THE ROLES OF DESIGN AND CYBERNETICS FOR PLANETARY PROBE MISSIONS.

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Abstract: Planetary probe missions—as part of an overall space exploration strategy—have helped us to experience and learn about planets and moons in our solar system, with sizable atmospheres. These engineering and scientific achievements contributed to our evolving understanding of the universe around us. While the natural phenomena of the world are independent of humanity, their scientific exploration is part of our human experience. The humanities discipline provides reflections from an anthropocentric point of view, while design requires an active participation by humans. Thus, from these three categories of Sciences, Humanities and Design, we can place scientists into the Science category, while engineers, designers, and other practitioners who create novel parts, systems, artifacts, and processes are part of the Design category. [1] 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. Complex multi-part systems, and mission architectures require system-thinking and integrated-thinking, where iterative methods are used. In a cybernetic sense, throughout project execution feedback is provided to the engineers and project managers (regulators) [2]. In 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. At a higher strategic level within the organizational hierarchy [3], there can be additional misaligned contributing factors to projects, turning a linear engineering development into an incomplete problem with changing requirements and without a clear possible solution. This is termed to be a wicked problem. [4] In comparison, design is a non-linear discipline [5], where the feed-back broadens the regulator's understanding and knowledge (variety [6]) allowing the designer to identify new previously unseen options from an added dynamic anthropocentric perspective. Design Thinking [7] not only accounts for usability, feasibility and viability, but harmonizes them in a human centered way. Designing items for human spaceflight, we call humanly space objects [8], requires special considerations, yet some of these could be applied to planetary probe missions as well. Through multiple divergence and convergence design phases, options are created to understand the problem at hand, from which the root problem is identified. Subsequently, design trade options are created, then the perceived best approach is selected for development. In this paper we discuss the generalized category and various aspects of planetary probe missions through the lens of cybernetics [9] and non-linear design, as applied to mission architectures, system design, operational processes, and ways of communicating the findings throughout all development and mission phases to various stakeholders. We will also discuss how the understanding and leveraging of cybernetics and human centered design can enhance current practices and innovative space technology developments [10], which are still dominated by engineering, technology and management approaches.

Introduction: The exploration of planets with sizable atmospheres in our Solar System is regularly ranked on the top of the National Research Council's Decadal Surveys [13]. Past missions, with their engineering and scientific achievements, contributed greatly to our evolving understanding of the universe around us. Yet, many questions remain about planetary history and evolution, requiring new in-situ missions to these destinations. Over the years, visits to these solar system targets are mostly limited to Mars, including several successful in-situ missions. In comparison, planetary probe missions to other planets and moons—namely Venus, Jupiter, Saturn, and its moon, Ti-tan—will be likely to face continuing challenges over the next years. Some of these challenges are related to re-sources—or viability—and some to technologies—or feasibility. As an added obstacle, national space agencies, including NASA, ESA, JAXA and others, face continuing fiscal pressures from their governmental funding sources, consequently influencing the priority orders of selected future missions and destinations. Furthermore, in-situ planetary probe missions are too expensive for the private enterprise, providing no relief to the community. At the same time, the planetary probe community is in a continuing quest to propose selectable mission concepts to stakeholders from the funding side, including agency managements at program and strategic levels, mission selection boards, and higher government level sources. Funding challenges also continually hamper technology development efforts. While the proposals are becoming increasingly sophisticated—which can be stated for proposals to all destinations—the proposing teams are repeatedly trying the same established routine, dominated by engineering, technology and management approaches, namely, using the same language, while expecting different outcomes, specifically, to be selected and funded for their proposed missions.

To offer new perspectives, in this paper we identify Fracture Points within the processes where new Design Dialogs and cybernetic approaches could augment the current state of practice, and could be leveraged, leading to preferred outcomes from the initial ideation phase, through the development and mission design, to the operational phases. First we introduce foundational concepts relevant to our discourse, including barriers to innovation at NASA, Wicked Problems, communications, cybernetics, non-linear Design [36] as a distinct discipline from engineering, Design Thinking, Design Dialogs, and Fracture Points. Then we identify specific Fracture Points where some of these new cybernetic and design based approaches could be inserted into the process of ideating, prototyping, designing, developing and flying these future missions, as applied to mission architectures, system design, operational processes at various scales (from projects to agency levels), and ways of communicating the findings throughout all development and mission phases to various stakeholders.

Foundational Terminologies: In this section we introduce and define topic-relevant foundational terminologies, including barriers to innovation at NASA, Wicked Problems, communications, cybernetics, design as a unique discipline, Design Thinking, Design Dialogs, and Fracture Points. More detailed introductions to these topics can be found in [3] [8] [10].

Barriers to innovation at NASA. The National Research Council (NRC) in its 2011 review [16] has stated that NASA's technology base is largely depleted, and future successes will depend on advanced technology developments. Subsequently, an internal NASA study identified barriers to innovation. Top level conclusions [10] from this unpublished study are in line with classical barriers described in numerous literature sources, including [17] [18] [19] [20][21][22]. The list includes the following findings related to NASA:

- Risk-averse culture.
- Low priority on innovation combined with short-term focus.
- Instability (e.g., funding uncertainties, project descopes and cancellations).
- Lack of opportunities.
- Process overload.
- Communication Challenges.
- Organizational inertia.

Innovation theory and practice provides recommendations to solve these issues [17] [18] [20] [22], including:

- *Creative ideation:* similar to Bootlegging, used at Google and 3M, where a certain small percentage of the work time could be used for developing innovative projects and ideas.
- *Innovation laboratories and creative spaces:* many of these have been implemented at NASA already (e.g., JPL's Innovation Foundry). [23]
- *Innovation funding:* for example, independent research and development (IRAD) funding, prizes (e.g., X PRIZE), awards, and grants, and Center Innovation Funds (CIF) under NASA's Space Technology Mission Directorate.
- *Skunkworks:* a similar approach has been implemented at NASA's Kennedy Space Center, called Swamp Works. [24]
- *Process streamlining:* including tailoring NASA Procedural Requirements (e.g., NPR 7120.8 and 7120.5).
- A *combination* of the above approaches.

These barriers could be further explored through the field of cybernetics [6] [9], as it can provide new insights that may lead to address them. As it will be discussed in this paper, such broadened understanding could involve research into trans-disciplinary fields, such as power relationships and structures, constraints and possibilities.

Wicked Problems: The term "wicked problems" describes problems, which do not have obvious solutions, due to changing requirements, and incomplete or contradictory bounding conditions. As a result of the often-complex interdependencies, a chosen solution to a wicked problem could lead to subsequent new problems. Rittel and Webber introduced ten general rules to describe Wicked Problems [4], which was synthesized and reduced to six general characteristics by Conklin [11]. These are:

- The problem is not understood until after the formulation of a solution.
- Wicked problems have no stopping rules, difficult to know when the problem is solved or solution is reached.
- Solutions to wicked problems are not right or wrong.
- Every wicked problem is essentially novel and unique.
- Every solution to a wicked problem is a "one shot operation".

- Wicked problems have no given alternative solutions.

Wicked Problems can't be simplified to hard or complex problems and solved by 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, over-constrained, and can't be solved through analytical thinking. They may require innovative solutions.

Roberts identified three strategies to tackle wicked problems [12]. Implementations of these strategies are influenced by management styles and institutional approaches, and can be described as follows:

- An *authoritative* approach places problem-solving responsibility to one or a few people. This may reduce the complexity of perspectives by eliminating competing views. However, it may eliminate key perspectives, potentially leading to less favorable outcomes.
- A *competitive* approach brings opposing views against each other. Here the preferred solution of stakeholders are compared and weighted against each other. However, it may lead to confrontations, and can dis-courage knowledge exchange, and disincentivize stakeholders to propose solutions.
- A *collaborative* approach involves all stakeholders working and converging towards a common best solution, agreed upon by all parties involved.

At a higher strategic level within the organizational hierarchy [3], there can be misaligned contributing factors to projects, turning a linear engineering project development into an incomplete problem with changing requirements and without a clear possible solution. [4]

As detailed in [3], strategic level NASA operations regularly encounter such Wicked Problems, which are spatially and temporally cyclical. These cycles are driven by government elections, annual government budgets appropriations, and NASA's technology and mission development timelines. A deeper understanding of these wicked problems could be gained through the mapping of cybernetic communication loops.

