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Artfully Exploring Quantum Physics

INTRODUCTION

Quantum mechanics has a reputation. In fact, quantum mechanics has many and varied reputations. These range from the impression that quantum mechanics, or perhaps physics in general, is hard and inaccessible, to the assertion that quantum mechanics is a bit like magic, with spooky events occurring at a distance and Schrödinger's undead cats. Much that is written of quantum mechanics plays up these mysterious aspects and enhances the mystical. What should not be lost sight of is that quantum mechanics is our most successful physical theory ever, with not one single experiment that contradicts it and quantitative verification of its predictions realised to an unprecedented degree of precision. In fact, quantum mechanics is a well-defined theory with a tried and accepted set of rules that explain the phenomena given by experimental measurements.

The last word in the above paragraph is the key. Quantum mechanics is a theory of measurement.[1] In fact, all of physics is a theory of measurement. It is just that classical physics—in particular Newton's laws of mechanics—has been so successful in explaining what happens at a macroscopic, human-sized level that we have been seduced into believing that Newtonian mechanics *is* reality rather than a mathematical description explaining what we will observe if we do certain experiments. It accords with our intuition. If I play pool, once I strike the cue ball I can look away, maybe listen to the clatter of scattered balls. When I turn around to see the white in the pocket, again, I still believe it travelled through the trajectory calculated by my friend Newton, even though I didn't make the experiments of repeatedly looking at the ball as it traversed the table.

This is fine at this macroscopic level, but it is not true at a quantum level, at the scale of the atomic, or for light at its most fundamental. The very act of observation has an effect. These effects must be taken into account and this is what quantum mechanics does. And the theory works—incredibly well—but at the expense of our intuition and the ontology of our (microscopic) particles between measurements, between observations. All that quantum physics (and really Newtonian physics as well) tells us about is the outcome of observations. The question "what is really happening?" is a metaphysical question—perhaps within the purview of physics—but one that cannot be answered by quantum mechanics itself.

A SHORT QUANTUM HISTORY

A hundred years ago Max Planck postulated that energy could only come in small lumps. If something oscillated with a given frequency, *f*, the size of the small packets of energy, *E*, was proportional to that frequency:

$$E = hf.$$

The constant of proportionality, *h*, is now called Planck's constant. This resolved a small problem in the physics of how solids radiate heat. Maxwell's laws of electromagnetism, which were developed in the nineteenth century, and Newtonian mechanics, predicted that the amount of light coming from a hot body should grow with increasing frequency. We know from experiment and our own observations that the intensity of light from something hot is peaked at a certain wavelength. If a poker is placed in a fire it glows red hot. If we use a bellows to make it hotter we can get it to glow white when the peak is in the middle of the visible spectrum. Hotter still and the peak moves to the higher frequency, shorter wavelength blue end of the visible spectrum. The classical description of this phenomenon postulated an "ultraviolet catastrophe," with there always being more light at the blue end. Planck's hypothesis showed that it is harder to excite light with higher (bluer) frequencies, thus truncating this growing ultraviolet tail. If he picked a very small, but non-zero number for his constant h¬, then he could reproduce the experiments exactly and the puzzle of the ultraviolet catastrophe was solved. The value in modern units of h=6.6 x 10^{-34} Joule-seconds. The fact that 6.6 x 10^{-34} (0.00…066 with 33 zeros after the decimal point) is a ridiculously small number is the reason that we never see this "quantisation" of energy (that can only come in discrete packets) on a macroscopic, human-sized scale.

