# Obliterating Thingness: an Introduction to the "What" and the "So What" of Quantum Physics

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## 1 Introduction

This essay is a short introduction to some core concepts and philosophical problems associated with quantum physics. We are writing it to respond to, and to enhance, conversations about the meaning of quantum physics that are currently underway in contexts beyond the physics laboratory.

*Far* beyond the physics laboratory. We are two physicists who regularly work with artists and designers. We increasingly hear from colleagues and students in these creative fields that quantum physics is an important source of ideas for their work, even though they may have never taken formal physics courses. In our personal experience, the ideas of quantum physics seem to be undergoing vigorous "cultural processing" in this historical moment, largely beyond the gaze of professional physicists.

"Cultural processing" is our own term. It is meant to loosely encompass anything that people do with the theories, empirical results, narratives, or methodologies of a scientific field that takes place outside the central institutions and practices of scientific research. It is an umbrella term for the many heterogeneous ways that some ideas from the world of science end up having meaning outside their original contexts.

Many scientists simply object to the idea that scientific ideas could have meaning outside their original contexts. We do not. First of all, any time that scientists themselves attempt to translate scientific ideas for a public audience, they are engaging in a form of cultural processing. The drive to share scientific ideas, and to re-express them in non-technical language, speaks to the potential for science to have meaning beyond a research paper or a technological application. It would be ridiculous to think that big ideas like relativity or quantum entanglement would have no importance beyond the lab; their non-technical relevance (including the potential for shaping worldview) is a part of why many scientists pursue, and share, their research in the first place.

We also believe that questions of the meaning of scientific claims already are (and should be) open to the input of non-scientists. Enabling interdisciplinary exploration into the philosophical, metaphorical, and generative potential of quantum physics concepts is one of our aims with this essay.

In the art and design world, we see a particular demand for greater understanding of quantum physics spurred by the influence of a single interdisciplinary feminist scholar, Karen Barad.[1] Barad (who herself was trained as a physicist) has opened up entirely new communities of interest in quantum phenomena. You do not need to be familiar with Barad's work to understand the rest of this essay, but we will refer to her as a central example of someone who takes the ideas of quantum physics to be deeply meaningful outside of the laboratory setting. Barad believes that the facts of quantum physics are so philosophically important that they wholly change how we should think about people, relationships, subjectivity, objectivity, nature, culture, and scholarship itself. Citing Barad, scholars in the arts, humanities, and many interdisciplinary fields now write about the "observer effect" and "entanglement" – technical physics concepts – in work that has a distinctly social or political (that is, not primarily physics-based) emphasis.

As much as we support the productive export of scientific ideas into new contexts (even when it sometimes involves misunderstanding them), there are certain forms of cultural processing that we consider problematic. Some of these also come up often in conversations with students and colleagues. The threads of thought that we take issue with are the ones that treat quantum physics concepts as if they provide scientific backing for certain spiritual or health-related claims wholly beyond the domain of established science. Speculating beyond the limits of current knowledge is perfectly fair game for anyone, and such speculations need not be responsible to the methods and knowledge of science in every context (for example, in science fiction). Yet we think it is important to be able to tell the difference, and to respect the things that set scientific knowledge apart from other forms of thought or belief.

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[1] Barad is faculty at the University of California, Santa Cruz. Her book *Meeting the Universe Halfway: Quantum Physics and the Entanglement of Matter and Meaning* (Duke University Press, 2007) is widely read in the humanities, in science studies, and in the arts, although it is interesting to note that she is almost entirely unknown among physicists.

Specifically, any claims of the sort “A physically causes B” are explicitly scientific claims. To be serious claims, they require a rigorous program of experimental verification to substantiate. Such substantiation, generally speaking, is absent for pseudoscientific claims like those involved in quantum healing and so forth. For example, consider the claim that thinking, through quantum physics, can somehow directly affect events in the world. This is not something that has a rigorous empirical foundation. Even if we take it as speculative, any possible mechanisms for physical causation need to be evaluated for consistency with everything else we know about how the world works. Precisely because we have such a sophisticated understanding of the forces involved in physical interactions (enabling a host of technologies from brain scanning to remote sensing), this is a high bar to clear. Any causal mechanism that is supposedly based on physics needs to be explainable *along with* and *in relation to* all the other physical causal mechanisms we already understand. In other words, any proposed physical mechanism for quantum healing needs to be explained in the same framework that explains MRI scans, thermal imaging, and all the other ways we already understand for communication with and about the body through known physics.

This is all a long way of saying: if it sounds too good to be true, it probably is. Quantum physics is not a trick or a way of evading the ordinary rules of nature. Quantum physics has some amazing implications, but it is very much grounded in the physical and the possible, describing processes that are going on in atoms, in computer chips, in lasers, and in nuclear bombs. Powerful stuff, but all well-understood, empirically founded, technologically activated physics.

In the next several sections, we will say more to define the scope of quantum physics, discuss some core representational and philosophical issues, and describe some of its key empirically-founded insights. Throughout, we will directly address possible philosophical conclusions one could draw from quantum physics, as well as try to clearly draw the line that divides science from pseudoscience.