Communications: Claude Shannon first introduced a general model of the communication process in 1948. [25] This model is flexible to be applied to a broad range of disciplines, from engineering and computer science to cognitive sciences, design, and various means of interactions. The model parses communication to piecewise components as shown in Figure 1. 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 who generates and wishes to transmit the Message. It may al-so 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 *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 interac-

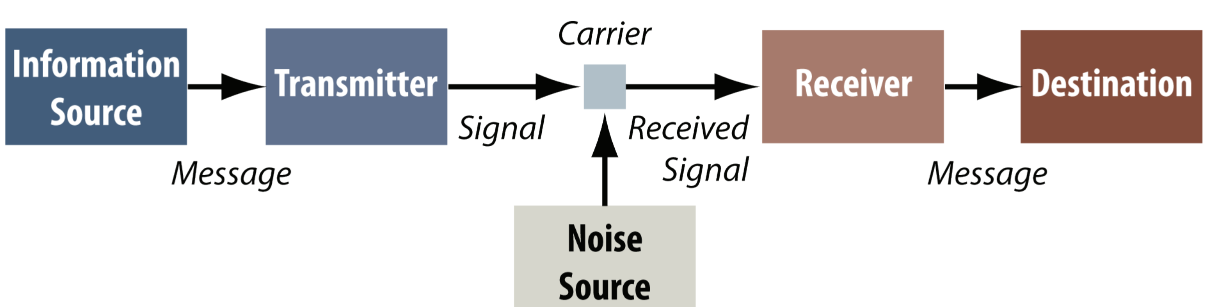

Figure 1: Shannon's schematic diagram of a general communication system with its eight elements.[25]

tions with gestures, or parallel data channels from a descending planetary probe, as was designed for the Huygens probe.

- 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 perceptional sensors, such as the ears and eyes, or receiving antennas that convert the signal into a message, based on the common code between the source and the destination.
- The *Destination*: is the person who cognitively interprets the message.

Shannon's model was created through the reduction of complex systems into a simple one. Simplified models typically do not capture all details of reality [26], and as George Box pointed it out, "essentially, all models are wrong, but some are useful" [27]. Therefore, to draw meaningful conclusions from models, the simplifications have to capture and weight all the key influencing factors, and ignore those, which have secondary effects on the modeled system. For example, communication systems are significantly more complex than shown in Figure 1, with 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. Real-life communications, on the other hand, are often bidirectional, with feedback loops, as they will be addressed below under cybernetics.

Cybernetics: is a trans-disciplinary field, initially defined by Norbert Wiener in 1948, as the "Control and Communication in the Animal and the Machine" [9]. The origin of the word, cybernetics, traces back to the Greek word Kybernetike (κυβερνητική), in relations to governing, steering a ship, and navigating. The words government and gubernatorial also refers back to this greek word. Cyberneticians study—among others—a broad range of fields, including philosophy, epistemology, hierarchy, emergence, perception, cognition, learning, sociology, social interactions and control, communications, connectivity, mathematics, design, psychology, and even management. Many of these areas overlap with other disciplines, such as engineering, computer science, biology, and anthropology, but instead of point designs, cybernetics focuses on an abstracted context to find underlying dynamics and understanding. Many of today's control and network systems associated disciplines, systems engineering, psychology and biology fields find their roots in cybernetics, and often associated with first-order cybernetics, related to the observed system. Further advancements in cybernetics looked at the system that is observing the system, called second-order cybernetics.

Within the field of cybernetics, the term "variety" was introduced by W. Ross Ashby, referring to the degrees of freedom of a system. For a stable system in dynamic equilibrium, its regulatory mechanism has to have greater or equal number of states than the environment or system it controls, as defined by the Law of Requisite Variety. Ash-by states his Law as "variety absorbs variety, defines the minimum number of states necessary for a controller to control a system of a given number of states". This Law also relates to Shannon's above discussed information theory [25], dealing with "incessant fluctuations" or noise in the communication system.

Cybernetic interactions can be discussed through three abstracted elements, which includes the system (or regulator); a process; and the environment. The system generates some change in its environment through the process. This change is then reflected through feedback that influences subsequent changes in the system. This circular causal interaction continues until a stopping criteria is reached. Hence cybernetics provides a way to look at things and focuses more on communications than control, but addresses them both in a circular way with forward and feedback loops. It considers language and related dialogs as basis of how we communicate. For example, as shown in Figure 2, when Actor A poses a question, Actor B is trying to understand its meaning. The answer is based on Actor B's understanding of the question, which is subsequently interpreted by Actor B from the feedback. Environmental noise can interfere with the communication loops, and need to be filtered out by the actors. This circular dialog may continue until a constructed middle-ground understanding is reached between the two actors.

Cybernetics related considerations play important roles in introducing new dialogs to space exploration

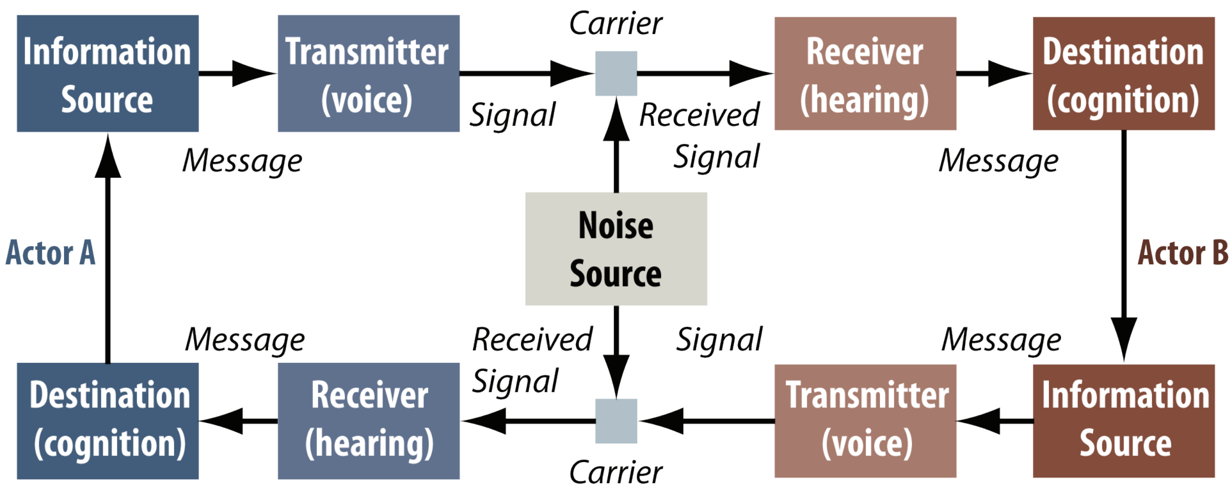

Figure 2: Shannon's diagram expanded to a circular communication loop between two actors.

and to planetary probe missions within, and can be applied at various fracture points as will be discussed below.

Design with a Capital D: "Scientists study the word as it is, engineers create the word that never has been." This statement by Theodore von Karman [14], the renowned founder of the Jet Propulsion Laboratory, 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 [1] this may make perfect sense. Acknowledging Archer's grouping of anthropocentric activities into Science, Humanities and a third distinct discipline, Design with a capital D, von Karman's statement clearly places scientists into the Science category and engineers, designers, artists, and other practitioners who create novel parts, into the Design category. Archer's categorization of science describes the metaphysical world of natural laws to be independent from humanity. 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 humanly designs considerations about how things ought to be. It introduces novel options and forms. Furthermore, Design is a non-linear discipline [5], where in a cybernetic sense the feedback broadens the regulator's understanding and knowledge (variety [6]) allowing the designer to identify new previously unseen options from an added humanly 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 between science and engineering, designed by subject matter experts well versed in both specialized fields.

Design Thinking and Design Dialogs: 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. 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, if time and resources are available. 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 [29], 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 stakeholders and technology.

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. Complex multi-part systems, and mission architectures require Systems Thinking [3] and Integrative Thinking, where iterative methods are used. These are currently employed at NASA, but with a strong technology focus. Integrative Thinking brings forward opposing ideas and opposing constraints, to find new solutions.

In a cybernetic sense, throughout project execution, feedback is provided to the engineers and project managers (regulators) [2]. In 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.