As a result of Planck's findings it became clear that the idealised notions of things being "particles"—for example pool balls—or 'waves'—light being the archetypical example—were only extremes on a continuum. Light in particular had already been shown by (among others) Thomas Young, through his famous double-slit experiment, to be a wave. Moreover, once he had developed his theory of electromagnetism, Maxwell had shown that there exists a wave solution with a propagation speed equal to that of light. It was therefore clear that light was an electromagnetic wave. The relationship between speed, *c*, wavelength, *λ*, and frequency, *f*, is given by $c=f\lambda$—the speed is the rate at which the wave "wiggles" times the distance it moves in each wiggle. Maxwell's equations also show that the momentum associated with a wave, *p*, is related to the energy in the equation,

$$E = pc,$$

noting that this is different to the equation for particles in Newton's mechanics, where $E=p^2/2m$, with *m* being the mass of the particle. Combining these with Planck's law for the quantisation of energy yields a relationship between the wavelength of light and its momentum such that

$$p = \frac{h}{\lambda}. \tag{I}$$

This suggests a particle-like quality to the quanta of the packets of energy of which Planck spoke. In 1905 Albert Einstein showed that if we take these particle-like characteristics of light seriously, we could explain another longstanding conundrum—the photoelectric effect.

The photoelectric effect, whereby electrons are ejected from a metal cathode by light to produce a current, can only be explained if we accept Plank's conclusion (as Einstein did) and only allow light to come in little packets, which we now call photons. The photoelectric effect only works if we use light with a frequency greater than a certain threshold. No matter how intense we make the light—and the *total* energy in the light depends solely on the intensity—no current flows unless the frequency is sufficiently high. Einstein realised that it requires an individual photon with sufficient energy of its own to knock out an electron from the surface of the metal. Turning up the intensity increased the number of photons, but each individual only had hf of energy. If this wasn't enough, the electron that absorbed it just wiggled around a bit, then lost its energy to the rest of the metal and so was never liberated from the surface. Hence the conclusion that light must at some level be made up of particles.

And yet this same light still undergoes diffraction and shows interference patterns as a wave if we shine it through two slits onto a screen. Turn down the intensity and we can detect each individual photon hitting the screen—a particle-like measurement—but over time these individual dots build up into the wave-like diffraction pattern. Light is both a particle and a wave, and what we see depends on what we look for.

Einstein's expression (I) states that the momentum of each photon is inversely proportional to the wavelength of the light. In his 1924 doctoral thesis, which won him the 1929 Nobel Prize for Physics, the French physicist Louis de Broglie took this expression and did some high-powered algebra to show that

$$p = {}^{h}/_{\lambda} \rightarrow \lambda = {}^{h}/_{p}.$$

Maybe the simplest algebra to ever win a Nobel Prize. His insight, of course, is that if light—thought of at a classical level as a wave—can have particle-like properties (momentum), then why couldn't particles with momentum have waves associated with them? They do. We now call them de Broglie waves. The clearest demonstration is perhaps the electron, the wave properties of which are essential for all electronics and, of course, underpin electron microscopy. Interestingly, J.J. Thomson "invented"[2] the electron in 1897 as a particle explaining cathode rays, winning the Nobel Prize in 1906. His son George Thomson was awarded the 1937 Nobel Prize for his work on electron diffraction, showing clearly that the electron is a wave!

So waves have particle-like properties and particles can behave like waves. What quantum physics really tells us is that the way we look at the world affects that which we observe. If we perform a photoelectric effect experiment, we see the particle properties of the photons. However, if we do a diffraction experiment, we see the wave qualities. The world, like art, is not independent of the observer. It is this so-called wave–particle duality and, further, the observer dependence of what we see that we attempted to explore in this project.

MODELING QUANTUM PHYSICS—BECKY

It was talk of a purple sulphur bacteria that photosynthesises with almost 100 per cent efficiency that attracted me to Professor David Hutchinson's research. He's been working on modeling how quantum coherence plays a role in this process.[3] Talking to him and seeing him draw diagrams and equations on the whiteboard, I could just about get some sense of what this meant; but by the time I was walking away down the corridor, my nascent understanding would start slipping away. But the idea of photosynthesis was pretty exciting—how could I have not realised that this reaction utilising light energy to produce sugars is what provides the majority of energy for life on earth? I looked at my vegetable garden with new appreciation, and spent some contented afternoons drawing the exuberant foliage of my brassicas. I went and spoke to a botanist too—who pointed out that as the bacteria being studied by David live close to volcanic vents deep underwater and utilise infra-red radiation, technically this wasn't photosynthesising but a type of chemical autotrope. I realised that I'd diverged a long way from David's research.

