PhysicSpace: From Quantum to Human Scale

Kevin Walker and Karin von Ompteda

Figure 1: Outputs from the *Average Football Game* project, with RCA students Jae Kyung Kim and Carrolynne Hsieh.

Abstract

We describe a month-long project about communicating physics concepts and methods through spatial and experiential installations in a public exhibition. A collaboration between MA students in Information Experience Design at the Royal College of Art and physics PhD students at Imperial College London resulted in an exhibition which rendered quantum interactions of particles and fluids at human scale using wood, lasers, projections, lenticular printing and digital technologies, in an atmospheric underground space in May 2014. This work, we believe, signals a new category of art-science collaborations, in between didactic museum displays, practical visualisations, and science-inspired art projects, aimed at communicating scientific concepts spatially, experientially and with artistic methods and critical narratives.

Keywords: Physics, design, art, installation, exhibition.

1. Introduction

Visualisation is about conveying complex information in a comprehensible form [49], and many science visualisations rely on traditional means such as pie charts, bar graphs and scatterplots [5, 72]. Art, by contrast, "presents layers of visual connections, analogies and metaphors, asking the viewer to complete the picture. Unlike visualization, its intent is to raise questions rather than provide answers" [49].

In this paper we describe a month-long project situated in the space between art and scientific visualisation. It was not about creating artworks informed or influenced by science; nor was it about visualising scieintific data. Rather, it was about communicating physics concepts and methods in a comprehensible form through spatial and experiential installations. A collaboration between MA students in Information Experience Design (IED) at the Royal College of Art (RCA) and PhD students in Physics at Imperial College London (ICL) resulted in an exhibition which rendered quantum interactions of particles and fluids at human scale in interactive, experiential installations, in an atmospheric underground space in May 2014.

We describe previous work leading up to the project, the project background, the methods and process during the collaboration; we then detail the resulting installations and the exhibition as a whole. We conclude with a discussion situating this work in relation to information visualisation, science communication, and artistic practice.

2. Previous work

Among the profusion of screen-based visualisations increasingly available online, we believe that there is a need for practice-led design research to explore criticality and narrative as well as new forms. We are thus engaged in interdisciplinary design research which attempts to balance scientific rigour and computational thinking with experimentation and creativity from an artistic perspective.

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A particular line of research has been in representing science and scientific data in physical, spatial, experiential forms. One of the authors (Walker) has many years experience in visualising science using technology in museums, in particular moving away from the screen by employing techniques of physical computing [25, 69]. Ishii, et al. [26] predict that flat, screen-based displays and interactions will soon disappear in favour of dynamic materials and physical manifestations of information.

Concurrently, scientific visualisations have moved off the screen and into physical form. For example Gwilt [18] has utilised 3D printing technology to embody digital information in static "data-objects." Empirical research [27] has shown that moving visualizations to the physical world can improve users' efficiency at information retrieval tasks.

One of the authors (von Ompteda) has been running *Critical Visualisation Workshops* at the RCA and elsewhere since 2010. In these workshops, which take their title and inspiration from Hall [20], students from various art and design disciplines render statistics in physical forms and from a critical perspective, exposing and exploiting the non-neutrality of data to tell deliberately subjective – yet statistically accurate – stories. The forms resulting from these workshops are often interactive and experiential, having included for example a swing set, a cake, melted glass bottles and forced smiles [38].

Von Ompteda is a Visiting Lecturer in the IED programme run by the other co-author (Walker). The programme launched in 2012 with 18 MA students and 7 PhD students. In Spring 2013, von Ompteda secured funding for a project with ICL researchers about urban data, including transport, energy, and weather. We called this project *DataSpace* and it resulted in interactive and experiential outcomes involving, among other materials, dripping honey and forged brass bells. The outcomes were showcased at the Victoria and Albert Museum in London in May 2013 (see spaceprogram.rca.ac.uk).

As the IED programme moved into its second year, we wanted to work more with scientists for our next big project. We secured funding from the Institute of Physics to work with physicists, aiming to render the concepts and methods they use in similarly physical, spatial, multisensory and experiential forms, resulting in a public exhibition.

Visualising quantum physics is inherently difficult due to the scale at which it operates, the abstract nature of its formulations, and the confusing, often counterintuitive effects produced [28]. Because the field is so specialised, visualisations tend to be created by physicists or computer scientists for university students who specialise in the subject [29, 61, 76]. Even with such resources, many physics graduate students continue to hold deep-rooted misconceptions about the subject even after one or two years of specialist instruction [56].

