The Demuth Prize Essay

"My own suspicion is that the universe is not only queerer than we suppose, but queerer than we can suppose." – JBS Haldane

The Meaning of Nothing

At the end of the year, when the onslaught of exams is over, I return home to face the toughest examiner of all: my little sister. I can now compute the decay rate of the Higgs boson, but I cannot explain what the Higgs field is made of. I can pinpoint where a quantum particle can be detected, but not where it was a moment before. And I can explain how we detect the stretching due to a gravitational wave, but not what is being stretched. Witnessing me stammering at the dinner table, my family must wonder what I've actually been studying.

In fact, my studies are precisely what make me unable to answer these queries. For every theory of physics comes with a wide range of interpretations, reframings which keep all the observable results the same, in which these questions may be trivial, unanswerable, or even meaningless. Today, we have lost the classical physicist's easy certainty and replaced it with a dizzying variety of provisional pictures of reality.

Philosophers of science call this position anti-realism, but I prefer to call it the storyteller's stance. Even when our experiments are exhaustive, we will always have a wide range of theories – different stories – which can account for them all. A good story obeys Chekhov's gun, with every element of reality playing an important role, while a great story is incomplete in just the right way, suggesting questions that push physics forward. In this essay I will argue, through my sister's questions, that the ambiguity of our stories is a fundamental strength. The freedom to keep our picture of reality provisional allows us to see further, to solve new problems, and ultimately to reach towards a deeper theory, one that is queerer than we can suppose.

Let us consider the simplest possible example. Take a sealed box and pump out the air. What remains inside is empty space. But what is empty space? What constitutes nothing?

The answer has radically changed over time. In the 19^{th} century, it was accepted that a wave could only exist inside a medium. A sound wave could not propagate in a vacuum, but light could, revealing that seemingly empty space must be occupied by an intangible, extraordinarily rigid medium called the luminiferous ether. Fizeau's measurement of the speed of light in flowing water showed that moving matter could partially drag ether along with it. In response to puzzling experimental results, Lorentz hypothesized that moving ether could in turn affect matter by subtly squeezing it. As experimental anomalies accumulated, Lorentz had to further assume that systems moving through the ether experienced a fictitious "local time".

The revolution came when Einstein cut the ether out of the story. He showed that Lorentz's ether contraction and local times could be simply explained in terms of the inherent behavior of spacetime itself. In Einstein's view, a moving object did not have to be forcibly squeezed shorter by the ether; instead, the very same object's length could simply vary depending on the reference frame.

In textbook accounts, this was the end of the debate, but it really was the beginning. Some physicists at the time regarded Einstein's special relativity as merely an mathematical trick, which ignored the real physical question of how the ether produced these effects. Over the next few decades, further experiments forced the ether theory to become more and more complex to accommodate the results. Eventually it was dropped, not because it had been completely ruled out (a rare thing in physics), but because it was not useful. Accounting for the ether's dynamics made theories more complicated for no material gain. It led physicists to ask questions that had no answer in experiment. And for a field in revolution, where experimental results were already hard enough to understand, this was enough to strike it out from the story. It was accepted that light waves could exist without any medium at all.

This episode was taken as a triumph for logical positivism, the philosophy that it is meaningless to speak of anything we cannot observe. However, there was nothing inherently wrong with giving the ether a role in our story. The ether was a genuinely useful idea in the 19th century because it prompted physicists to look for local explanations of electromagnetic effects, rather than settling for "action at a distance". Maxwell had a tremendously detailed picture of how the ether behaved, which made his theory difficult for contemporaries to understand, yet it led him to the revelation that light was an electromagnetic wave. The very same ether could act, in two different eras, as a wellspring for creativity or a straitjacket.

The tension between structure and minimality survives in the Standard Model of particle physics. The recently discovered Higgs boson is often described as an excitation of the Higgs field, which pervades all of space. Some philosophers of science characterize the Higgs field as a modern revival of the ether, but the two differ in important ways.

Throughout the 20th century, we found that quantum particles could be described as excitations of quantum fields. As the physicist Steven Weinberg emphasized, such fields may simply be viewed as mathematical scaffolding around the particles. They are a complication, but a very useful one, because there are few ways that fields can interact with each other, giving us strong constraints on how the corresponding particles can. Furthermore, quantum fields such as the Higgs field are minimal. The ether was a mechanical medium, with properties like elasticity, deformation, and velocity. By contrast, the Higgs field has no properties except for its value, an abstract number at every point in spacetime. It costs us much less to give the Higgs field a role in the story.