I decided that if I was to respond meaningfully to David's work, I needed to acquire a basic understanding of quantum mechanics rather than focus on his very specific area of research. I went back to the beginnings of quantum mechanics, reading about how the quantum world was first glimpsed through the gaps in classical physics. At the start of the nineteenth century, Young's double-slit experiment proved that light behaved like a wave, forming interference patterns after passing through two narrow slits. But in the early twentieth century, other experiments showed that light behaved like particles, called photons. If the double-slit experiment is repeated, using single photons at a time, they still show an interference pattern. However, if an attempt is made to observe the photons passing thorough one or other of the slits, in order to understand this puzzling phenomenon, they then start instead to behave like particles. Ousting the classical idea of the objective observer, here the observer can be seen to affect what is being observed.

These basic and intriguing tenets of quantum mechanics provided me with a manageable research question: how could I make art that spoke about the wave–particle duality of light; and the idea of the observer being part of and influencing what is observed? I did a lot of drawing and pondering until I settled to the idea of using the translucency of porcelain to try to embody these notions. I cut wave patterns into the clay, either side of thin slabs. When the slabs were slapped down onto a hard surface, the wave patterns front and back merged, producing interference patterns. This was something novel and visually interesting—I'd found a way in. While interference is a generic wave phenomenon, it leads to efficient transport of charge (on particles) in David's research so is intrinsic to the photosynthesis research and underpins quantum wave–particle duality. This essence of quantum physics is displayed here in a wave phenomenon encapsulated in a material representation.

I formed the slabs into cubes, both to enable them to be lit from within and in reference to Einstein's statement that "God doesn't play dice with the world," made when he was struggling with the probabilistic nature of quantum mechanics.

As David works with equations, I was keen to incorporate some into my work, and selected Maxwell's equations for light propagation, in addition to Schrödinger's equation, the fundamental equation of physics for describing quantum behaviour. I carved these into the inside surfaces of some of the cubes or boxes, expecting that when lit up they would be visible on the outside. This proved not to be the case—but on reflection this actually made more sense, as they were there underlying what was going on, but not actually visible. I made holes in a couple of the boxes to reference light as a particle. Another was embossed with kale leaves, so that my enthusiasm for photosynthesis made it into the work, too. The surfaces were milky white, enigmatic and almost flat in some lights, but also picking up different tones of natural and artificial light on their ripples, changing as the light changes and as the observer moves around them.

