100 Years of the Quantum

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Abstract: As quantum theory celebrates its 100th birthday, spectacular successes are mixed with outstanding puzzles and promises of new technologies. This article reviews both the successes of quantum theory and the ongoing debate about its consequences for issues ranging from quantum computation to consciousness, parallel universes and the nature of physical reality. We argue that modern experiments and the discovery of decoherence have have shifted prevailing quantum interpretations away from wave function collapse towards unitary physics, and discuss quantum processes in the framework of a tripartite subject-object-environment decomposition. We conclude with some speculations on the bigger picture and the search for a unified theory of quantum gravity.

"...in a few years, all the great physical constants will have been approximately estimated, and [...] the only occupation which will then be left to the men of science will be to carry these measurement to another place of decimals." As we enter the 21st century amid much brouhaha about past achievements, this sentiment may sound familiar. Yet the quote is from James Clerk Maxwell and dates from his 1871 Cambridge inaugural lecture expressing the mood prevalent at the time (albeit a mood he disagreed with). Three decades later, on December 14, 1900, Max Planck announced his famous formula on the blackbody spectrum, the first shot of the quantum revolution.

This article reviews both the spectacular successes of quantum theory and the ongoing debate about its consequences for issues ranging from quantum computation to consciousness, parallel universes and the very nature of physical reality.

THE ULTRAVIOLET CATASTROPHE

In 1871, scientists had good reason for their optimism. Classical mechanics and electrodynamics had powered the industrial revolution, and it appeared as though their basic equations could describe essentially all physical systems. Yet some annoying details tarnished this picture. The amount of energy needed to heat very cool objects was smaller than predicted and the calculated spectrum of a glowing hot object didn't come out right. In fact, if you took the classical calculation seriously, the prediction was the so-called ultraviolet catastrophe: that you would get blinded by light of ultraviolet and shorter wavelengths when you looked at the burner on your stove!

In his 1900 paper, Planck succeeded in deriving the correct shape of the blackbody spectrum which now bears his name, eliminating the ultraviolet catastrophe. However, this involved an assumption so bizarre that even he distanced himself from it for many years afterwards: that energy was only emitted in certain finite chunks, or "quanta". Yet this strange assumption proved extremely successful. Inspired by Planck's quantum hypothesis, Peter Debye showed that the strange thermal behavior of cold objects could be explained if you assumed that the vibrational energy in solids could only come in discrete chunks. In 1905, Einstein took this bold idea one step further. Assuming that radiation could only transport energy in such chunks, "photons", he was able to explain the so-called photoelectric effect, which is related to the processes used in present-day solar cells and the image sensors in digital cameras.

THE HYDROGEN DISASTER

In 1911, physics faced another another great embarrassment. Ernest Rutherford had convincingly argued that atoms consisted of electrons orbiting a positively charged nucleus much like a miniature solar system. However, electromagnetic theory predicted that such orbiting electrons would radiate away their energy, spiraling inward until they got sucked into the atomic nucleus after about a millionth of a millionth of a second. Yet hydrogen atoms were known to be eminently stable. Indeed, this was the worst quantitative failure so far in the history of physics, under-predicting the lifetime of hydrogen by some forty orders of magnitude!

Niels Bohr, who had come to Manchester to work with Rutherford, made a breakthrough in 1913. By postulating that the amount of angular momentum in an atom was quantized, the electrons were confined to a discrete set of orbits, each with a definite energy. If the electron jumped from one orbit to a lower one, the energy difference was sent off in the form of a photon. If the electron was in the innermost allowed orbit, there were no orbits with less energy to jump to, so the atom was stable. In addition, Bohr's theory successfully explained a slew of spectral lines that had been measured for Hydrogen. It also worked for the Helium atom, but only if it was deprived of one of its two electrons. Back in Copenhagen, Bohr got a letter from Rutherford telling him he had to publish his results. Bohr wrote back that nobody would believe him unless he could explain the spectra of all the atoms. Rutherford replied, in effect: Bohr, you explain hydrogen and you explain helium and everyone will believe all the rest.

Bohr was a warm and jovial man, with a talent for leadership, and that business of explaining all the rest soon become the business of the group that rose around him at Copenhagen. The second author had the privilege to work there on nuclear physics from September 1934 to June 1935, and on arrival asked a workman who was trimming vines running up a wall where he could find Bohr. "I'm Niels Bohr", the man replied.