One could protest that by embracing this minimality, physicists are turning away from the fundamental questions, such as what the Higgs field *really is*. I disagree. The simplicity of the Higgs serves as both a tool for calculation and a firm foundation for speculation.

For example, in some "composite Higgs" models, the Higgs field emerges as a condensate, formed of new particles that behave similarly to quarks and gluons. In a more ether-like option, condensed matter physicists have shown that a relativistic theory can emerge within special types of matter, which play the role of the mechanical medium. For example, the electrons inside graphene behave almost precisely like relativistic particles in our world, explaining some of graphene's remarkable electrical properties. At low energies, these electrons cannot see the absolute rest frame defined by the graphene lattice, putting Lorentz's ad hoc fixes on a concrete footing. Physicists have been able to unearth these extensions to the Standard Model precisely because of the simplicity of the Higgs in the Standard Model itself.

More radically, it has been proposed that the entire Standard Model could emerge as in graphene, as the internal dynamics of a lattice theory. To the physicist, there is nothing wrong with such a philosophical reversal. But I personally find such proposals strange because they aren't strange enough. It seems almost too easy for fundamental physics to resemble what we find in blocks of metal. However, "lattice QCD" computations have productively used such ideas to simulate part of the Standard Model, achieving greater precision than any other method. Hence the flexibility of interpretation of the Higgs field and others like it, whether ultimately emergent or fundamental, is both an important tool and the reason I cannot answer my little sister's first question.

Let us return to the box. So far, I have been neglecting an important aspect of "nothing". For even if we shield our box against electromagnetic radiation, and cool it down to absolute zero, a sufficiently sensitive detector placed inside will still see a nonzero electromagnetic field. This is a consequence of the Heisenberg uncertainty principle. The electromagnetic field behaves quantum mechanically, which ensures that it cannot be precisely zero everywhere.

Since quantum fields are formidably abstract, let's consider a single quantum particle instead, such as the electron. In the Copenhagen interpretation, the state of an electron is described by a wavefunction, whose value at a point describes only the probability of finding the electron there. Even when an electron settles into the lowest energy state, its wavefunction remains spread out over some range. Upon a measurement of position, the wavefunction "collapses" to a sharp peak at some random point in this range.

The Copenhagen interpretation focuses relentlessly on the results of measurements, for which it accounts beautifully and minimally. It leaves questions about the wavefunction's nature or the mechanism of collapse completely unanswered, and it refuses to say where the electron was *before* the collapse, dismissing such counterfactual speculation with the pithy slogan "unperformed measurements have no results".

This glib philosophy has led to sharp reactions. The noted philosopher of science Imre Lakatos described it as a "new and unprecedented lowering of critical standards" which led to an "anarchist cult of incomprehensible chaos". More recently, the metaphysician Tim Maudlin has condemned it as "incomprehensible nonsense" and an "intellectual rot" that has overthrown the "authority of reason and evidence".

These strong emotions are warranted, but the condescension is not. To understand the working physicist's position, it is useful to consider pilot wave theory. This alternative to the Copenhagen interpretation is often championed by realist philosophers, who would prefer that measurable properties, such as the position of a quantum particle, should always be well-defined. In this interpretation, the wavefunction is a classical field, like the electromagnetic field, called the pilot wave. Every particle always has a definite location, but it is "guided" by interaction with its pilot wave, allowing it to perform feats impossible for ordinary classical particles, such as quantum tunneling. Hence, the subtlety of quantum mechanics is dispelled by describing a quantum particle as *both* a classical particle and a classical field, in a literal interpretation of wave-particle duality.

For those who have struggled with the subtleties of quantum mechanics, this simple story sets off alarm bells. For one thing, where is the probability? If the electron really has a definite position, then why is it measured to be seemingly random, even after the electron settles into its lowest energy state? The answer is that the pilot wave is postulated to unpredictably shuffle about the location of the electron until its position reaches “quantum equilibrium” and matches with the predictions of the Copenhagen interpretation. This shell game is assumed to occur too quickly to detect. Worse, once it is over, the electron is predicted to hover in midair, perfectly still. Velocity measurements indicate otherwise, so pilot wave theory simply assumes they are all mistaken. Apparently, there is a *real* velocity, but it cannot be measured, and any attempt to do so yields something else. These ad hoc fixes allow pilot wave theory to avoid contradiction with the empirically verified uncertainty principle.