There are several artists working with quantum physics. For example Edward Tufte, best known in the visualisation community for his practical books, also creates sculptures based on the wave and particle diagrams of physicist Richard Feynman [60]. Among well-known artists, Grenville Davey [8] and Conrad Shawcross [54] create works based on string theory. Victoria Vesna [63] has become well-known in the art-science community, working particularly with nanosystems including quantum interactions. Other artists working with physics include Tauba Auerbach [2] and Mira Schendel [7]. Libby Heaney [22] and Julian Voss-Andreae [66] are perhaps unique in having been formally trained in quantum physics before moving into primary careers as artists. At the time of our project, the ICL Physics department had an artist in residence, Geraldine Cox, but she was not involved in the project. [6]

3. Project background

PhysicSpace, as we called our project, ran for four weeks in April 2014. Twelve RCA students took part, and the Institute of Physics put us in touch with various physics PhD students, all from ICL, of which four were selected:

3.1. David Trevelyan

David Trevelyan creates multiscale simulations of instabilities in complex, non-Newtonian fluids, working in an applied area bordering with mechanical engineering. In such fluids, polymer chains become entangled, but this depends on timescale; the effect can be seen in a simple form using cornstarch mixed with water [67]. When they undergo circular motion, such fluids create near-chaotic toroidal vortices. These quantum instabilities cannot be studied experimentally because every atom cannot be modelled, so Trevelyan couples large- and small-scale computer simulations, using Python scripts.

3.2. Vignesh Venkataraman

Vignesh Venkataraman works in theoretical physics, studying open quantum systems, exemplified in popular examples such as Schroedinger's Cat and the double slit experiment. In particular, he studies systems that exhibit non-Markovian behaviour – that is, systems with memory, whereby states further back than the previous one have an effect on what is currently happening. When quantum particles interact with things, he explained to us, they display more classical behaviour.

3.3. Mercedes Gimeno-Segovia

Mercedes Gimeno-Segovia works in applied physics, specifically on one of the first implementations of an optical quantum computer to overcome Moore's Law, by exploiting the quantum property of superposition, in which a single particle can simultaneously have two states. Collectively, individual photons could, in theory, simultaneously calculate all possible solutions to a mathematical problem, analogous to massively parallel processing in digital computing.

Gimeno-Segovia also utilises the quantum phenomenon of entanglement, in which two particles share the same state, and can even "teleport" that state over long distances (143m experimentally, as of this writing). This is specifically manifested in photons via the polarisation of light. She entangles two particles, measures their state, and repeats this many times.

3.4. Claudio Polisseni

Claudio Polisseni works on controlled quantum dynamics. When excited under certain conditions, molecules can emit photons that can be used for quantum information processing applications such as cryptography. He deposits a layer of molecules on a waveguide chip and excites them with laser light, then measures the results. The molecules are kept in a vacuum at –270 degrees Celsius, in Polisseni's lab deep in a sub-basement of Imperial College. "Physics," he told us, "happens in a dark place."

4. Methods & process

The RCA students were asked to choose one of the physicists to work with in developing a way of representing his or her concepts and methods, in order to bring quantum physics to human scale. All of the scientists were very good communicators. The tools and apparatus they used, from lasers to waveguides to quantum systems, provided a material basis for physical and interactive ways to communicate the science. As for the scientists, all wanted to explore new forms of science communication, and all were specifically interested in art.

Students worked individually, in pairs or threes, each group working with a physicist, visiting the labs and discussing the science. It was not easy, but there was much fertile material to inform creative work, and students enthusiastically supplemented this with readings, including those suggested by us and some they found themselves. They watched video of lectures by Feynman, and visited an exhibition at the nearby Science Museum about the Large Hadron Collider.

They concurrently began developing their own ideas and explorations with materials and techniques for display and interaction. Oliver Smith, for example, attempted to model quantum concepts in the Processing programming environment, but quickly found it limiting. There are physics libraries for such environments, but they are designed for game development, and even in 3D environments they are focused on classical models of Newtonian forces, in order to simulate realistic behaviour.

Some of the students were concurrently, if perhaps unwittingly, utilising physics concepts in another IED project called *Exploded Screen*, which explores new types of experiential moving image displays. Student projects included dynamic fluid simulations, relative perceptions of time, and particle projections incorporating steam and water (see explodedscreen.rca.ac.uk).

Students met with von Ompteda weekly to look at work in progress and refine their focus. We observed that the students were becoming fairly well versed in quantum physics, able to assist each other's conceptual understanding and push the practical work forward both in terms of accurate science communication and engaging visitor experience.

Our general advice to the students was to communicate a single concept in a simple, compelling way, encouraging them to be ambitious in terms of scale, paying attention to materials, experience, context, interactivity, and atmosphere.

5. The installations

5.1. flow.instability

Carrolynne Hsieh and Jae Kyung Kim (RCA) worked with Trevelyan (ICL). His double-cylinder computer simulations model instabilities in liquid argon, a complex fluid whose properties cannot be described using Newtonian concepts such as viscosity. Fluid dynamics can be imaged directly, but at the molecular level are typically simulated [23, 24] and is visualised using tools and libraries such as MatPlotLib [33], PyMol [46] and VMD [65].

According to the Lennard-Jones Potential model used by Trevelyan, when molecules of liquid argon are far apart, they do not sense each other; hence there is no attraction. As they move closer together, they become increasingly attracted to each other, but when they are too close they repel each other. This is not unlike human behaviour, according to space proxemics [19]. People seek security in numbers [47], but there are (culturally variable) comfort zones of personal space.