# 2 The Scope and Form of Quantum Physics

*Quantum physics, quantum mechanics*, and *quantum theory* all refer to the same thing: our physical theory for phenomena on very small size scales (comparable to, or smaller than, the individual molecules and atoms that make up materials around us). A *theory* in physics is much more than a set of ideas. It expresses quantitative relationships between things we can measure, which means it involves equations. There are clear criteria for determining whether a theory in physics is a successful one or not. To be successful, it must be able to account for experimental results that have already been obtained, and, more importantly, be able to predict the outcomes of future experiments. Successful theories become integrated into the working practice of physics. A central part of that research is to explore the consequences and applications of the theory, as well as to continually develop more rigorous tests that probe its scope and limitations. Any robust and repeatable observation that is in conflict with the theory may require a revision to or replacement of the theory. If this does not occur, and evidence in support of the theory grows, it becomes even more deeply ingrained in how we do and think about physics.

Quantum theory is one of the most successful physical theories ever developed. Since its foundation in the early twentieth century, this theory has been tested through decades of rigorous experimentation. Its track record of accurate prediction is astonishing, allowing countless technologies to be designed on the basis of those predictions. Every digital camera and smartphone in the world is a testament to the success of quantum theory, as is every nuclear power plant. Quantum theory is so fundamental to our understanding of nature that it underlies entire fields of scientific research (e.g. chemistry). Quantum physics is thus not at all speculative. It is not a form of philosophy, and it is not something that is principally expressed, or employed, through verbal language. At its center is a practical toolkit of equations that technical experts use to model, understand, and design a wide range of structures and phenomena that involve light, electrons, and atoms.

One of the most remarkable lessons from 20th century experimental physics is that light and electrons and atoms require a very different kind of description than macroscopic objects and events. There are *two* important points here. First, nature is not the same on every scale. On small scales, bits of matter move and interact in completely different ways than bodies in a room or planets around a star. Second, we discover that the equations we need to describe and predict those motions and interactions are of a completely different character, too.

If you are not used to thinking about how equations relate to things in the world, it might be hard to imagine what we mean by equations having a "different character." It might also be hard to believe that talking about equations is important in a supposedly non-technical introduction. The core content of quantum physics is expressed through equations, and one of the key points we want to make is that there is ambiguity any time you try to translate those equations into words. This opens up philosophically interesting (and possibly problematic) territory, so it is worth highlighting.

Whether we are talking about macroscopic or microscopic phenomena (large or small scales), physics deals with things like motion, interactions (like collisions), forces, causality, and changes in physical systems over time. To take an especially simple example, imagine that some asteroids in deep space collide and a chunk of rock goes hurtling away into space. The role of a physical theory is to do something like provide an equation to describe the motion of that rock. The equation will contain symbols that stand for the measurable properties of the physical system. The mathematical relationships between symbols in the equation serve as a model for the physical relationships between the properties themselves. That model can be manipulated to learn things about the physical system, like where the rock will be at a future time.

However, if we consider a single electron flying through empty space, we are in the realm of quantum physics and we need to use a different equation. Let's compare the equations we would use in the macroscopic and microscopic cases, to talk about some of their differences (don't worry - you do not need to do any mathematics to follow the discussion).

An equation we could use to describe the motion of a rock hurtling through empty space might look like this:

$$x(t) = x_0 + vt. \tag{1}$$

Each symbol in this equation has a meaning that we can express in plain language.[2]

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[2] Note that, in this equation as well as any other used in physics, it doesn't matter what the symbols actually are as long as we know what they represent, or how to use them.

The symbol $x(t)$ represents the position of the rock, along its direction of motion, as a function of time. The symbol $x_0$ represents the position of the initial asteroid collision that sent off the rock at some speed. The symbol $v$ represents the speed or velocity of the rock as it hurtles through space. And $t$ represents the time that has elapsed since the rock started moving.

Now, in contrast, here is an equation we could use to describe an electron freely traveling through space:

$$\Psi(x,t) = \frac{1}{\sqrt{2\pi\hbar}} \int_{-\infty}^{\infty} \phi(p) e^{ipx/\hbar} e^{-iEt/\hbar} dp. \tag{2}$$

You will immediately notice that it looks *a lot* more complicated. While the first equation used only algebraic operations, this one depends on calculus (note the long curly integration symbol) and has imaginary numbers in it (the $i$), which is why quantum physics is not usually taught early in an individual's education. The most important point we want to make about this equation is that, in contrast to what we did with the previous equation, we cannot simply tell you what each symbol in the equation means. Arguably, nobody can.

This is a key thing that makes quantum physics weird. How can we have a successful equation, but no consensus on how to talk about what that equation means?

In the macroscopic case, computing $x(t)$ lets us track the position of the rock. The position and time, as well as the velocity and initial position of the rock (that is, all the things that are in the equation) are things we can measure any way we choose, and in any order, and we should find that when we plug everything in, the equation holds true. We treat measurable physical properties in macroscopic physics as if they have definite physical reality and definite relationships to one another, which we can represent directly with mathematical relationships.

In the quantum case, the analogous symbol to $x(t)$ is $\Psi(x,t)$. It has a name - the wavefunction for the electron - but it does not have a single clear interpretation or meaning that we can tell you in simple language. There are computational recipes we can use to manipulate $\Psi(x,t)$ to predict something, but that prediction will be statistical in nature, specifying a probability for finding the electron in a certain place at a certain time, rather than specifying that a specific position that the electron will be at a specific time. We will find, through these computations, that the electron could be in many different places. There is no way to predict exactly which will be actual location if we perform the physical measurement. The wave function mathematically encapsulates all the possibilities. What it does not do is tell us is what underlying physical mechanism leads to the need for a probabilistic description in the first place. That is, it does not tell us what the electron itself actually is, nor how it ends up behaving in this odd way.

