**Six Things Everyone Should Know About Quantum Physics**

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Quantum physics is usually just intimidating from the get-go. It's kind of weird and can seem counter-intuitive, even for the physicists who deal with it every day. But it's not incomprehensible. If you're reading something about quantum physics, there are really six key concepts about it that you should keep in mind. Do that, and you'll find quantum physics a lot easier to understand.

**Everything Is Made Of Waves; Also, Particles**

There's lots of places to start this sort of discussion, and this is as good as any: everything in the universe has both particle and wave nature, at the same time. There's a line in Greg Bear's fantasy duology ([The Infinity Concerto](http://www.amazon.com/Infinity-Concerto-Songs-Earth-Power-ebook/dp/B00J52FMDE/) and [The Serpent Mage](http://www.amazon.com/Serpent-Mage-Songs-Earth-Power-ebook/dp/B00J48FER8/)), where a character describing the basics of magic says "All is waves, with nothing waving, over no distance at all." I've always really liked that as a poetic description of quantum physics-- deep down, everything in the universe has wave nature.

Of course, everything in the universe also has particle nature. This seems completely crazy, but is an experimental fact, worked out by a surprisingly familiar process:

Of course, describing real objects as both particles and waves is necessarily somewhat imprecise. Properly speaking, the objects described by quantum physics are neither particles nor waves, but a third category that shares some properties of waves (a characteristic frequency and wavelength, some spread over space) and some properties of particles (they're generally countable and can be localized to some degree). This leads to some lively debate within the physics education community about whether it's really appropriate to talk about light as a particle in intro physics courses; not because there's any controversy about whether light has some particle nature, but because calling photons "particles" rather than "excitations of a quantum field" might lead to some student misconceptions. I tend not to agree with this, because many of the same concerns could be raised about calling electrons "particles," but it makes for a reliable source of blog conversations.

This "door number three" nature of quantum objects is reflected in the sometimes confusing language physicists use to talk about quantum phenomena. The Higgs boson was discovered at the Large Hadron Collider as a particle, but you will also hear physicists talk about the "Higgs field" as a delocalized thing filling all of space. This happens because in some circumstances, such as collider experiments, it's more convenient to discuss excitations of the Higgs field in a way that emphasizes the particle-like characteristics, while in other circumstances, like general discussion of why certain particles have mass, it's more convenient to discuss the physics in terms of interactions with a universe-filling quantum field. It's just different language describing the same mathematical object.

**Quantum Physics Is Discrete**

t's right there in the name-- the word "quantum" comes from the Latin for "how much" and reflects the fact that quantum models always involve something coming in discrete amounts. The energy contained in a quantum field comes in integer multiples of some fundamental energy. For light, this is associated with the frequency and wavelength of the light-- high-frequency, short-wavelength light has a large characteristic energy, which low-frequency, long-wavelength light has a small characteristic energy.

In both cases, though, the total energy contained in a particular light field is an integer multiple of that energy-- 1, 2, 14, 137 times-- never a weird fraction like one-and-a-half, π, or the square root of two. This property is also seen in the discrete energy levels of atoms, and the energy bands of solids-- certain values of energy are allowed, others are not. Atomic clocks work because of the discreteness of quantum physics, using the frequency of light associated with a transition between two allowed states in cesium to keep time at a level requiring the [much-discussed "leap second"](http://www.slate.com/articles/health_and_science/science/2015/06/next_leap_second_june_30_dangers_to_software_military_gps_banking_air_traffic.html)added last week.

Ultra-precise spectroscopy can also be used to look for things like [dark matter](http://physics.aps.org/synopsis-for/10.1103/PhysRevLett.115.011802), and is part of the motivation for a [low-energy fundamental physics institute](http://www.forbes.com/sites/chadorzel/2015/06/30/should-we-have-an-institute-for-low-energy-fundamental-physics/).

This isn't always obvious-- even some things that are fundamentally quantum, like [black-body radiation](http://www.forbes.com/sites/chadorzel/2015/05/21/the-surprisingly-complicated-physics-of-a-light-bulb/), appear to involve continuous distributions. But there's always a kind of granularity to the underlying reality if you dig into the mathematics, and that's a large part of what leads to the weirdness of the theory.

**Quantum Physics Is Probabilistic**

One of the most surprising and (historically, at least) controversial aspects of quantum physics is that it's impossible to predict with certainty the outcome of a single experiment on a quantum system. When physicists predict the outcome of some experiment, the prediction always takes the form of a probability for finding each of the particular possible outcomes, and comparisons between theory and experiment always involve inferring probability distributions from many repeated experiments.

The mathematical description of a quantum system typically takes the form of a "wavefunction," generally represented in equations by the Greek letter psi: Ψ. There's a lot of debate about what, exactly, this wavefunction represents, breaking down into two main camps: those who think of the wavefunction as a real physical thing (the jargon term for these is "ontic" theories, leading some witty person to dub their proponents "psi-ontologists") and those who think of the wavefunction as merely an expression of our knowledge (or lack thereof) regarding the underlying state of a particular quantum object ("epistemic" theories).

In either class of foundational model, the probability of finding an outcome is not given directly by the wavefunction, but by the square of the wavefunction (loosely speaking, anyway; the wavefunction is a complex mathematical object (meaning it involves imaginary numbers like the square root of negative one), and the operation to get probability is slightly more involved, but "square of the wavefunction" is enough to get the basic idea). This is known as the "Born Rule" after German physicist Max Born who first suggested this (in a footnote to a paper in 1926), and strikes some people as an ugly ad hocaddition. There's an active effort in some parts of the quantum foundations community to find a way to derive the Born rule from a more fundamental principle; to date, none of these have been fully successful, but it generates a lot of interesting science.