The installation thus brought Trevelyan's simulations to human scale with a walk-through structure, approx. 4m in diameter by 2m high, with two concentric rings as in Trevelyan's computer model. The spaces between the rings were carefully designed so that in order to pass each other, people would need to turn sideways in uncomfortably close interactions.

For the surface, the students designed an arrangement of wood pieces which began chaotically but resolved into a more orderly pattern, intended to mirror the way Trevelyan conducts his research – the molecular behaviour he studies appears chaotic at first sight but has a general trajectory, and he turns the observed values into ordered data by averaging the data repeatedly to derive the overall flow of molecules. The result was compelling both visually and experientially, effectively communicating both the interactions between particles/visitors and a movement from chaos to order as visitors moved inward. The final installation is shown in Figure 2.

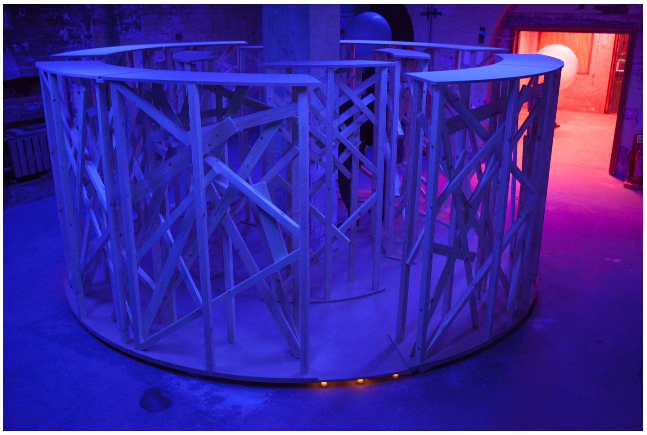

Figure 2: *flow.instability* by Carrolynne Hsieh, Jae Kyung Kim (RCA) and David Trevelyan (ICL).

5.2. Observation

William Fairbrother (RCA) worked with Gimeno-Segovia (ICL). A quantum computer uses "qubits" which can simultaneously represent a 1 and 0, as against a binary bit in a digital computer which only takes a single state. But when observed, the superposition of a qubit is destroyed and it occupies a single state. The quantum state of a qubit is typically visualised using a representation called a Bloch sphere [11]. The optical quantum computer being developed by Gimeno-Segovia utilises photons which can be simultaneously polarised horizontally and vertically, travelling through waveguides on a chip.

Fairbrother chose to create a large lenticular print of a close-up image of the pupil of an eye, simultaneously dilated and constricted. Lenticular technology uses grooves to channel light from two different images, similar to the waveguides in the optical quantum computing chip described above. Fairbrother's print was backlit so that the light was channeled outward to the observer, who would see a different state depending on the point of observation – thus the medium was the message to a certain degree. To address the brief of translating quantum physics to human scale, in this piece the viewer had to move around the piece to view the two different states.

To create the image itself, Fairbrother visited an optometrist to have his pupil dilated, before and afterward having it photographed by a professional photographer. He noted that like the photons observed by Gimeno-Segovia, his own eye was observed very closely; the fact that it was subsequently observed by exhibition visitors gave it the dual quality of something which both observes and is observed. The spherical shape of the eye also, coincidentally, resembles a Bloch sphere. Gimeno-Segovia noted that in her work she sometimes moves between feelings of elation and frustration – emotional states which are indicated physiologically by the dilation or constriction of the pupil [3]. Fairbrother aimed to create a nonconventional image to illustrate these dualities, which might also serve as an iconic image to start conversations about science [12]. The final piece is shown in Figure 3.

Figure 3: *Observation* by William Fairbrother (RCA) and Mercedes Gimeno-Segovia (ICL).

5.3. Discretisation

Riah Naief (RCA) worked with Trevelyan (ICL), specifically referencing a method of virtual experiments used by the latter which render a continuous model of molecular behaviour in discrete steps, whereby nanosecond exposures of light afford individual observations of a system. Single molecules have typically been imaged in this way using flourescence microscopy [51, 53].

Naief's kinetic installation mirrored this process. A large upward-facing fan at the base of a cylindrical aluminium and plastic structure suspended a number of lightweight polystyrene spheres in continuous circular motion. She experimented with different sized fans and construction techniques to achieve an optimal motion around the centre of the chamber. The installation was exhibited in complete darkness, and a strobe light revealed discrete states of the system in motion, like individual frames in a film experienced through persistence of vision; it therefore bridges static and kinetic visualisations, being in constant motion but visible only in discrete snapshots. Trevelyan remarked that the effect was like being inside one of his computer models, as the viewer was able to see unaided and at human scale discrete views of a system in continuous motion. The installation is shown in Figure 4.

5.4. Resonance, Revenant

Oliver Smith (RCA) worked with Venkataraman (ICL) to create an installation simulating the transfer of energy between particles on the quantum scale, which occurs as a result of each particle's frequency. It specifically modelled at human scale a system exhibiting non-Markovian behaviour – that is, a system with memory, in which previous states affect the current state.