Measurement also matters in the quantum physics mathematics in a way that it does not matter for classical physics computations. When we manipulate the equation for the rock, we do not need to take into account whether we measure the velocity first or the position first. When we manipulate the quantum physics equation, we have to explicitly account for the types of measurement that are made and their order. The order of measuring the properties of the electron matters, and each type of measurement actually changes the wave function itself.

Thus the way quantum equations function is simply different. They do not have terms in it that relate to simple, nameable *things* nor to permanent and independently knowable *properties* of those things. Quantum theory gives us a probabilistic description of many possibilities. Nobody knows for sure why these recipes work, nor how to talk about the relationship between the mathematical operations and the underlying physical nature of the electron itself.

The point is that it does work. Both equations given in this section work, just in different contexts (macro versus micro). Both equations are idealizations, and real scenarios often require more complex versions (to take into account forces due to gravity or due to other particles, for example). But, when the conditions are close to the ideal, the equations function predictively and descriptively, in their different ways. Macroscopic physical reality can be described with equations that have nameable things and well defined properties. Microscopic reality requires probabilistic equations with a less direct relationship between the symbols and anything we can simply name or define.

## 3 The Boundary Between Theory and Interpretation

We seem to be stuck accepting that quantum mechanics equations are just different. Most importantly, they make no unambiguous references to the structure or form of physical reality prior to specific measurements. Quantum physics does not tell us what the electron *is*, or what the wave function *means*. To go the extra step of assigning words to the things that are represented in this scheme, we have to pick a particular *interpretation*.

The interpretation is a set of philosophical commitments associating the terms in quantum mechanics equations, and the phenomena observed in laboratories, with specific meanings. This step is necessary if we want to say things like "in quantum physics an electron is..." or "when the electron went through the apparatus, what happened was...." The point is that such sentences will come out differently if we make different interpretational choices.

Thus, and this is the punchline of this section (and a key punchline of the whole essay) *there is no single quantum ontology.*[3] A quantum ontology would be a scientifically supported way of answering questions like these: What is actually going on with the electron flying through space? Is the electron itself actually "spread out," physically embodying many possibilities at the same time? Does $\Psi$ correspond to a real physical thing, or does it capture something only about what is knowable about a situation? Could there be multiple versions of reality - multiple universes, even - in which the electron is in all of the different places that are expressed as possibilities in $\Psi$? Is the randomness we observe - the need for a probabilistic description - something fundamental to the universe, or an expression of limited knowledge?

All of these are questions about the structure of physical reality on the quantum scale, and none of these questions can be answered unambiguously by the physical theory itself. While quantum theory is wildly successful and well proven as a tool, it leaves open major questions about how the universe actually works.

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[3] "Ontology" is a word from the field of philosophy that refers to a theory of "what is" in the universe. It is often contrasted with "epistemology," describing a theory of how we know about things in the universe.

Most non-technical writing about quantum physics does not emphasize this point. Authors typically pick an interpretation and explain quantum physics from within that framework. It is hard enough explaining the weirdness of quantum physics within a single interpretation, much less trying to explain that everything could be completely different if we picked another. But if you are interested in asking about the meaning of quantum physics "outside the lab," we think that it is important to acknowledge that there is no consensus on the meaning of quantum physics "inside the lab."

This point is relevant, for example, if you are reading Karen Barad. She takes quantum ontology as the starting point for rethinking all ontology (as well as epistemology and ethics, in fact). To do so, she must commit to an interpretation in order to have a quantum ontology to start with. In her case, she picks an interpretation that is widely favored among physicists (for historical and cultural reasons, not because there is any evidence supporting it). In this interpretation[4], something like an electron is treated as a fundamentally indeterminate entity prior to measurement. This means that it does not have well-defined properties (like location, or velocity) until it is measured. Measurement (which need not be measurement by conscious humans, but could be some form of interaction with an environment as well) creates definiteness. Barad takes this as a fundamental fact of how the universe operates: definite properties, and definite things, only emerge through interactions. The notion that anything, on any scale, has a persistent and well-defined identity, is thus called into question.

Our point is that you might end up with quite different philosophical conclusions if you started with a different interpretation of quantum physics. In some, entities like electrons (and everything else) have perfectly well defined properties. To account for quantum phenomena, we know that it is impossible to have complete access to information about those properties (otherwise, different forms of equations, more like the classical case, would work). But definite things and definite properties may in fact exist.

A final note for this section on interpretation is that the lack of a single clear interpretation does not mean that the nature and structure of the universe is a philosophical free-for-all. There are many speculative or imagined ideas about quantum physics that are simply inconsistent with empirical facts or the scientific method (like quantum healing claims, as we mentioned in the introduction). What an interpretation of quantum physics deals with is the meaning we assign to (a) terms that show up in equations or (b) phenomena that are observed in well-controlled, repeatable physics experiments, like the kind that are described in peer-reviewed research publications. If an author or speaker claims to discuss the physical, causal implications of quantum physics and there are no equations or rigorously-performed quantum physics experiments involved (at least in the background), it is not actually about quantum physics, in any interpretation. Period.

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[4] Which is known as the "Copenhagen interpretation," referencing the place where it was mostly developed by Niels Bohr.