THE EQUATIONS FALL INTO PLACE

Despite these early successes, physicists still didn't know what to make of these strange and seemingly ad hoc quantum rules. What did they really mean?

In 1923, Louis de Broglie proposed an answer in his Ph.D. thesis: that electrons and other particles acted like standing waves. Such waves, like vibrations of a guitar string, can only occur with certain discrete (quantized) frequencies. The idea was so new that the examining committee went outside its circle for advice on the acceptability of the thesis. Einstein gave a favorable opinion and the thesis was accepted. In November 1925, Erwin Schrödinger gave a seminar on de Broglie's work in Zurich. When he was finished, Debye said in effect, "You speak about waves. But where is the wave equation?" Schrödinger went on to produce and publish his famous wave equation, the master key for so much of modern physics. An equivalent formulation involving matrices was provided by Max Born, Pasquale Jordan and Werner Heisenberg around the same time. With this new powerful mathematical underpinning, quantum theory made explosive progress. Within a few years, a host of hitherto unexplained measurements had been successfully explained, including spectra of more complicated atoms and various numbers describing properties of chemical reactions.

But what did it all mean? What was this quantity, the "wave function", which Schrödinger's equation described? This central puzzle of quantum mechanics remains a potent and controversial issue to this day.

Max Born had the dramatic insight that the wave function should be interpreted in terms of probabilities. If we measure the location of an electron, the probability

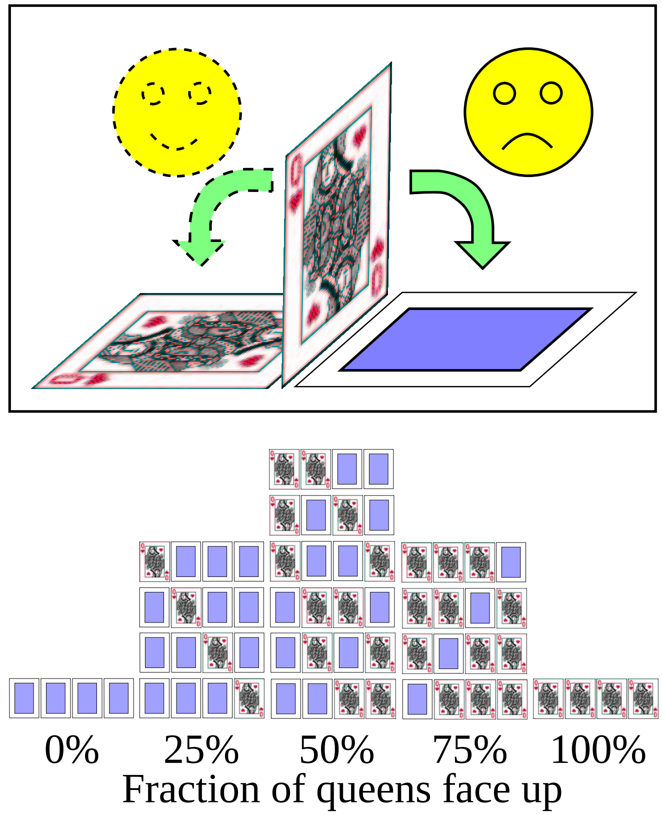

FIG. 1. According to quantum physics, a card perfectly balanced on its edge will by symmetry fall down in both directions at once, in what is known as a "superposition". If an observer has bet money on the queen landing face up, the state of the world will become a superposition of two outcomes: her smiling with the queen face up and her frowning with the queen face down. In each case, she is unaware of the other outcome and feels as if the card fell randomly. If our observer repeats this experiment with four cards, there will be $2 \times 2 \times 2 \times 2 = 16$ outcomes (see figure). In almost all of these cases, it will appear to her that queens occur randomly, with about 50% probability. Only in 2 of the 16 cases will she get the same result all four times. According to a 1909 theorem by the French mathematician Borel, she will observe queens 50% of the time in almost all cases (in all cases except for what mathematicians call a set of measure zero) in the limit where she repeats the card experiment infinitely many times. Almost all of the observers in the final superposition will therefore conclude that the laws of probability apply even though the underlying physics is not random and God does not play dice.

of finding it in a given region depends on the intensity of its wave function there. This interpretation suggested that a fundamental randomness was built into the laws of nature. Einstein was deeply unhappy with this interpretation, and expressed his preference for a deterministic Universe with the oft-quoted remark "I can't believe that God plays dice".

