Strange Entanglements: an art-science installation exploring the spooky world of quantum entanglement

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Abstract

"Entanglements" is an interactive apparatus that explores the fundamental phenomenon of quantum entanglement and how it can frame and activate relationships with the universe. Through a novel interface that combines sight, sound and touch, actual quantum entanglement phenomena are created and expressed through unique sonic signatures. The term "entanglement" is widely used, but what actually is it? In this paper, we describe the phenomenon and the artwork, and how it challenges fundamental assumptions about space, time and our relationships with the subatomic and cosmic realms.

Keywords

Media art, quantum physics, entanglement, relativity, temporality, experiments, data sonification, phenomenology, epistemology, ontology

Introduction

This paper describes an arts-science installation that explores quantum entanglement – a 'spooky' phenomenon where quantum particles interact at a distance, that fundamentally challenges intuitive notions of linear time, causality and observer-independent physical reality. Whilst quantum entanglement has been discussed and debated for almost a century, the topic has recently gained currency through the Nobel-prize winning work of physicist Anton Zeilinger, whose theories around entangled photons have been empirically demonstrated beyond reasonable doubt.

The artwork, pictured below (see Figure 1) is an interactive apparatus that creates, detects, and amplifies actual quantum entanglement events, which are translated into sonic and haptic forms, designed to draw the audience into the quantum realm in a way that is poetically expressive and manifests interconnections between us and the universe.

Project Background

Quantum Entanglement The term 'entanglement' is widely used, in both the disciplines of art and science, but what actually is it? Quantum entanglement is a fundamental property of subatomic entities which dissolves the classical notions of time and space, and creates connections across the cosmos - it is the defining characteristic of quantum physics. [1]

When two subatomic particles or photons of light become entangled, they are in a fundamentally connected state, even if they become separated, where one instantaneously 'feels' what is happening to the other. This more than challenges classical notions of space and time - such entangled particles or systems collapse the structure of spacetime as we nominally perceive and understand it. As this entails a kind of instantaneous communication which seems to break the law that nothing can travel faster than the speed of light, Einstein called such "action at a distance …spooky". [2] But there is more - such entities exist in a form where differentiation does not exist, they are neither one nor two, existing in a state different than 'this' and 'that', but something other, a 'primary reality'. Signals or data from quantum systems exist in this state of "primary reality", a form of being more fundamental than the meanings we later construct as described by Anton Zeilinger. [3]

Quantum Temporality The realm of the subatomic is more than governed by uncertainties, as is described by Heisenberg's famous principle; a key characteristic of quantum phenomena is that they are indeterminate until measured - entangled particles do not have the physical capacity to carry discrete or individual qualities. This means that if you are trying to measure a property like the position of particles in an entangled system you cannot, because position does not exist for them in any macroscopic sense. Also, it is impossible to predict specific future events based upon knowledge of current events, as there is no link between past and future events on a quantum scale. Thus the concept of causality, central to classical physics, is rendered meaningless in the subatomic realm. Heisenberg championed the abstract nature of this, and was against Schrodinger's attempts to visualise such counter-intuitive qualities (including alive/dead cats); conversely, Einstein sought to visualise the workings of the entire universe, in a way, to "know the mind of God". [4]