# 4 Core Ideas of Quantum Physics

We have argued that there is no single framework for discussing quantum phenomena through language. Short of listing empirical results and providing equations and recipes to predict them, there can be no "interpretation-free" description of the microscopic world.[5]

Nevertheless, an equally important point is that no matter what physical reality corresponds to the equations of quantum physics, it is a weird one. Weird, meaning inconsistent with what you would expect based on macroscopic experience.[6]

What we want to do in this section is call out some of the core facts of quantum physics that, regardless of how we interpret them, are in conflict with the intuition and experience we have on the macroscopic scale. We will use a mix of analogies, hypothetical examples, and a little bit of our own invented language, in a deliberate attempt to avoid some of the most common (and tightly interpretation-bound) pedagogical constructs, letting us hopefully emphasize the interpretation issues more clearly.

## 4.1 Quantization

Quantum physics gets its name from one core fact: at the smallest scale, nature is "digital" not "analog." Think of the difference between a digital and an analog clock. In the digital clock the smallest "chunk" is a second, whereas an analog clock runs continuously. The second-hand can be in between two one-second tick-marks on the clock dial. Physical entities like matter and light come in smallest chunks, like the bits and bytes of digital information. So do properties of those physical things, like their motion energy, or their electric charge. *Quantum* (plural *quanta*) is the name given to an individual chunk.

This fact, by itself, means that the rules of the game are different on a microscopic scale. Basic physical quantities like energy and momentum can only be exchanged in certain specific quantum units. This imposes constraints on the interactions that are possible among quanta of matter or light. In physical interactions, quanta can only exchange energy or momentum in whole quantum "chunks," and never in smaller amounts. In the macroscopic world, it is as though a tea kettle heats up by gradually warming up from zero to the boiling temperature, spending at least a tiny moment at every temperature in between. In analogous microscopic systems, there are specific steps to any such process, and there simply is no "in between."

## 4.2 Non-thingness

Electrons and other particles that make up matter are themselves quanta. Photons (individual "chunks" of light) are quanta. So what are quanta? Well, that's where

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[5] Arguably, even the choice of the way that the equations are constructed is linked to interpretation, although ultimately all successful formulations of quantum physics need to be mathematically equivalent wherever they link to descriptions or predictions of well-established quantum phenomena.

[6] This point is argued nicely in the book *Quantum Ontology: A Guide to the Metaphysics of Quantum Mechanics* by philosopher of science Peter Lewis (Oxford University Press, 2016). Lewis argues that while there is no single quantum ontology, all possible interpretations of quantum physics are philosophically significant.

we hit the interpretation problems described in the previous section. There is no single way to talk about what they are, so let's focus instead on what they are not. The single most important idea to grasp about quanta is that they are *not things*. This is at the heart of the radical weirdness of quantum physics.

Let's define what we mean by *things* so that this statement gains some weight. Things are objects that operate by the familiar rules and logic of the macroscopic world. Examples include coffee, cats, cars, carpets. *Things* take up space. If they move, they do so in a continuous way along a single trajectory in space. They cannot be in two places at once. They cannot jump instantly from one place to another. Things have physical properties, like their size, location, or speed of motion. Those properties may change over time, but at any single moment, the properties have definite values that can be used to describe the thing in question. Things continue to exist when we're not looking at them. If they are created or destroyed, compounded or broken apart, there is a single narrative we can use to describe what happened.

None of the statements we made about things, above, can be applied in a straightforward way to describe how quanta work.

Of course, it isn't simple to say "instead, quanta work like this," because while the empirical facts are well established, the words we would use to describe them are tied to specific interpretations. Given a single scenario involving an electron in a laboratory, one physicist might be comfortable describing its behavior by saying "the position of an electron is intrinsically undefined, all we know is that it behaves as if it were in many places simultaneously." Describing the same physical scenario, another might say "an electron is a spread-out entity that does not have a single location." Or, "the electron always has a single, definite location, but knowledge of that location is deeply impossible."[7] Or even, "many parallel universes exist, and in each of those, a copy of the same electron exists at a different place."[8] These are a just a few of the many radically different (and quite radical) statements linked to different interpretations of the electron's non-thingness. The equations describing all of these statements are the same. The observed behavior of the electron is the same in each case. The electron's departure from everyday physics is the same. The words, and the worldviews that accompany them, may be quite different.

Since we view non-thingness as a central feature of quantum physics, we would like to help you to build some intuition for it through analogy. Humans work all the time with abstract concepts that have some non-thing-like behaviors. For example, money.

To explore money as an analogy for conceptualizing quanta, imagine that you have some dollar bills in cash and you deposit them into your bank account using an ATM machine in Chicago. You put real physical money into the machine at a specific location. But you know that as soon as the machine counts the bills and credits your bank account, any meaningful relationship to tangible dollar bills is lost. When you held the dollar bills, the money had a well-defined place: it was in your hand. Once you deposit in the bank, where exactly is it?

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[7] A seminal collection of papers (some are technical and others non-technical) focusing on this viewpoint is *Speakable and unspeakable in quantum mechanics: Collected papers on quantum philosophy*, J. S. Bell, Cambridge University Press (2004).

[8] To dig deep into the philosophy of the so-called many-worlds interpretation of quantum physics,you might want to take a look at the collection *Many Worlds? : Everett, Quantum Theory, and Reality* , Saunders , Simon, Barrett, Kent and Wallace, eds., Oxford University Press (2010). Beware that some of the essays are a little technical, but not all of them.

