The quantum does not reduce to discrete bits

Roger Schlafly

June 17, 2013

Abstract: There is no way to reduce physics to information theory. Matter is not just empty space with isolated bits of information. The quantum is not digital data, logic, probability, or information. There is a long history of trying to understand the ethereal mysteries of quantum mechanics by reduction to discrete information, as if the universe were a giant ghostly digital computer without the hardware. These attempts have failed, and should be seen as evasions of the central truths of quantum mechanics. In short, there is no it from bit.

Submitted to the FQXi.org 2013 Essay Contest answering: "It from Bit or Bit from It?"

Author Bio: Roger Schlafly has a BSE from Princeton U, and a PhD in Mathematics from U California Berkeley, under I. Singer. He blogs at DarkBuzz.com.

Introduction

Physics is the study of matter and energy, but the suggestion has been made that information is more fundamental. I consider different ways in which physics might be reduced to bits of information, but argue that none of these is more fundamental than quantum mechanics.

Matter is not empty space

The history of science could be viewed as systematically denying the substantiality of matter. The ancient Greek philosopher Democritus suggested that matter is made of atoms. Two millennia later, determination of the size of atoms indicated that there was vast empty space between atoms. When the atom was probed a century ago, it turned out to be mostly empty space, with the mass concentrated in a small nucleus. There were electrons in orbitals, but the electrons appear to be just point particles with no width or volume. When the nuclear forces became understood via the Standard Model, the nucleus itself appeared to be mostly empty space. Even the proton turns out to be mostly empty space, as it is composed of three quarks, and each quark is just a point particle.

It is now commonplace to say that modern physics has proved that there is no such thing as solid matter because it is almost entirely empty space. For example, a recent Radiolab broadcast said:

> It's comforting to think that if you take an object — a rock, let's say — and break it down into tinier and tinier more elemental parts, that that's exactly what you end up with: smaller and smaller particles until you reach the smallest. And voila! Those are the building blocks of everything around us.
>
> But as Jim Holt, author of "Why Does the World Exist?" points out … that's an old worldview that no longer jives with modern-day science. If you start slicing and sleuthing in subatomic particle land — trying to get to the bottom of what makes

> matter — you mostly find empty space. Your hand, your chair, the floor … it's all made up of mostly of nothing.

John Archibald Wheeler took this idea to its logical conclusion, and suggested that matter may only have an information content, and no substance at all. Even those electrons and quarks may not be particles at all, and might be just manifestations of bits of information. He was famous for his colorful views of physics.

As logical and appealing as this progression of ideas is, it has little to do with reality. It is not true to say that modern-day science teaches that atoms are mostly empty space. First, there is no such thing as empty space, as modern physics teaches that it is filled with pervasive fields that used to be called the aether. These fields include the electron field, the Higgs field, and the dark energy field. Second, atoms are held together by nuclear and electromagnetic fields, and those fields fill up atoms and material objects as surely as water fills the ocean.

The electron can be observed as a particle, but it is not a point particle. According to quantum electrodynamics, the electron can be viewed as a particle or a field. Even if viewed as a particle, it has a bare mass and bare charge that we never see, as it is surrounded by a cloud of virtual electrons and photons. We have no theory of an electron as a particle, because our theories require the surrounding cloud in order to make sense of the electron.

The electron is a *quantum*, not a particle or field. The quantum has no classical counterpart, and we use particles and fields as useful intuitive models.

Quantum mechanics gives an explanation for how quanta can fit together to form solid stable matter. Part of the story is that the Pauli Exclusion Principle keeps identical electrons apart. But there is no magic action-at-a-distance, as would be required if matter were really mostly empty space. The electrons have wave functions and electric fields, and they stay apart by filling the intermediate space with fields.

Thus it is a myth that matter is mostly empty space, and matter is certainly not reducible to ghostly bits of information.

How bits arise in quantum mechanics

Quantum mechanics is popularly described as a discretization of classical physics. Whereas a classical observable might vary continuously from one value to another, the quantum one makes discrete jumps.