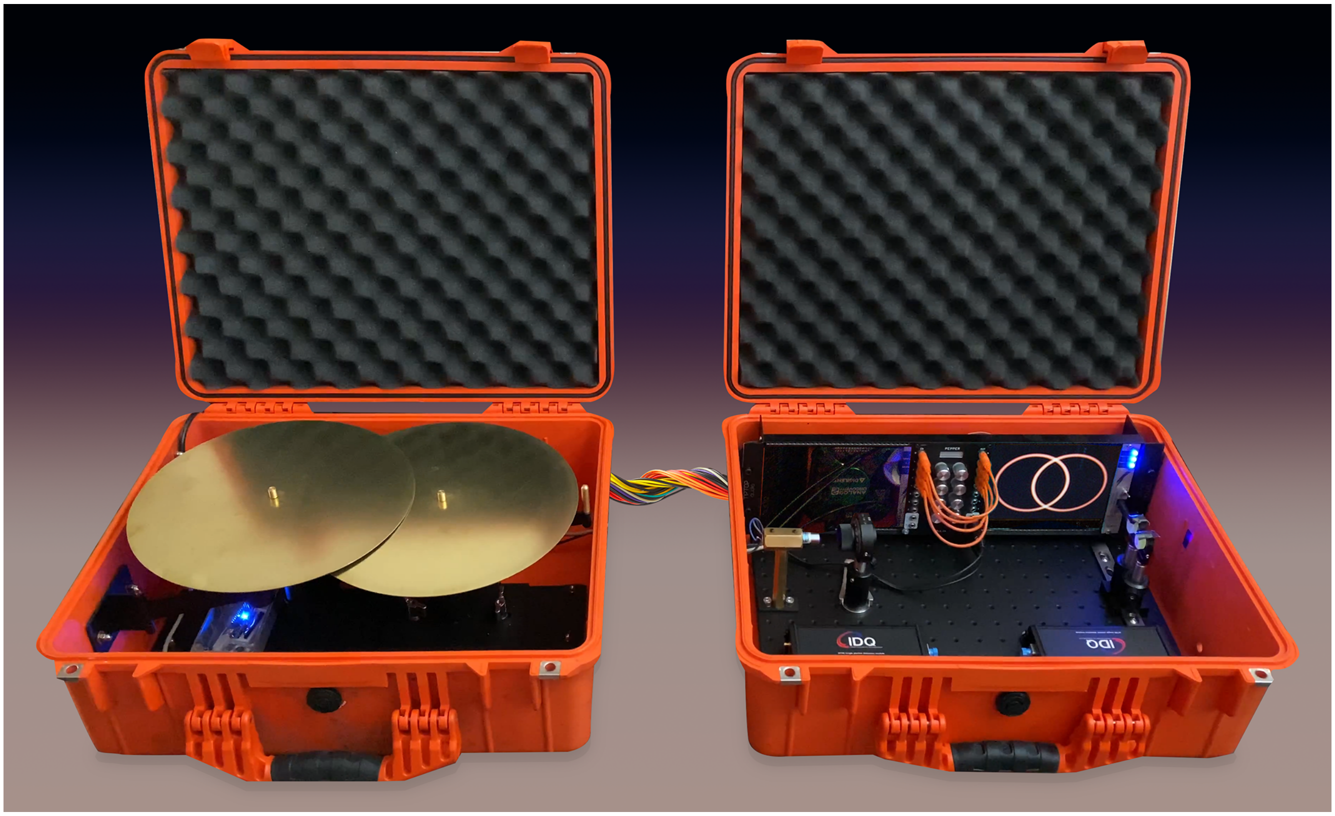

Figure 1. The ‘Entanglements’ apparatus © C Henschke

Another key feature of the quantum realm, which Einstein didn’t like either, is that any measurable properties of subatomic phenomena are completely random. Einstein’s infamous response to this was that ‘God does not play dice’ with the universe. There is a trick nature plays upon us with randomness and time - even though it has been experimentally proven that entanglement signals travel faster than the speed of light, the data in these signals is “objectively random”. [5] Luckily for Einstein, it is precisely this “randomness of the individual quantum event, of the measurement result, that keeps entanglement from violating the impossibility of signalling faster than light”. [6] Quantum particles may communicate with each other instantaneously, but their messages are purely random; thus we cannot “influence what is being sent ... to communicate some new information”. [7] Such quantum systems are therefore non-local, but cannot be used to transmit knowledge-data: the random roll of the dice preserves the rules of relativity. A strange situation indeed.

Quantum Ontology Although randomness may not be unique to data from quantum experiments, what is unique and spooky is that such data can be part of completely different future experimental arrangements, such as occurs with the ‘quantum eraser’ experiment. In this relatively simple experiment, two entangled particles are created, one is measured, then, by a subtle trick, the setup is changed, and the other is measured. This seems to affect the result of the earlier measurement, or ‘erases’ the information about which kind of setup was used in the previous part of the experiment. Zeilinger’s view of such entanglement experiments is “explicitly epistemic (what is entangled is our knowledge of events)”. [8] Whether this is purely epistemic or ontological is a century-long debate that is still far from resolution.

Philosopher-physicist Karen Barad states it is an ontological change, we shape the nature of reality of past events: “after it [the particle] has already hit the screen and gone through the apparatus, I am able to determine its ontology, afterwards.” [9] This has dizzying implications for classical notions of spacetime, and the idea of ‘local realism’, which is that physical reality exists independently of humans and measurement, and that actions upon one object cannot instantaneously affect another object, in line with the concept of causality. But quantum entanglement experiments refute all of this - no wonder Einstein said that it was ‘spooky’!