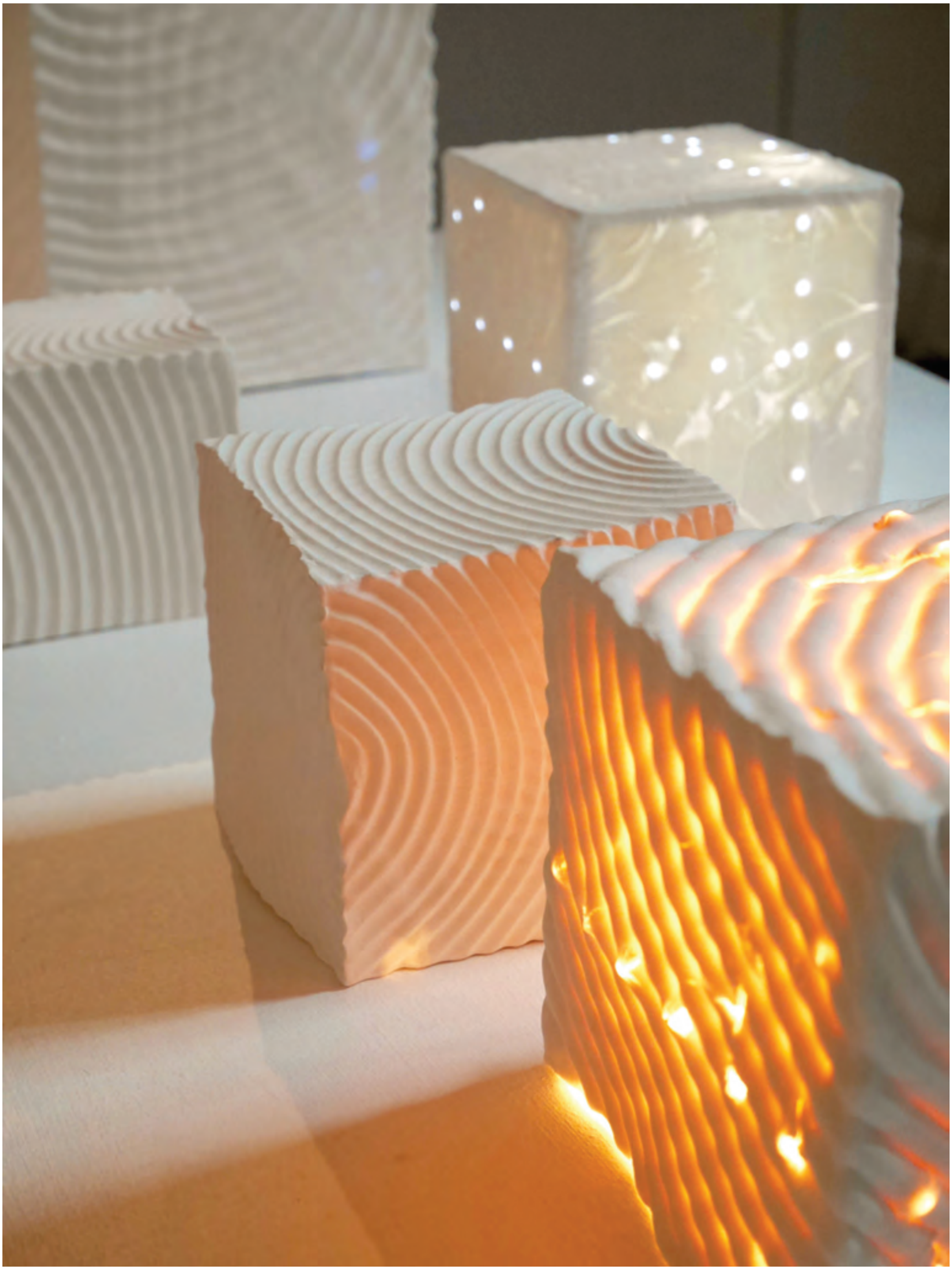

Figure 1. Detail from Becky Cameron, *Modelling Quantum Physics* (2015).

