Demystifying Quantum Mechanics

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Abstract

The narrative around the various mathematical and physical techniques broadly known as quantum mechanics has suffered due to the influence of social pressures. The incredible strengths of the theories and their predictive powers have become subject to a number of sensationalized story lines, which we refer to here as "quantum mysticism". In this paper we demonstrate a three-pronged counterattack which combats these forces. A precise use of terms coupled with an accurate and intuitive way to describe the behavior of discrete and microscopic phenomenon effectively demystifies quantum mechanics. We don't go into the mathematical details here to keep our discussion accessible to the layperson. After our demystification the discipline withholds its incredible predictive power without scaring away a rational thinker. In fact quantum mechanics is an entirely rational, intuitive, and accessible discipline. The world is full of mystery; however, a discipline devoted to quantifying and rationalizing behaviors of certain specific systems is hardly the place to go searching for mystery.

Introduction – Examples of Quantum Mysticism

The story for me began early in high school, when I read John Gribbin's "In Search of Schrödinger's Cat" [Gribbin, 1984]. At the time I had read another of Gribbin's nice overviews and wanted more. The overview of quantum mechanics was good, I would later confirm, but still troubled me. The book implied that there was something extremely strange about quantum mechanics, but the reader wasn't up to the level to understand what it was yet. He described the EPR experiment, thought experiments such as Schrödinger's cat and others, and the work of John Bell. These things lead up to Alan Aspect's experiment and are presented as evidence that, and I paraphrase: "things are weird":

> "In the world of the very small, where particle and wave aspects of reality are equally significant, things do not behave in any way that we can understand from our experience of the everyday world...all pictures are false, and there is no physical analogy we can make to understand what goes on inside atoms. Atoms behave like atoms, nothing else." - John Gribbin

Aren't there always analogies? This is, after all, what it means to have a theory which we can represent symbolically or communicate amongst ourselves. This kind of mystical narrative being tacked on to quantum mechanics did not begin with Gribbin. In fact, compared to some literature, he is a saint. Here are some examples of authors writing about the supposed weirdness of quantum mechanics:

> “The more we delve into quantum mechanics the stranger the world becomes; appreciating this strangeness of the world, whilst still operating in that which you now consider reality, will be the foundation for shifting the current trajectory of your life from ordinary to extraordinary. It is the Tao of mixing this cosmic weirdness with the practical and physical, which will allow you to move, moment by moment, through parallel worlds to achieve your dreams.” — Kevin Michel
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> “Quantum physics findings show that consciousness itself created order" -- Lynn McTaggert
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> “[T]he atoms or elementary particles themselves are not real; they form a world of potentialities or possibilities rather than one of things or facts.”
> — Werner Heisenberg
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> "Quantum mechanics was, and continues to be, revolutionary, primarily because it demands the introduction of radically new concepts to better describe the world" - Alain Aspect
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> "For those who are not shocked when they first come across quantum theory cannot possibly have understood it." - Niels Bohr
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> “If we attempt to attribute an objective meaning to the quantum state of a single system, curious paradoxes appear: quantum effects mimic not only instantaneous action-at-a-distance, but also, as seen here, influence of future actions on past events, even after these events have been irrevocably recorded.” – Asher Peres

As I encountered this kind of discussion, I assumed that I was not able to see these difficulties because I had not learned the material to the required advanced level. Perhaps I was not shocked only because I had not yet understood it well enough. At this point I had just begun to study differential equations, so I chalked it up to my inexperience and ignorance and vowed to try harder.

As I moved on into University level education, I took quantum mechanics courses at Yale in both the physics and the engineering departments. It was useful to get two different approaches. As quantum mechanics is usually taught to undergraduates in physics, it is essentially a course in applied differential equations. This is not a bad thing. Applying Schrödinger's equation for the wavefunctions of electrons to the central potential of an atom enables one to predict the emission lines (color of emitted light) of the photoelectric effect. This is arguably the biggest success of quantum mechanics. Techniques were applied in the engineering department to materials such as semiconductors as well as to considerations of a signals engineer, giving useful applications of the theory.