H. Poincare wrote a seminal 1911 paper "On the Theory of Quanta", saying:

> Here is the profoundest revolution that natural philosophy has undergone since Newton. … [abstract]
>
> A physical system is capable of only a finite number of distinct states; it jumps from one of those states to another without going through a continuous series of intermediate states. [paper]

Poincare had previously written about the atomic hypothesis as if it were just a convention. But when he studied the work of Perrin on atoms and Planck on radiation, he became the leading advocate of the quantum theory. An American magazine breathlessly reported

Poincare's conclusions with a 1912 article titled, "Does Everything Go By Jerks?" It suggested that nature could be "one vast cinematograph", with discrete atoms of energy and time. The next year Niels Bohr published his model of the atom, with discrete energy levels for electron orbitals.

A century later, quantum mechanics is bedrock physics, and there is a widespread view that everything goes by jerks.

If the world were really finitary and jerky, then it would be natural to suppose that the world is some sort of digital computer, with processing bits being the fundamental operation.

The first obvious problem with the computer analogy is that digital computers are deterministic, while quantum mechanics is probabilistic. I review some quantum fundamentals in order to explain how the bits arise, and why probability is just an interpretation.

The core of the theory of quantum mechanics is an algebra of observables. These include position coordinates, momentum, energy, spin, electric charge, and anything else that is measurable as a real variable. The key fact is that the observables do not necessarily commute. That is, the position X and the momentum P have the property that XP is not equal to PX. They differ by a multiple of Planck's constant.

To observe a system, we need a representation of the observables on a Hilbert space of possible system states. That means that a vector ψ represents the state of the system, that an observable A acts on ψ to give a new state $A\psi$, and that two vectors ψ and ψ' can be combined to get a number $<\psi|\psi'>$. The latter is like an ordinary dot product and gives 0 when the vectors are orthogonal.

If an observable A is measured is measured on a system state ψ, the expected value is $<\psi|A\psi>$, also written $<\psi|A|\psi>$. It is a real number.

An actual lab measured value may not match the expected value exactly. Real numbers never match exactly in the lab, with quantum mechanics or any other scientific theory. The standard deviation, or sigma, is also an observable with an expected value. Thus, the mechanics might say that a particle will be observed at a distance of $5.24 \pm .03$ meters. Then a measurement is likely to be between 5.21 and 5.27.

Thus the theory makes probabilistic predictions in the sense that it gives a range of likely outcomes for measurements. But every other branch of science does something similar, and this is not why quantum mechanics is said to be probabilistic.

Quantum mechanics is said to be probabilistic because is predicts probabilities. Here is how. Suppose that the observable A is a *yes-no* (Boolean) observable, such as asking whether an electron is in a particular region of space. *Yes* means 1, *no* means 0, and no other values are observed. Then the expected value $<\psi|A|\psi>$ will be in the range [0,1]. If the value is 1, then you can be sure of a *yes*, and if the value is 0, then you can be sure of a *no*. If the value is in between, then it can be interpreted as a probability of a *yes*. This interpretation is called the *Born Rule*. Max Born suggested it as one possibility in a 1926 paper footnote, and got a Nobel Prize for it in 1954.

Probability is just an interpretation

Probabilities are used throughout experimental science, but do not play a more essential role in quantum mechanics. Testing the Born Rule is just a special case of testing an expected value of an observable, where the observable is a *yes-no* variable. An experiment does not really say whether there is any genuine randomness. It just says that if the expected value of a *yes-no* observable is 0.65, and you do 100 experiments, then you should get about 65 *yes* outcomes.

The theory also gives error estimates on those expected values, and those estimates can be compared to experiment. But the variance is just another observable, and the experiment that tests those error estimates is really just testing the expectation value of the variance observable. Thus the predictions of quantum mechanics can all be understood without the probability concept.

To be specific, if an observable A has zero expectation for a state ψ, then expected value of the variance is $<\psi|A^2|\psi>$. If this is zero, then measuring A can be predicted with perfect accuracy. If the variance is non-zero, then it predicts the error bounds on the measurement of A.