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. Design Thinking could be important for 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, find new solutions and new ideas, that didn't exist before. Using a double diamond visual representation, as shown in Figure 3, the design process is used to address two key questions. The first phase is used to define the right problem or opportunity, and in the second phase is set out to find the right solution. 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 a 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 though a prototype (e.g., breadboard, brassboard). This process is best suited to an early development stage, from Technology Readiness Level (TRL) 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 [28], which uses prototypes to speed up the process of innovations, because

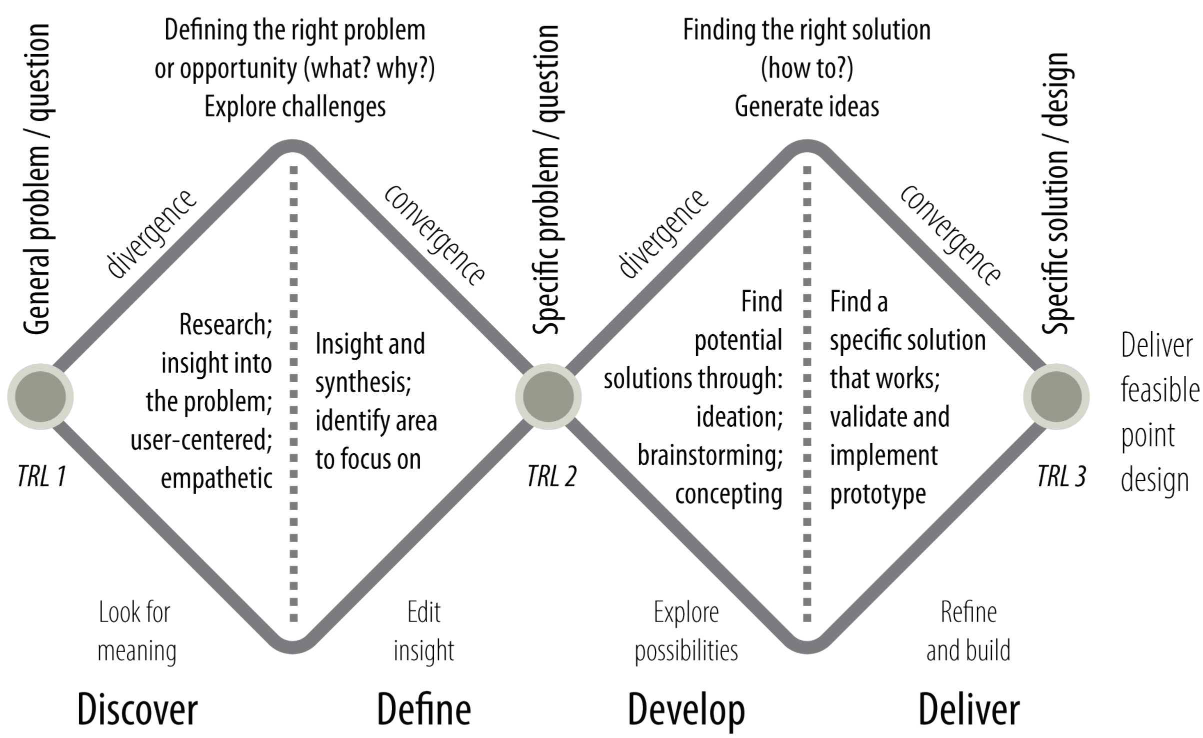

Figure 3: Double diamond of design with approximate Technology Readiness Level matching.

creating them will allow the practitioner to understand the strengths and weaknesses of the artifact or process being designed. This strategy starts with a human centered approach, balancing and harmonizing desirability or usability, with technical feasibility, and economic viability.

If Design Thinking is introduced at NASA, it should include designers along with engineers, technologists, and scientists, in the early stages of the process. This is expected to introduce more creativity, beyond the purely analytical approaches. It would also help to "deep dive" into stakeholder needs, through discussions and observations. But there are insufficiencies with a design thinking approach. Brainstorming is a vaguely defined concept, which should be replaced with focusing problems in Design Dialogs [37]. A design methodology should incorporate cybernetics to the prototyping phase, with strong considerations for the Law of Requisite Variety. (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.) Iterative cybernetic feedback loops would enhance the variety of the designer, who could make better choices in subsequent iterations, with a setout goal to bene-fit the stakeholders. The outcomes could be evaluated through a systematic approach to harmonize the opportunities and constraints. A relevant model discussing design conversations is depicted in Paul Pangaro's model of co-evolutionary design [30]. As shown in Figure 4, 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 (namely how to design a better design process); and
- A conversation to create a new language.

These cybernetically circular conversations are the basis to reach agreements. These agreements strengthen the teams 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 bound options, new languages are needed. Such new languages 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 Dialogs, leading to new languages, new discourses, and subsequently arriving to preferred outcomes. Adopting Design Dialogs at space agencies could open up the mission and technology design trades beyond today's options, which are limited by and increasingly specialized language.

Fracture Points: The term "fracture point" is derived and defined here by the primary author of this paper as an outcome of Design Dialogs with other researchers at the Royal College or Art, who are members of an emerging Design Collective. It refers to touch points within designs, developments, operational processes or organizational structures, where changes can be introduced. These fractures may already exist in a system, and could scale in size from a small hairline fracture to a full break. In other instances, designers could identify potential points in the system where new fractures could be introduced with inserted design processes, leading to changes, improvements, or positive disruptions. From a cybernetic perspective, in an organizational chart the boxes represent people and their positions in the system hierarchy, while the connecting lines represent the

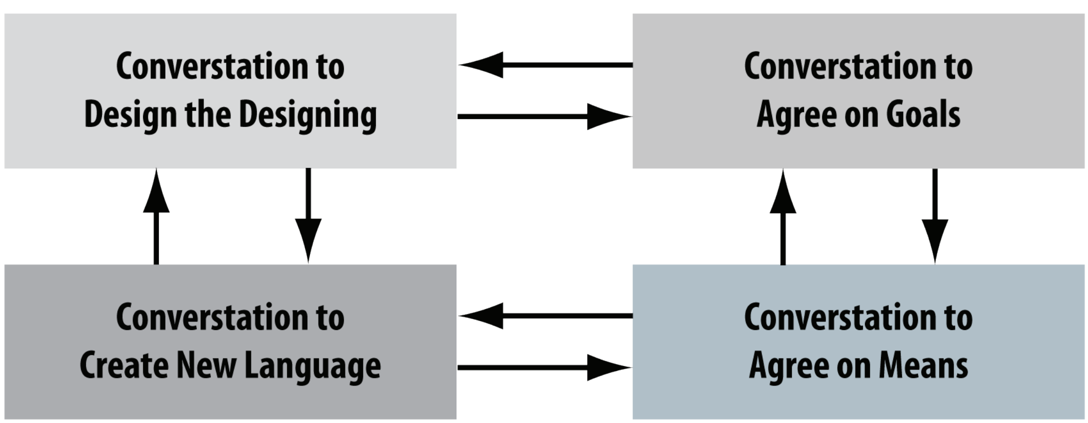

Figure 4: Model of co-evolutionary design by Pangaro, with influences from Dubberly, von Foerster, and Geoghegan. [30]

cybernetic control and feedback loops. Fracture points can occur at any of these bidirectional circular dialog loops between the entities. In this paper we are identifying several fracture points, which are applicable to planetary probe missions or to a broader system.

Design and Cybernetics to Broaden Variety for Future Planetary Probe Missions: NASA's organizational culture is still dominated by persistence on Apollo scale large an expensive flight projects. These include the ongoing developments of the Space Launch System (SLS), the Orion capsule, the James Webb Space Telescope, all of which exceeded their initially planned flagship class budgets. Future plans include the Asteroid Return Mission (ARM), and a subsequent human mission to Mars by the middle of the 2030's. One may argue that space exploration is expensive, that all the low hanging fruits are already taken, and to push boundaries we need larger and more capable missions. A counter argument may point out the cost of brute force approaches, which worked during the Apollo era, when resources were not limited to current levels, and under today's fiscal realities the dream of recreating the glorious past is not realistic. These of course are simplified and cherry picked arguments, and the extent of contributing factors—both within the Agency and outside—form a wicked problem with no obvious solutions [3]. At the same time, these large scale plans and coexisting funding environment presents a particular challenge for NASA to introduce new missions, including scientific in-situ exploration of planetary environments. One approach can be proposing future missions the same way as it has been done over the past decades, and expecting better outcomes. Another approach could be to introduce new ways of looking at the issues and finding alternative solutions. In this paper we advocate the latter approach, by introducing new perspectives to a well established and at times rigid processes, thus broadening the options space through the concepts and models of cybernetics, wicked problems, design dialogs and fracture points. We believe that even presenting new models and starting new discourses through the material presented in this paper may lead to novel options and benefits to the community.

