldview. Thus an epistemological rupture represents changes in both the psychology of the subjective individual and the collective worldview. For example, moving from a geocentric to a heliocentric view of the universe, or looking at mass differently in the theories of Newton (Newton, 1687) and Einstein (Einstein, 1916). Cognitive models can develop and evolve in stages or discontinuously.

First-order change: see Second-order change, and (Levy, 1986).

Habitation Readiness Levels (HRL): similar concept to Technology Readiness Levels and Concept Maturity Levels, with a focus on space habitat concepts. It is beneficial to assess and compare habitat designs and configurations, which are relatively incompatible. The scale, just like the TRL scale, ranges from 1 to 9. HRL 1 addresses habitation systems research, including human factors, crew systems, and life support research; HRL 2 to 4 is concerned with conceptual and functional feasibility of technology. Within this subcategory, HRL 2 looks at habitation designs and concepts; functional and task analysis. HRL 3 covers internal configuration functional definition and allocation, and use of reduced scale models. HRL 4 refers to full-scale, low-fidelity mockup evaluations. HRL 5 and 6 address demonstration of the technology. Within this subcategory, HRL 5 covers full-scale, high fidelity mockups, human testing and occupancy evaluation. HRL 6 refers to habitat and deployment field-testing. The highest HRL, from 7 to 9, addresses testing of the technology and technology operations. Here HRL 7 involves pressurized habitat prototype testing; HRL 8 covers actual systems completed and "flight qualified" through test and demonstration; and HRL 9 refers to an actual system "flight proven" through successful mission operations. Connolly (Connolly et al., 2006) also provided a cross mapping between HRLs and TRLs. An HRL-based approach supports structured analysis and a comparison basis between habitation concepts at various planetary destinations, which includes the Moon and Mars. (See also Technology Readiness Levels, and Concept Maturity Levels.)

Human centered design: According to IDEO's approach, *"it's a process that starts with the people you're designing for and ends with new solutions that are tailor made to suit their needs. Human-centered design is all about building a deep empathy with the* *people you're designing for"* (IDEO, 2016). The level of human centeredness can vary, as exemplified and discussed under the term "humanly."

Humanly: I am proposing the term "humanly" to describe space objects that are related to humans in the context of space exploration. It is an adjective, from "human" + "ly" in the same way as Nigel Cross used the word "designerly" from "designer" + "ly". So why is it "humanly" and not "human centered?" Because it provides a distinction between various levels of human centeredness for space objects. Asteroid are space objects, as they are stable, tangible and visible. Yet they are not connected to humans. The level of human centeredness also varies between objects created for space exploration by humans. A rocket nozzle is a space object, yet more of an engineering object than human centered. Yet it helps humans to reach orbit and beyond. A life support system in a space habitat supports basic physiological needs, yet these are engineering systems. Space habitats and their elements—including the Cupola—are supporting physiological, psychological and safety needs. The level of human centeredness increases. Yet, there is still a heavy focus on engineering. Ultimately, we can create space objects that interact with the astronauts, support conversations, learning, higher level needs, with a human centered focus. Thus the term "humanly" encompasses the full range of objects created by humans in connection with expanding human boundaries into space. Human centered design in the design world has a specific meaning as discussed in the previous entry. In comparison, engineering design at NASA, specifically robotic missions, do not start with the people they are designing for. Indirectly it does, but primarily it is targeted to answer a scientific question that subsequently benefits human understanding. Yet space hardware or space instruments are humanly space objects. Consequently, I am proposing the term "humanly" to provide a distinction between a narrowly focused meaning of "human centered design" and space objects created by humans for space exploration with varying scales of human centeredness.
(See also Human Centered Design.)

Investment casting: lost wax method for creating sculptures or other metal objects.

Keystone graphics: are visual representations of complex concepts that are captured in a single image, and can convey the intended message better than long text-based descriptions. It is a graphical element that tells the whole story about the mission concept. At JPL the people who work on these are called visual strategists. They have industrial design or graphic design backgrounds and well versed in visual communications. Keystone graphics as boundary objects are discussed in Section 7, and Appendix D.

Language: is the means of communication used between people and animals. It is a formalized system that may include symbols, sounds, gestures, and signs. It encodes meaning and provides distinction and information entropy. It provides an encoding commonality between conversing actors.