Sure, the ATM creates a computer record, and that computer record is located somewhere (probably duplicated in many places). Yet it doesn't seem right to say "the money becomes bits stored in a computer." If the whole transaction were recorded on paper instead of bits on a computer, it would still be the same money. Money-in-the-bank is an abstract concept that does not necessarily depend on the form of any particular record we use to keep track of it.

This abstract concept of *money in the bank* or *a dollar you own* is the concept that behaves much like quanta do. Dollars that you own do not always have a well-defined trajectory in space, and we cannot always sensibly ask where they are at any given moment. Suppose you deposit some dollar bills into the ATM in Chicago, and later fly to L.A.. You can withdraw your money from an ATM there. Would you say the money was somehow in L.A. before you went there? How did it "know" you were going to L.A. and not New York? If you had chosen to go to New York, you would have been able to withdraw it there. In a sense, then, your money is equally present anywhere that is connected to the same bank network, and where you find it at any given moment depends on where you initiate a bank transaction. This is a lot like the way that a quantum lacks a well-defined location in an apparatus, until it is measured.

Along these same lines, the money does not need to pass through points in between two locations where you enact transactions with it. We would not say that between your transaction in Chicago and your transaction in L.A. that the money must have been in a city like Denver, somewhere in the middle. Of course, if you go to Denver, you can make your money be there by initiating a bank transaction there instead. But would it have been there without you? Would it have been in any of the cities along any route from Chicago to L.A.?

The lack of definite trajectory in this example is similar to the behavior of electrons and photons and other quanta. It is a weird comparison, because money is an invented abstraction, and electrons and photons and other quanta are constituents of the touchable, viewable physical world. Yet, the intuition you have for the way money works is a useful start for grasping the non-thingness of quanta.

One useful feature of the analogy is the way that your transactions play an active role in determining where your money is. In the physical world, if someone or something interacts with a quantum, it changes the quantum's behavior. This is known as the "observer effect," although it does not necessarily require a conscious observer. Consider a quantum like an electron that is sent through an apparatus in which it can travel multiple paths. We discover that it does different things depending on where (on which path) we place our detectors. That is, the act of detecting the quantum actively changes what it does.

One thing that the money analogy *cannot* capture is that the mere existence of multiple possible paths can affect the outcome for individual electrons passing through an apparatus. This is a bizarre thing, that is not at all true for money in the bank. The mere presence of a path through Denver as one route from Chicago to L.A. does not change the behavior of your money. In a physics experiment, different outcomes will happen if more paths are present, even if every measurement only ever shows it on one single path. This is exactly the kind of experimental result that leads to the interpretative disagreements we described before: is there a guiding force that makes the electron act as if it were in many places at once? Is the concept of *location* just something we can't use with electrons, when we are not actively observing them? Are there many copies of the same electron simultaneously taking all possible paths in many universes?

In the end, even if some analogies can help provide some intuition about what we mean by non-thingness, we are likely to hit dead ends with every analogy that uses words or familiar everyday concepts. The familiar, and the everyday, is rooted in the macroscopic world, and the microscopic world simply plays by different rules.

## 4.3 Randomness

All quantum phenomena display randomness.

We encounter randomness everyday on a macroscopic scale, but the randomness in quantum physics is of a different character. For example, consider flipping a coin and obtaining a random result - heads or tails. The way this differs from quantum randomness is that in macroscopic random events there are knowable (at least in principle) reasons why a particular outcome occurs. You could make a movie of the coin flip, analyze the air currents, and reconstruct how the exact finger motion and trajectory of the coin through the air resulted in it landing heads-up. In other words, we can construct a single coherent narrative of the coin, from the moment it was thrown to the outcome of the experiment. It may be challenging in practice to predict or fully analyze the outcome of a coin flip, but it isn't impossible in principle.

On the quantum scale, predicting or fully analyzing the outcomes of random events is impossible, even in principle. (Well, to be fair, there are some disagreements about how far to go with the "even in principle" statement, which we'll explain in a moment). One issue is that there is no way to continuously measure ("take a movie of") a random quantum process without physically interacting with it and affecting the outcome of the process. There is no single coherent narrative describing a quantum process leading to the prediction with certainty of an experimental outcome. The logic that quantum random events follow in physics experiments is inconsistent with the idea that the entities have well-defined and knowable reasons for any given outcome.

Let's elaborate on the terms "well-defined" and "knowable." What we have discovered empirically in physics experiments[9] is that we have to give up on the idea of well-defined and/or knowable reasons for random events. Any form of randomness has a logic to it that we can analyze, and the logic of quantum randomness is inconsistent with the idea that there are knowable or definite causes for specific random outcomes.

A quantum system analogous to a coin flip might be an experiment in which we send quanta through an apparatus and then measure a certain property that has a 50% probability of having one value (call it "A") and a 50% probability of some other value (call it "B"). For example, it could have 50% probability of facing up or facing down. Between the beginning and the end of the experiment, was it facing up or down? Was there some cause or reason responsible for an individual quantum ending up facing up or facing down? Is that reason something that we could know? We cannot answer these questions in the same way that we can for a

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[9] Specifically, physics experiments testing something called "Bell's inequality." The details are straightforward but lengthy to explain so we have opted not to cover them here. This is a critical set of concepts and experiments to research further, though, if you want to learn more about how deeply strange the quantum world actually is.

coin flip, but to say more in words about what *is* going on, we have to take on a particular interpretation.[10]

For example, one interpretation of quantum randomness says that the quantum does not have actual properties until measured. This is taking non-thingness to the extreme, to say that definite properties only exist in certain moments, like measurements, and not in the moments in between. In this interpretation, randomness is truly fundamental, and no story or set of reasons can explain why quanta manifest as they do in any individual case.