The pilot wave itself also has strange properties. We expect to be able to measure classical fields, but the pilot wave cannot be directly measured. Classical fields were introduced to avoid nonlocal “action at a distance”, but when the particle is measured, the pilot wave instantly collapses. The collapse is postulated to be faster than light but coincidentally completely undetectable, making pilot wave theory almost impossible to reconcile with relativity. Furthermore, “Bell test” experiments confirm that this problem cannot be removed in any refinement of the theory.

The reason most physicists are hesitant to accept pilot wave theory is that it appears to have the ether’s flaws. In exchange for the classical intuition of definite particle trajectories, the theory drastically increases the complexity of our world. It suggests many natural questions about the nature of the pilot wave and particle, then gives them unnatural answers which are hidden from observation. That is why, when physicists working on quantum foundations were polled at the 2011 conference *Quantum Physics and the Nature of Reality*, precisely zero vouched for the pilot wave. The interpretation is like an art teacher who sings the praises of creative freedom, yet berates any who draw outside the lines.

I focus on the negatives of pilot wave theory to illustrate why physicists do not take it as the basis of a realist interpretation of quantum mechanics. However, Copenhagen is by no means the only option. For example, in the “many worlds” interpretation, the collapse of superpositions upon measurement is replaced with inclusion of the observer in the superposition. In other words, an observer does not measure whether an electron is here or there; instead the observer enters a superposition of seeing the electron “here” and seeing the opposite. The problem is that we clearly don’t *experience* such a superposition, so we must only “live” in one branch or the other. The problem of collapse is hence replaced with the problem of “self-location” in the universal wavefunction.

As queer as it sounds, the many worlds story can be useful. For instance, when describing quantum effects in the very early universe, there is no clear observer and so no clear point of collapse. It is more straightforward to implicitly adopt the many worlds attitude and compute the statistics of the universal wavefunction.

Yet another approach is quantum Bayesianiam, which flips the many worlds script: rather than having all observers living inside a universal wavefunction, the wavefunction lives in each observer’s mind, representing merely their subjective knowledge. This explains wavefunction collapse as simply the acquisition of new knowledge, but has the possibly disturbing implication that the wavefunction of a system depends on the observer. In fact, even this feature can be useful in quantum information theory, especially to emphasize its links with classical information theory.

Quantum mechanics weighed heavily on Kuhn's mind when he wrote about scientific revolutions. Kuhn was trained as a physicist, and appreciated how the Copenhagen interpretation permitted a different set of questions than classical physics. But he couldn't have anticipated the embarrassment of riches we have today. We collectively have a deep and fluent intuition for the behavior of the quantum world, made all the better by our ability to change interpretations at will. Philosophers may call this metaphysical confusion, but I call it a source of inspiration, and it is the reason I cannot answer my sister's second question.

Her third query relates to the hidden actor in our description of nothing: the stage of spacetime itself. It is distinct from objects like the Higgs field, which merely live on it. More precisely, when we specify a configuration of a field, we give its value at every time and place. The set of all such times and places is spacetime.

Popular books describe spacetime as a rubber sheet, which is distorted by masses and vibrated by gravitational waves. Does spacetime really have such mechanical properties?

If we imagine spacetime as the graph paper on which physics is drawn, Galilean physics and special relativity both showed that it has no absolute rest. This meant that two pictures of motion through spacetime, one at rest on the graph paper and one uniformly moving through it, were completely observationally equivalent. They simply belonged to two observers in uniform relative motion.

Einstein was led to general relativity by formally extending this symmetry of special relativity to the idea of "general covariance". Early on, he realized that any theory with general covariance would be grossly indeterminate. For example, one might expect that a Sun sitting still at some point in space would remain at that point, but a covariant theory also allowed for the Sun to suddenly spring into motion, tracing a wild path through spacetime. This was the same nondeterminism that troubled Einstein in quantum mechanics, and it led him on a long and fruitless search for alternatives.

The eventual resolution was the realization that, once again, the two pictures were perfectly observationally equivalent. The second picture simply corresponded to an observer who had chosen a peculiar set of coordinates, like a distorted projection of the globe. Despite the distortion, in both cases all physical observables matched: the Sun unambiguously traveled in a straight line. As such, Einstein could rescue determinism by simply identifying the two pictures as representing exactly the same physical motion.