Resonance, Revenant translated these unseen shifts into an immersive experience using sound and light. Bare loudspeaker cones were arranged on the floor, facing upward, with a ring of light around the base of each to indicate its state. This echoed the cone shape used to visualise quantum particles in an open quantum system [75]. The cables connecting the loudspeakers to an amplifier were left visible, though carefully arranged, to reinforce the objects' connections to each other in a system. Speakers with shorter cables between them signified more closely coupled pairs, and cable lengths were kept flexible to facilitate changes in connections and couplings based on self-selecting frequencies. The installation is shown in Figure 5.

Figure 4: *Discretisation* by Riah Naief (RCA) and David Trevelyan (ICL).

The transfer of energy between particles, typically represented in the scientific literature using two- and three-dimensional graphs [48], was represented in the installation when a speaker was activated with both sound and light, and nearby speakers would then appear to absorb some of the energy given off. The energy lost from one speaker to another eventually returned to the original speaker, with some loss of energy along the way.

The sound of bells was chosen for their role as a human signalling mechanism. Collectively the tones combined to create harmonic tones and oscillations, further reinforcing the perception of a complete system, and also stimulating in visitors not only an auditory response but a visceral, whole-body felt sensation.

Figure 5: *Resonance, Revenant* by Oliver Smith (RCA) and Vignesh Venkataraman (ICL).

Visitors were encouraged to move around the space, exploring the system's output with their eyes and ears, looking for patterns. Smith took care to simplify the output of the system in order to clearly communicate his intentions, whilst still retaining enough mystery to maintain visitors' interest. "This," he explained, "boils down to a simulation of a simulation, using Processing to mirror the work (in a simpler way) and pare down its output to the most interesting, engaging essentials.” [57]

Smith explained his decision not to encase the loudspeakers as follows:

> *The models in Vignesh’s research are defined by conditions and parameters and therefore have no explicit form. The observations he makes don’t rely on the form of the system or, even, parallels with real world particles but are defined by looking at the effects, the outcomes of each variation*. [58]

His approach was thus to keep the form of the objects as close to their behaviour as possible – sound-emitting devices, for example should be clearly identifiable as loudspeakers. This avoided the explicit metaphors often used in science communication, instead “mirroring the scientific simulation whereby each item is described by a set of properties and connections.” [57]

For the lights, Smith used projection mapping, with a short-throw projector, to project circles of light around each loudspeaker. The projector (an Optoma GT760) proved so effective in projecting at an extremely oblique angle that it was almost hidden along one wall while covering most of the floor of the room with projected imagery. Visitors could thus walk around the installation without obscuring the projected lighting, for the most part, giving the piece a further magical quality.

5.5. Average Football Game

Charles Rickleton (RCA) worked with Trevelyan (ICL). To predict fluid dynamics at a molecular level, many thousands of computer simulations must be carried out. The data has a high noise-to-signal ratio, and so must be averaged and repeated many times in order to extract meaningful data. Coincidentally, the data emerging from Trevelyan’s simulations, when each iteration is layered atop one another, bore a striking similarity to von Ompteda’s data-driven approach to type legibility. [40] Time-series overlays are a common way of visualising scientific results [50], particularly in molecular dynamics [15].

Rickleton took inspiration from the RCA bar, which has a table football game. Rickleton recognised the game as a system which similarly undergoes many iterations, with ample variety to keep players interested yet with an ultimately bounded space of possibilities. His resulting installation faithfully communicated the scientific ritual of repeated experimentation, while integrating elements of performance, participation and emergent design.

Rickleton took on the role of referee, first creating a bespoke uniform by altering a scientific lab coat in the RCA’s spray booth. Further colour-coded lab coats/uniforms were provided for players, and for “lab assistants” who would stand by taking notes. The bar loaned the football table for the duration of the exhibition, and Rickleton augmented it by cutting sheets of thick watercolour paper to fit precisely onto its surface. He created an “inking station” consisting of a small table for a series of balls, a squeeze bottle of ink, and a pair of rubber gloves with sponges attached to the palms.

During play, Rickleton, whistle in mouth, acted as an agent in the system, keeping very precise time and closely observing and monitoring the game. He slid a sheet of paper onto the surface of the table, carefully inked a ball and dropped it into the centre. Players (at one point including Trevelyan) donned their coloured coats, lab assistants took their places, and play proceeded as it would in a normal (“average”) table football game. Gameplay is shown in Figure 6.

After each game, the paper was removed and hung up (Figure 1), revealing distinct patterns in the form of “heat maps,” as Trevelyan described them, out of the chaotic system. The installation made explicit table football as a system with rules, positions and procedures, and Rickleton had created a visual mechanism for recording data from it over time.

Figure 6: *Average Football Game* by Charles Rickleton (RCA, pictured centre) and David Trevelyan (ICL).

5.6. Quantum Burn-in

Laura Gottlieb, Xinglin Sun and Francesco Tacchini (RCA) worked with Polisseni (ICL). In Polisseni’s experiments, molecules emit photons when shot with a laser, but only for a few nanoseconds after their lifetime. What results is an image of various molecules emitting light at different intensities, as shown in Figure 7.