CURIOUS CATS AND QUANTUM CARDS

Schrödinger was also uneasy. Wave functions could describe combinations of different states, so-called superpositions. For example, an electron could be in a superposition of several different locations. Schrödinger pointed out that if microscopic objects like atoms could be in strange superpositions, so could macroscopic objects, since they are made of atoms. In particular, seemingly innocent "microsuperpositions" could turn into "macrosuperpositions". As a baroque example, he described the famous thought experiment where a nasty contraption kills a cat if a radioactive atom decays. Since the radioactive atom eventually enters a superposition of decayed and not decayed, it produces a cat which is both dead and alive in superposition.

Figure 1 shows a simpler version of this *Gedanken* experiment that we will call Quantum Cards, again turning a microsuperposition into a macrosuperposition. You simply take a card with a perfectly sharp bottom edge and balance it on its edge on a table. According to classical physics, it will in principle stay balanced forever. (In practice, this unstable card will of course get toppled in no time by say a tiny air current, so you could take a card with a thick bottom edge and use Schrödinger's radioactive atom trigger to nudge it one way or the other.) According to the Schrödinger equation, it will fall down in a few seconds even if you do the best possible job of balancing it, because the Heisenberg uncertainty principle states that it cannot be in only one position (straight up) without moving. Yet since the initial state was left-right symmetric, the final state must be so as well. The implication is that it falls down in both directions at once, in superposition. If you could perform this thought experiment, you would undoubtedly find that classical physics was wrong and the card fell down. But you would always see it fall down to the left *or* to the right, seemingly at random, never to the left and to the right simultaneously as the Schrödinger equation might have you believe. This apparent contradiction goes to the very heart of one of the original and most enduring mysteries of quantum mechanics.

The Copenhagen Interpretation of quantum mechanics, which evolved from discussions between Bohr and Heisenberg in the late 1920s, addresses the mystery by asserting that observations, or measurements, are special. So long as the balanced card is unobserved, its wave function evolves by obeying the Schrödinger equation – a continuous and smooth evolution that is called "unitary" in mathematics and has several very attractive properties. Unitary evolution produces the superposition where the card has fallen down both to the left and to the right. The act of observing the card, however, triggers an abrupt change in its wave function, commonly called a "collapse": the observer sees the card in one definite classical state (face up or face down) and from then onward only that portion of the wave function survives. Nature supposedly decided which particular state to collapse into at random, with the probabilities determined by the wave function.

Although this provided a strikingly successful calculational recipe, there was a lingering feeling that there ought to be some equation describing when and how this collapse occurred. Many physicists took this to mean that there is something fundamentally wrong with quantum mechanics, and that it would soon be replaced by some even more fundamental theory that provided such an equation. So rather than dwell on ontological implications of the equations, most workers forged ahead to work out their many exciting applications and to tackle pressing unsolved problems of nuclear physics.

That pragmatic approach proved stunningly successful. Quantum mechanics was instrumental in predicting antimatter, understanding radioactivity (leading to nuclear power), accounting for materials such as semiconductors, explaining superconductivity, and describing interactions such as those between light and matter (leading to the invention of the laser) and of radio waves and nuclei (leading to magnetic resonance imaging). Many successes of quantum mechanics involve its extension, quantum field theory, which forms the foundation of elementary particle physics all the way to the present-day experimental frontiers of neutrino oscillations and the search for the Higgs particle and supersymmetry.

MANY WORLDS OR MANY WORDS?

By the 1950's, this ongoing parade of successes had made it abundantly clear that quantum theory was far more than a short-lived temporary fix. And so, in the mid 1950's, a Princeton graduate student named Hugh Everett III decided to revisit the collapse postulate in his Ph.D. thesis. Everett pushed the quantum idea to its extreme by asking the following question: *"What if the time-evolution of the entire Universe is always unitary?"* After all, if quantum mechanics suffices to describe the Universe, then the present state of the Universe is described by a wave function (an extraordinarily complicated one). In Everett's scenario, that wave function would always evolve in a deterministic way, leaving no room for wave function collapse or God playing dice.