Another curious aspect of such experiments is our relationship to, or ‘entanglement’ with, such systems as we observe or measure them. Karen Barad argues that when we interact with such quantum systems, we become part of the experimental setup, we ourselves become entangled with the subatomic entities, in a quantum-physical sense. Barad states: “Instead of there being a separation of subject [the apparatus] and object [of investigation], there is an entanglement of subject and object”. [10]

Both Zeilinger and Barad agree that this is deeply connected to the nature of and our understanding of the physical universe. Thus such experiments are in essence 'experimental metaphysics'. Barad states "experimental metaphysics, … is just an indicator of the fact that there has never been a sharp boundary between physics, on the one hand, and metaphysics or philosophy, on the other." [11] Zeilinger's 'metaphysical' quantum physics experiments were recognised with the awarding of a Nobel prize in physics in 2021.

Art and quantum physics

Motivational forces Exploring the realms of indeterminacy and metaphysics, and raising questions about the nature of being, is curiously shared by artists and quantum physicists. The origin of this project can be traced to a deep discussion Chris Henschke had with Anton Zeilinger in 2016 as he was opening an exhibition at the Natural History Museum in Vienna, called 'Wie Alles Begann', where Henschke was showing an artwork about the Higgs Boson. During his discussion with Zeilinger they spoke about art and quantum physics, and the relationship between 'primary reality' and quantum data, and Zeilinger told him that "just because it's random doesn't mean it's arbitrary". Henschke recalled an intuitive realisation that something deep is going on with the stochastic nature of nature on this level, and that art can explore it in ways that science can't - as he said to Zeilinger, "artists can find expression in this randomness, but in a way that doesn't have to be (scientifically) right." Another motivation is that Zeilinger exhibited an entanglement experiment at the Documenta 13 arts festival, which Henschke felt was a call to artists to respond to. Henschke and Gifford both feel it is important to challenge Zeilinger's 'science-as-art' and create art that challenges science, within its own domain, through engaging with the science in an expressive and non-didactic way, raising questions rather than dictating answers.

Thus Henschke felt compelled to develop a project that is an experiment / experience that seeks to connect people with this most mysterious phenomenon, in a very real way, to create a moment of connection with the subatomic and cosmic that may transcend the everyday. Through incorporating precision scientific detection devices, this project is not simply speculative or metaphorical, but it is also not didactic or scientifically reductive. This art apparatus is designed to liberate this compelling phenomenon from the exclusivity of the laboratory, and allow people to experience and engage with quantum entanglement in a poetic and expressive way. Embracing the qualities of nature on its most fundamental level, the artwork seeks to manifest perhaps such compelling interconnections between us and the universe.

The technological objects used in particle physics are agents in their own right – they are the mediators between the subatomic and macroscopic realms. And, as physicist-philosopher Andrew Pickering states, subatomic phenomena, such as particles or photons, are themselves "instances of material agency – they are objects that do things in the world." [12]

The authors see the manifestations of entanglement as more than just measurable outputs used to validate scientific hypotheses – they are the expressions of the phenomena in their own right. As Manuel DeLanda stated: "The characteristics [of such phenomena] allow both light and sound to produce distinctive effects on animal and human brains, effects that may be used for expressive purposes ... by human artists. But possession of a nervous system is not necessary to make expressive use of colour or sound. Even humble atoms can interact ... in a way that literally expresses their identity." [13]

Verschrankung Perhaps there is a different way to disentangle at least the understanding of the term, if not the phenomena, which is to go back to the source. In 1935 Erwin Schrödinger wrote an unnamed paper in support of Einstein's reaction to the strange and seemingly impossible qualities of quantum phenomena. The original paper uses the German word 'Verschränkung', which is mainly translated as 'entanglement' but can also mean 'intertwining' or 'interleaving', and its linguistic structure can be unfolded to mean 'filing into a cabinet the wrong (or) hidden way' (translations by Jurgen Henschke). It also has a unique usage in music vocabulary, denoting an end of a phrase in a melody which is also the start of the second phrase. Thus using sound as a form of expression seeks a more poetically meaningful interpretation.