This seemingly innocuous idea demoted an object's location in spacetime to an arbitrary convention of a given coordinate system. Specific points in spacetime became meaningless; observationally one could only speak of coordinate-independent ideas, such as whether or not two particles met. Einstein interpreted this radically, summarizing his theory by saying: "People before me believed that if all the matter in the universe were removed, only space and time would exist. My theory proves that space and time would disappear along with matter." In his hardline view, spacetime had no independent existence.

Despite Einstein's position, the idea of an independent spacetime has survived. There have been formulations without it, such as twistor theory, where the fundamental objects are not spacetime points but possible meetings of particle trajectories. However, they tend to be fearsomely mathematically complex. The fact remains that spacetime is an incredibly useful and intuitive tool. Our brains are hardwired for notions of space and time, and they can play an invaluable role in the story if they are introduced carefully.

If we stick with spacetime, we still must account for the ambiguity that Einstein pinpointed. This "gauge fixing" is often done by restricting the allowed coordinate systems. For example, the ADM formalism forces coordinates to unambiguously split apart space and time. This is essential for numerical simulations of relativity: we can't expect a computer to compute how a system changes over time if we don't tell it what time is. Alternatively, one can treat a given spacetime as a fixed, ether-like background whose vibrations are gravitational waves, giving a picture useful for both popular imagery and scientific work.

Both of these approaches are directly against the spirit of relativity, as Einstein imagined it. They work best when spacetime curvature fluctuations are small. But this is the simplest and most intuitive case, and hence a natural starting point, especially in theories that attempt to go beyond classical gravity. For example, loop quantum gravity begins by splitting apart space and time, while string theory begins with a fixed background. Despite much heated discussion, neither is a fatal flaw. General relativity is in a certain sense the simplest possible theory of gravity, and the deep philosophical principles Einstein saw in it may turn out just to be low-energy accidents.

Appeals to principles have an unsteady track record in fundamental physics. They often boil down to rejecting theories using the biased, incomplete intuition of a less fundamental one. I do not think that deep principles do not exist; I believe, without evidence, that a final theory will tell us unambiguously what is real and what is not. But I know that only experiment will lead us there. The Large Hadron Collider has probed lengths fifteen orders of magnitude smaller than the eye can see, and the truth lies fifteen more below.

Established physics is a straightforward hierarchy of nested theories: chemistry emerges from atomic physics, which emerges from nuclear physics, which in turn emerges from the Standard Model, with one neat story for each layer. But when we push to the edge of our knowledge, we find a patchwork of confusion. As we look deeper, seemingly fundamental ideas may disappear, reappear, or become irrelevant. The data that will someday bring us to the next layer are ambiguous or incomplete, and we cope by making our stories of the world equally so. These complexities of interpretation appear even when we analyze "nothing" at all, as we saw for the Higgs field, quantum fields in general, and spacetime itself.

A metaphysician may charge that physicists today can calculate the value of everything but know the meaning of nothing. They are correct. Fundamentally, I cannot answer any of my sister's questions; I cannot explain what is inside an empty box. Our current theories are provisional, tangled, even contradictory, while the truth may be queerer than we can today suppose. But it is precisely by allowing ourselves to tell such wild stories about nothing that we will someday glimpse the nature of everything.

References

- Van Fraassen, Bas C. *The scientific image*. Oxford University Press, 1980.
- Agashe, Kaustubh, Roberto Contino, and Alex Pomarol. “The minimal composite Higgs model.” *Nuclear Physics B* 719.1-2 (2005): 165-187.
- Levin, Michael A., and Xiao-Gang Wen. “String-net condensation: A physical mechanism for topological phases.” *Physical Review B* 71.4 (2005): 045110.
- Davies, Christine TH, et al. “High-precision lattice QCD confronts experiment.” *Physical Review Letters* 92.2 (2004): 022001.
- Lakatos, Imre, and Alan Musgrave, eds. *Criticism and the growth of knowledge: Volume 4: Proceedings of the International Colloquium in the Philosophy of Science, London, 1965*. Cambridge University Press, 1970.
- Bell, John S. “Speakable and unspeakable in quantum mechanics.” *Cambridge University* (1987).
- Penrose, Roger, and Malcolm AH MacCallum. “Twistor theory: an approach to the quantisation of fields and space-time.” *Physics Reports* 6.4 (1973): 241-315.
- Baumgarte, Thomas W., and Stuart L. Shapiro. *Numerical relativity: solving Einstein's equations on the computer*. Cambridge University Press, 2010.
- Wilson, Kenneth G., and John Kogut. "The renormalization group and the epsilon expansion." *Physics Reports* 12.2 (1974): 75-199.