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What Quantum Mechanics *Doesn't* Show

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Abstract: Students often invoke quantum mechanics in class or papers to make philosophical points. This tendency has been encouraged by pop culture influences like the film *What the Bleep do We Know?* There is little merit to most of these putative implications. However, it is difficult for philosophy teachers unfamiliar with quantum mechanics to handle these supposed implications in a clear and careful way. This paper is a philosophy of science version of *MythBusters*. We offer a brief primer on the nature of quantum mechanics, enumerate nine of the most common implications associated with quantum mechanics, and finally clarify each implication with the facts. Our goal is to explain what quantum mechanics *doesn't* show.

Students often invoke quantum mechanics to make philosophical points. This tendency has been encouraged by pop culture influences like the film *What the Bleep do We Know?* However, despite the fact that there is little merit to these invocations, it can be difficult to respond in a clear and careful way. This paper is a guide to handling such occasions. We offer a brief primer on the nature of quantum mechanics, enumerate nine of the most common implications associated with quantum mechanics, and finally clarify each implication with the facts. Our goal is to explain what quantum mechanics *doesn't* show.

What Quantum Mechanics Says

At its core, quantum mechanics (QM) is a mathematical theory that specifies the probability of observing a certain outcome given an initial state of a physical system. From the initial description of the system, each distinct possible outcome is assigned a specific probability. Usually the physical systems described by QM are very small, composed of only a few particles at most, but in principle the theory applies to systems of any size and, in special circumstances, the tiny changes

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that occur on a micro level can be amplified up to the macro level, as when a Geiger counter signals the decay of a single radioactive atom by emitting an audible click. The accurate prediction of outcomes is pretty much the only uncontroversial part of the theory. In particular, *how* reality must be in order to yield those outcomes remains a matter of hot dispute, and many would say, a complete mystery. A description of the underlying reality leading to those outcomes is called an interpretation.[1]

What distinguishes QM from classical physics, from theories such as Newton's laws of motion and gravitation and Maxwell's theory of electromagnetism (light)? Why is it regarded as a revolutionary change in our view of the universe? As just noted, this depends in part on how the mathematical formalism is interpreted. But, in general, there are five differences that mark a profound shift from classical mechanics. These five differences are not the only ones that separate QM from classical theories, but they highlight the distinctive conception of physical reality inherent in QM. Most (but not all) interpretations of QM agree on these differences:

1. While classical theories are completely deterministic, in QM outcomes are not deterministic; that is, a process beginning with a specific initial condition can lead to many, perhaps an infinite number, of different resulting states.[2] The formula yielding a probability for each possible outcome is called the *wave function* of the system. To say that the wave 'collapses' is to say that the system goes from having the potential for a range of outcomes to a single measured result.

2. While classical theories provide full information about the state of a system, in QM all aspects of the state of a system cannot, even in principle, be fully specified *to an arbitrary degree of accuracy*.[3] For instance, one cannot say exactly what both the position and momentum of a particle is at a specific moment in time. This is not a matter of our failing to know the precise properties, but of those properties *not obtaining* simultaneously at that time (or at *any* time). This feature of QM is described by the Heisenberg uncertainty principle, which states that certain pairs of properties, such as the momentum and position of a particle or the energy of an event and its time of occurrence, cannot have precise values conjointly.

3. Even more radically, in certain circumstances many properties of quantum objects, such a particle's direction of spin, don't exist *at all* (not merely with limited

specificity, as with Heisenberg uncertainty) until they are observed or measured.[4] This doesn't hold for classical objects, which always have definite properties even when unobserved. Note: "observation" and "measurement" are typically used interchangeably in describing QM.