As an extreme example, let ψ represent an electron whose spin has just been measured in a particular direction, and let A be spin in a perpendicular direction. Then A has eigenvalues $\pm.50$, expectation $<\psi|A|\psi> = 0$, and.variance $<\psi|A^2|\psi> = .25$. This is another way of saying that a spin measurement will give +.5 or –.5, with both possibilities being equally likely. Looking at just the expectation value of 0 alone is a little misleading, because a spin of 0 is never observed, but including the variance gives a more complete picture of what is going on. In this case the observable A^2 has a variance of $<\psi|(A^2-.25)^2|\psi> = 0$, reflecting the fact that the square of the spin will surely be measured as .25. Thus the various expectation values of the observables give all of the necessary information.

It is better to just say that quantum mechanics predicts the expected values of observables. That is what the formulas really do, and that is how the theory is tested. The Born Rule adds an interpretation as probability in the case of a *yes-no* observable. But that interpretation is just metaphysical fluff. There is no experimental test for it. The tests are just for the expected values, and not for the probabilities.

The best argument for quantum mechanics being probabilistic occurs when an observable A has discrete spectrum. A *yes-no* observable has a spectrum of just 0 and 1, and many other oberservables also have discrete spectrum. Then maybe a system can be put into an eigenstate so that an exactly precise prediction can be made, and the system seems deterministic. But if a state is a superposition of two eigenstates, then the measurement seems probabilistic because a measurement of A gives one of two discrete possibilities. The situation is analogous to a coin toss that must yield either heads or tails. But the coin itself is not restricted to two discrete possibilities as it is tossed; the discreteness comes about because of the way it is measured. The coin itself may be deterministic.

Likewise a quantum mixture of two eigenstates could be a deterministic object that only seems like a coin toss because of the way that it is measured. Whatever uncertainty there is may be entirely due to our lack of knowledge about the state, and the discreteness imposed by the measuring process.

Thus I do not believe that it is either necessary or very useful to talk about probabilities in quantum mechanics. You could say that the probability gives a way of understanding that the same experiment does not give the same outcome every time, but it does not give any more quantitatively useful information. This understanding is nothing special because every other branch of science also has variation in experimental outcomes.

The textbooks usually say that ψ is some sort of probability density or amplitude. But ψ is complex-valued or maybe even spinor-valued, and it requires some computation to get a probability. It is not a probability. That computation is precisely the expectation value described above. Sometimes the textbooks admit that the quantum probabilities require special interpretation because they can be negative. I say that negative probabilities are not probabilities and that the probabilities are no more essential to quantum mechanics than to any other physical theory that does real number computations.

Having eliminated probability, it is impossible to say whether quantum mechanics is deterministic or not. It often makes predictions of non-zero variances for observables, but so does every other scientific theory. Quantum mechanics seems slightly different because even if you are able to prepare a system to have a zero variance in one observable, it will still have non-zero variance in a non-commuting observable. It is debatable whether determinism is even a scientific issue.

It is also impossible to say whether the wave function is real in some ontological sense. All we know for sure is that we can infer possible wave functions from observations, and then predict observables from the time evolution of those wave functions. Whether or not those wave functions collapse is a matter of interpretation.

Other interpretations add extraneous concepts. The many-worlds interpretation requires a vast array of unobservable universes. The Bohm interpretation requires non-causal entities that are never observed. Von Neumann's interpretation requires action-at-a-distance wave-function collapse. Wigner's requires consciousness. The ensemble interpretation tries to avoid unnecessary assumptions, but it fails to predict individual events. The truly minimal interpretation does not introduce unphysical concepts like nondeterminism and nonlocality. The Copenhagen and consistent histories interpretations come closest to this ideal.

No hidden variables

Thus the quantum mechanics bits only arise from observables, with discreteness coming from the spectrum. But is it possible that someone will find some new formulation of quantum mechanics where the bits play some more essential role?