This is also the aspect of the theory that leads to things like particles being in multiple states at the same time. All we can predict is probability, and prior to a measurement that determines a particular outcome, the system being measured is in an indeterminate state that mathematically maps to a superposition of all possibilities with different probabilities. Whether you consider this as the system really being in all of the states at once, or just being in one unknown state depends largely on your feelings about ontic versus epistemic models, though these are both subject to constraints from the next item on the list:

**Quantum Physics Is Non-Local**

The last great contribution Einstein made to physics was not widely recognized as such, mostly because he was wrong. In a 1935 paper with his younger colleagues Boris Podolsky and Nathan Rosen (the "EPR paper"), Einstein provided a clear mathematical statement of something that had been bothering him for some time, an idea that we now call "entanglement."

The EPR paper argued that quantum physics allowed the existence of systems where measurements made at widely separated locations could be correlated in ways that suggested the outcome of one was determined by the other. They argued that this meant the measurement outcomes must be determined in advance, by some common factor, because the alternative would require transmitting the result of one measurement to the location of the other at speeds faster than the speed of light. Thus, quantum mechanics must be incomplete, a mere approximation to some deeper theory (a "local hidden variable" theory, one where the results of a particular measurement do not depend on anything farther away from the measurement location than a signal could travel at the speed of light ("local"), but are determined by some factor common to both systems in an entangled pair (the "hidden variable")).

This was regarded as an odd footnote for about thirty years, as there seemed to be no way to test it, but in the mid-1960's the Irish physicist John Bell worked out the consequences of the EPR paper in greater detail. Bell showed that you can find circumstances in which quantum mechanics predicts correlations between distant measurements that are stronger than any possible theory of the type preferred by E, P, and R. This was tested experimentally in the mid-1970's by John Clauser, and a series of experiments by Alain Aspect in the early 1980's is widely considered to have definitively shown that these entangled systems cannot possibly be explained by any local hidden variable theory.

The most common approach to understanding this result is to say that quantum mechanics is non-local: that the results of measurements made at a particular location can depend on the properties of distant objects in a way that can't be explained using signals moving at the speed of light. This does not, however, permit the sending of information at speeds exceeding the speed of light, though there have been any number of attempts to find a way to use quantum non-locality to do that. Refuting these has turned out to be a surprisingly productive enterprise-- check out David Kaiser's [How the Hippies Saved Physics](http://www.hippiessavedphysics.com/) for more details. Quantum non-locality is also central to the problem of information in evaporating black holes, and the "firewall" controversy that has [generated a lot of recent activity](http://www.bbc.com/earth/story/20150525-a-black-hole-would-clone-you). There are even some radical ideas involving a mathematical connection between the entangled particles described in the EPR paper and [wormholes](https://www.quantamagazine.org/20150424-wormholes-entanglement-firewalls-er-epr/).

**Quantum Physics Is (Mostly) Very Small**

Quantum physics has a reputation of being weird because its predictions are dramatically unlike our everyday experience (at least, for humans-- the conceit of [my book](http://dogphysics.com/book_info.html) is that it doesn't seem so weird to dogs). This happens because the effects involved get smaller as objects get larger-- if you want to see unambiguously quantum behavior, you basically want to see particles behaving like waves, and the wavelength decreases as the momentum increases. The wavelength of a macroscopic object like a dog walking across the room is so ridiculously tiny that if you expanded everything so that a single atom in the room were the size of the entire Solar System, the dog's wavelength would be about the size of a single atom within that solar system.

This means that, for the most part, quantum phenomena are confined to the scale of atoms and fundamental particles, where the masses and velocities are small enough for the wavelengths to get big enough to observe directly. There's an active effort in a bunch of areas, though, to push the size of systems showing quantum effects up to larger sizes. I've blogged a bunch about [experiments by Markus Arndt's group](http://scienceblogs.com/principles/2013/11/12/interference-with-10000-particle-particles-matter-wave-interference-with-particles-selected-from-a-molecular-library-with-masses-exceeding-10000-amu/) showing wave-like behavior in larger and larger molecules, and there are a bunch of groups in "cavity opto-mechanics" trying to use light to slow the motion of chunks of silicon down to the point where the discrete quantum nature of the motion would become clear. There are even some suggestions that it might be possible to do this with suspended mirrors having masses of several grams, which would be amazingly cool.

**Quantum Physics Is Not Magic**

The previous point leads very naturally into this one: as weird as it may seem, quantum physics is most emphatically not magic. The things it predicts are strange by the standards of everyday physics, but they are rigorously constrained by well-understood mathematical rules and principles.

So, if somebody comes up to you with a "quantum" idea that seems too good to be true-- free energy, mystical healing powers, impossible space drives-- it almost certainly is. That doesn't mean we can't use quantum physics to do amazing things-- you can find some [really cool physics in mundane technology](http://www.forbes.com/sites/chadorzel/2015/04/15/how-your-morning-starts-with-quantum-physics/)-- but those things stay well within the boundaries of the laws of thermodynamics and just basic common sense.

So there you have it: the core essentials of quantum physics. I've probably left a few things out, or made some statements that are insufficiently precise to please everyone, but this ought to at least serve as a useful starting point for further discussion.