4. While classical theories allow for physical values to be continuous (i.e. an object can have any amount of mass, kinetic energy, angular momentum, etc. within its possible range), in QM values of physical properties are *quantized*, meaning that objects can only have such values in a series of discrete steps.[5] In QM—unlike classical mechanics—a physical system cannot exist in a state between two values separated by the minimal amount allowed by quantum physics (sometimes called the *Planck unit* for that parameter, e.g. length, time, energy, etc.). For instance, the elections around a nucleus must jump abruptly from one energy level to another rather than pass through a continuous series of gradual changes in moving from one level to the next.
5. While classical theories are *local*, allowing one event to affect another only through a continuous transmission of a signal (an energy transfer) from the first event through adjacent points until it reaches the second, in QM some events can affect the occurrence of other events at distant locations instantaneously. QM is said to be *non-local* in this sense.[6] This phenomenon occurs when two particles are *entangled* while being spatially separated by an arbitrarily large distance. If a measurement is made of a given property of one particle, the other particle immediately acquires a predictable value for its corresponding property, such as spin, which it *did not have* prior to the measurement made on its companion particle.

Finally, a concept that is frequently invoked in discussions of QM is that of a *superposition*, so it will be helpful to clarify this notion before proceeding. A system is said to be in a superposition when the description of that system (its wave function) assigns it a non-zero probability of being in one state and *at the same time* a non-zero probability of being in a different, incompatible state. The number of distinct states that the system could be in at a time is not limited to two, but is in principle indefinitely large.

We turn now to some of the proposed implications of QM, first presenting the evidence thought to support the suggested implication, then stating carefully what actually follows from the theory. In each case, either QM does not imply the result or it does so only under certain, usually minority, interpretations. And so in each case there is no reason to think that QM *must* have the implication under consideration.

Myth #1: QM Implies that Nature Can Have Contradictory Properties

It is sometimes claimed that QM shows that contradictory statements can both be true. The most famous evidence for this claim is probably the thought experiment known as Schrödinger's Cat, in which the fate of the imprisoned animal is dependent on the random decay of a radioactive atom.[7] If the atom decays, a poison is released in the box in which the cat is held, killing the cat; if it doesn't, the cat remains alive. Prior to opening the box to see which outcome has occurred, it is suggested, the cat is both dead and alive and only the actual observation of the cat forces the animal into a single definite state of life or death. And so, contradictions are sometimes true.

It is not just thought experiments that are cited in favor of this myth. Consider the wave-particle nature of quantum objects. The minimal massless units of electromagnetic radiation, photons, as well as tiny particles with mass, such as elections, protons, and neutrons, are said to be both particles and waves simultaneously. Wave-particle duality is substantiated by the famous *double-slit* experiments in which beams of these objects clearly behave as waves, exhibiting wavelike interference patterns in their intensities at different locations, and as particles when they are measured as existing fully and completely at a single point in space (e.g. at the slit through which they passed or on the screen behind the slits).[8] But wave-like properties are incompatible with particle-like properties: the object both is a wave and is not a wave. Hence, contradictory statements are sometimes both true at once.

The Facts

QM does not imply that nature can have contradictory properties. While this is one possible interpretation of QM, it is not a necessary consequence of the theory.

First, even in QM, nature is never literally observed to be in contradictory states at the same moment. No particle or system of particles is ever measured *at the same time* to have conflicting properties, since each measurement returns a single value for the parameter under investigation. In general, this is an inevitable consequence of measurement, since detecting the state of a system destroys its superposition, thereby "collapsing the wave function" and forcing it to take on a definite value for the measured quantity. It is true, however, that things can display *apparently* incompatible properties when observed in different ways (and at different moments in time), behaving like waves in one instance and like particles in another. But it is not contradictory to suppose that things behave differently at different times.

Second, we can specify the states of systems without contradiction if we are more precise in our description of them. First, we should simply deny that being in a *superposition* of A and B is equivalent to being *both* A and B simultaneously. For instance, in the case of Schrödinger's cat, we should deny that it is both dead and alive prior to observation. Second, we can consistently describe the state of a system in a superposition of A and B as being in a state such that <if it is observed/measured then it will return the result A with so and so probability and will return the result B with such and such probability>. There is no contradiction in that description of the cat, once again, since it avoids attributing inconsistent properties to the cat. Analogously, for wave-particles, we should say that the object is in a state such that <if it is measured in way X then it will appear to be a wave, and if it is measure in way Y, then it will appear to be a particle>. No contradiction here.