The installation used an afterimage, which the team called a “bug of human vision,” as a visual metaphor of Polisseni’s experiments in counting the reflections from each molecule. Visitors entered a darkened space and approached a small red light. When they reached a particular distance, a series of bright lights flashed for a split second, leaving an afterimage in the visitor’s eyes. This is shown in Figure 7.

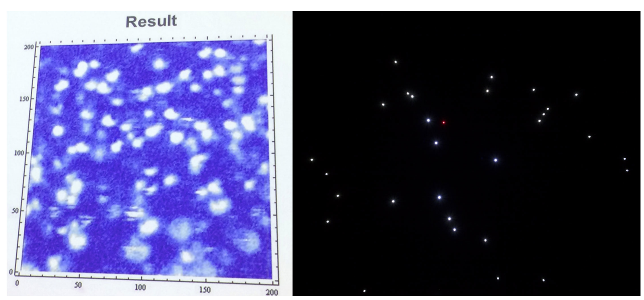

Figure 7: Experimental result from [45], and *Quantum Burn-in* by Laura Gottlieb, Isil Sun, Francesco Tacchini (RCA) and Claudio Polisseni (ICL).

After a few prototypes, the effect was achieved with a concave MDF panel mounted on a timber structure, approximately 2m square, painted black, with holes drilled for 60 LEDs. An ultrasonic sensor mounted on the board measured visitors’ distance. The students mapped the intensity of the 60 most visible molecules in one of Polisseni’s images to brightness values of the LEDs (though the positioning of the LEDs did not precisely match the positions if the molecules in the image). After testing with 256 levels of intensity, the team determined that people were not able to distinguish such subtle variations, and so averaged the intensities to three levels. The flash lasted 25 milliseconds.

5.7. System Bath

Meng Yang (RCA) worked with Venkataraman (ICL). His scientific process involves simulating quantum systems (collections of particles) in an environment called a bath. Such system-bath couplings are again typically visualised using 2D and 3D graphs [48, 75].

Yang created three handheld geodesic structures to represent different types of bath. Each had an open portion, and the interior of each was lined with mirrors. A quantum system was represented by a small laser encased in a plastic ball. The ball was dropped into one of the structures by a visitor, who had to wear goggles for safety reasons while viewing the laser; the ball could then be picked up and rotated to move the laser around inside. This was meant to echo the observation process followed by Venkataraman. Yang researched various kinds of polyhedra, and each of her structures was, appropriately, laser-cut before assembly. One of the final exhibited pieces is shown in Figure 8.

Figure 8: *System Bath* by Meng Yang (RCA) and Vignesh Venkataraman (ICL).

5.8. Observation Collapse

Ruixian Ma (RCA) worked with Gimeno-Segovia (ICL). In her work on superposition, the state of an individual particle cannot be fully known and so is described with a probability cloud. When observed, a position becomes known and the particle is described by what is called an *eigenstate*. This act of observation thus collapses the wave function into a known particle position. Eigenstates are typically visualised as multicoloured clouds within a cubic matrix [32].

Ma's installation scaled up a quantum computing chip, representing quantum particles moving through a system in the form of ultraviolet light-sensitive liquids moving through transparent tubes, suspended in a rectangular wooden frame. He used a series of solenoids driven by a microcontroller to pump the liquids. The solenoids made a distinctive, rhythmic clicking sound. When visitors came close to observe the system, they were detected by an ultrasonic sensor, which caused the liquids to stop moving, thus illustrating the concept of observation collapse. The installation is shown in Figure 9.

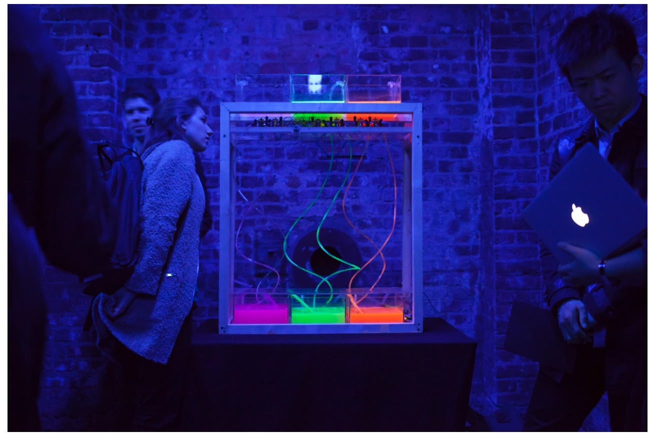

Figure 9: *Observation collapse* by Ruixian Ma (RCA, pictured right) and Mercedes Gimeno-Segovia (ICL).

5.9. Quantum Love

Xiaotian Sun (RCA) worked with Venkataraman (ICL). Two quantum particles can become entangled then separated. Subsequently taking a measurement of one has an instantaneous effect on the other, regardless of their distance. However, the act of interacting or measuring simultaneously breaks the connection between the two particles – again visualised in the scientific literature primarily in two-dimensional graphs [21].