Modeling complex systems in a meaningful way is not trivial. As stated by Laurence J. Peter [32], "some problems are so complex that you have to be highly intelligent and well informed just to be undecided about them." We hope that our simplifications will capture key elements of these complexities, facing technology and mission concept development activities at NASA. Looking at NASA through cybernetics and the concept of Wicked Problems is highly beneficial, as multi-directional interactions could be modeled through closed signal feedback loops, which may provide invaluable insights into this problem space. Mapping of key element of this system from the government level down to the projects, and including external entities to NASA is shown in Figure 5, where all connections represent bidirectional control and feedback loops, and potential fracture points, where improved dialogs may lead to preferred outcomes. (Detailed descriptions of NASA's Wicked Problems for space technology development are given in [3].) This approach is particularly useful and important to identify fracture points where changes could be introduced, as innovation barriers at NASA span across numerous fields. These include, but not limited to, resource and regulatory fields, governance and management through internal and external hierarchies, strategy and policy at various levels, tactics and programmatics, interactions with stakeholders, portfolio execution and tracking, science requirements, technology needs, education and public outreach. These influences occur on varying timescales and at diverse geographical locations. Hence, understanding these interconnections through dynamic budget cycles could benefit strategic thinking, planning and execution and could reduce innovation barriers at NASA and other government-directed environments. It may also help proposers and technology developers to frame their discourse with regulators to achieve favorable outcomes, for example getting technology projects funded or flight projects selected.

NASA's simplified organizational model, shown in Figure 5, includes internal and external entities on a hierarchical arrangement. At the lowest level, projects operate under linear disciplines, where given the development requirements and resources the project teams regulate execution within the available resource allocation and given schedule. Project activities are coordinated at the Program Office level, located at NASA Centers. These activities can still be considered under linear disciplines. At the strategic levels, NASA's activities are coordinated under four Mission Directorates, which falls under the NASA Administrator at the Agency level. Above NASA, at a global strategic level the US Government Offices of the Executive Branch, and Committees of the Legislative Branch work with NASA on the annual President's Budget Request and budget appropriations, respectively. NASA also works with external entities, including the National Research Council, which provides science directions and justifications for future missions; a broad set of aerospace industry companies, other government agencies, academia, and the public. All of these connections require dialogs, where design and cybernetics can improve understanding and out-comes.

Looking at the Wicked Problems NASA faces during its annual budget cycles, the most relevant bidirectional connections between the actors in Figure 5 are represented by the connected dashed lines. Giving just one example, at the project level design dialogs occur between multiple actors, both inside and outside of the project. For example, the Project Manager interacts with the project team members; with management at higher levels in the organization-al hierarchy (e.g., with the Program Office at the Center, and the Mission Directorate at NASA HQ); and with external contractors. Team members also maintain peer-to-peer dialogs throughout the project execution. These dialogs help to keep projects on track to achieve their set out performance goals. On a temporal scale, technology projects progress through a process of ideation, designing, building, testing and use, as shown in Figure 6. (By definition the innovation process is only completed when the initial idea is fully developed and put into use.) Therefore, design dialogs also occur at temporal scales between project members and stakeholders, for example during project progress reporting, and at Key Decision Point reviews. Thus, mapping NASA's internal and external interactions through Wicked Problems may help the proposers to understand the complexities they face when submitting their proposals. Proposal selections are not strictly

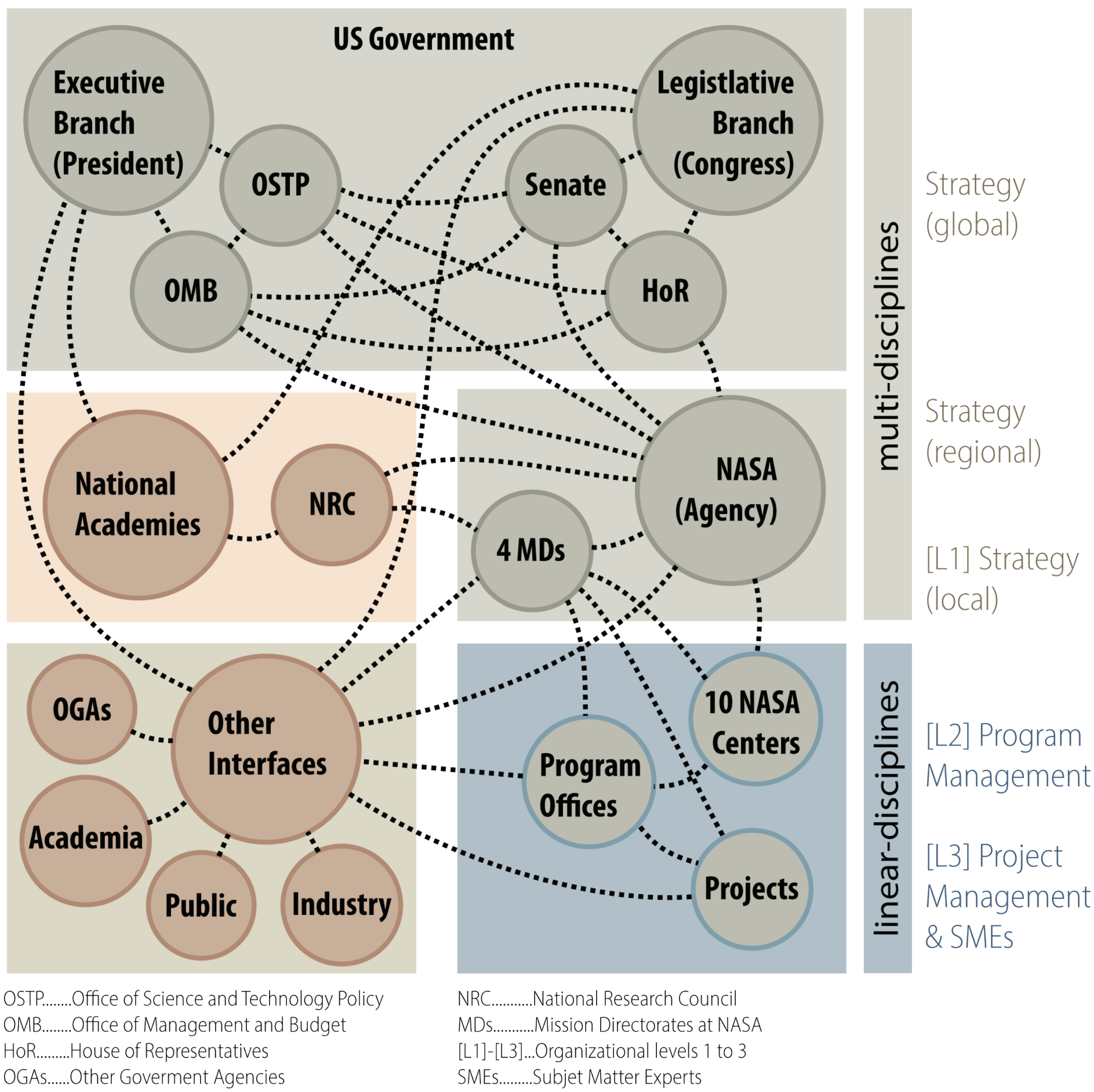

Figure 5: Wicked Problems for NASA; all connections represent bidirectional control and feedback loops, and potential fracture points, where improved dialogs can lead to preferred outcomes. [3]