Maslow's Hierarchy of Needs (HoN): Abraham Maslow developed his motivational theory between the early 1940's and 1970's (McLeod, 2014). Maslow's Hierarchy of Needs (HoN) initially included five levels (Maslow, 1943, pp.372-383), which were subsequently extended to eight levels (Maslow, 1970, p.2&104). His initial five hierarchical stage model included physiological needs (e.g., metabolic, shelter, reproduction), safety needs (e.g., security, stability, health), love and belonging needs (e.g., family, friendship, intimacy), esteem needs (e.g., achievement, respect, recognition), and self-actualization needs (e.g., personal fulfillment, growth, creativity). At the lower levels, basic or deficit needs motivate people to meet them. For example, hunger or thirst becomes an increasingly strong motivator as time passes, until they are met. Maslow proposed that once a need is met at a certain level of this hierarchy, the person moves to fulfill the next level above it, towards self-actualization. The eight stage model included the initial five needs listed before, but Maslow added between esteem needs and self-actualization needs: the *"cognitive needs for sheer knowledge (curiosity) and for understanding (the philosophical, theological, value-system-building explanation need);"* and aesthetic needs related to *"the impulses of beauty, symmetry, and possibly to simplicity, completion, and order"* (Maslow, 1970, p.2). Maslow topped the list with transcendence needs, by which he meant *"for the person to grow toward full humanness, towards actualization of his potentialities, toward greater happiness, serenity, peak experiences"* (Maslow, 1970, p.104). (See Section 3.2.7.)

Metaphysics: is the branch of philosophy that deals with the first principles of things, including abstract concepts such as being, knowing, substance, cause, identity, time, and space. Metaphysics has two main strands: that which holds that what exists lies beyond experience (as argued by Plato), and that which holds that objects of experience constitute the only reality (as argued by Immanuel Kant, the logical positivists, and David Hume). Metaphysics has also concerned itself with a discussion of whether what exists is made of one substance or many, and whether what exists is inevitable or driven by chance (see The New Oxford American Dictionary). It is a branch of philosophy seeks to study reality. It deals with questions like "What is there?;" "What exists?;" "What is it like?;" and "What is its nature?"

Mockup: is a low fidelity model of a system or structure that is used to demonstrate feasibility during the early stages of the development. Mockups are typically situated in the low-TRL to medium-TRL range. Prototyping and building mockups is a typical iterative design activity, which are currently utilized at JSC's Habitability Design Center (HDC) in support of planning human exploration missions, and at JPL's Innovation Foundry for planning robotic missions. During the design process the study teams identify functions, then brainstorm with a broad group of experts, including astronauts as users. This helps to flush out a few concept designs. The best concept is then translated to a mockup, which becomes a point of departure for a new iteration. One example is JSC's Habitat Demonstration Unit (HDU), which was developed through rapid prototyping.
(See also Analog.)

Ontology: An ontology can be defined as a narrative of being or existence through categorization and relationships. It defines entities and entity types within a framework, and seeks to describe how these are grouped according to similarities and differences, how they correlate within a hierarchy. Ontology is part of metaphysics, which is a branch of philosophy. Marianne Talbot from Oxford University, Faculty of Philosophy, discussed this topic in her iTunes U podcast titled *"Metaphysics and Epistemology." She stated: "Metaphysics is the study of reality. It deals with questions like 'what is the..?,' 'what exists?'… and 'what is its nature?' There is a branch of metaphysics called ontology… … your ontology is your list of what exists. So, … If you believe in God on your list of what exists, you have God. If you don't believe in God in your list of what exists, God does not* *feature. But chairs probably would, lecturers probably would. Necklaces, things like that, probably list on your feature that exists.“* (See also Performative Ontology)

PAFTD: or Project Assessment Framework Through Design. It is a projects assessment tool developed as part of this research. It is a conversation-based tool seeking strategic level information on the assessed projects to inform strategic leadership on the health of the project. The synthesized information is presented to strategic leadership, broadening their variety and support their strategic decision making. PAFTD is influenced by Stafford Beer’s Viable System Model, Design Thinking, Design Conversations and balanced score cards. (See Section 5 and Appendix B.)

Paradigm: According to the online dictionary (dictionary.com), it describes a framework that consists of the basic assumptions, ways of thinking, and methodology that are commonly accepted by members of a scientific community. Such a cognitive framework is shared by members of any discipline or group. (See also Worldview.)