Sun related this to two lovers in a long distance relationship, unable to get close. Her installation focused on the communication between a pair of two balloons, each 1m in diameter, and each in a different coloured room to illustrate that they could be separated at a distance. Each balloon was outfitted with sensors and wireless radios, sharing its position with the other, which could be observed on a monitor in each room. The installation is shown in Figure 10.

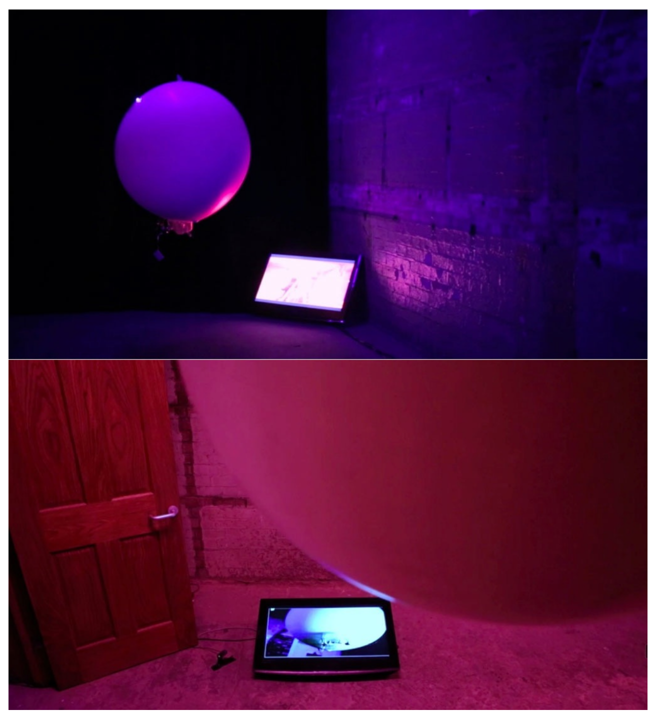

Figure 10: *Quantum Love* by Xiaotian Sun (RCA) and Vignesh Venkataraman (ICL). Stills from [34].

6. Exhibition

We considered various locations for the exhibition. Many were ruled out because most of the students' installations required partial or complete darkness. We also sought someplace slightly mysterious and with some character, not a standard white-box gallery. Shoreditch Town Hall in London rents out its basement for events and exhibitions. It is a labyrinth of rooms which we deemed suitably mysterious and afforded control over lighting. For rooms not in complete darkness we added coloured gels to the existing flourescent tubes in each room.

Choosing this space meant that students each had their own room to exhibit what were, in some cases, quite large installations. It gave visitors a sense of discovery as they wandered from room to room, and each installation took on a larger life with the coloured lighting and the different character of each room. The building dates to 1865 and the basement has scarcely been altered since then, with peeling paint, original fireplaces and other features.

For *Average Football Game,* Rickleton strung up a wire across the middle of his room – a long entry hall which we also choose as the site for a bar during our opening night, in keeping with the football table. The hanging outputs from this unusual printing device served to carry *Average Football Game* from humble bar accessory to performative installation, and their placement down the centre of the room also demarcated the installation from the common space of bar and thoroughfare. This was helped too by the coloured lab coats hanging on the adjacent wall. This room was lit somewhat more brightly than the others, in an ice blue which coincidentally linked it to one of our previous installations in a nearby London Underground station [42], providing some continuity for visitors and across our work.

The bell chime sounds of *Resonance, Revenant* were audible right at the entrance to the exhibition, as it was sited in a room just to the side of the entryway. Sound was important throughout the exhibition to help lead visitors from one room to the next. The rhythmic clicking of solenoids in *Observation Collapse* led visitors from the entry hall to the next room, lit a in darker, more eerie blue. *Discretisation's* whirling chamber of balls could then be heard before it was seen, and then seen only in strobing flashes. *System Bath* was sited in a small room with existing shelves, to suit the intimate experience of handling the geodesic laser balls; a pair of protective goggles sat on the shelf next to each, and the red laser light emanating from each set them in contrast with the dark blue light in the room. *Quantum Burn-in* required complete darkness and was originally designed as a 5m-wide freestanding spiral structure. The students found a suitable long, dark corridor and enclosed it with black fabric at either end. Inside, a few small LED tea lights were placed along the walls for a modicum of visibility. (Tacchini also designed an ingenious wayfinding system with side-lit, laser-etched signs along with phosphorescent printed leaflets.) In the corridor, Gottlieb's recorded voice prompted visitors forward; only one or two were allowed at a time, and a queue formed outside the curtain. On the other side, visitors exited to encounter the huge wooden structure of *flow.instability* in the largest room in the basement; the bare wood of the installation reflected the bluish cast of the lights. Just beyond, visible through the chaotic pattern on the surface of the structure, were two adjacent rooms, each lit a different colour and each with a large balloon hovering inside, occasionally giving off a small flash as it sent its location to its entangled partner. (See Figure 2.)

The exhibition ran for one week in May 2014. It was called *Physics Happens in a Dark Place*, taking its name from Polisseni's remark on the first day of the project.