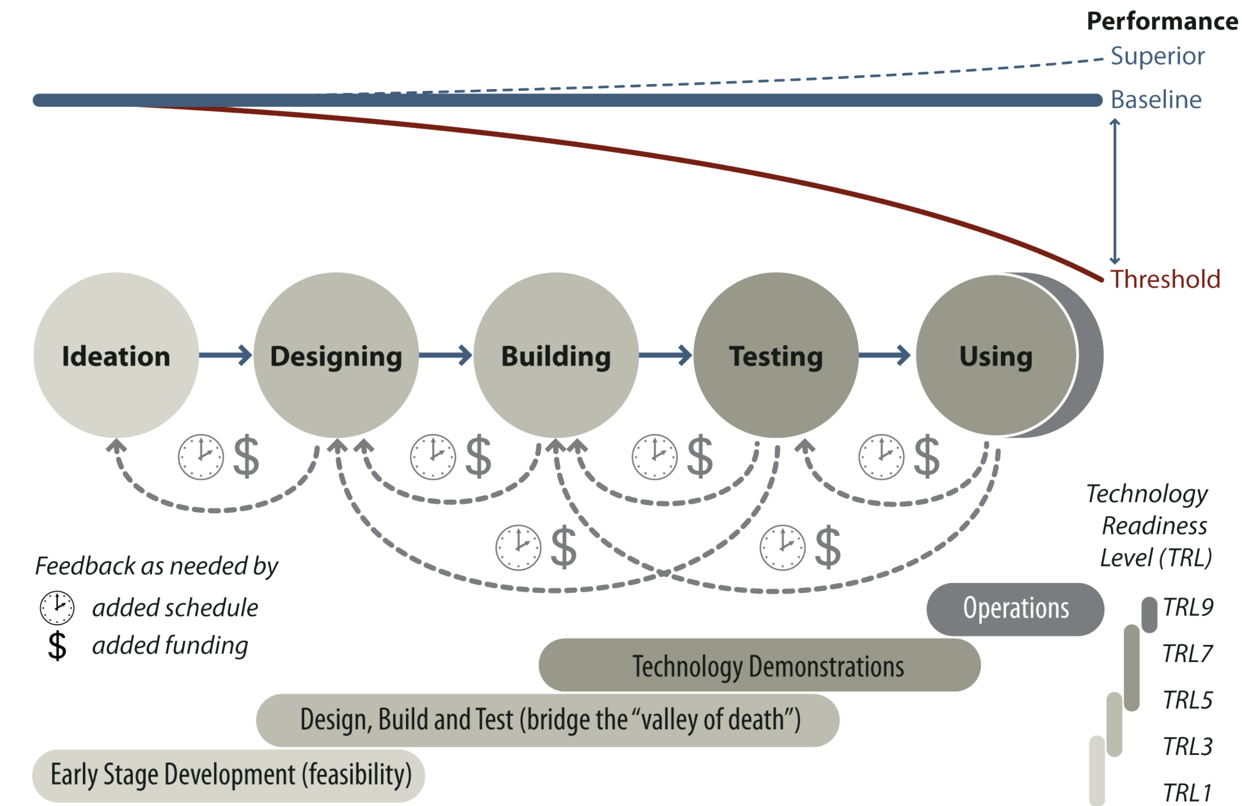

Figure 6: Fracture points can be identified within the activity circles, and control-feedback loop connections, where improved dialogs may lead to preferred outcomes.

driven by science, technology, mission architecture, and related costs, but also a number of strategic level considerations, which they need to be aware of.

Assessing the seven innovation barriers at NASA, we can conclude that most of them can be traced back to regulatory sources, or in a cybernetic sense to controller decisions and the directions they set at various levels of the hierarchy. Risk-averse culture is driven by an institutional culture, where people are rewarded for incremental successes and punished for failures. Low priority on innovation, short-term focus, and the lack of opportunities are all driven by budget uncertainties. These uncertainties also result in instability of the environment, which often includes project descopes, cancellations and re-phasing. Since failures can result in negative career impacts, enforcing and tracking procedural requirements can provide protection by pointing to full compliance, but it also leads to overall process overload. Spatial distribution of a large workforce across NASA Centers around the country may introduce significant communication challenges, especially when travel is highly regulated, and combined with fiscal uncertainties it can result in an less responsive system than desired from a dynamic organization.

After setting the stage with this brief overview, we can now provide a few examples where cybernetics can be used to frame any of these interactions, and identify notional fracture points, where design considerations can potentially lead to new perspectives, better understanding, and broaden the choices for planetary probe missions and for interactions in general at various fracture points. The examples address considerations for internal and external communications, language, information, organizational culture, design environments, management, and probe missions.

Figure 7 shows a simplified model of a circular cybernetic loop, which we use as a reference in subsequent discussions. It consists of three elements, the Regulator, the Process that the Regulator uses to interact with the environment, and the Environment. For a dynamic equilibrium, the variety of the Regulator needs to be in balance with the variety of the process, but in the real world both the Process and the Environment have increasingly larger (or equal) variety than the Regulator. This can be balance in multiple ways. First, the Regulator can enforce regulatory processes on the environment, in effect limit the variety of the Process and the Environment. In a feedback loop in-formation is provid-

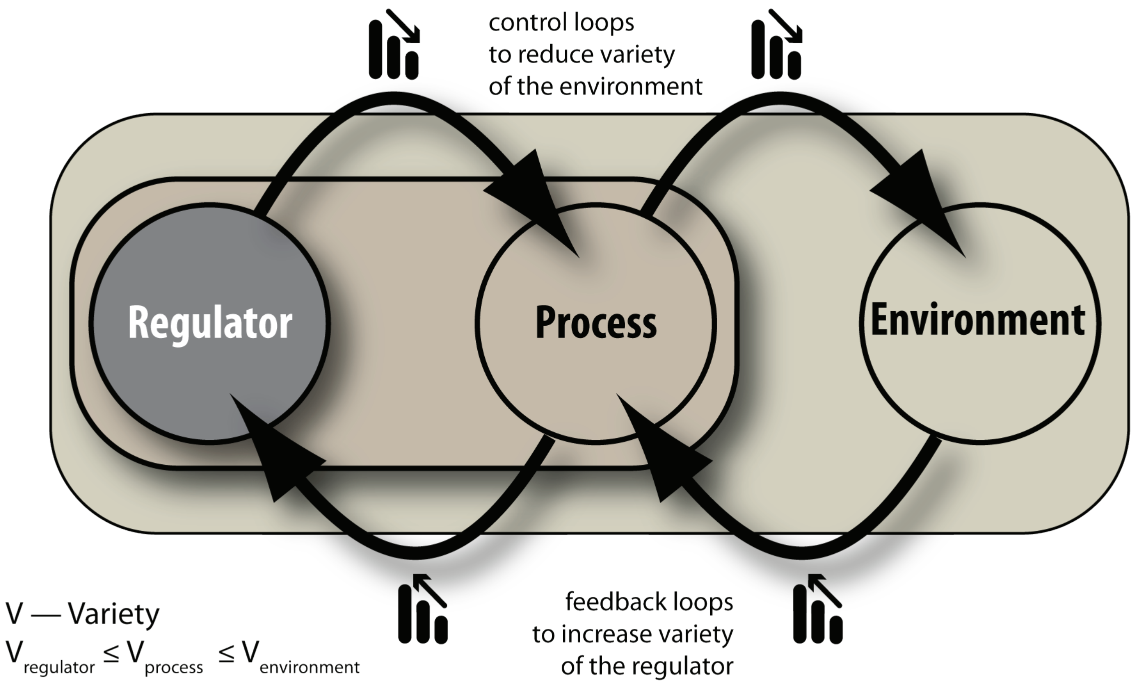

Figure 7: Simplified model of a circular cybernetic loop.

ed back to the Regulator from the Environment through the Process, which can increase the Regulator's variety. Understanding and leveraging this circularity is important to find the desired equilibrium from the Regulator's perspective.

Discussion on Communications, Language, and Information: 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 short hand provides a familiar and efficient exchange for discussion points. This language evolved over decades to address specific topic-relevant questions. At venues like IPPW, among subject matter experts, or within Agency settings it is expected that the meaning of the sentences and abbreviations are understood. But as shown through this example, the language gradually becomes 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 by filtering the information through the language. It might be done unconsciously and without recognizing the imposed limitations. Thus, the short-term efficiency-gain gets into 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 come up with new insights based on this increased variety. Therefore, language represents a fracture point, where the introduction of new languages to the dialogs can open new information channels, leading to new insights and options.