Later I continued my graduate education in physics and took further courses in quantum mechanics. Amongst many others I was privileged to attend lectures from Jochen Heisenburg, where I received my PhD in physics at the University of New Hampshire, and from Allain Aspect who gave a guest lecture at the University of Bern, where I was doing postdoctoral work building, testing, and interpreting results of particle detectors including those for a NASA mission. Finally after further studies during a two year stay in Oxford, England I decided to focus on a single aspect of the quantum mysticism which I felt was a low hanging fruit, and wrote "The Emperor Has No Nonlocality" [Saul, 2015].

Much of quantum mysticism appears affected by the psychology of the emperor's new clothes, in that people are told that if they understood the mathematics, they would see how strange and nonintuitive the theory is. The average person is thus tempted to pretend to see it, when in fact this mysticism is not really there. In fact the theory is a working and successful physics, sometimes described as the best tested theory of all time. There is currently no need today for the extra marketing effect of mysticism, which prevents understanding and hinders further advances.

We can put the majority of the arguments for quantum mysticism to rest with a three pronged attack. Our procedure is to affect the corpus of quantum mechanics with these minor adjustments:

1) Precise use of the word "photon";
2) Removal of the term or concept of "non-locality";
3) Dissolution of hard boundary between classical and quantum mechanics.

Each of these three steps might be only a cosmetic effect, depending on your previous exposure to the literature and the physics. Those familiar with applied quantum mechanics are not likely to find anything new here. All three do nothing to the predictive power and physical prowess of the theory. Instead they fit our requirement of a polishing job, trimming of excess material that has marred the more respectable parts and eliminating various roads down which new students or laymen might mistakenly tread.

Before we begin it is worthwhile to note that we are not attempting to promote a fully mechanical picture of the world, nor to claim that there are no mysteries. In fact, the world is full of mysteries on every scale. Our procedure will be a boon for the would-be mystic as well as for the would-be quantum mechanic, as it will enable them both to avoid searching in the wrong place for what they seek. Quantum mechanics as a discipline of physics resolves a small subset of the world's mysteries with a self-consistent model. While the tools of the a quantum mechanic can predict the behavior of an electron in a Hydrogen atom with amazing accuracy, they don't at present answer many questions such as why electrons have the mass they do, what is the seat of the electromagnetic field, why electrons come in three flavors, or where the Hydrogen was created, to list only a few examples. I should hardly need to point out that there are plenty of real mysteries out there.

1) Precise use of "Photon"

There are many ways that precise language has become important in modern physics. Relativity is perhaps the strongest example of this, in that previous notions such as "length" and "simultaneity" have become ambiguous and, in certain contexts, therefore unacceptable. It behooves the physicist to use terms with great precision, as even if a line of discussion is clear between colleagues in the laboratory, the layman or student might imagine another potential meaning to words when ambiguities are present. Such a reader will then be forced down a different interpretation which can lead to great confusion.

To be clear, it is not that physicists and authors have been incorrect in their use of the word "photon", but that they have been imprecise. Let's clean up the confusion.

Definition: *A photon is the quantized emission or absorption of electromagnetic radiation*

Note that a photon as thusly defined is an *event* rather than an entity. This might seem contradictory to some verbiage which describes for example emitted photons from excited neon gas then entering the eye. In this case the language is slightly imprecise, but there is no question what has occurred. The light emitted from the neon gas was emitted by electrons moving from one allowed energy state to another – a quantized emission process. These quantized emissions are photons – and the light produced by these events propagates through the intervening space and enters the eye.

This distinction clears up the so-called "wave particle duality" which is sometimes stated as a mysterious aspect to quantum mechanics. In fact it makes good intuitive sense. The wave nature of light is the propagation – the laws describing the evolution with time and space of an electromagnetic disturbance. The particle-like nature is that quantization of the emission or absorption – that nature requires the light to be emitted or absorbed in discrete amounts. There is nothing strange about this.