But hold on! Recent experiments lend support to the claim that a single system is literally in two incompatible states *at once*.[9] If a system is in a superposition of two states and the measurement doesn't interfere with that state, then it can remain in the superposition without collapsing into one or the other as a result of the observation. In that case, the two measurements returning inconsistent properties (e.g. wave or particle, dead or alive) pose a greater mystery. It is a delicate matter to carry out such a measurement, but researchers claim that it can be done. In one of the most striking examples, a metal paddle composed of roughly a trillion atoms and just barely visible to the naked eye has been put into a state of vibrating and remaining at rest at the same time!

However, we can resolve these cases, too, without admitting contradictions, by a more careful specification of the state as suggested above. For the vibrating/non-vibrating paddle, we should specify its state as <if measured in a way that does not destroy the superposition, 50 percent of the measurements will yield *vibrating*, while 50 percent will yield *non-vibrating*>. Note that these measurements are made at different times. However puzzling this state might be—and no one could legitimately claim to understand the underlying reality of such a system—this description is not equivalent to both vibrating and not vibrating at the same time.

Myth #2: QM Implies that the Law of Excluded Middle is False

The law of the excluded middle (LEM) says that every meaningful proposition is either true or not true; there is no third "middle" option. In metaphysical terms, this implies that for any property and any object, that object either has that property or it doesn't.

Some suggest that QM requires the falsity of this principle. Consider again Schrödinger's cat. Instead of saying that Schrödinger's cat is *both* alive and dead, we might say that the cat is *neither* alive nor dead (until the cat is observed, of course). If being alive is equivalent to not-being-dead, then according to LEM the cat must be either alive or dead. A second example is that of particle position. It is sometimes said that prior to measurement, a particle is neither at a particular position nor not at it, and that only upon measurement does the particle take on a definite location. It turns out that many properties of quantum objects have this elusive quality, including the momentum and spin of particles, the polarization angle of light and others.

The Facts

QM does not imply that LEM is false. This is neither an implication of the formalism of QM nor of the dozen or so standard interpretations of QM.

Suppose we grant that it is true that the cat is neither dead nor alive and that particles often are neither here nor there. This doesn't imply the falsity of LEM since these turn out not to be exhaustive possibilities for the cat or the particle—they are not contradictories between which there is no middle. Being in a *superposition* of being alive or dead is a third possibility, and isn't equivalent to either being alive or being dead. The law of excluded middle continues to hold: either the cat is in that superposition or it isn't; either the cat is alive or it isn't; either the cat is dead or it isn't. If the cat is in a superposition, then we can conclude that it isn't alive and that it isn't dead.

We can express this somewhat formally as follows. LEM says that for all meaningful propositions, either the proposition or its negation is true. Let A = the cat is alive. One might have supposed that the negation of this claim is that the cat is dead. QM shows that this isn't so. There are *two* ways for the cat to be not-alive: the cat can be dead or the cat can be in a superposition of being neither alive nor dead. Hence, if the cat is in a superposition, then it is true that the cat is not alive. And since either A or ~A remains true, LEM holds even in the quantum case.

Myth #3: QM Implies that We Control All of Reality by Our Choices

Due to the connection between choice of observation and resulting reality posited by QM, it is sometimes suggested that human choices ultimately control all of reality. The double-slit experiment is putative evidence of this. When a sequence of particles is directed toward a barrier with two openings in it, we can either measure which opening each particle goes through, or we can simply measure the intensity—the number of particle hits—on a screen behind the slits (without determining which slit each particle passed through). If we measure the former, each particle exhibits particle-like behavior, passing through one slit or the other and never both. If we measure the latter, we find wavelike behavior, as if the particle passed through *both* slits in wavelike fashion, creating a pattern of alternating intensities on the screen behind the slits. It appears that our choice of measurement compels a change in the natural world.

The Facts

It is a myth that QM entails that observers have complete control over outcomes. It does not. On even the most mind-friendly interpretations of QM, there is no robust control of mind over matter.