Discussion on organizational culture and management chain fracture points and circularity: A good working environment is highly dependent on the understanding and implementation of the roles and responsibilities within its hierarchy. Edison showed that organizational leadership, understanding and accepting educated risk postures—including failures—and diversity at the workplace are all key elements to promote a dynamic and innovative environment. Obviously playful and pleasant work environments are preferred over impersonal and bureaucratized places. Sharing opinions and allowing for constructive criticism through dialogs are key to generating and implementing new ideas. [22] Edison also found that people at any level work harder when involved with interesting and rewarding work (where they are empowered to act the role of a Regulator), and given meaningful rewards to foster individual ambitions and needs (where they their variety is broadened by enabling new options to select from them at will). While this may sound evident, it is not always implemented at workplaces. For example, if a manager at any level is too controlling and does not delegate responsibilities to the appropriate lower levels, it may result in multiple simultaneous outcomes. In the forward control loop the manager (Regulator) reduces the variety of the workforce at a lower level by making all the decisions [38]. This makes the particular Regulator feel in charge and provides satisfaction to him/her. However, this often demotivates people at the lower levels in the organizational hierarchy and may ignore good ideas. This was discussed as the authoritative approach under Wicked Problems. At the same time the provided feedback to the Regulator, can be either attenuated or divergent. The Regulator prefers attenuated feed-back, as divergent feedback may provide an overwhelming amount of information, which may be too much to process. However, attenuated information may leave out some of the key elements, which is needed for further considerations by the Regulator. This has multiple implications. For example, a manager elevated from a linear project level to a strategic level needs to recognize that the skills set at the two hierarchy levels are different. Under a linear discipline the goal of the Regulator is to keep the process or project execution on track by making appropriate control decisions. At the strategic level the goal is to be open and absorb all the internal and external information necessary to evaluate the potential options, and subsequently down select to the most appropriate one that benefits the organization. This could be aided by strategic level portfolio assessment tools, such as the newly developed Project Assessment Framework Through Design (PAFTD) tool that evaluates project performance at the strategic level and provides attenuated information to senior management to broader their understanding of relevant factors influencing their projects, which can lead to a broadened Regulatory variety and better strategic decision making. [33] A fracture point for managerial change is based on appointing someone with the right skills for the new position, with an attitude of openness to absorb variety for foster better strategic decision making, and someone who creates a balanced workspace by delegating responsibilities to the appropriate levels, thus building a recursive organizational structure, where appropriate regulatory functions are delegated and performed at every level within the hierarchy.

One potential way to introduce culture change to organizations—opposed to indoctrinating the new hires to linear process driven methods—is to educate and train a next generation of non-linear thinkers and to bring them into the workforce at both NASA and the broader aerospace enterprise. An appropriate program, potentially fashioned after RCA's Innovation Design Engineering (IDE) and Global Innovation and Design (GID) programs [34], could train a new generation of non-linear thinkers with trans-disciplinary expertise in design, engineering, cybernetics, and management. Introducing these approaches to an organization from the ground up could gradually change the culture and foster new dialogs and activities through design doing and prototyping. Therefore, a fracture point for organizational culture change lies at entry-level hiring of graduates with new skills.

Discussion on design environment fracture points and circularity: Design environments, such as JPL's Innovation Foundry, are ideally suited to embrace Design Dialogs and cybernetics, as these are the places where novel ide-as and future mission concepts are envisioned. JPL's A-Team develops new approaches to explore, develop and evaluate early stage mission concepts. It uses collaborative methods with participation of subject matter experts. Similarly to Technology Readiness Levels (TRL), JPL uses Concept Maturity Levels (CML) on the same scale to assess mission architectures. A-Team projects typically fall under the CML 1 to 3 range, where feasibility is demonstrated. These approaches often respond to a science question with an appropriate mission concept. An early stage mission concept development environment could be a fracture point, where the processes could be augmented with a preliminary divergence/convergence phase (see Figure 3), to explore the environment between a general problem and a specific problem, and by the introduction of new languages to reach beyond analogies and previous mission concept examples.

Using this approach is not suitable at higher TRLs or CMLs, where the project or the mission are already in an implementation phase and multiple design trades are no longer evaluated. This approach is driven by the high development costs of space technologies and missions, resulting in a down selection of technologies from feasible low-TRL options, and execution of a point designs, as it is too costly to parallel-develop multiple options to a later stage down selection.

Dialogs among the team members, team dynamics, and team makeup play pivotal roles in developing and accepting a new design language. Bringing scientists, subject matter experts, technologists, engineers and designers together could provide sufficient diversity, leading to the emergence of a new language with new options and potential outcomes, if the team is given the proper guidance. The team should be encouraged to move beyond concept assessments and 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. As shown in Figure 4, the activity lead must be concerned with guiding the conversations to agree on the goals, means, and keep an openness for new languages and dialogs. At the same time, the design process need 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 meeting with large invited memberships are often wasted resources and do not achieved desired outcomes. Thus, selecting customized team memberships for each meeting is also a fracture point.

Discussion on external communications and public outreach fracture points and circularity: Storytelling is a highly important process to communicate NASA's messages to various stakeholders, ranging from interactions with the government during the Programming, Planning, Budgeting, and Execution (PPBE) process, to interactions with the public. Customizing and delivering a coherent message to diverse audiences is the responsibility of the communications departments within each organization, making them fracture points for introducing changes. These departments control the message of the organization and need to customize it to each stakeholder. Clearly, talking to members of the Office of Science and Technology Policy requires different messaging than talking to third graders. Still, there are managers at NASA who believe that a "consistent message requires the use of the same PowerPoint slides without change". Messaging is a key strategic activity, where the information provided to stakeholders has a purpose to guide their understanding of Agency activities, and to initiate dialogs. If the messages are not at the appropriate 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 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 examples to the whole agency. For example, IPPW have been using planetary probe relevant poster designs to bring attention to its annually reoccurring and highly successful conferences (see Figure 8). Engaging the public may lead to much needed advocacy, and involving the next generation leads to young people with expanded horizons (broadened variety), allowing them to dream, and choose from more possibilities when deciding on their future. In a cybernetic sense, a dialog develops between NASA and the external audience. NASA's messaging controls the information, thus reducing variety for the audience with the goal to achieve clarity. If there is misunderstanding, the feedback allows refining the message and re-transmitting it with adjustments. The circular communication loop continues until the variety regarding the intended message reaches a common equilibrium. At times the feedback is not available, in which case the clarity of the message has a direct impact on the interpretation from the environment. Thus, another fracture point can be identified at the communications departments within organizations, where targeted use of design and cybernetics can make a significant impact.

Discussion on probe mission fracture points and circularity: During atmospheric entry, the environment interacts with the aeroshell. Aerodynamic heating and pressure forces need to be in a dynamic balance with the aeroshell's control capabilities (which can be either passive or active). Here the Regulator is the aeroshell, the process is the control, and the Environment is the planetary atmosphere. During planetary entry the goal of the Regulator is to keep the environmental effects within its variety and achieve a controlled and safe entry. The control system is built with a broad variety to respond to any of the foreseen environmental interactions. For example, an ablative aeroshell is sized for the expected heat pulse, heat flux, atmospheric drag, and shock layer gas physics. It is a passive system, with sufficient built in variety to control safe atmospheric entry. Interestingly, these passive controls are built into the system in prior cybernetic loops, between a group of engineers, and technologists, who used iterative engineering design processes to build these controls into the aeroshell, using validated models to predict the environment. Both of these control loops (the hardware creation loop and the atmospheric entry loop) are set up to strictly control the input conditions. They are spatially and temporally decoupled. The engineering regulatory loop is used to build the aeroshell, and the entry loop to control the environmental dynamics.

At present it may seem that all of the elements of a space mission and contributing systems are well established, including engineering, systems, technological approaches, using the same subject matter experts and design environments, while missions are often managed through highly process driven approaches. As these solutions and their incremental advancements worked well in the past, new requirements and resource limita-

Figure 8: Sample IPPW posters by T. Balint.

tions necessitate to rethink these issues. For example, on future missions (e.g., during human missions to Mars) we will need to land significantly larger masses on the surface, and financial constraints may limit the number and scope of future probe missions (e.g., probe missions to Saturn or Venus).

In the early stages of a development-cycle both human and robotic mission concepts follow the same progression and design steps as shown in Figures 3 and 6. However, the requirements can be non-linear, and may form Wicked Problems when all strategic level internal and external considerations are factored in, along with the strictly scientific, technical and resource drivers. Finding novel solutions beyond incremental developments we need use out of the box thinking. There are numerous examples for novel solutions in use or under development, using methods, such as cross pollinating from other fields, and looking at current solutions from different perspectives to identify novel outcomes.