7. Discussion

The project as a whole represented the position and approach of the new IED programme – these installations were more conceptual, spatial and experiential than traditional forms of science communication; yet the physicists all ensured that the results were scientifically accurate, effectively representing their processes and practices. According to Venkataraman:

> *It could be very easy for them to just hear what I said, pick up some random thing, and just try and make something out of it. But I think there was real dedication to making sure that what they did was very representative of the kind of work I do, and that it was true to the physics.* [34]

The main failing we identified upon opening was insufficient explanation for each piece; if anything, we erred too far on the artistic and experiential side – reflecting a longstanding trend in museums and galleries against labelling or describing works of art [35]. We addressed this on the second day of the exhibition by posting more complete explanations on the project web site (spaceprogram.rca.ac.uk).

The project therefore exposes tensions between art, design and visualisation, and the relation of each to science communication. We discuss these next, in relation to the words in the title of our programme – information, design, and experience – which align neatly with Van Wijk's [62] discussion of visualisation as a science, a technology, and an art form.

7.1. Information vs. critical visualisation

First, regarding information visualisation, we originally considered representing the scientists' quantitative data arising from their research, instead of their concepts and methods, following the model of von Ompteda's *Critical Visualisation Workshops*. We also considered exhibiting them alongside a concurrent exhibition called *Beautiful Science* at the British Library, which contained classic historical examples of scientific visualisation from Florence Nightingale, John Snow and others. For our first project meeting, we asked the physicists to bring a dataset for students to work with, in Microsoft Excel format. Trevelyan brought only the first ten lines of his data, as the entire dataset would crash Excel; Gimeno-Segovia wanted to bring a larger dataset, but her MacBook couldn't handle the volume of data. These responses illustrate the huge volume of "big data" generated merely in individual physics experiments; at the extreme other end, the Large Hadron Collider at CERN generates 160,000 gigabytes of data per day [1].

Representing large datasets, whether on-screen or in physical form, is not in itself an insurmountable challenge. Elsewhere in the IED programme we apply the steps of computational thinking – breaking down a dataset into manageable chunks, looking for patterns, abstracting the findings, then generating something new – to conceptual design problems [14]. Indeed, at CERN a grid of computers is used first to reduce the volume of data to a manageable size before analysis [1]. Van Wijk's [62] characterisation of visualisation as a science has come to pass in the decade since his writing, as visual analytics and data science now appear to be established fields.

During discussions between the students and von Ompteda, it became clear that before interpreting the data, it was important to attain some understanding of the complex concepts and methods used by the scientists – for the sake of visitors to the exhibition as well as the students creating it. Indeed, Fry suggests a strategic, scientific approach to visualisation, focusing on the story to be told before beginning with the data itself [20]. In the scope of our four-week project, a few core concepts and approaches therefore became the primary focus.

As discussed in the introduction, we aim to balance the communicative function of our work with a critical perspective. According to West et al., "The narratives framing data creation and representation circumscribe what we can see and know, and how we see and know" [73]. While many information visualisation systems "offer incredible quantity and variation, they usually lack any self-critical function and simply stream forth without discrimination" [16]. Offenhuber calls the deliberately rhetorical function of visualisations "visual anecdotes" [37]. These came through as students shifted from visualising data to visualising concepts and methods. Just prior to this project, the students had worked with laboratory biologists, investigating the site of scientific investigation, and had used their visual and critical skills to unpack and question the tools, methods and procedures of empirical investigation. Rickleton, for example, stated, "The space within science that I'm interested in is the kind of rigour, and the almost absurd levels of repetition sometimes, to make sure that there's an exact truth that [scientists] can state…" [34].

How much understanding of scientific concepts, processes and bias are necessary to understand a given information visualisation? Or rather, is the "information" in information visualisation restricted to quantitative data, or could it encompass abstract concepts, qualitative findings, single and multiple perspectives? Information in physics is seen to be a more fundamental concept than matter [17, 31], and one definition of information is a measure of how difficult something is to describe [36]. Claude Shannon famously translated qualitative data (the English language) into quantitative data, to create a mathematical means of communication which is the basis for our sea of digital data today [52]. Visualisation does the opposite – translating all those numbers back into readily understandable narrative forms. Depending on the dataset, stories can emerge from the journalistic conventions of who, what, where, and when. Why and how are often more interesting however, and involve interpretation, whether by artists or data journalists [71].

If we interpret Samsel's [49] definition of visualisation – conveying complex information in a comprehensible form – quite broadly, then visual narratives qualify, but perhaps only if they are grounded in empirical data. According to this definition, the work described in this paper qualifies as visualisation, though just barely, being grounded in scientific data but not depicting it directly.

7.2. Design vs. visualisation

According to Samsel:

> *Collaborations between visualization, art and science have the potential to communicate the science to a broader audience; increase scientists' ability to explore their research; and potentially find solutions to significant problems of our time.* [49]

Missing from the above definition is explicit mention of designers, though we define visualisation as a design process, whether undertaken by scientists, artists or specialists. Our programme has the word "design" in its name, yet our practice often overlaps with art (and occasionally science). We reconcile this by treating design as a verb, not a noun – a process undertaken for the purpose of communication, often specifically aimed at making the complex comprehensible.