Instead of getting collapsed by measurements, seemingly innocent microscopic superpositions would rapidly get amplified into most Byzantine macroscopic superpositions. Our quantum card in Figure 1 would really be in two places at once. Moreover, a person looking at the card would enter a superposition of two different mental states, each perceiving one of the two outcomes! If you had bet money on the queen coming face up, you would end up in a superposition of smiling and frowning. Everett's brilliant insight was that the observers in such a crazy deterministic but schizophrenic quantum world could perceive the plain old reality that we are familiar with, as described in Figure 1. Most importantly, they would perceive an apparent randomness obeying precisely the right probability rules, as the bottom panel of Figure 1 illustrates. The situation is more complicated, and still controversial, for the asymmetric case when the probabilities for different outcomes are not equal.

Everett's viewpoint became known as the "many worlds" or, perhaps more appropriately, "many minds" interpretation of quantum mechanics because each of one's superposed mental states perceives its own world. This viewpoint simplifies the underlying theory by removing the collapse postulate, implying that there is no new undiscovered physics that makes these superpositions go away. The price it pays for this theoretical simplicity is the conclusion that these parallel perceptions of reality are all equally real, so in a sense it involves less words at the expense of more worlds.

EXPERIMENTAL VERDICT: THE WORLD *IS* WEIRD

Everett's work was largely disregarded for about two decades. The main objection was that it was too weird, demoting to mere approximations the familiar classical concepts upon which the Copenhagen interpretation was founded. Many physicists hoped that a deeper theory would be discovered, showing that the world was in some sense classical after all, free from oddities like large objects being in two places at once. However, such hopes were largely shattered by a series of new experiments.

Could the apparent quantum randomness be replaced by some kind of unknown quantity carried about inside particles, so-called "hidden variables"? CERN theorist John Bell showed that in this case, quantities that could be measured in certain difficult experiments would inevitably disagree with the standard quantum predictions. After many years, technology allowed researchers to conduct these experiments and eliminate hidden variables as a possibility.

A "delayed choice" experiment proposed by the second author in 1978 (see Figure 2) was successfully carried out by Carroll Alley, Oleg Jakubowics and William Wickes in 1984, showing that not only can a photon be in two places at once, but we can decide whether it should act schizophrenically or classically seemingly after the fact!

The simple double slit interference experiment, hailed by Feynman as the mother of all quantum effects, was successfully repeated for ever larger objects: atoms, small molecules and most recently a carbon-60 "Buckey Ball". After this last feat, Anton Zeilinger's group in Vienna has even started discussing doing it with a virus. If we imagine, as a *Gedanken* experiment, that this virus has some primitive kind of consciousness, then the many worlds/many minds interpretation seems unavoidable, as has been emphasized by Dieter Zeh. An extrapolation to superpositions involving other sentient beings such as humans would then be merely a quantitative rather than a qualitative one.

In short, the experimental verdict is in: the weirdness of the quantum world is real, whether we like it or not. There are in fact good reasons to like it: this very weirdness may offer useful new technologies. According to a recent estimate, about 30% of the U.S. gross national product is now based on inventions made possible by quantum mechanics. Moreover, if physics really is unitary (if the wave function never collapses), quantum computers can in principle be built that take advantage of such superpositions to make certain calculations much faster than conventional algorithms would allow. For example, Peter Shor and Lov Grover have shown that one could factor large numbers and search long lists faster this way. Such machines would be the ultimate parallel computers, in a sense running many calculations in superposition. As David Deutsch has emphasized, it will be hard to deny the reality of all these parallel states if such computers are actually built.

QUANTUM CENSORSHIP: DECOHERENCE

The above-mentioned experimental progress of the last few decades was paralleled by a new breakthrough in theoretical understanding. Everett's work had left two crucial question unanswered: first of all, if the world actually contains bizarre macrosuperpositions, then why don't we perceive them?