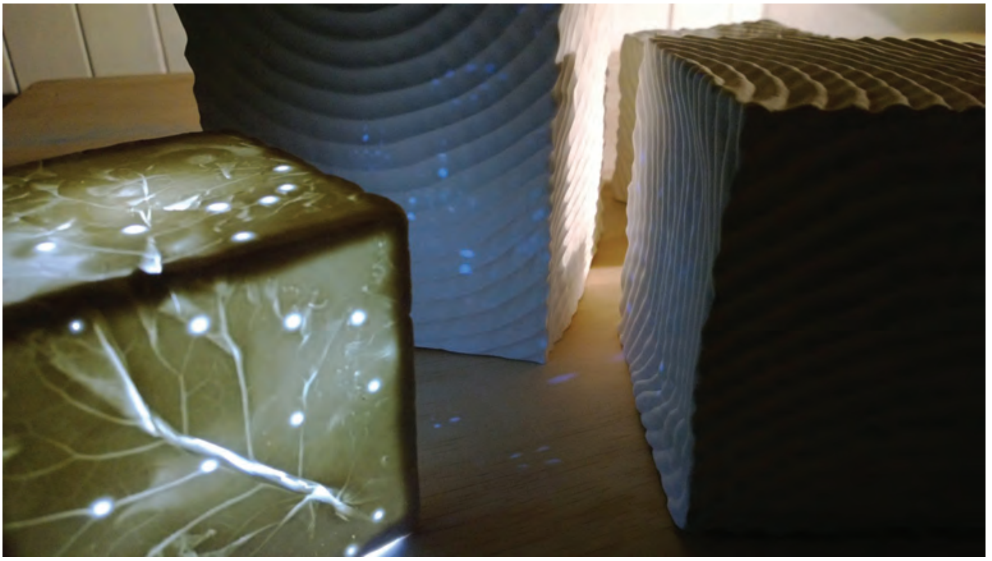

Figure 2. Detail from Becky Cameron, *Modelling Quantum Physics* (2015).

At the start of this collaboration, my knowledge and view of science was pretty much a classical one—that science was objective, rational and uninvolved. But at a quantum level, the world turns out to be much more complex, puzzling, and also interesting. I've been challenged by my reading on the subject of quantum mechanics, especially its implications for viewing the world as not necessarily within our rational understanding, but very much one which we do not stand back from—a participatory universe.

THE MEASUREMENT PROBLEM—HOLLY (PAINTING) AND JIMMY (CONCEPTUALISATION)

We came to this project as keen consumers of modern popular science—an enthusiasm which was seriously tested once we started talking to David about what he actually does. In a certain sense, as far as subject matter goes, we never got past the gulf between how physics is presented in the media and how David spoke about it.

A simple example—we had never had it explained to us how it was that the act of observation "changed" an observed particle, and an enormous amount of popular science seems to go out of its way to obfuscate the process behind this really very basic exchange of electrons. We are not being too dramatic when we say that we felt we had been led to believe that scientists were somehow affecting the outcome of experiments with their minds; as if all of physics were engaged in the kind of magical thinking that routinely gets people committed for 30 days' observation. Popular science is littered with just these sorts of woolly explanations—throw in a bit of time travel, a few alternate universes, and some stretched-out twin brothers meeting their aged siblings after a trip at light speed, and you've got half a physics documentary right there.

We spent a very long time discussing, and trying to understand, the details of David's assertion that physics is at heart a theory of measurement. There is quite often, in art circles, an attempt to deny that measurement—or that overarching pejorative term, the dreaded "calculation"—has, or at any rate should have, any part to play in the production of a work of art. This is in part because the public—and more than a few artists—have been convinced that art is a variety of mystery religion that drags its insights from far-off, unseen lands into general view.

Our discussions convinced us of two things. One, that it is absurd to pretend that the role of calculation in art is minor or of no real importance. Second, that the real mystery behind science is rather more like what artists do than either side might care to admit. Scientific modeling via the method of theories is really not unlike artistic modeling via the medium of visions. A scientist tallies inchoate information until, through a creative act, he or she encompasses it in a new theory. The artist takes what is difficult to talk about and, using imagination, moves it into a framework where it can be considered. The difficult-to-perceive becomes perceptible, and the act of synthesis between these two states remains as mysterious as the reality of the atom. But do these "visions" happen because of innate genius, or the favour of the gods? Perhaps they happen via a certain facility for measurement.

Figure 3. Holly Aitchison, *The Measurement Problem* (2015).

Our painting is, seen simply, a meditation on how we measure in order to represent. A more complex view might see it as attempting to marry existing artistic concerns of ours—how time and changes of viewpoint tend to change methods of representation—to the problem physicists have speaking to the "reality" of the microscopic world when the available methods of measurement yield contradictory stories—the wave and the particle.

When photography was invented and started to shoulder some of painting's burden, a philosophical schism opened up which is still not really being dealt with—namely, that a photograph is a split-second capture of one moment from one perspective, while a painting done from life represents an enormous amount of time, decision-making and multi-level perspectives, occurring between two live subjects—artist and model. *The Measurement Problem* engages with this, amid a prismatic view of time and information. We even literally use one of the laser beams from the device that David uses to study Rubidium atoms, interjected into what is otherwise almost entirely a realistic painting of our living room, painted from life. In fact, the room acts in one sense as a model of David's experimental chamber, with viewing points set up 60º from one another, but requiring rather more abrupt and subtle paradigm shifts from the viewer than simple laserbeam pin-point accuracy.