From Henschke's understanding of these 'entanglements' of experimental physics and philosophy, they believe that in observing entangled systems, we indeed create their material capacity to be 'knowable'. Thus, through such interactions with the quantum realm, we create the macroscopic reality we exist in as it creates us, in an ongoing and emergent "dance of agency", to quote Pickering. [14]

Art apparatus This 'art apparatus', like a scientific apparatus acts "as a locus of nonhuman agency ... … emergently produced in real-time", using 'post-camera' single photon capture technologies and data sonification as an interface between human and quantum agencies. [15] The development of the apparatus was an interdisciplinary process, combining contemporary and historical skills and technologies – the development of the material elements combines digital coding craft and the precision metalwork craft of Andrew Hustwaite; and the project was developed in collaboration with quantum physicist Professor Jared Cole.

The apparatus is housed within two connected road-cases. One case contains a custom built photon entanglement device, comprising a laser and detectors and synthesiser. The other contains an interactive audio-haptic interface, designed in the form of the two interlocking brass disks. This design is informed by the two interlinked circles of light that are produced when photons become entangled. This ‘entanglement rainbow’ is in a sense the visual signature of the concept of entanglement, a form that is both one and two entities. The use of an identical pair of roadcases is inspired by quantum phenomena – like two entangled entities before they are examined to reveal their inner nature, they are indistinguishable. So, from the outside, it is not possible to see which one contains the scientific apparatus and which ones expresses the phenomena as art.

When the user touches or turns the interconnected brass disks, they complete the circuit, which activates the apparatus. Photons of light are pulsed through a Barium Borate (BBo) crystal, creating entangled photons, through a process known as ‘Spontaneous Parametric Down Conversion’. Although invisible to the naked eye, the entangled photon pairs are detected with precision single photon detectors via fine optic fibres. The use of precision scientific components allows one to reach scales far from unaided human perception - single photon detectors work on picometre and nanosecond scales. The pair of detectors emit nanosecond pulses into a logic analyzer, and when it detects two photons at the same instant, signifying entanglement. These signals are fed into a ‘Bela Pepper’ audio computer, with a custom created digital sound synthesiser instrument, created by Author 2 (see ‘technical setup’ below for further information).

In a sense the entangled photons of light pluck the instrument, giving a kind of agency and voice to the quantum phenomena. There is also a screen that displays the ‘entanglement rainbow’ when triggered. The sounds are emitted through the custom made resonant brass plates, so the acoustic forms can be felt as well as heard, giving a literal feel of the phenomena.

When an entanglement occurs, it is manifested as a duophonic tone. Each tone acoustically expresses and extends the moment in time when the entanglement was detected; then the tone decays into two endlessly descending ‘Shepard’ tones. In a way that plays with the mathematical formalisms within quantum theory, this expresses both the unique interconnected instants when the photon pairs become entangled, in a state called ‘quantum coherence’, and then, as this state decays into ‘decoherence’ the sound itself decays.

The translation of quantum correlation signals into sound does not seek to convey scientifically meaningful information; instead it expresses the entanglement events. The indeterminate beauty underlying our reality is manifested in the stochastic cadences of the synthesiser tones. As each tone is probabilistically unrepeatable, it seeks to bring the audience out of the everyday and find a resonance with the uniqueness of each moment of being as it occurs. This has a phenomenological quality akin to the state of cosmic connection that hit Henri Bergson as he waited for a sugar cube to dissolve in his tea, realising that he was sharing that moment with the sugar cube and the entire universe - such events are “not something thought but something lived” [16]

Technical setup

Creating and detecting quantum entanglement in a suitcase posed some challenges. Particles were entangled, as mentioned above, by passing photons in a laser beam through a particular crystal with certain properties that encourage spontaneous parametric down conversion, whereby the light is frequency converted down one octave, in this case from visible violet light to invisible infrared of half the frequency. Quantum theory states that light energy is quantised into discrete bundles of energy related to its frequency (or wavelength) via the formula:

$$E = hv$$

where E is energy, h is Planck’s constant, and is the frequency. This means that a beam of light of a particular frequency comprises indivisible bundles, called photons, of that quantum of energy. The law of conservation of energy implies that conversion of light to half the frequency must therefore entail a splitting of each of these down-converted photons into two photons. These split photons are *entangled* [17].

The split photons are differentially refracted, meaning they exit the crystal in pairs heading in predictable different directions. This gives rise to the signature ‘entanglement rings’ interference pattern shown in Figure 2. It also means that two separate photon detectors can be placed slightly apart to detect the split photons. Detecting these entangled photon pairs then required suitable placement of two single photon detectors, and observing when both detectors fired simultaneously. The temporal resolution for these detectors operating at that frequency of light is 10 nanoseconds. The detectors themselves signal a photon detection by sending a voltage spike to their output cable. Thus to observe an entanglement event required calibrating two voltage time series to a 10 nanosecond resolution.