The answer came in 1970 with a seminal paper by Dieter Zeh of the University of Heidelberg, who showed that the Schrödinger equation itself gives rise to a type of censorship. This effect became known as *decoherence*, because an ideal pristine superposition is said to be coherent. Decoherence was worked out in great detail by Los Alamos scientist Wojciech Zurek, Zeh and others over the following decades. They found that coherent quantum superpositions persist only as long as they remain secret from the rest of the world. Our fallen quantum card in Figure 1 is constantly bumped by snooping air molecules, photons, *etc.*, which thereby find out whether

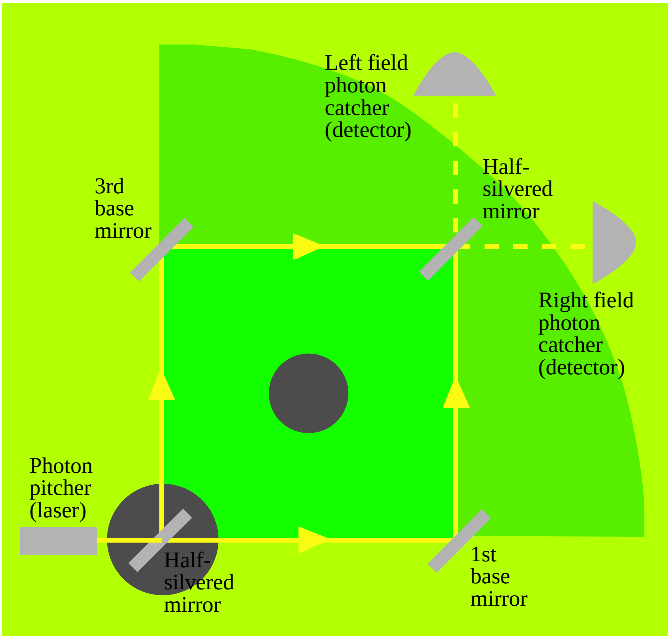

FIG. 2. The delayed choice experiment. The figure shows a so-called Mach-Zender interferometer in the guise of a baseball diamond. The half-silvered mirror on home plate reflects half the light that strikes it towards 3rd base and lets the rest through towards 1st base. Two ordinary mirrors then reflect this light towards 2nd base, where the two beams strike another half-silvered mirror. The setup is such that the two beams headed for left field will cancel each other through destructive interference, i.e., all photons fired from home plate will be detected in right field, none in left field. This implies that each photon took *both* the 1st and 3rd base routes in superposition. If we remove the half-silvered mirror at second base, we detect half of the photons in left field and half in right field, and we know which baselines each photon traveled along. We can therefore choose whether the individual photons should act schizophrenically or not. Indeed, we can delay this choice until seemingly after the fact! Let us turn on the light source for only a billionth of a second, during which time it emits, say, 1000 photons. At the speed of light, the photons travel about a foot during this time. Let us therefore wait a leisurely 10 or 20 billionths of a second after the light source is turned off before we decide which experiment we want to do. The two photon convoys headed for 1st and 3rd base will be separated by many meters by then, unable to communicate with each other. If we want to demonstrate that each photon followed both routes at once, we need only wait and note that no photons make it to left field. If we want to find out which way each photon went, we swiftly remove the 2nd base mirror before the photons have had time to reach it.

it has fallen to the left or to the right, destroying ("decohering") the superposition and making it unobservable. This is somewhat analogous to the way in which interference effects in classical optics would get destroyed if perturbations along the light path messed up the phases.

The most convenient way to understand decoherence is by looking at a generalization of the wave function called the *density matrix*. For every wave function, there is a corresponding density matrix, and there is a corresponding Schrödinger's equation for density matrices. For example, the density matrix of the quantum card fallen down in a superposition would look like this:

$$\text{density matrix} = \begin{pmatrix} a & c \\ c^* & b \end{pmatrix}.$$

The numbers a and b are the probabilities of finding the card face up or face down respectively, and would both equal one half in our case. Indeed, a density matrix having the form

$$\text{density matrix} = \begin{pmatrix} a & 0 \\ 0 & b \end{pmatrix}$$

would represent a familiar classical situation — a card that had fallen one way or the other, but we didn't know which. The off-diagonal numbers in the matrix (c in our simple example) thus represent the difference between the quantum uncertainty of superpositions and the classical uncertainty (mere ignorance).

A remarkable achievement of decoherence theory is to explain how interactions between an object and its environment push the off-diagonal numbers essentially to zero, for all practical purposes replacing the quantum superposition by pure classical ignorance.

If your friend observed the card without telling you the outcome, she would according to the Copenhagen interpretation collapse the superposition into classical ignorance (on your part), replacing c by zero. Loosely speaking, decoherence calculations show that you don't need a human observer to get this effect — even an air molecule will suffice.