There are very good analogies to describe this situation. For example, a harpsichordist plays "notes" which are quantized emissions of sound. We aren't surprised that a single note can enter into more than one set of ears at once, and we are also not surprised that a single photon goes through two slits in a two-slit experiment. When sounds are emitted and absorbed discretely, sometimes the word "phonon" is used.

The discretization of light emission or absorption can be seen to appear mathematically, as eigenvalues of a differential equation which governs the behavior of the electron (e. the Schödinger equation). This is quite similar to the way that only certain harmonic notes emerge from a fixed-length string, as the differential equations that describe the motion there also have certain quantized states. The geometry, and the states, are quite different – but they both involve an element of discretization due to physical boundary conditions. Another example is water droplets falling from a spout. In a certain regime, physical processes determine that only discrete and specifically sized drops can fall. This is a quantization and what gave the theory its name as well as its predictive power.

Example: Radio wave photons

Many authors have made the imprecise statement “all light is made of photons.” An improvement to this would be to say that “all light is emitted and absorbed as photons.” However this still isn't precise, because not *all* light is created by this type of quantized emission. An instructive example is to consider the emission of light by alternating current in a radio station antenna emitting radio waves. Where is the photon here? We could assign the “broadcasting day” as the photon, an event beginning as the station powers up and begins to emit light, and ending as the station powers down and stops. This agrees with our definition to some degree as it is an emission event, however it is not quantized in the same way that the emissions of an electron moving from one energy level to another in an atom is quantized, nor in the same way that the pressure radiation from a harpsichord string plucked by a mechanism is quantized. The acceleration of valence electrons in a conductor is not quantized like the energy levels of bound electrons. There are many emission mechanisms for light (which is always and only that which occurs when a charge is accelerated), from bremsstrahlung to synchrotron, which are not quantized in the way typically meant when we say the word photon. Their emission mechanisms do not depend on Plank's constant in the formulas.

Sadly, the imprecise nature of describing a photon as a corpuscle rather than an emission or absorption phenomenon has penetrated many areas of physics education. The analogy with sound is useful here, as we could make a similar statement: “All sound is notes.” In the right context this becomes true, but alone it is imprecise. It is true that Hilbert space, or the mathematical space of all functions, can be described as quantized in terms of coefficients of orthogonal polynomials. In the case of sound, this means that we can decompose a sonic signal (a propagating variation of pressure) into a set of amplitudes of discrete frequencies of sines and cosines. In doing so we have “discretized” a signal. This is what analog to digital converters do, and effectively they make a quantized (or discretized) approximation to a continuous signal. In that sense, we could also say that all electromagnetic fields are photons, as we can indeed take an arbitrary and time-varying field configuration and express it in sines and cosines of specific frequencies. In this sense, all electromagnetic fields mathematically "are photons," as they are treated in quantum electrodynamics (QED). However this does not fit our precise definition. To avoid ambiguity the mathematical decomposition of fields as functions into orthogonal polynomials such as sines and cosines of different frequencies should be described as such, rather than with the confusing shorthand often given when describing QED to the layman. While Feynman diagrams describing electromagnetic field forces as exchanges of "photons" have mathematical utility, they are not a physical model. This becomes clear when one tries to explain an attractive force between two bodies via a virtual particle exchange. The virtual exchange particle must then have a momentum opposite to its direction of motion. Such an entity, used to describe a component of a mathematical model, should be made distinct from the physical quantized emission or absorption event which we call a photon.

The description of light emission as the photoelectric effect and subsequent understanding of atomic physics led to a solution to the "ultraviolet catastrophe" and enabled technologies such as lasers and much more. We should respect this success with a reasonable and consistent terminology. Photons are the quantized emission or absorption of light, and as such there is no mysterious side to wave-particle duality or the nature of photons, any more than there is mystery to the quantized nature of sound from a vibrating string.