First, there's a trivial sense in which its true that our choices affect reality (that's why our choices in life matter!). In QM, anytime we probe a system to determine one of its properties, that causal interference with the system will affect it, changing its further development in some way. This is just as true of classical systems as it is of quantum systems. If you touch an object to determine where it is, you will have changed the state of that object; if you shine a light on it to determine its position, that too will change its state. Making a measurement to detect a quantum state similarly involves interfering with that state. For instance, detecting which slit a particle went through interferes with it and hence affects its behavior in striking the screen behind the slits. So the fact that observations can change reality is no surprise in itself. That's equally a classical phenomenon.

Second, in fairness, there's something different about the way observations of quantum systems can change their evolution through time. In the classical case, the observation affects the outcome but doesn't radically change the *kind* of physical system involved. In the quantum case, the observation can change the fundamental nature of the entities detected, for instance, from being wavelike things to being particle-like things. That's a genuinely puzzling divergence from a classical understanding of the physical world. Hence, there is *something* to the claim that we control quantum reality—or, more precisely, that measurements do.

Nonetheless, our control of how nature manifests itself is extremely limited. Although it is true that our choice of experimental set-up sometimes determines the *kind* of outcome produced (e.g. whether wavelike or particle-like), that gives us no control whatsoever over the specific outcome of each particular event. We cannot make a particle pass through one of the slits rather than the other, nor can we compel a particle to land at any particular location on the screen. Those results are governed purely statistically by the equations of QM. The pattern is predictable, but individual events are not. So this is not the kind of control that easily translates into interesting philosophical assertions of mind over matter.

Myth #4: QM Implies that Consciousness Creates Reality Itself

Consciousness is the foundation of reality! According to this view, it is only when a conscious observer detects the state of a system that its constituents emerge from a superposition to acquire definite properties, such as position, momentum, and specific causal effects. And so, without minds, there would be no universe in which definite events occur. This myth suggests that Berkeley's idealism was not far from the truth!

The Facts

This is neither an implication of the formalism of QM nor of the dozen or so standard interpretations of QM. These standard interpretations do not require that a conscious being be *aware* of a measurement for that measurement to have taken place; so long as a physical record is preserved—for instance, in a computer—that *could* causally affect some other system (including a conscious being), that event counts as a measurement. Since it is measurements that collapse the wave function, forcing reality to take on a definite state, reality does not need minds in order to have the specific properties that it does.

However, there is one minority view on which this myth is a reality. This interpretation is sometimes called the "consciousness causes collapse interpretation."[10] It is probably least popular among physicists, though it is the one rather disingenuously presented as fact in the film *What the Bleep Do We Know?* In its defense, however, one might point out that it cannot be disproven any more than Berkeley's idealism can.

Myth #5: QM Implies that We Have Free Will

The quantum mechanical description of reality does not ascribe a unique outcome to each initial configuration of a physical system. Rather, an array of many different outcomes is possible, each of them assigned a precise probability of occurring. Hence, nature is indeterministic. One might conclude from this that human choices are therefore not determined by the prior states of our brains or bodies and hence that we have free will.

The Facts

QM does not imply that we have free will.

First, free will requires more than indeterminism at the quantum level. Free human actions are macro-events. And so even if QM posits an indeterminacy at the micro-level, there is no guarantee that this sort of indeterminacy can "trickle up" into the macro level. Given that human actions and choices take place at an immensely complex level of physical organization involving billions of interactions at the micro-level, perhaps whatever indeterminacy exists at the micro-level is washed-out by the time events reach the level of human consciousness. To put this another way, it is controversial at best whether that there is a sort of "butterfly effect" in which small changes at the quantum level "bubble up" into changes at the macro level as some philosophers of free will have surmised.[11]

Second, free will requires more than indeterminism at the macro-level. Free will has other legitimate requirements like control, connection to mental states, intentionality, etc. In other words, while indeterminism is necessary for free will (at least according to incompatibilism), it is not sufficient for free will. At best, the failure of determinism allows the *possibility* of freedom, a possibility that would be excluded on some theories of freedom (e.g. libertarianism) by a strictly deterministic universe.

Myth #6: QM Implies that the World is Governed Solely by Chance

Because QM requires indeterminism in the outcomes of certain events, some people have concluded that nature is governed entirely by chance. Nothing is fixed from one moment to the next; anything can happen.

The Facts

QM does not imply that the world is governed solely by chance.