The detection of synchronous spikes from the two single photon detectors was achieved using a Digilent Analog Discovery 2 programmable oscilloscope, connected to a Raspberry Pi computer. An example of a detected entanglement event is shown in Figure 2, where the spikes from the two photon detectors are temporally coincident. The oscilloscope provides an SDK allowing its signal to be processed in realtime in a custom computer program. In order to ensure accurate time measurements, the two channels of the oscilloscope were multiplied together prior to ingesting in the analysis program, so that the sensitive time correlations would be preserved.

When an entanglement event was detected, the custom program on the Raspberry Pi would respond in two ways. Firstly it would display an animation of the idiosyncratic ‘entanglement ring’ interference pattern, through a custom program written in SDL. Secondly it would send out a notification via Open Sound Control to a Bela synthesizer unit. The Bela board is a platform for realtime audio analysis and synthesis, running on top of the BeagleBoard pocket computer. It is configurable as a Eurorack modular unit (called Pepper), which is the configuration used in this installation.

The Bela Pepper was programmed to create a generative soundscape, intended to convey a feeling of a quantum rain of indeterminate particles, awaiting wave-state collapse. This was realised through an audio equivalent of a particle system, with each particle corresponding to a single sound programmed to behave as a Shepard's tone - an audio illusion that creates the impression of a continuously falling or rising tone [18]. The combined effect of a number of these simultaneously falling and rising tones, with slightly stochastic fall-rates, was quite suspenseful. On receiving a notification of an entanglement event, the moving rain of audio particles would freeze for several seconds, implying a sense of coherent and collapsed quantum probabilities.

The sound output of the Bela module was sent out of the first roadcase and into the second (see Figure 1). The second roadcase contained the interactive physical elements of the installation, primarily comprising the two overlapping brass discs reminiscent of the entanglement ring visual motif. These brass discs were interactive in that they were both touch sensitive (through resistive touch sensing) and mounted on a spindle which detected their rotation. Furthermore, these brass discs were themselves sonically actuated by audio drivers underneath, so they acted as loudspeakers, and provided the sonic output for the installation.

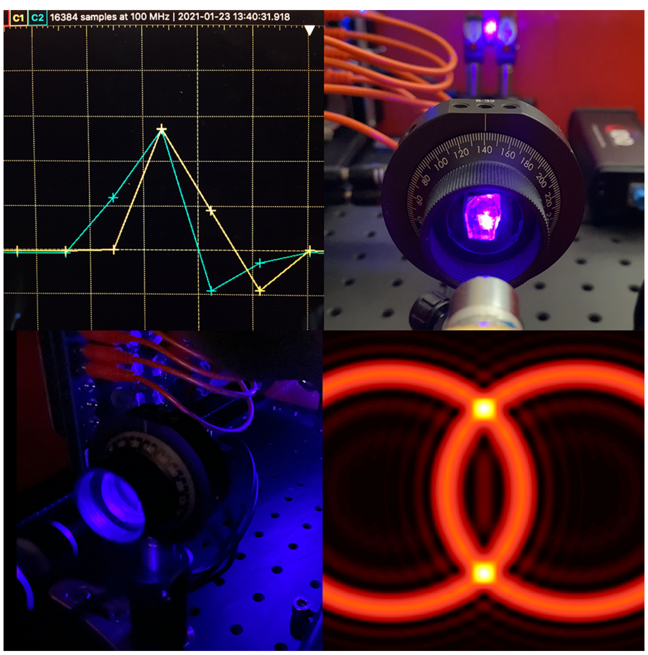

Figure 2. Details of the apparatus (clockwise from bottom right) Entanglement 'rainbow' rings; laser and Bela Pepper synthesiser; signal correlation signifying detected entanglement; crystal and detectors. © C Henschke & T Gifford.

In practice the entanglement events were relatively numerous. In order to aesthetically moderate the frequency of entanglement audiovisualisations, a counter was implemented that accumulated entanglement events up to a threshold, at which point an audiovisual representation of the entanglement was triggered, as described above. The Bela Pepper module has 8 physical knobs which allowed the adjustment of various parameters of the generative soundscape, including the accumulation threshold. This was deemed practically important, since different installation contexts may imply different appropriate temporal frequencies of spectacular audiovisual triggers.