2) Removal of Nonlocality

Many authors refer to certain behaviors of quantum mechanical systems as “non-local.” This confusion has led to no end of odd speculation and theories, most of which are not in any way useful to understanding the nature of the physical systems in question. In an attempt to find the heart of the matter, I addressed one of the most accessible statements of the supposed problem, which has been republished several times due to its simplicity. For this we must thank the author, David Mermin. In his Physics Today article on the topic [Mermin, 1985], he challenges the reader to come up with a solution to his thought experiment which involves local physics. I came up with an answer which satisfies the requirements [Saul, 2015].

The heart of the difficulty appears to be a basic misunderstanding of the difference between a measurement and an ascribed physical quantity. For an example, let's consider mass. We might say an object has a mass M, and make some definitions of this in terms of things like gravitational force, or resistance to other accelerations. In doing so we declare the object to have a mass M, with utility for our predictions. We might then try to measure this mass. Our measurement will be with a certain device, with a certain calibration, at a certain time. The measurement will always have some error, and within some limits the measurement will have a probabilistic nature. In other words, we can never know *exactly* (with infinite precision) the mass M. This does not mean that we cannot say the object has a mass M, it is just that we understand the limits of measurement and finite precision. As freshman laboratory classes teach, we report the mass with an error bar to indicate our uncertainty.

When this understanding of measurement is applied to some other systems, the difference is more striking. Mass on a large scale appears continuous, however we know now that it is most often not. Something like the spin-up or spin-down state of an electron in a given magnetic field is not at all continuous. A detector of spin-up or spin-down has no intermediate result it can report. None the less, the probabilistic nature of measurement still holds. Some authors such as Bell [1964] tried to demand a later measurement to be exactly predicted by the state of an object which is to be measured, and found an interesting contradiction. This they referred to as “nonlocality,” as the probabilities of the measurement could be correlated to an measurement of another object at a great distance. However such correlation of probabilities is hardly unique to quantum mechanics. Indeed everyone has had the experience of binary-choice measurements in the macroscopic world. The basic “which hand is the coin in” game for children is an example – as soon as one sees that the coin is not in one hand –

suddenly one knows the state (coin or no coin) in the other hand. This is precisely the type of non-locality which is being referred to. Probability may seem very strange in a number of situations, another great example being the Monty Hall problem, but it is nothing that is new or unique to quantum mechanics.

To be more specific we should describe the spin up – spin down experiment in more detail, and what experiments like Alain Aspect's team really did, rather than the imprecise descriptions which tried to make them sound mysterious. In simplistic form, the setup is known as the EPR experiment as it was described as a thought experiment by Einstein, Podolsky, and Rosen. Two spinning particles are created such that their spins are correlated, due to the conservation of angular momentum we know one spins with the same axis as the other but in the opposite direction. To describe the predicted measurement of the system without knowing the spin vectors of the two particles requires a probabilistic approach. Measurement of one particle then immediately indicates something about the other particle – even when they are extremely far apart.

Is this strange? Not at all. Our knowledge of a system is not embedded physically in the system, and for knowledge to be correlated between different far away portions of a system should not be strange to us. For example, consider that you hear somebody arrive in your house, and assume it is your friend. You hear him looking in the cupboard in the next room. Now, you look out the window and see your friend outside. Suddenly, your description of the person in the next room has instantly changed. Is this a bizarre nonlocal effect? No, it is common sense. You now have a superposition of other possibilities for who it is in the next room. You open the door and see that it is your sister. “Oh hi! I thought you were at work” you say. Does this mean that the state vector representing your sister's workplace has suddenly changed despite its remote location? Yes. Is this a mysterious new physics being revealed about the world? No. Quantum non-locality is this same behavior. Sadly a misunderstanding of the difference between an ascribed physical quantity and a measurement, the difference between our knowledge of a system and the actual state of a system, has led to endless speculation such as the “multiple-worlds view” or “parallel universes”. Such possibilities, interesting though they may be in their own right, are not required by quantum mechanics. The Feynman technique of path-integration, while mathematically useful, does not mean that all paths really are taken any more than an investor whose Kelly criterion analysis included different possible market outcomes imagines that the market might do two things at once. The so-called “wavefunction collapse” is merely a statement that the observer has determined something about a system and is in no sense a physical process in the system itself.