Perceptional boundary: A distinction exists between the environment and our cognition. This distinction is defined by a boundary. I termed it as the “perceptional boundary.” (Note: the term “perceptional” was used instead of the typical “perceptual” term, as it is referring to the cognitive process combined with perception instead of the biological sensing process.) It represents a distinction that affords crossing. We communicate across our perceptional boundary, utilizing our sensory system, which sets limits to the information flow and the perceived variety of the environment. It is a circular and bi-directional loop. The sensing organs allow us to differentiate one thing from another, which is the source of information. A distinction between signals translates to information entropy. Sense organs facilitate signal flow from the environment to our cognition. Language and gestures provide the feedback from our cognition to the environment.

Perceptual cycle: Ulrich Neisser found that James J. Gibson’s “bottom up” and Richard Gregory’s “top down” theories can’t explain all of the perceptional experiences under all circumstances. He pointed out that a purely data driven approach would make people mindless robots, while a purely prior knowledge driven approach would make them dreamers without physical grounding. To resolve this impasse, he proposed a model, and called it a “perceptual cycle,” where the top down and bottom up processes work in a circular way (Neisser, 1976, p.20). In this circular process our cognitive models (or schemata) provide expectations (hypothesis) for given contexts. If the sensory input disagrees with this hypothesis, then it does not fit an existing schema, and in line with Piaget’s approach the schema is either extended, or a new schema is created for a new experience. Thus, Neisser’s perceptual cycle model, combines the cognitive psychology models of Gibson and Gregory. It plays and important role in understanding how we think, create, invent and innovate, and in general interact with the world. It also implies that the complexity and fidelity of our abstracted cognitive model of the world improves through circular conversations with our environment.

Performative ontology: The term performative ontology was introduced by Andrew Pickering in his book, titled “The Cybernetic Brain: Sketches of Another Future” (Pickering, 2010, Kindle, p.22). In my research I have adopted the performative ontology term, and defined it as an epistemological approach to my cognitive model, applied to real world situations. It relates to the dynamic and adaptive evolution of a person’s cognitive model of the perceived phenomenal world, including how these are grouped into the schemata and hierarchy. It also looks at distinctions that differentiate one thing from another, or highlight similarities between them. The structured hierarchies of personal knowing (Polanyi, 1962)(Polanyi, 1966) of our models form our ontology. Yet our model is not static, not a simple cognitive reflection of the observed world. It evolves through new observations, tacit knowledge emerges to communicable personal knowledge as novel experience patterns form and incorporated into our schemata. The performative aspect takes this cognitive approach further and defines the cybernetic brain as an acting machine and not a thinking machine (Pickering, 2010, p.49). Our cognitive models are not merely informing us about our environment through incoming information, but they help us reassemble novel concepts. This makes our ontology performative. It refers to a brain that interacts with the world and can perform in any new situation it encounters, instead of just cognitively processing the incoming information. With strong links to cybernetics, it is used to enact a “forward-looking search” (Pickering, 2010, p.18). Due to its temporal nature, as the performative ontology evolves it will either reinforce or displace prior understanding. Thus, in my research, the term “performative ontology” represents a meaningful description of an ever-changing personal cognitive model of the environment. (See Section 4.)

Prototype: see Mockup, where prototypes and mockups are discussed together. (See also Analog.)

Radical Constructivism: see Constructivism.

Second-order change: Amir Levy described an organization through four nested elements: its paradigm, within it its mission, then its culture, and core-processes. Through first-order change (Levy, 1986, p.10) the organization operates within its unchanged paradigm, where it may change its core-processes, culture, and mission. To make real changes to an organization, it needs second-order change (Levy, 1986, p.7), changing from the outside. This needs to start from a paradigm shift, which in turn would influence its mission, its culture and its core processes.

Self-actualization: see Maslow’s Hierarchy of Needs (HoN).

Tacit knowledge: Michael Polanyi introduced the term “tacit knowledge” (Polanyi, 1966, p.9-11) as opposed to explicit knowledge (Polanyi, 1966), in his book titled “Tacit dimensions.” Polanyi stated: *“we can know more than we can tell”* (Polanyi, 1966, p.4). He discussed Meno’s paradox by Plato, about the search for a solution to a problem, where we either know what the problem is, then we know the solution, or we don’t know what the problem is, then we wouldn’t know what we are looking for (Polanyi, 1966, p.22). Tacit knowing addresses this hidden knowledge. Tacit knowing could account for a) a valid knowledge of a problem; b) the person’s capability to pursue it, guided by its sense to approaching its situation, and c) a valid anticipation of the yet indeterminate implication of the discovery arrived at in the end.