Designers stand at the interface between people and complex information. It is important for designers to be able to go into a foreign knowledge set and understand it well enough to communicate it. According to Samsel a common understanding and language between art, science and visualisation should achieve this [49]. However, designers' *lack* of understanding – even deliberate misunderstanding – can also be an asset, as they stand on the outside having to learn new knowledge themselves. Sciences like quantum physics need translation in ways which go beyond simplified explanation and metaphor to convey their inherent awe and wonder, as this is a field which is often dreamy, philosophical and poetic, as well as cold and analytic.

Hall [20] discusses the danger of a purely design-led approach, as the most interesting relations between two datasets, for example, are often semantic, not structural. While the goal of scientific research is knowledge, the goal of design is the production of artefacts; knowledge is thus a means for design, and an end for science [40]. Contemplating her design of *Discretisation*, Naief compared the scientific process to that of experimentation in art and design:

> *[Ideas] come from this virtual world, and they've been put into this quite literal environment. That's what I put into [my] piece – not only to increase the tangibility of [Trevelyan's] practice, but to increase the scale, to make it a more human experience.* [34]

Designers, like scientists, have a responsibility to consider the consequences of their practice, and designers can and should question and provoke, albeit from an informed stance; whereas scientists are often constrained by institutional, professional and procedural controls. Hall details visualisation as a critical practice by placing focus on "the framing, gathering, connecting and arraying of data." [20]

7.3. Visualisation vs. experience

Discussing art in the context of visualisation, Samsel states, "Unlike visualization, its intent is to raise questions rather than provide answers" [49]. Yet visualisation as an art form has quickly risen to prominence, fulfilling Hall's [20] prediction that it would open up the field; the IEEE VIS Art Program stands as evidence. In critical visualisations created by artists, the focus is not on usability or aesthetics but on intent, and this, according to Viegas and Wattenberg, "provides a coherent category of work with important distinguishing characteristics from scientific visualizations" [64].

Having argued for a broader notion of "information" in information visualisation, we now question the term "visualisation." Von Ompteda has used the term "data manifestation" to describe the work arising from her *Critical Visualisation Workshops*, wherein three-dimensional, physical work "provides a much-needed counterpoint to our increasingly prevalent interaction with information on screen" [39]. And there appears to be evidence [27] that physical data representations are better than on-screen visualisations for information retrieval, one of the core foundations of the visualisation literature [55].

Despite Ware's insistence on the predominance of visual information [72], our aim is to transform information into experiences which are immersive, multisensory and multimodal. This is based on our expanded definition of information; on strong evidence linking memory formation and sensory, emotional arousal [4, 44]; on the literature on experiential learning [10, 30]; and on the research [68] and practical experience [69, 70] of Walker in designing installations and activities aimed at meaning making in museums. Key to our design process is consideration of the context, as well as the form, in which information (however broadly defined) is experienced. According to Dewey [9], art derives its power as an intensified form of experience, and meaning making can be seen and measured in the personal, social and physical contexts in which it is experienced, as well as in relation to the tools (whether artworks or visualisations) which mediate our relations with information [68]. While a great deal of research has been conducted on the understanding of visualisations [5] as well as didactic science museum exhibits [13], further work is needed to investigate how people make meanings from physical and experiential manifestations of information.

The installations in our exhibition were all very different, but all of a piece, because they were all born from the same place. In our shift from numeric quantities to ideas and practices, the data was not left behind. On the contrary, bringing quantum physics to human scale reveals a link between the interactions of particles and those of humans. As a complex system, social phenomena are comprised of many small transactions between individuals in what Pentland calls "social physics;" he sees "big data" as more useful in describing social phenomena than statistics such as those that students have reacted against in von Ompteda's *Critical Visualisation Workshops* [43]. However, we agree with Arber [1] that ascribing complex analytical ability to machines masks the human decisions and intentions behind their creation and programming, and points again to the need for human judgement and criticality.

As big data ceaselessly gets bigger, we suggest an expanded notion of information which includes narrative, and is grounded in an understanding of the contexts in which it is collected and experienced; a critical approach to visualisation as a design process which is informed but benefits from an outsider perspective to facilitate effective communication; and a broadening of the field of visualisation to encompass physical manifestations and experiential installations with an artistic sensibility.

8. Conclusion

Our exhibition was a success in many ways. There were an estimated 700 visitors during the week of the exhibition, and almost all feedback (from scientists and artists as well as visitors as a whole) was positive. One review said "It's like stumbling into a forgotten Tesla laboratory" [59].

Reflecting on the journey from his dark basement lab to our dark basement exhibition, Polissemi said, "In science, you really push the boundaries of human knowledge, but only in a very, very limited corner. And you can lose the more general picture." He was pleased to see visitors queuing up to see the *Quantum Burn-in* installation based on his work. "*There* was somebody who would never come to the lab – never even know me – but is queuing to see what I do, which [the students] represented so well" [34].

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