Another interpretation is to say that the quantum does have properties between measurements but to know them would require knowing everything about the entire universe. In this interpretation, there is a story that explains why the quantum ends up manifesting in a particular way, but that story potentially involves what is happening billions of light-years away. Does that make it unknowable in principle? We could debate what we mean by “in principle” and land on different sides of the argument, but it certainly involves a different scale of unknowability than the practical unknowability of the outcome of a coin flip.

And yet a third direction of interpretation says that the quantum does have properties between measurements but to fully know and characterize them we would need to have access to many worlds in which every possible outcome is equally real. (And, of course, there are yet other interpretations that say other things).

Again, we all agree that quantum (microscopic) randomness isn’t the same as macroscopic randomness, because that’s what experiments show us. But when we shift to trying to explain what that means, every rigorously supported option has dramatic consequences in terms of how we think about physical reality and knowability.

With all that said, this is another place we need to caution against over-reading the implications. The fact that randomness is a seemingly incontrovertible aspect of fundamental reality does not mean we live in an “anything goes” universe, or that highly precise predictions are impossible. Quantum randomness is built into the equations of quantum theory. While those equations can only make statistical predictions, the statistical predictions are of very high quality. We have to know where electrons will go, to high accuracy, when we design technologies like computer memory. We have a great deal of knowledge about what quanta will do in most situations that quantum physics addresses, it is just knowledge that pertains statistically to the behavior of many quanta as an ensemble rather than exactly predicting the behavior of each single quantum.

## 4.4 Entanglement

The final quantum oddity that we want to highlight is *entanglement*. Entanglement is a term for a way that quanta can have fixed and definite relationships to one another while still individually showcasing the same deep quantum randomness. In

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[10] The interpretation options described in this section are loosely related to the interpretation options presented previously, but different interpretations can take a mix of stances on different aspects of quantum behavior, like randomness. There is such a large set of possible interpretations of quantum physics that we have decided not to attempt to enumerate or name any particular subset, but just to attempt to illustrate some of the differences as they apply to an individual concept like randomness.

a sense, certain relationships themselves become more definable than the things doing the relating.

To set up an illustration of this concept, first imagine you have two coins and you give one to a friend who then leaves town. You agree that at a certain time of day, you are both going to do a little coin-flipping experiment and record your results. At the appointed time, you toss your coin fifty times, and they toss their coin fifty times. Both sets of coin flip results are random. If you call your friend afterwards and compare results, there should be no correlation between what you measured and what they measured.

However, if the coins behaved like quanta and experienced entanglement, there could be a correlation. That is, there could be a relationship between individual coin flip events that were happening at a great distance from one another. With "quantum coins" you could find that both of you experienced random results with no pattern of heads or tails, but every time you obtained heads, your friend obtained tails, and vice versa.[11] That is, the coins seemed to have some kind of magic connection, because there is no plausible way for the two ordinary coins to physically influence each other across large distances.

So, obviously, this kind of odd random-but-connected behavior does not actually happen for coins. It does happen for quanta. It's not magic; it is a feature fully described in the mathematical theory used by physicists, but it is certainly dramatically different from the way that macroscopic reality works. What we see is that relationships among quanta can be preserved by nature despite the individual quanta behaving randomly. Moreover, these relationships are maintained even when the quanta are separated enough that no physical signal (that is, one traveling at the speed of light or slower) could possibly reach from one to another in time to explain how they "know" about each other. Importantly, entanglement *cannot* be used to instantaneously communicate information from one place to another, because that would require a *causal* connection between the two quanta. Entanglement is a *correlation* and not a causal link of the kind that is necessary if you want to send a signal from one place to another. Nevertheless, it is deeply, deeply weird.

Not only is it weird, it's well proven. The deep oddness of entanglement is showcased by physics experiments that prove that distantly-separated quanta behaving randomly still show, when we compare results after the fact, that their properties were linked.[12]

Entanglement is something that happens constantly in nature, but the long-distance correlations that are studied in experiments (and to which the imaginary "quantum coin" analogy refers) only seem to be possible in exceptionally well-controlled environments. Interactions with other quanta disrupt entanglement relationships, even as they create new entanglement relationships on a more local scale. For this reason, entanglement does not offer a plausible mechanism for long-distance interactions among complex real systems like, say, human brains (or anything within

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[11] Entangled quanta need not always give such clearly linked measurement results, but they always exhibit some form of correlation or relationship in the measurement results. For example, it could be that the properties of the coins were linked less perfectly, so that 80% of the times in which you obtained heads your friend obtained heads too. This would still be different from what we expect in the macroscopic world, in which there is no way for ordinary coins in ordinary coin-tosses to have such a relationship.