Physicists have a long history of trying to inject more *realism* into quantum mechanics. What they mean by this is that some sort of *hidden variables* can be added to the theory so that observations correspond to values of those hidden variables. The concept is contrary to the whole spirit of quantum mechanics, and all attempts have failed.

The hidden variable interpretation has been ruled out by the quantum mechanics textbooks since about 1930. Einstein, Bohm, Bell, and a few others tried to resurrect the idea, but they were always proven wrong. While a lot of work has gone into this issue, most physicists consider the Bell test experiments to be the definitive proof that the hidden variable theories are impossible.

As an example of a physicist who yearns for a hidden variable theory, Lee Smolin wrote recently, in response to an Edge.org question:

> I worry that we don't really understand quantum phenomena. …
>
> But there is another possibility: that quantum mechanics does not provide an explanation for what happens in individual phenomena because it is incomplete, because it simply leaves out aspects of nature needed for a true description. This is what Einstein believed and it is also what de Broglie and Schroedinger, who made key steps formulating the theory, believed. This is what I believe and my lifelong worry has been how to discover that more complete theory.
>
> A completion of quantum mechanics which allows a full description of individual phenomena is called a hidden variables theory. Several have been invented; …

A recent paper on a probabilistic interpretation of quantum mechanics argues:

> There is something about quantum theory that is different in character from any physical theory posed before. To put a finger on it, the issue is this: The basic statement of the theory — the one we have all learned from our textbooks — seems to rely on terms our intuitions balk at as having any place in a fundamental description of reality. The notions of "observer" and "measurement" are taken as primitive, the very starting point of the theory. This is an unsettling situation! Shouldn't physics be talking about what is before it starts talking about what will be seen and who will see it? [Fuchs, 2010]

Actually physics has a long history of talking about what will be seen, without determining the underlying reality. Thermodynamics, relativity, atomic theory, and strong nuclear forces all had theories for what was seen first. Even today, we have good theories for dark matter and dark energy observations, without being able to say what is.

One purpose to hidden variable theories is to give a mathematical realization of probabilities. If the observables are random variables, then it is natural to assume that they are functions of some measure-one parameter space. If some physical significance to that parameter space can be found, so much the better. However if you do not subscribe to a probabilistic interpretation, there is less reason to look for such a space. Even if you do, probability theory has its own interpretations and paradoxes, and it is not clear that any theory of physical probabilities would be any more satisfactory than quantum mechanics.

The hidden variable theories have nonlocal or other unphysical properties, and have not caught on. I believe that all such theories are doomed, for reasons detailed in my essay, "Nature has no faithful mathematical representation." [FQXi.org 2012 essay contest]

Bits do not have free will

The simplest model of a bit is that used in ordinary digital computers. It is off or on, representing 0 or 1. Once put in an off/on state, it stays that way for repeated reads. There are logic operations like AND, OR, and NOT that can transform one or more bits.

Another type of bit is the *fuzzy bit*. This can have any real value in the interval [0,1], and the value can be interpreted as a probability. Logical operations can be applied to the bits in a deterministic manner.

Yet another type is the *stochastic bit*. It is read as 0 or 1, but it can also be put in a randomized state where either possibility is equally likely. Once read as 0 or 1, it stays that way unless another operation flips it or puts it back into a randomized state. The idea is that 64 stochastic bits could simultaneously represent all the integers from 0 to $2^{64}-1$.

Quantum computers are a little like the computer with stochastic bits. The great hope is that quantum computers could be exponentially faster than conventional computers on certain types of problems by using quantum superposition to calculate many quantities at once.

Unfortunately these bit models are misleading. A quantum computer is an experiment in quantum mechanics, and the laws of quantum mechanics do not simplify so readily into bits.

John H. Conway and Simon B. Kochen have argued that the quantum behavior of electron and photons can be described as quanta having their own free will. Assuming basic principles of quantum mechanics and our ability to conduct random experiments, they showed that the electron seems to have a mind of its own when deciding what to do.