As we examined cross-pollinating ideas, it was evident that many EDL systems show resemblance to other terrestrial approaches, which are based on hundreds of years of terrestrial evolution, providing effective solutions for pressing needs. Umbrellas provide a portable and deployable barrier between individuals and their unwanted rainy surroundings. Similarly, once deployed prior to atmospheric entry, ADEPT (Adaptable, Deployable Entry Placement Technology) is designed to protect the payload against atmospheric heating and the larger cross-sectional area is sized to permit larger landed masses to the surface of Mars (see Figure 9). As umbrellas can close for better portability, ADEPT can be stowed during launch to fit inside the fairing of its launch vehicle. Another solution for the same entry problem can use inflatable multi-ring constructions, called HIAD (Hypersonic Inflatable Aerodynamic Decelerator), shown in Figure 10. Inflatable systems can be also used for light and versatile wheel designs on the surface of Titan for better terrain handling, and the Tumbleweed rover concept that would use the light wind on Mars for traversing, similarly to the tumbleweeds in the Arizona desert. Protecting the payload during landing is another challenge, where cross-pollinating ideas of airbags from cars or inflatable costumes from games provide similar approaches to the Pathfinder and Mars Exploration Rovers airbags (see Figure 11). With increased landing mass airbags become non-feasible solutions. As shown in Figure 12, rocket assisted landing has been used on a C130 Lockheed-Hercules airplane, and a similar ap-

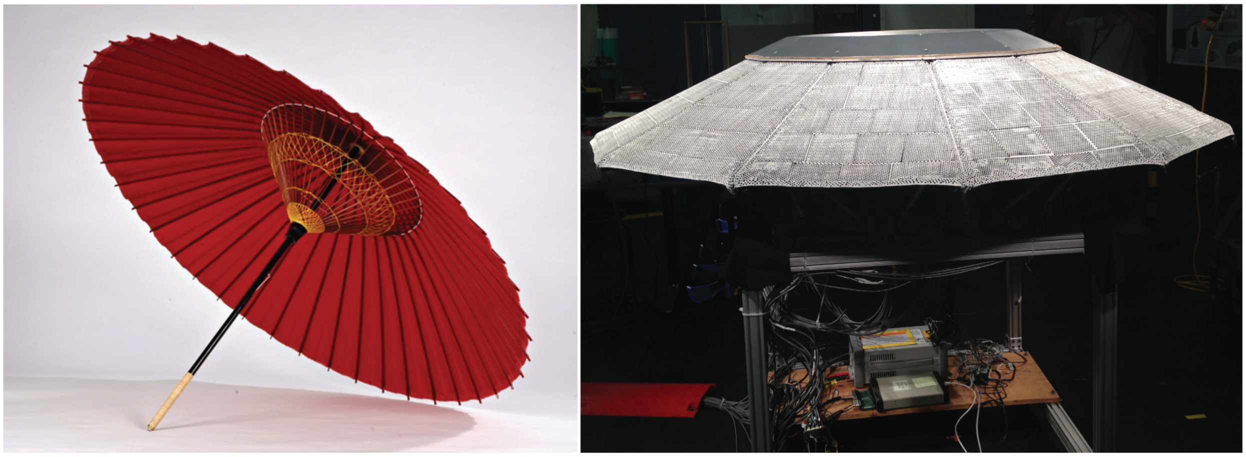

Figure 9: Cross pollinating ideas: Japanese umbrella and ADEPT (Adaptable, Deployable Entry Placement Technology) concept.

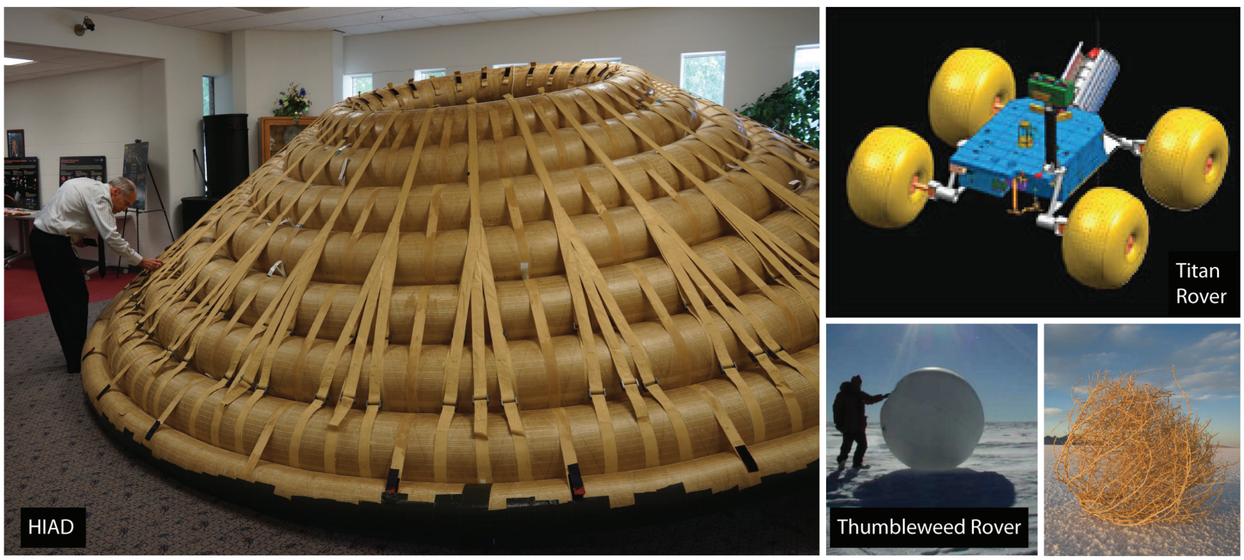

Figure 10: Cross-pollinating ideas: inflatable solutions from the HIAD entry system, to Titan rover wheels, and Tumbleweed Rover concepts.

Figure 11: Cross-pollinating ideas: protecting "payloads", from car airbags for humans to Pathfinder/MER airbags for science instruments.

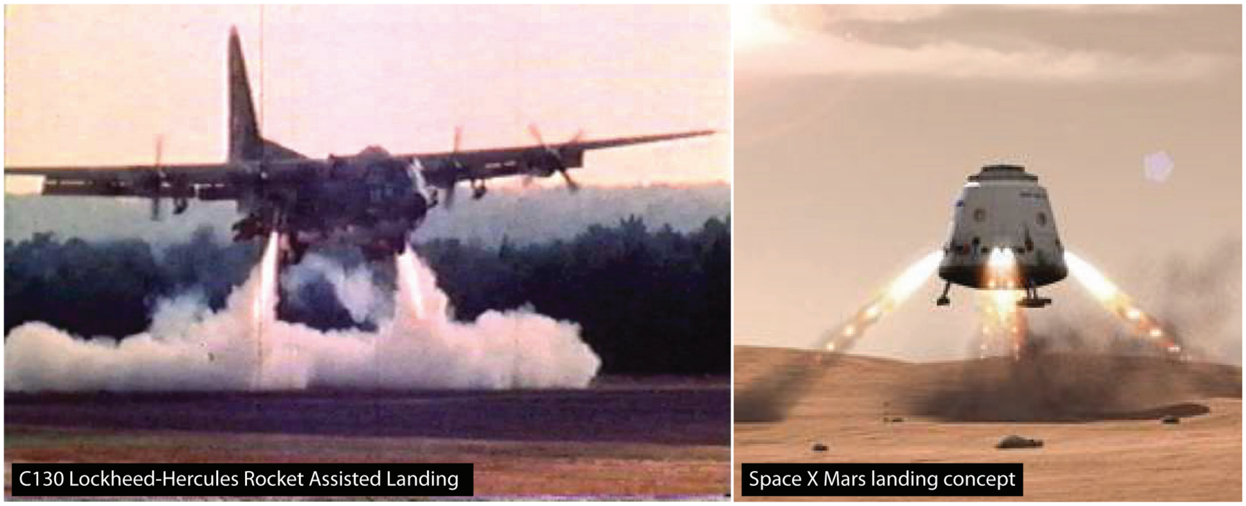

Figure 12: Cross-pollinating ideas: Rocket Assisted Landing of a plane and an artist's concept of a Mars lander.