Decoherence explains why we do not routinely see quantum superpositions in the world around us. It is not because quantum mechanics intrinsically stops working for objects larger than some magic size. Instead, macroscopic objects such as cats and cards are almost impossible to keep isolated to the extent needed to prevent decoherence. Microscopic objects, in contrast, are more easily isolated from their surroundings so that they retain their quantum secrets and quantum behavior.

The second unanswered question in the Everett picture was more subtle but equally important: what physical mechanism picks out the classical states — face up and face down for the card — as special? The problem was that from a mathematical point of view, quantum states like "face up plus face down" (let's call this "state alpha") or “face up minus face down” (“state beta”, say) are just as valid as the classical states “face up” or “face down”. So just as our fallen card in state alpha can collapse into the face up or face down states, a card that is definitely face up — which equals (alpha + beta)/2 — should be able to collapse back into the alpha or beta states, or any of an infinity of other states into which “face up” can be decomposed. Why don’t we see this happen?

Decoherence answered this question as well. The calculations showed that classical states could by defined and identified as simply those states that were most robust against decoherence. In other words, decoherence does more than just make off-diagonal matrix elements go away. If fact, if the alpha and beta states of our card were taken as the fundamental basis, the density matrix for our fallen card would be diagonal to start with, of the simple form

$$\text{density matrix} = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix},$$

since the card is definitely in state alpha. However, decoherence would almost instantaneously change the state to

$$\text{density matrix} = \begin{pmatrix} 1/2 & 0 \\ 0 & 1/2 \end{pmatrix},$$

so if we could measure whether the card was in the alpha or beta-states, we would get a random outcome. In contrast, if we put the card in the state “face up”, it would stay “face up” in spite of decoherence. Decoherence therefore provides what Zurek has termed a “predictability sieve”, selecting out those states that display some permanence and in terms of which physics has predictive power.

SHIFTING VIEWS

The discovery of decoherence, combined with the ever more elaborate experimental demonstrations of quantum weirdness, has caused a noticeable shift in the views of physicists. The main motivations for introducing the notions of randomness and wave function collapse in the first place had been to explain why we perceived probabilities and not strange macrosuperpositions. After Everett had shown that things would appear random anyway and decoherence had been found to explain why we never perceived anything strange, much of this motivation was gone. Moreover, it was embarrassing that nobody had managed to provide a testable deterministic equation specifying precisely when this mysterious collapse was supposed to occur. Even though the wave function technically never collapses in the Everett view, it is generally agreed that decoherence produces an effect that looks like a collapse and smells like a collapse.

An informal poll taken at a conference on quantum computation at the Isaac Newton Institute in Cambridge in July 1999 gave the following results:

1. *Do you believe that new physics violating the Schrödinger equation will make large quantum computers impossible?* 1 yes, 71 no, 24 undecided
2. *Do you believe that all isolated systems obey the Schrödinger equation (evolve unitarily)?* 59 yes, 6 no, 31 undecided
3. *Which interpretation of quantum mechanics is closest to your own?*
   - (a) Copenhagen or consistent histories (including postulate of explicit collapse): 4
   - (b) Modified dynamics (Schrödinger equation modified to give explicit collapse): 4
   - (c) Many worlds/consistent histories (no collapse): 30
   - (d) Bohm (an ontological interpretation where an auxiliary “pilot wave” allows particles to have well-defined positions and velocities): 2
   - (e) None of the above/undecided: 50

The reader is warned of rampant linguistic confusion in this area. It is not uncommon that two physicists who say that they subscribe to the Copenhagen interpretation find themselves disagreeing about what they mean by this. Similarly, some view the “consistent histories” interpretation (in which the fundamental objects are consistent sets of classical histories) as a fundamentally random theory where God plays dice (as in the recent *Physics Today* article by Omnès & Griffith), whereas others view it more as a way of identifying what is classical within the deterministic “many worlds” context. Such issues undoubtedly contributed to the large “undecided” vote on the last question.

This said, the poll clearly suggests that it is time to update the quantum textbooks: although these infallibly list explicit non-unitary collapse as a fundamental postulate in one of the early chapters, the poll indicates that many physicists — at least in the burgeoning field of quantum computation — no longer take this seriously. The notion of collapse will undoubtedly retain great utility as a calculational recipe, but an added caveat clarifying that it is probably an not a fundamental process violating the Schrödinger equation could save astute students many hours of frustrated confusion.