The revelations of David Bell and various experiments which confirmed the predictions of the EPR gedanken are not useless. They represent improved experimental abilities in manipulation of light and signals as well as a better understanding of measurement theory. However they do not indicate any physically nonlocal behavior, nor anything mysterious per se. Quite the opposite, they quantify and make rational certain behaviors of certain systems. They imply that measurement is a probabilistic process, and that the result of a measurement will never be exactly determined by an internal state. They demonstrate the importance of understanding that a particle detector has a noise threshold and false positive detection rate, as well as how to use coincidence detection in a statistically consistent manner. Hindsight suggests that this is obvious, as we know from Claude Shannon's mathematical theory of communication that all communication is also a probabilistic process, and measurement can be modeled as a communication. Thus we have a situation similar to early measurements of the speed of light. Today such experiments might be considered to be equivalent to measuring the length of a meter stick, and thus seem trivial. However at the time they were a milestone for physics.

3) **Deemphasis of the Quantum / Classical false dichotomy**

For various reasons, people have falsely touted quantum mechanics as a fundamentally different science from classical physics. As physics progressed to explaining and predicting systems of one nature to systems of other natures, there became a necessity to name these disciplines. Such names are always imperfect and overlapping. “Quantum mechanics” mostly refers to solutions to a new set of problems, specifically those involving discrete or quantized behavior of chemical atoms.

There have been a multitude of changes which arrived with the improved understanding of atomic theory, including many useful technologies. However the dichotomy between classical and quantum physics is false, and must be de-emphasized, if we are to demystify quantum mechanics and proceed in our quest for improved understanding and improved pedagogy of the prized physics material.

Some people might describe quantum mechanics (and relativity) as “non-Newtonian.” In a sense they are right. However, in the same sense, Boltzmann's kinetic theory of gases and Maxwell's theory of electromagnetism are also non-Newtonian. As Newton said, “If I have seen further it is only by standing on the shoulders of giants.” In this case, the giants include Newton himself, and the great innovators of quantum mechanics were the ones standing on *his* shoulders.

One way this can be seen to be true by looking at the notation of quantum mechanics. The importance of the Hamiltonian (a description of total energy in classical mechanics) is often apparent in quantum mechanics. Classical physics concepts completely underly quantum mechanics, including momentum, angular momentum, energy, potentials, and fields, in addition to the differential calculus. Coulomb's law is essential to describe the electric field in a hydrogen atom.

Some authors suggest that the statistical treatment of an electron as a wavefunction is a fundamental change in the way we view a system. However, the mathematics is the same as that which we use to define physical quantities in fluid mechanics. In gas dynamics, physical quantities such as the temperature and density are physically defined as integrals over a distribution function that describes the gas. These quantities are defined in the kinetic theory as an integral of a probability distribution of the atoms in the gas. This is exactly what quantum mechanics does when describing quantities of, for example, electron position and momentum in terms of the wavefunction. There are new quantities which emerge due to the nature of the system under consideration, most obviously Plank's constant h.

However this hardly makes the physics a fundamentally different beast, any more than parameters of any new system you might wish to consider would also make it so.

For the case of the electron, its behavior can be loosely described as analogous to that of a storm system in an atmosphere. Though we can see clearly that a storm exists, and describe the motion of its average center, there is not a clear border but rather a statistical distribution. Similarly we might have various uncertainties in the motion. The analogy is not perfect but it shows how the physics of wavefunctions and the probabilistic treatments of quantum mechanics are not fundamentally at odds with classical mechanics. Rather, they build on classical mechanics – and extremely successfully.