If the world of quantum mechanics is reducible to bits somehow, then they would have to be bits with their own free will. Computer bits do not have free will, and the whole concept of free will is contrary to what has traditionally been considered desirable in a computer bit. Thus the quantum world is not reducible to bits, as the term has long been understood.

The free will deniers often argue that the world must be either determinist or random, and that neither comports with our intuitions about free will. But that is a false dichotomy, as quantum mechanics teaches us that the world is not necessarily either determinist or random, and may be something in between.

The concept of free will may be philosophically troublesome, so similar arguments may be made without mentioning free will. Electrons and photons are nothing like computer bits.

Qubits and quantum logic

There remains the possibility that the world is reducible to some sort of quantum bits and quantum logic. Transmitting a photon can carry information, and if we define a quantum bit to be whatever information a photon can transmit, then photons do carry quantum bits.

The most widely recognized utility for sending quantum bits is in quantum cryptography. Here is a brief summary of how that works.

A photon (or electron) cannot be measured to determine its state (before the measurement). You can measure one observable, but that leaves an uncertainty in a non-commuting observable. That is what the Heisenberg Uncertainty Principle tells us. The act of measurement changes the quantum by collapsing the wave function and forcing a certainty in one observable, while leaving an uncertainty in another.

This basic feature of quantum mechanics can be used for Alice to send messages to Bob. Alice sends a quantum beam to Bob, with instructions to measure each quantum with one of two non-commuting observables, such as spin. An eavesdropper Eve may try to measure the quanta in transit, but she does not know the sequence of observables that Alice and Bob have prearranged. If Eve guesses wrong about the choices of observables, then she will create uncertainties in what Bob measures, and her interference can be detected.

So what is Alice sending here, ordinary bits or quantum bits? Bits are ultimately used for cryptography, but something more complex is being sent. If it were just a bit, then Eve could measure it and resend it. A quantum state is being sent, and quantum mechanics is required to describe it.

Quantum cryptography is sometimes claimed to be more secure than conventional cryptography, because it relies on physics instead of mathematics. However quantum cryptography suffers several disadvantages. It cannot authenticate messages as coming from a particular sender. It cannot send messages over the internet. And it is subject to various hardware vulnerabilities. It can be combined with conventional cryptography to ameliorate some of these problems, but then it has no clear-cut advantage over just using the conventional cryptography.

Thus quantum cryptography is a way of demonstrating the quantum spin states of quanta, but no more. You can say that it is a way of transmitting quantum bits, but the bits are just regular quantum states.

It has also been suggested that some sort of funny logic or quantum logic is suitable for the truth values of quantum mechanics. For example, in the double slit experiment, a light beam is shined at a double slit, and the photons detected on the other side must have gone through the slits. It seems logical to say that the photon must go through one slit or the other, so that if it doesn't go through one it goes through the other. But the interference fringe cannot be understood that way.

The law of excluded middle says that if (A or B) is true, and A is not true, then B is true. So maybe the statement that a photon goes through a particular slit does not have a simple true/false value, but rather some quantum logic value, and the law of the excluded middle does not apply to such values. These quantum truth values would be quantum bits of another sort.

Unfortunately, such esoteric quantum logics have not simplified the theory of quantum mechanics, and there is no reason to believe that the theory is masking some more fundamental fuzzy logic structure for nature.

There are many ways to understand the double-slit experiment. The simplest is to use the Asher Peres slogan, "unperformed experiments have no results." That is, it does not make sense to ask whether the photon goes through a particular slit unless you actually make a measurement at the slit. Then no special quantum logic is needed.

Black holes

Not content to search for quantum information mysteries here on Earth, some physicists have looked to black holes. Stephen Hawking and others have debated whether information is lost in black holes, and there is no consensus.

If quantum mechanics is viewed as a probability theory, then we expect the probabilities to add up to one. When it predicts future probabilities, we expect those to add up to one also. Mathematically, this is often seen as being guaranteed by unitarity of the time evolution of the wave function. Unitary operations are reversible, so some people say that information is conserved over time.