First, although the evolution of events is in some respects probabilistic, in others it is stubbornly fixed. Certain properties of particles are unchanging: electrons retain the same charge and rest mass, the rest mass of photons remains zero, neutrinos do not interact with the electromagnetic force, quarks always respond to the strong force, etc. In addition there are many conservation laws that constrain what can happen in particle interactions, including the familiar laws of conservation of energy and momentum, but also less familiar laws such as conservation of baryon number, electric charge, spin, etc. And finally there are such constancies as the speed of light and the law of gravitation.

Nonetheless, all events *permitted* by the laws of QM have some chance of occurring, no matter how unexpected or bizarre they might be. The wave function for a system assigns a non-zero probability to each physically possible outcome of that initial state. You might pop out of existence in the next moment, or more optimistically, your perfect date might materialize on Friday night, but the chances of such a thing happening are not worth bothering to calculate. So the myth is false: not all aspects of the world are governed by chance even though some may be.

Myth #7: QM Implies that There is a Multiverse

QM is said to imply that our universe is just one among a vast multitude of universes. Many different conceptions of a multiverse are on offer by contemporary cosmologists. Here are four multiverse possibilities:[12]

A. An exact duplicate of our own cosmic neighborhood exists at some vast distance from us in *this* universe. You have many doppelgangers in this universe.

B. Our universe has more spatial dimensions than we perceive. String theory hypothesizes a minimum of nine or ten spatial dimensions (in addition to that of time). Universes (so far) inaccessible to us exist in those other dimensions.

C. On the "Many Worlds" or Everett interpretation of QM, each time a measurement or interaction takes place, reality splits into parallel universes in which each possible outcome is concretely realized as a distinct universe. You have doppelgangers who are slightly different from you being created at every moment.

D. Universes spring into existence from "big bangs" occurring in an inflationary field that itself might well continue to expand to infinity, both temporally and spatially. New universes are born every moment at various locations in the expanding field due to quantum fluctuations in that field.

While none of these possibilities is confirmed, all have advocates. It is important to note that there remain at least an equal number of skeptics who reject all such theoretical posits.

The Facts

Neither the formalism of QM nor its standard interpretations entail the existence of such exotic universes. In fact there is only one interpretation of QM, the many worlds interpretation, that implies a multiverse, and until there is good reason to favor such an interpretation over its rivals, QM by itself does not support the existence of such metaphysical excess. What's more, only some possibilities for multiverses explicitly invoke quantum physics, so in general, the question of whether QM is correct and whether there is some sort of multiverse are distinct questions.

Myth #8: QM Implies that Einstein's Theory of Relativity is Mistaken

The most common reason for thinking that QM entails the falsity of relativity is because the latter precludes the transmission of information at speeds faster than the speed of light. However, QM seems to imply the transmission of information at speeds faster than the speed of light, because it allows for "action at a distance."

According to QM, for certain physical systems composed of multiple parts at spatial distances from each other, observing one part of the system, and thus coming to know a specific value for one of its properties, results in another part of the system instantaneously coming to have a corresponding value. According to QM, those parts did not have the observed values prior to measurement; hence the observation of one seems to *cause* the second to take on its correlated value, apparently in violation of special relativity. Systems of particles exhibiting such instantaneous sensitivity to measurements of their parts are said to be *entangled*. Entanglement has been shown to exist between particles at large distances from each other, up to many kilometers apart. Since the transmission of information is instantaneous, and instantaneous travel is faster than the speed of light, QM apparently entails that relativity is mistaken.

The Facts

QM does not imply the falsity of relativity, or at least, it does not imply the falsity of relativity on the grounds that there is instantaneous action at a distance.