Team X: Under JPL’s Innovation Foundry the Concept Shop consists of two project development teams, the A-Team and Team X. After feasibility is demonstrated, for example through A-Team studies, TeamX performs point design studies, at Concept Maturity Level (CML) 4. (See also A-Team.)

Technology Readiness Level (TRL): It is used to assess technology maturity with similar definitions by NASA, Department of Defense (DoD), the European Space Agency (ESA), and the oil and gas industry among others. It is beneficial to assess and compare technologies and design concepts, which are relatively incompatible. The scale set from 1 to 9 (Mankins, 1995), representing the following: 1) Basic principles observed and reported; 2) Technology concept and/or application formulated; 3) Analytical and experimental critical function and/or characteristic proof of concept; 4) Component and/or breadboard validation in laboratory environment; 5) Component and/or breadboard validation in relevant environment; 6) System/subsystem model or prototype demonstration in a relevant environment; 7) System prototype demonstration in an operational environment; 8) Actual system completed and qualified through test and demonstration; 9) Actual system proven through successful mission operations.
(See also Concept Maturity Levels, and Habitation Readiness Levels.)

Top down theory: One of the key considerations of perception and cognition is to identify if perception of our phenomenal world relies on a) information received directly through the bodily sensors, or b) if previous knowledge by the person and expectations also adds to the cognitive interpretation. Richard Gregory, a British psychologist, proposed an indirect “top down” constructivist theory. He stated: *“The brain makes sense of the world by making predictions”* (Gregory, 1970, p.162). His approach combines sensory and contextual information to recognize patterns. For example, in a noisy environment we may understand a word when included in a sentence more than the word alone, as our cognition can provide the appropriate filtering and interpretation. This is also a guessing process through the formulation of a perceptual proposition between the sensory input and our knowledge, as a word may have many meanings. Thus *a priori* knowledge can be very influential in the cognitive processes.
(See also Bottom up theory, and Perceptual cycle.)

Variety: Within the field of cybernetics, the term “variety” was introduced by W. Ross Ashby (Ashby, 1956, p.124), referring to the degrees of freedom of a system (Ashby, 1956, p.129) or more specifically to the distinct states of a given system and its environment. For a stable system in dynamic equilibrium, its regulatory mechanism has to have greater or equal number of states (variety) than the environment it is striving to control; this is the definition of Ashby’s Law of Requisite Variety (Ashby, 1956, p.206). Ashby states his Law as: *“only variety in R (regulator) can force down the variety due to D (disturbance); variety can destroy variety”* (Ashby, 1956, p.207). That is, variety absorbs variety, defines the minimum number of states necessary for a controller to control a system of a given number of states. Stafford Beer referred to cybernetics as *“the science of effective organization,”* and variety as *“the measure of complexity in a system, defined as a number of its possible states”* (Beer, 1974, p.5).

Viable System Model (VSM): Management cybernetics is a subdivision of cybernetics, established by Stafford Beer in the 1960’s (Beer, 1974, p.22) (Beer, 1981, p.157). It looks at the regulatory and guidance mechanisms that govern the operations of organizations at any scale, from companies to societies. Beer was influenced by Maturana and Varela, and looked at organizations as autopoietic systems, which are dynamic, living, self-organizing, and can reproduce and survive their changing environment (Maturana & Varela, 1980, p.xvii-xxiv). Stafford Beer’s Viable System Model (VSM) (Beer, 1981, p.157) is a conceptual model to understand organizational structures and rules, and to identify touch points, where changes and alignments can be made to benefit operations. As organizations have less variety than the environment they operate in, they need appropriate strategies to be responsive. Organizations are autonomous (that is, viable) systems, and in line with VSM, they require five key system functions to operate effectively. These are, in decreasing hierarchical order: System 5: Strategy / Policy / Identity; System 4: Intelligence; System 3: Control; System 2: Management / Coordination; System 1: Executions / Operations. These organizational functions are recursive, where the same generic types of hierarchies between regulators and controlled elements can be applied at all scales. This recursiveness provide strength, robustness, and integrity to the organization. (See Section 3.2.12, and Autopoiesis.)