The paradox is that matter falling into black holes appears to be irreversible, and so information appears to be lost. Some people argue that the information could later be radiated back out.

However if probability is not a physical quantity, then there is less reason to believe that its conservation is physically significant. There is no known experiment that can tell us whether unitarity is true or false. There are some interpretations of quantum mechanics that obey strict unitarity, and there are others where a measurement causes a non-unitary wave-function collapse. It would be a major advance if one of these interpretations were proved correct, and others proved incorrect.

Matter falling into black holes is not the only thing that appears irreversible. Every quantum measurement and every increase in entropy also appear to be irreversible. For example, lighting a match increases entropy and no one has proved whether or not a wave-function collapse is necessary. It is not clear that the question is even a scientific one.

Perhaps lighting a match moves quantum information into some inaccessible part of the universal wave function, where no future experiment can detect it. Or maybe the quantum information just disappears.

One of the curses of quantum mechanics is that it has left physicists endlessly arguing about the ontology of hidden information that can never be observed.

In a recent interview, David J. Gross said:

> Nonetheless, we have a big problem: Physics explains the world around us with incredible precision and breadth. But further explanation is highly constrained by what we already know. … Einstein famously criticized Heisenberg for focusing only on observable entities, when there can be indirect evidence for entities that cannot be seen.

Einstein had made his reputation by giving an interpretation of special relativity in terms of observables, without trying to explain the cause of the FitzGerald contraction or the Lorentz local time and mass. He later became dissatisfied with a theory of observables, and wanted a more “complete” view of reality.

Physics is now in the embarrassing situation that we can explain what is observed, but we cannot explain what is not observed. If you ask whether some ill-defined quantum information can disappear into a black hole, no one can give a definitive answer. Maybe it is time to turn the question over to the sort of philosophers who like to ask, “If a tree falls in a forest and no one is around to hear it, does it make a sound?”

Conclusion

Quantum mechanics was discovered by Heisenberg and Schroedinger, and perfected by Dirac and von Neumann by about 1930. A great deal has been learned since then, but Bohr’s view of quantum mechanics is still good. The reality is in the observables. When he said that “there is no quantum world”, he meant that there is no underlying mechanistic micro-realistic model. In particular, there are no underlying bits.

References

Dark Buzz, http://www.darkbuzz.com

Does every thing go by jerks?, The Literary Digest, Apr. 13, 1912, p.751.

Nature has no faithful mathematical representation, Roger Schlafly, FQXi 2012 essay contest, http://fqxi.org/community/forum/topic/1283

Poincaré's proof of the quantum discontinuity of nature, Jeffrey J. Prentis, Am. J. Phys. 63(4), April 1995, http://wase.urz.uni-magdeburg.de/mertens/teaching/seminar/themen/ajp_poincare_quanta.pdf

QBism, the Perimeter of Quantum Bayesianism, Christopher A. Fuchs, 2010. http://arxiv.org/abs/1003.5209

Solid as a Rock, Radiolab podcast, Dec. 31, 2012, http://www.radiolab.org/blogs/radiolab-blog/2012/dec/31/solid-rock/

Stability of Matter in Quantum Mechanics, Elliott H. Lieb and Robert Seiringer. http://arxiv.org/abs/1111.0170 http://www.ams.org/journals/bull/2013-50-01/S0273-0979-2011-01366-0/home.html

The Strong Free Will Theorem, John H. Conway and Simon B. Kochen, Notices of the AMS. Volume 56, Number 2, Feb. 2009. http://arxiv.org/abs/0807.3286 http://www.ams.org/notices/200902/rtx090200226p.pdf

Waiting for the Revolution, David J. Gross interview, Simons Science News, May 24, 2013. http://www.simonsfoundation.org/features/science-news/waiting-for-the-revolution/ http://www.wired.com/wiredscience/2013/06/qa-david-gross-physics/all/

What should we be worried about? Quantum mechanics, Lee Smolin, 2013 Edge.org question, http://www.edge.org/response-detail/23778