This is because while entanglement is real, instantaneous *causal* transmission of a signal from one event to another is not. There is no transfer of energy between the distant events. It has been convincingly demonstrated that entanglement cannot be used to send a signal from one location to another. Although it is true that certain properties of distant entangled particles are perfectly correlated just as QM predicts, locally they appear to be completely random, so there is no information encoded in them that one could read as a message from the other location without receiving additional information from that other location in the classical way at or below the speed of light. Hence, since there is no information transmitted over a distance faster than the speed of light, QM is compatible with special relativity in this regard.[13]

Myth #9: QM Implies that the Principle of Sufficient Reason is False

The principle of sufficient reason (PSR) says that there is an explanation, a reason, for every true proposition. But if QM is right, then the occurrence of certain events—those that arise by chance—have no explanation. For instance, no amount of observation or knowledge of the current state of the system will reveal the exact moment at which a radioactive atom will decay. Hence QM implies that the PSR is false.

The Facts

Of all of the myths cited in this paper, this one may be a reality. Whether it is so depends on the correct interpretation of both QM and PSR.

Regarding the first, one defense of the PSR from the threat of QM is to adopt the interpretation of David Bohm.[14] On this view, there are "hidden variables" that explain seemingly random events within QM, supplying causes for all events. The world turns out to be fully deterministic on this picture, and our inability to predict quantum events is due to our ignorance of these hidden variables rather than any genuine indeterminism. And so QM is no threat to PSR.

However, the Bohmian interpretation of QM is an unpopular view and most scientists concede that the best interpretation of QM is one that posits genuine indeterminacy in the world. So there is a good case to be made that QM falsifies the PSR. However, whether this case is convincing depends on the scope of PSR.

What counts as an explanation for the truth of a proposition? There are many options here, and at least some are compatible with contingent explanation. For example, suppose (along with David Hume) that giving the cause of an event is sufficient for explaining the event. In that case, QM need not imply that PSR is false, since probabilistic causation may still count as causation, and so every QM event will have a cause and therefore an explanation. So if the PSR allows that events that occur with only a statistical probability are explained by citing that probability, then QM is consistent with the PSR.

That said, it must be granted that QM poses a serious challenge to the PSR and that defending PSR requires adopting minority views of QM or explanation or both.

In sum, QM is a fascinating theory, but its philosophical implications are often overblown. At best, QM "makes room" for interesting philosophical positions that require further argumentation to establish.

Notes

The authors would like to thank Sarah Roberts-Cady, Henry Tregillus, and two anonymous reviewers for *Teaching Philosophy* for extremely detailed and helpful feedback on earlier drafts of this paper.

1. We don't describe the various interpretations of quantum mechanics in this paper. For an overview of ten of them, see Rosenblum and Kuttner, *Quantum Enigma*, chap. 15, "What's Going On? Interpreting the Quantum Enigma" (pp. 203–20), and several of the entries in the *Stanford Encyclopedia of Philosophy* under "Quantum Mechanics."

2. Rosenblum and Kuttner, *Quantum Enigma*, pp. 128–9; Albert, *Quantum Mechanics and Experience*, p. 35.

3. Albert, *Quantum Mechanics and Experience*, p. 15.

4. Rosenblum and Kuttner, *Quantum Enigma*, pp. 166, 185.

5. Ibid., chap. 5, "How the Quantum Was *Forced* on Physics" (pp. 55–72).

6. Rosenblum and Kuttner, *Quantum Enigma*, p. 188; Albert, *Quantum Mechanics and Experience*, p. 70.

7. Rosenblum and Kuttner, *Quantum Enigma*, chap. 11, "Schrödinger's Controversial Cat" (pp. 143–153).

8. Rosenblum and Kuttner, *Quantum Enigma*, chap. 7, "The Two-Slit Experiment: The Observer Problem" (pp. 87–99); Albert, *Quantum Mechanics and Experience*, pp. 12–14.

9. Here is a recent example of large objects being in superposition: http://www.nature.com/news/2010/100317/full/news.2010.130.html.

10. Rosenblum and Kuttner, *Quantum Enigma*, 238–42, 249–50.

11. See, for example, chapter 11 in Robert Kane's *A Contemporary Introduction to Free Will* (Oxford University Press, 2005).

12. Multiverses are described in Carroll, *From Eternity to Here*, chap. 14, "Inflation and the Multiverse."

13. Albert, *Quantum Mechanics and Experience*, p. 72.

14. Rosenblum and Kuttner, *Quantum Enigma*, 213–15; Albert, chap. 7, "Bohm's Theory" (pp. 134–79).

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