Vitruvian virtues: the first western text on architecture, called “De Architettura,” was written in the 1st century BC by Marcus Vitruvius Pollio (Vitruvius, 1960). In it Vitruvius declared that architecture consists of three key elements, namely utilitas, firmitas, and venustas. That is, they have to have utility (or function); they have to be firm (or well built); and need delight. Ranulph Glanville, called these fit-for-purpose, well-constructed, and delightful, sometimes stated as fabrication, function, and form (Glanville, 2009, p.2). These elements can also be applied to design.

Wicked Problems: The phrase “wicked problem” was first used in social planning to describe a problem, which does not have an obvious solution, due to changing requirements, and incomplete or contradictory bounding conditions. Furthermore, as a result of the often-complex interdependencies, a chosen solution to a wicked problem can result in subsequent new problems. Horst Rittel and Melvin Webber introduced ten general rules to describe wicked problems (Rittel & Webber, 1973, pp.160-167). These are: 1.) There is no definite formulation of a wicked problem; 2.) Wicked problems have no stopping rules; 3.) Solutions to wicked problems are not true-or-false, but good-or-bad; 4.) There is no immediate and no ultimate test of a solution to a wicked problem; 5.) Every solution to a wicked problem is a “one-shot operation”; because there is no opportunity to learn by trial-and-error, every attempt counts significantly; 6.) Wicked problems do not have an enumerable (or and exhaustively describable) set of potential solutions, nor is there a well-described set of permissible operations that may be incorporated into the plan; 7.) Every wicked problem is essentially unique; 8.) Every wicked problem can be considered to be a symptom of another problem; 9.) The existence of a discrepancy representing a wicked problem can be explained in numerous ways. The choice of explanation determines the nature of the problem’s resolution; 10.) The planner has no right to be wrong. Wicked problems cannot be simplified to hard or complex problems and cannot be solved by incorporating additional considerations or by including more stakeholders. For these, the initial problem definition and the outcome are bidirectionally linked, and the stakeholders may have radically different perspectives, motivations, and drivers towards the issues. Hence, an optimal outcome is dependent on the perspective of a stakeholder, instead of being universally correct. Wicked problems are often ill defined and over-constrained, and cannot be solved through analytical thinking. Addressing them may require innovative solutions and good strategies.
(See Section 3.5.3, and Section 5.)

Worldview: represents a perspective on the world at any scale, from an individual to an organization, or even broader. It is a cognitive framework shared and accepted between disciplines and members of a group. It encompasses basic assumptions and methodologies, and ways of thinking. (See also Paradigm.)

Abbreviations

AA	Associate Administrator at NASA, Head of a Mission Directorate
ACCD	Art Center College of Design (Pasadena, CA)
ADEPT	Adaptable, Deployable Entry Placement Technology
ADP	Advanced Development Program at Lockheed Martin
AES	Advanced Exploration Systems under NASA HEOMD
AMASE	Arctic Mars Analog Svalbard Expedition
ARC	NASA Ames Research Center (Moffett Field, CA)
ARM	Asteroid Redirect Mission
ARMD	NASA Aeronautics Research Mission Directorate
ASG	Agency Strategic Goals
ATHLETE	All–Terrain Hex–Limbed Extra–Terrestrial Explorer
BAH	Booz Allen Hamilton (management consulting services company)
BAMS	British Art Medal Society
BEAM	Bigelow Expandable Activity Module
BIM	Building Information Modeling
BOE	Basis of Estimate
Caltech	California Institute of Technology (Pasadena, CA)
CIF	Center Innovation Funds under NASA STMD
CJ	Congressional Justification
CML	Concept Maturity Level (from 1 to 7; CML 8 corresponds to PDR)
CMU	Carnegie Mellon University (Pittsburgh, PA)
CNC	Computer Numerical Control (machine)
COTS	Commercial Off the Shelf
C&O	Communications & Operations
CR	Continuing Resolution
CxP	Constellation Program
DAM	Digital Aided Making at RCA
DARPA	Defense Advanced Research Projects Agency
Desert-RATS	Desert Research and Technology Studies
DRA	Design Reference Architecture
DRM	Design Reference Mission
EBM	Electron Beam Melting
ECLSS	Environmental Control and Life Support Systems