Conclusion

A key question raised by expressive manifestations of the quantum phenomena is the relationship between the phenomena and the observer. Whether appearing as a signal on a screen, numerical data, or a sonic tone, such signals are both things and signs of things, a "coalescence" of physical forms and knowledge. [19] As ethnographer of experiments Arpita Roy states, 'the signal is real ... not because it is materially present...[but] because the physicist recognizes or receives it.' [20] In other words, such signatures are a combination of matter and meaning; they are both ontological and epistemological. Physicist John Bell, who was the first to re-visit Einstein and Schrodinger's unfinished entanglement conundrum in the 1960s, asked provocatively whether a quantum phenomenon needs a system "with a PhD" to observe it and thus make it real? [21] Does someone in an art exhibition interacting with an apparatus such as this make it real?

This was something Henschke dwelled upon during the dark days and nights of the long lockdown in Melbourne in 2020. Over the year he gradually designed the experiment, and ordered the components, and was playing with the laser and BBo crystal, concocting setups which he thought might possibly shift us out of the pandemic reality we found ourselves in, daring to believe in Everitts "manyworlds" interpretation of quantum physics (where each quantum interaction creates a pair of parallel worlds). Such an interpretation is for the conceptually adventurous (or maybe those going stir crazy).

There may not be entanglement phenomena in all of the events triggered by the photon detections, but there will be some. However, this is not the point of such a device - it is not a scientific device, and does not have to be 'right' all of the time, although as it utilises science: it is 'art-through-science'. Yet using such scientific components produces entanglement phenomena. The knowledge that there is entanglement within the system shapes the subjective experiences, the sounds signify the events and the moments we perceive them, in a way that expresses the random, indeterminate and unknowable qualities of this system. And regardless of whether it is always scientifically accurate, or is more an 'art apparatus', it is a locus of human and quantum agencies, it is a way to perhaps intuitively comprehend or sense the quantum realm. When dealing with objects or systems that are in part unknowable, creating a sense of estrangement can be a way to sense such a state. Scientist Hans Rheinberger describes the process of engaging with such apparatuses and phenomena as "an engagement with the material world that, on the one hand, requires intimacy with the matter at hand, and, on the other, disentanglement, the capacity of rendering strange – of estrangement." [22]

In seeking to resolve the argument between Einstein, Schrodinger and Heisenberg, regarding ways to understand quantum systems, founding particle physicist Niels Bohr "plumbed the very depths of knowledge to the formation of ideas themselves" and realised that in both empirical and aesthetic senses, perception precedes knowledge. [23] In Bohr's own words, 'the concept of observation is in itself so far arbitrary as it depends upon which objects are included in the system to be observed' - in other words, the experimental setup, including the user whose touch activates the apparatus, can be seen as being part of the quantum system they create. [24]

In a system such as this, knowledge and perception shape each other, in an ongoing process of meaning generation. Zeilinger says that quantum data, the raw expression, exists in a state of primary reality more fundamental than meaning – this is an ontological form; however, in order to gain an understanding of the meaning of the data, we frame the experience and data, giving it an epistemological form. Human / quantum interactions create "an entanglement of matter and meaning" as Barad states, or an emergent dance of ontology and epistemology. [25] And when we see / hear / touch / feel signals from the entangled phenomena emerging from an apparatus such as "Entanglements", we are at once creating and tuning into the song of the entanglement, as we dance with it and the universe.

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Authors Biographies

Chris Henschke is an artist who works with analogue and digital media, using methods and materials from experimental science, and has undertaken experimental interdisciplinary collaborations with scientists since 1991. Residencies include the National Gallery of Australia, 2004; an Asialink residency at Chulalongkorn University Bangkok, 2007; two residencies at the Australian Synchrotron, 2007 and 2010; and an ANAT Synapse residency with the CSIRO in Clayton, 2018-2019. He has a Doctorate of Philosophy from Monash University (2013-2017), comprised of on-site research / practice at the European Organisation for Nuclear Research (CERN), Switzerland, as part of the 'art@CMS' collaboration program.

Dr Toby Gifford is a designer, creative coder, and interdisciplinary media arts practitioner, with a particular interest in virtual/augmented reality and immersive installation. He has worked across industry and academia at the intersection of art and technology, with extensive professional experience in software programming and systems design. His research spans a broad range of areas including: application of artificial intelligence to the creative industries; environmental sensing for ecosystem health monitoring; and modelling and data visualisation to aid design.