Others might suggest that the complex (or even higher dimensional in the Dirac theory) nature of the electron wavefunction is an oddity. Again, we have similar examples in classical physics. Imaginary numbers have seen practical use in mathematics and engineering for centuries [for a great review, see Nahin, 1998]. The engineer is familiar with using complex numbers to describe electric currents, and the plasma physicist is familiar with using a complex index of refraction. Imaginary numbers do sound quite mystical, but in fact they are well grounded and can be visualized as a means to keep track of multiple dimensions. For the case of the electron wavefunction, the Madelung transformation provides further insight as to why the Schrödinger equation and the complex wavefunction hold, as they can be transformed into a fluid equation similar to the Navier-Stokes equation of classical fluid mechanics.

It is also worth pointing out that as we are well into the 21st century, quantum mechanics itself is old enough to be referred to as a classical theory. The quantum formalism is not new and mystical, but is in fact a few generations old, extremely well established, and grounded in experiment. If we can honor this legacy with precision in description and language, we will enable the next generation of physicists to make greater strides forward, as well as helping all interested parties to better understand the world around them.

Discussion

The so-called Copenhagen interpretation is sometimes described as saying that physical systems don't have physical properties until they are measured. This is disingenuous at best, and today an unnecessary diversion from the successful predictions of the quantum theory. There is no need to claim that properties like mass, spin, momentum, and energy don't exist. Assuming the existence of model parameters such as these is the only way that models of the world can work. Such assumption underlies our model of the world around us on all scales. Rather, we can say that their *measurements* don't exist until they are measured. This should hardly be a mysterious thing. Nowhere in the corpus of quantum mechanics is there evidence that defined physical quantities are directly affected by our opinions or our consciousness. It is only our knowledge of these quantities which is affected by our consciousness.

Quantum tunneling is also sometimes referred to in a mystical way. Again, the theory is accurate but its description is imprecise and deceptive. For example, consider an inflated balloon. If we know the temperature of the gas in the balloon, we can then give the average energy of a gas molecule in the interior. We might determine that this energy is less than that required to penetrate the balloon envelope and escape. However, we find that the balloon slowly deflates over time. This might be referred to as tunneling. The solution is in understanding that the average energy is not enough to describe the system. Many of the molecules are moving at above the average, and are jostled by collisions and other external effects. Thus some gain enough energy to tunnel through the barrier. Similarly, a particle in a potential well might have an average energy which suggests it is trapped. The quantum mechanical calculation allows us to determine the probabilities of its acceleration by random fluctuations and determine its probability of escaping. These random fluctuations are sometimes called zitterbewegung and are similar to a classical Brownian motion.

Another quantum related concept in popular literature is “quantum computing”. Computing today often refers to discrete operations and so the phrase at first appears as a redundancy. However quantum computing refers not to discrete computing itself but to a type of computer in which the correlations of the building blocks (bits or qbits) are not tied together with software but directly inherent to their construction. This is well beyond the scope of this paper but I include it here to point out that advances in this field are not ruled out by our conclusions here. A functioning quantum computer, if it ever could be built, does not require mystical non-local behavior of systems. It merely requires physical bits which can be coupled in a specific manner directly rather than via reading them – electronic transfer – and switching, as is done in a conventional transistor based computer.

The anthropologist might be interested to delve further into why the discipline of quantum mechanics has seen this erosion or mystification in some narratives. The answer is again beyond the scope of this brief paper, but we see in many disciplines a tendency of obfuscation and sensationalism. Sometimes these are considered beneficial for various reasons. In the case of quantum mechanics, these reasons are, if they were ever valid, now well past their prime.

As children discover at an early age, our models of the world around us have limits, which can be quickly reached by repeatedly asking “why?”. Quantum mechanics is no different. Any aspect of the theory quickly runs into the unknown with a couple well placed “why” questions. Why is Plank's constant what it is? Why is there an electromagnetic field? Why is there a zitterbewegung? These are great questions for tomorrows physicists to answer. However this is also true of any other theory. An emphasis on the currently existing and well tested quantum mechanics in its range of applicability itself as somehow mysterious detracts from the value of this powerful and well tested theory. We owe it to the founders of the theory and their insights as well as to the physicists of tomorrow to disengage from such counterproductive discourse.

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