Figure 4. Holly Aitchison, *The Measurement Problem* (2015), detail.

At one point in our discussions with David, we wondered whether the methods used to measure an atom might not be usefully compared to sheet music. The marked note resembles the particle and its quality—one beat, two beats in weight, or whatever—while the time measurement of the stave was like the wave function—the notes hung upon it give a sense of the wave's "rhythm." He felt it was an admirable comparison, and it is useful for understanding the painting. The sheet music seen in the woman's hands is *Brilliant Corners* by Thelonious Monk. Think of the ageless lost African races, millennia of microorganisms, an entire globe of culture and the billion other things that went into creating the human called Thelonious Monk who played the opening phrases of that composition on the 1957 album of the same name. It is undeniable that more of those human qualities are perceptible in the hearing of that track on the record than in the cold reading of its sheet music. And yet, we can indeed read it and re-create it, after a fashion.

It has been customary to demand much of both art and science in terms of explanations, given that the Western world's crisis about how to replace religion since the Enlightenment has not yet quite played itself out. A useful, modern appreciation of both fields should underscore that they both face the same problems as all of us when it comes to working out what is real, and what is more or less abstracted dialogue. We got a much more grounded sense of what physics is and does out of this project, a sense that we hope will become more normal and useful for those still being encouraged to expect miracles.

Figure 5. Holly Aitchison, *The Measurement Problem* (2015), detail.

CONCLUSION

The Art and Light Project has successfully brought together artists and scientists from across the Dunedin community and created a forum for dialogue and understanding. Some beautiful art has been created which culminated in a well-attended exhibition at the Otago Museum. More than 60 years ago, C.P. Snow wrote[4] in his wonderful little book of warning, *The Two Cultures*, that "There seems to be no place where the cultures meet. I am not going to waste time saying that this is a pity. It is much worse than that." This exercise has attempted to bridge a little of that gap between the cultures of science and the arts. Moreover, I think that both artists and scientists alike would agree that the distinction is an artificial one. To illustrate this we have tried to express in this article the similarities in method and thought between creation—for they are both creative processes—in art and science.

Moreover, the science we have tried to portray through this art and this article can be difficult to grasp. The exhibition itself has been a vehicle that has enabled us to engage with an audience that would not perhaps normally be exposed to quantum science. As a public outreach and educational exercise, this project has therefore been a resounding success. More importantly, it was a lot of fun.

David Hutchinson is the Director of the Dodd-Walls Centre for Photonic and Quantum Technologies and a member of the Department of Physics at the University of Otago.

Holly Aitchison is an autodidactic artist who lives and works in Dunedin teaching art to people with special needs. Holly worked with Jimmy Currin on the conceptualisation of *The Measurement Problem*.

Based in Dunedin, **Becky Cameron** holds an MA in art conservation, and in 2013 completed a Bachelor of Visual Arts with Honours at the Dunedin School of Art. She has been exhibiting since 2008, and her most recent project, "Te Ao Huri Huri/The Turning World," was shown as a part of the Dunedin Matariki Festival in July 2014. Cameron's practice explores landscape, memory, belonging and home.

Jimmy Currin is a musician, artist and critic from Dunedin.

1. B-G Englert, *On Quantum Theory*, arXiv:1308.5290 [quant-ph] (2013).
2. *Images of Science: Essays on Realism and Empiricsm*, eds PM Churchland and CA Hooker (Chicago: University of Chicago Press, 1985).
3. *Quantum Effects in Biology*, eds M Mohseni, Y Omar, GS Engel and MB Plenio (Cambridge: Cambridge University Press, 2014).
4. CP Snow, *The Two Cultures* (Cambridge: Cambridge University Press, 1959).