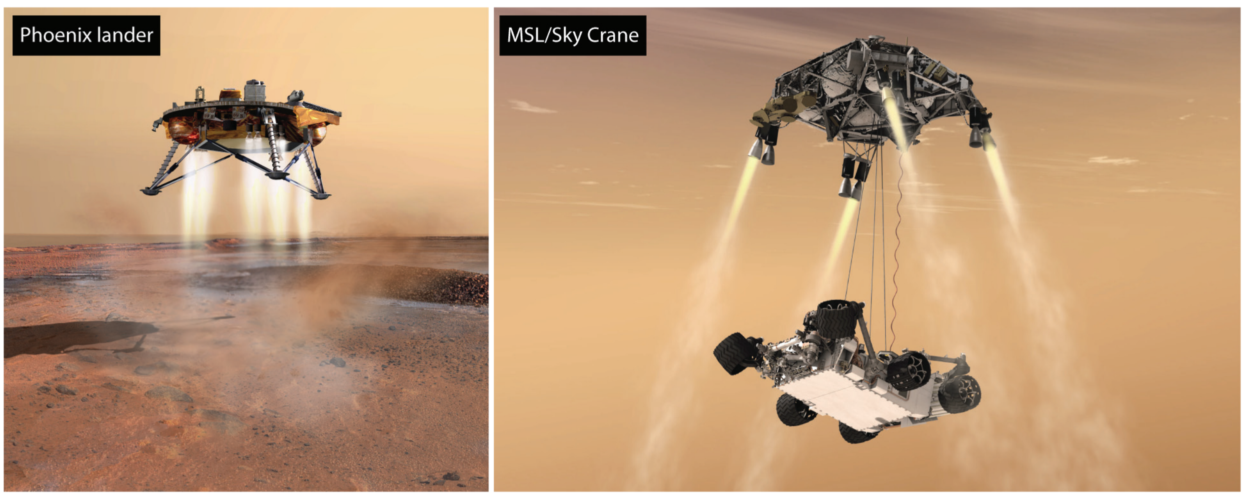

Figure 13: Inverting the meaning: Artist's concepts of landing on Mars with Phoenix, and MSL/Sky Crane.

proach is proposed by SpaceX to soft land a capsule on Mars, during a future human exploration mission.

Another way to change perspectives could be achieved through inversion. Planetary lenders from Apollo's Lunar Excursion Module (LEM) through the Viking landers, to the Phoenix lander on Mars, designs used a configuration where the propulsion system was mounted below the landers. The Mars Science Laboratory team turned this around, and move the steerable landing engines above the rover. This change of perspective on landing surprised and even shocked many experts when it was first announced, and until the highly successful landing in 2012 the team had to answer numerous questions on the technical feasibility of this configuration (see Figure 13). Changing the perspective on Thermal Protection Systems (TPS) is exemplified through the Woven TPS (WTPS) project (see Figure 14). To date ablative aeroshells were designed, built and customized to their planet or moon specific atmospheric entry environments, resulting in individual a broad number of options. These included high-density carbon-phenolic for the Galileo probe at Jupiter and the Pioneer-Venus probes at Venus; mid-density TPS (e.g., mid-density Phenolic Carbon, ACC) for Genesis during Earth return, and low/mid-density TPS (e.g., Avcoat, PICA, SLA) for Apollo and Stardust Earth returns, and mars missions, including the Viking landers, Pathfinder, MER, MSL, and Phoenix. WTPS turned this around by providing a single customizable TPS solution to almost all destinations, making the ratio of ablation and insulation layers customizable depending on the destination and entry environments. It moved the perspective from many TPS solution for many destinations, to starting from a single TPS solution and using it for all destinations. Furthermore, the same material is being used on the Orion capsule, for its 6 load bearing compression

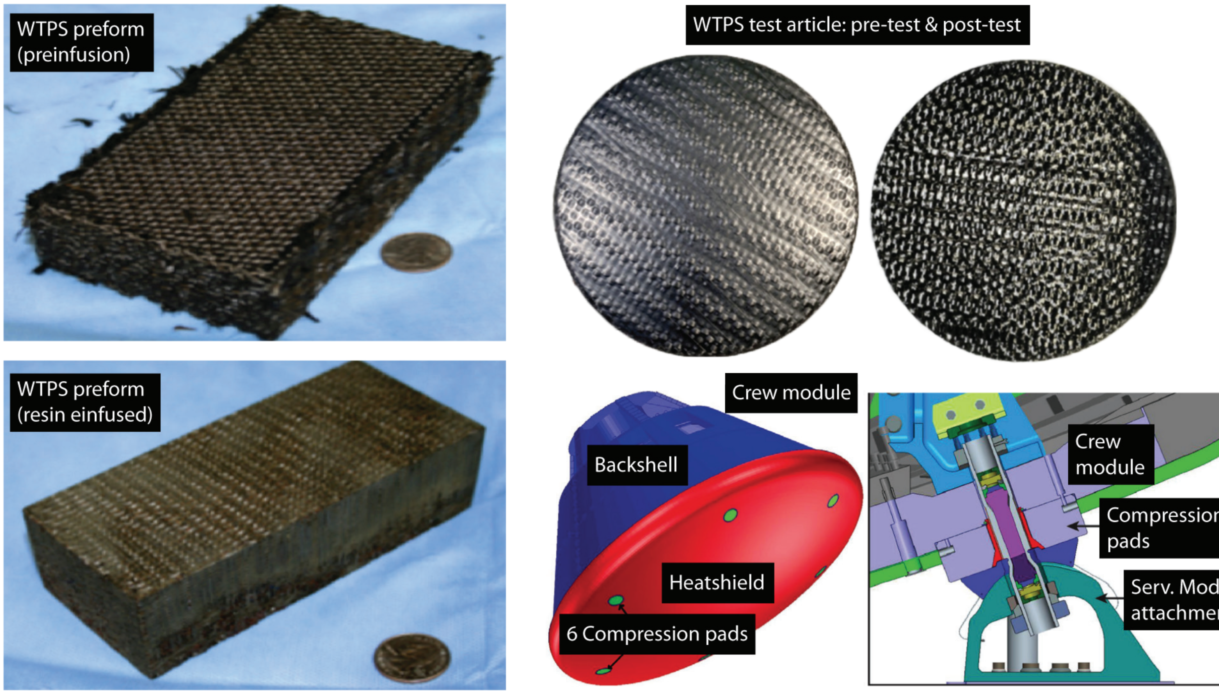

Figure 14: Inverting the meaning: Single solution to multiple uses and destinations, including the Woven Thermal Protection System (WTPS), and compression pads on the Orion module.

pad, with combined TPS functionality. The production of the 3D woven carbon blocks is also unique, as it is done on weaving equipment over a hundred years old, proving that not everything needs to be the newest, the fastest, or most technologically advanced, and new solutions can be created from existing old products, by combining them in novel ways. [35]

The list of examples and considerations presented here are far from complete, and were used for illustration purposes only, the same way as cars rolling off an assembly line provide insights into the workings of the assembly line on which they were created. In this analogy, the assembly line is represented by the design framework, consisting of design dialogs to advocate new languages and discussions, out of the box thinking, and approaching problems through the perspective and circularity of cybernetics, in order to better understand the interactions between the various contributing elements.

Conclusions: Planetary exploration faces many challenges, related to limited resources, technological complexities, and other organizational and innovation barriers. In-situ explorations introduce additional hurdles compared to flyby and orbiter missions. Many of these challenges could be solved through brute force engineering approaches, if appropriate resources would be available. Unfortunately this is not the case. Over the past decades the community have been proposing reasonably sized and costed planetary probe missions, by pointing to the needs of the scientific community to help understanding our world, and providing arguments for technological feasibility. Repeated proposals, using virtually the same approaches and thinking have led to the same outcomes of numerous positive feed-backs from the review boards, but without the selections of missions. This circular loop between the proposers and the regulators, who select the missions, continuously led to the same outcomes.

To turn this trend around, we need to look for novel approaches. While pointing these out, our intended purpose for this paper was not to provide firm answers, recipes, and plug-in point solutions, but to identify fracture points within the established processes, where realignments could be realized using new perspectives through cybernetic and design approaches to augment the current state of practice. These fracture points include the introduction of new languages emerging from Design Dialogs; changing the organizational culture by having management with the appropriate variety for their positions; leveraging divergence and convergence cycles during design activities; and better customization of messages towards stakeholders, all through circular dialogs. It is further exemplified by initiating this dialog between us, the authors of this paper, and the users (audiences and readers), by introducing new concepts and terminologies to a well established and fixed aerospace engineering vocabulary, thus providing a new perspective to assess issues facing the community. As a potential outcome, these new languages could 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.

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