EDL	Entry, Descent, and Landing
ESA	European Space Agency
FFRDC	Federally Funded Research and Development Center
FY	Fiscal Year
GCD or GCDP	Game Changing Development Program, under NASA STMD
GDP	Gross Domestic Product
GRC	NASA Glenn Research Center (Cleveland, OH)
GSFC	NASA Goddard Space Flight Center (Greenbelt, MD)
GID	Global Innovation and Design at RCA/Pratt Institute/Keio University
GOA	Government Accountability Office
GWU	George Washington University (Washington, DC)
HCD	Human Centered Design
HDU	Habitat Demonstration Unit
HERA	Human Exploration Research Analog
HEOMD	NASA Human Exploration and Operations Mission Directorate
HIAD	Hypersonic Inflatable Aerodynamic Decelerator
HIDH	Human Integration Design Handbook
HI-SEAS	Hawai'i Space Exploration Analog and Simulation
HRL	Habitability Readiness Level (from 1 to 9)
HoN	Hierarchy of Needs by Abraham Maslow
HOR	House of Representatives
HQ	NASA Headquarters (Washington, DC)
HRP	Human Research Program
H-SPACE	Hungarian Space Conference
IAC	International Astronautical Congress
IAF	International Astronautical Federation
ICMB	Intercontinental Ballistic Missile
ICT	Information and Communication Technologies
IDE	Innovation Design Engineering at RCA
IFC	Industry Foundation Classes
IEEE	Institute of Electrical and Electronics Engineers
IP	Intellectual Property
IPAO	Independent Program Assessment Office at NASA
IPPW	International Planetary Probe Workshop

IRAD	Independent Research and Development (fund)
IRVE	Inflatable Reentry Vehicle Experiment
ISS	International Space Station
ISU	International Space University (Strasbourg, France)
IOM	Institute of Medicine
ITAR	International Traffic in Arms Regulations
JPL	Jet Propulsion Laboratory/California Institute of Technology (Pasadena, CA)
JSC	NASA Johnson Space Center (Houston, TX)
JWST	James Webb Space Telescope
KDP	Key Decision Point
KSC	NASA Kennedy Space Center
LDSD	Low Density Supersonic Decelerators
LED	Light Emitting Diode
LoF	Laws of Form by George Spencer–Brown
MBA	Master of Business Administration
MBSC	Model Based Software Components
MD	Mission Directorate
MIT	Massachusetts Institute of Technology (Cambridge, MA)
MPhil	Master of Philosophy
MS or MSc	Master of Science
MSS	Master of Space Studies (a Masters program at ISU)
NAE	National Academy of Engineering
NAS	National Academy of Sciences
NRC	National Research Council
NASA	National Aeronautics and Space Administration
NEEMO	NASA Extreme Environment Mission Operation
NIAC	NASA Innovative Advanced Concepts at NASA STMD
NPR	NASA Procedural Requirements
NRC	National Research Council (of the National Academies)
OCT	Office of the Chief Technologist (NASA HQ)
OGA	Other Government Agencies
OMB	Office of Management and Budget (Executive Branch)
OSTP	Office of Science and Technology Policy (Executive Branch)
PAFTD	Project Assessment Framework Through Design

PBR	President’s Budget Request
PDR	Preliminary Design Review
PE	Program Executive
POTUS	President of the United States
PPBE	Programming, Planning, Budgeting and Execution
PRG	Program and Resource Guidance
R2	Robonaut 2 by NASA
R5	Valkyrie humanoid robot by NASA
R&D	Research and Development
RCA	Royal College of Art (London, UK)
RISD	Rhode Island School of Design (Providence, RI)
RMO	Resource Management Office
ROI	Return on Investment
SBU	Strategic Business Unit
SEI	Space Exploration Initiative
SEV	Space Exploration Vehicle
SI	Strategic Integration (group at NASA STMD)
SICSA	Sasakawa International Center for Space Architecture/University of Houston
SLA	Stereolithography
SLM	Selective Laser Melting
SLS	Space Launch System
SME	Subject Matter Expert
SoA	State of the Art
SoK	State of Knowledge
SoP	State of Practice
SSTIP	Strategic Space Technology Investment Plan
STEM	Science, Technology, Engineering and Mathematics
STMD	NASA Space Technology Mission Directorate
STO	Senior Technical Officer
SU	Singularity University (Moffett Field, CA)
SWB	Subjective well-being
TPS	Thermal Protection System
TRL	Technology Readiness Level (from 1 to 9)
US	United States

VIP	Very Important Person
VR	Virtual Reality
VSM	Viable System Model
WBS	Work Breakdown Structure
WIP	Work In Progress (mid–year shows at the RCA)
W-TPS	Woven Thermal Protection System
WWII	World War II
X-Hab	eXploration Habitat
Zero-g	Zero Gravity

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