[12] For a non-technical explanation of the idea behind these experiments see *The mystery of quantum cakes*, P. Kwiat and L. Hardy, American Journal of Physics, 68, 33 (2000).

human brains). Any electron or photon in your brain is constantly interacting with the rest of the matter in your brain, and thus cannot maintain an entangled state with other quanta in the outside world. Any time we are discussing complex structures of quanta (like complex chemical structures, or biological structures), long-distance entanglement effects are suppressed to the point of being irrelevant, simply because of constant interactions between quanta and their neighbors.

# 5 Quantum to Macroscopic

The previous section established that the microscopic universe behaves in fundamentally different ways than the macroscopic universe. The macroscopic, everyday physical realm is the realm of *things* with definite properties and definite trajectories through space. Randomness occurs, but outcomes are still linked to a sequence of specific causes. Physical relationships between physical objects are deeply tied to the physical objects themselves (we can't talk about the force exerted by the lamp on the table without there being a lamp and a table). In abstract thought, we have concepts like money or love that may violate these precepts, but physical things do not.

On the microscopic scale, quanta play by different rules. Even though they are physically real entities, they defy description as *things*. They show a different logic underlying their random behavior, and they demonstrate entanglement.

How does one set of rules and behaviors transition into the other? That is, how do the behaviors of quantum non-things build up to create the behaviors of macroscopic things?

Nobody knows how this works.

One possibility that physicists have considered is that it is a matter of the sheer size of the system. This would mean that there is a physical mechanism that acts on systems above a certain mass, inhibiting quantum weirdness, making it act like a macroscopic thing. Quite a few experiments are being carried out today that look for a potential size scale beyond which quantum features are suppressed due to gravity. No clear macroscopic to quantum boundary yet has been found, and many physicists believe there is no such boundary.

We do know that the more a quantum system interacts with its environment, the more thing-like it tends to become, because little particles in the air, or electromagnetic fluctuations in the environment, for example, can cause quanta to lose their non-thinginess extremely quickly. That is why most quantum phenomena only manifest in very strict laboratory conditions. The quanta must be isolated from the air in vacuum chambers and all interactions with the quanta must be delicately controlled.

In any case, we can never directly access the quantum world. We can only know its effects on macroscopic measurement apparatuses. In a sense, we only access a translation of the micro-scale into the framework of macro things familiar to human experience. The quantum-to-macroscopic boundary is therefore a kind of "language boundary." Just as with translations from one human language to another, there will always be some information that is lost in the process. Since we cannot shrink ourselves down to the quantum scale, we may face fundamental limitations in understanding what the universe is like on the other side of the micro/macro divide.

Not only do we not know exactly how the quantum world actually works, but we don't know how the multiplicity of random quantum possibilities end up translating to a single measured outcome, which is what we actually see. How exactly does the measurement process affect the behavior of a quantum? Why and how do the interactions with the environment or with a measurement apparatus make a quantum go from a non-thing to a thing? Does this happen instantaneously? Is this "transition" from non-thing to thing more like an illusion, or does it correspond to a distinct change in the rules of physics?[13]

As you can see, there are many open questions about how the rules change from micro to macro. *That* they change is, however, a simple empirical fact. And it is an important point to remember when talking about how quantum physics might relate to the human realm. Even the tiniest dust grain you can imagine has enough quanta within it, and is in such a constant state of interaction with its environment, that it loses quantum behavior. That tiniest bit of dust is a *thing* with a definite place and definite physical properties. Even if atoms within the grain of dust may, at individual moments, experience entanglement phenomena with each other or with their environment, the dust grain as a whole is not meaningfully entangled with anything else. If it drifts randomly in the wind, that random behavior is of the macroscopic variety, amenable to a narrative description in terms of cause and effect. The equations a physicist would use to describe the grain of dust are simple, classical equations.

This is an important point to make because most of the things we care about in our everyday lives as humans are much larger than a grain of dust, and thus are even farther away from the quantum scale. People, notably. As far as physics is concerned, people are distinctly macroscopic entities, displaying none of the behaviors that quanta display, even if the quanta within our own bodies are busily doing their own thing in their full strangeness. The details end up being irrelevant on our scale: even if there is technically some entanglement that occurs between the outermost electrons of atoms in the layer of dead skin when my hand touches yours, this has no measurable or perceivable consequences of any kind for either of us. It is a curiosity of the natural world that it occurs, but it is not directly important for understanding how you and I interact.

# 6 So what?

Alright, quantum physics is strange. But so what? What, if anything, does this have to do with everyday life, and the problems and questions that we face as humans? There are a few ways you might answer this.

First, you could say "nothing." You can get by, and most people do, without ever explicitly paying attention to quantum physics at any time in your life.

Second, you could say "well, it is of practical importance to technology," because it is. Whether you care or not, you use devices all the time that employ quantum

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[13] In the many worlds interpretation of quantum mechanics everything behaves with quantum weirdness, even us. When we observe a quantum (via some measurement apparatus) we actually become entangled with the measurement apparatus and with the quantum. The different branches of the universe different versions of us will see different measurement results. This is an example of an interpretation in which our experience of a different set of rules for the macroscopic realm is more like an illusion.

physics. So the fact that quantum theory was developed and that it continues to be explored today has clear links to practical applications with economic value.

Third, like scholar Karen Barad, you could say "everything," because it tells us that the universe does not respect the basic preconceptions about reality that we develop as inhabitants of the macroscopic realm. Thus, perhaps our entire philosophical worldview, and even our vocabulary (which is normally quite bound in a thing-based ontology) should completely shift. If, on a fundamental level, relationships are more definable than the things doing the relating, should that challenge how we view the concept of a relationship on any scale? If, on a fundamental level, the properties of entities are indeterminate until interactions occur, should we give up any formal distinctions between subject and object in every context? These are the kinds of philosophical leaps you might take if you commit to a certain interpretation of quantum physics and take quantum ontology as the final word.

Fourth, you could say, "even if quantum physics is not directly relevant to daily life, challenging one's worldview is generally valuable and quantum physics does do that." We do not go as far as Karen Barad does. We are not comfortable committing to a particular interpretation of quantum physics, for one thing. Furthermore, the fact that the universe behaves in strange ways on a micro scale does not, to us, *imply* anything in particular about the way that things actually function on other scales.

But we believe that quantum physics *can* provide productive challenges to a person's worldview in ways that fall far short of a sweeping overhaul of ontology, epistemology, and ethics. Many applications of quantum ideas to macro-scale phenomena function best when considered as metaphors. They are rich metaphors. Opening up to thinking about non-thingness, indeterminate identity, blurry subject-object boundaries, and the dissolution of narrative may all be constructive things to do in our contemporary social and political moment, even if that context has little to do with the actual physics. It might give us some new inspiration, and new points of view, for thinking differently.

We also think that to grasp quantum physics unavoidably means *unlearning* ideas about how the world itself works that are grounded in macroscopic experience. Because there is no single clear ontology implied by quantum physics, nature does not give us any solid or satisfying replacements for the naive ideas we are forced to give up. To us, this is humbling, in a way that offers a counterbalance to some of the posturing we observe from scientists. Too often scientists and science communicators adopt the role of an authority full of answers, leading them, in the quantum physics case, to sweep problems of interpretation under the rug. In our view the unsettled interpretation of quantum physics – our persistent stuckness, as physicists – is one of the most important things about it. Even though quantum physics has unquestionably expanded our knowledge of the world, it also forces us to consider that some knowledge may be impossible. Moreover, here we stand a full century after the development of quantum physics, and yet we are arguably no closer to resolving basic questions about *what is* in this universe we inhabit.

As a final note, we recently described this essay and the notion of "obliterating thingness" to School of the Art Institute of Chicago grad student Joshi Radin. In response, she immediately quipped "obliterating thingness sounds like an experience you can get on drugs. Why do you need quantum physics?"

It was a good point, so we just want to reiterate: non-thingness in quantum physics is not about "everything affects everything else" or a breakdown of physical barriers in the world. It is not something that, for us, translates to the head-space of feeling oneness with the universe or peace or comfort. That's quantum "woo" talking, not quantum physics. The way that quantum physics obliterates thingness is in the way that it undermines our ability to use language, and the thought structures associated with it (like narrative), to label and describe what we observe in nature when we test its behavior on small scales. It has more to do with a breakdown of our ability to represent reality in ways that feel like they make intuitive sense, leaving us with equations and recipes but no clear understanding of what they actually mean.

To us, there is a different feeling that comes along with contemplating quantum physics, and it is nothing like a sense of peace or wholeness or connectedness. It is a feeling of deep humility, often tinged with frustration. It does not matter how many years you spend as an expert in quantum physics, how much confidence you have in the project of science, or how hard you try to make quantum physics make sense. You will often still find yourself wanting to scream "what the fuck, universe?" while staring at even the most basic experimental results. Quantum reality deeply undermines the sense-making processes we are used to being able to perform as humans. A hundred years of effort has yet shown no way out of the fog. It is possible that the fog is permanent. And that is deeply, deeply humbling, to us, even as we still experience wonder in the power of scientific inquiry. That deep humility is something we do hope to share more broadly. It is a form of cultural processing that we personally value and hope to add to the rich interdisciplinary conversations underway about what all of this means.

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# 8 Further Reading

Our intent is for this essay to complement other available readings out there that introduce quantum physics in non-technical language. Thus, we have deliberately avoided going through many of the pedagogical examples (the well-known "double slit experiment" for example) that often anchor those introductions. We have also deliberately avoided some of the common vocabulary - like wave-particle duality - because we want to highlight that such vocabulary choices are linked to specific quantum interpretations. Keep these points in mind to make the best use of this essay in conjunction with some of the readings below, or others that you find on your own. Also look through the footnotes for some additional references.

1. Raymer, Michael. "Quantum Physics: What Everyone Needs to Know", Oxford University Press (2017).

   All the basic elements of quantum physics, including some potential applications, explained to non-scientists in a precise, yet simple and pedagogical text. This is a great first encounter with quantum phenomenology.

2. Albert, David Z. "Quantum mechanics and experience”, Harvard University Press (1992).

   A slightly technical exposition of the many interpretations of quantum mechanics and their limitations. This book is not meant as a first encounter with quantum physics. It is a good book for those who have already a basic understanding of quantum phenomena, and want to dig into their different philosophical interpretations.

3. Whitaker, A. "Einstein, Bohr and the Quantum Dilemma", Cambridge University Press (1996).

   A very detailed account of the development of quantum theory, focusing on its history and its philosophy.

4. Barad, K. "Meeting the universe halfway: Quantum Physics and the Entanglement of Matter and Meaning" , Duke University Press Books (2007).

   An intriguing non-technical book in which quantum phyics is connected to science studies, feminist, poststructuralist, and other critical social theories.