The Austrian animal behaviorist Konrad Lorenz mused that important scientific discoveries go though three phases: first they are completely ignored, then they are violently attacked, and finally they are brushed aside as well-known. Although more quantitative experimental study of decoherence is clearly needed, it is safe to

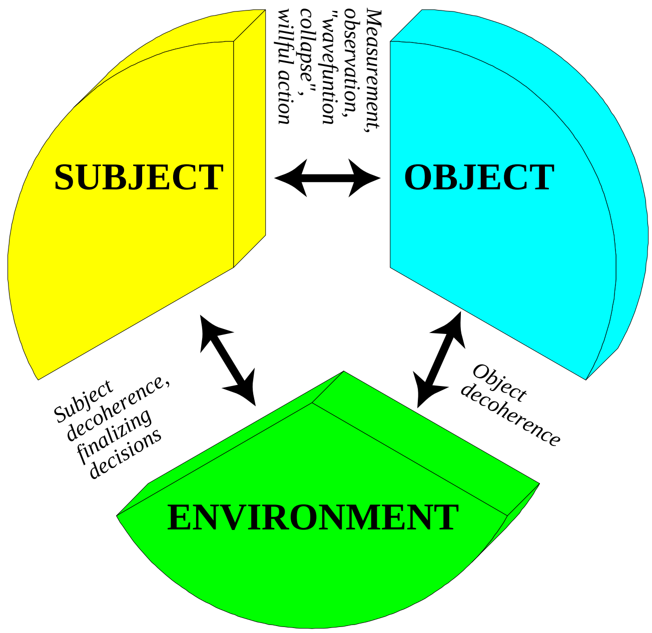

FIG. 3. An observer conveniently decomposes the world into three subsystems: the degrees of freedom corresponding to her subjective perceptions (the subject), the degrees of freedom being studied (the obj ect), and everything else (the environment). As indicated, the interactions between these three subsystems can cause qualitatively very different effects, which is why it is often useful to study them separately.

say that decoherence has now reached the third phase among quantum physicists — indeed, a large part of current quantum computing research is about finding ways to minimize decoherence. The poll suggests that after spending the sixties in phase 1, Everett's idea that physics is unitary (that there is no wave function collapse) is now shifting from phase 2 to phase 3, replacing the collapse interpretation as the dominant paradigm.

HOW DOES IT FIT TOGETHER?

If unitarity and decoherence are taken seriously, then it is instructive to split the Universe into three parts as illustrated in Figure 3. As emphasized by Feynman, quantum statistical mechanics splits the Universe (or, in physics jargon, its "degrees of freedom") into two subsystems: the object under consideration and everything else (referred to as the *environment*). To understand processes such as measurement, we need to include a third subsystem as well: the *subject*, the mental state of the observer. A useful standard technique is to split the Schrödinger equation that governs the time evolution of the Universe as a whole into terms that describe the internal dynamics of each of these subsystems and terms that describe interactions between them. These different terms have qualitatively very different effects.

The term giving the object dynamics is normally the most important one, so to figure out what the object will do, all the other terms can usually be ignored. Consider the quantum card example in Figure 1, with the "object" being the (position of) the card. In this case, the object dynamics is such that the card will fall left and right in superposition. When our observer looks at the card, this subject-object interaction will make her mental state enter a superposition of joy and disappointment over winning/losing her bet. However, she can never be aware of her schizophrenic state of mind, since interactions between the object and the environment (in this case air molecules and photons bouncing off of the card) cause rapid decoherence that makes this superposition completely unobservable.* It would be virtually impossible for her to eliminate this decoherence in practice since the card is so large, but even if she could (say by repeating the experiment in a dark cold room with no air), it wouldn't make any difference: at least one neuron in her optical nerves would enter a superposition of firing and not firing while she looked at the card, and this superposition would decohere in about 10^{-20} seconds according to recent calculations.

There could still be trouble, since thought processes (the internal dynamics of the subject system) could create superpositions of mental states that we do not in fact perceive. Indeed, Roger Penrose and others have suggested that such effects could let our brains act as quantum computers. However, the fact that neurons decohere much faster than they can process information (it takes them about 10^{-3} seconds to fire) means that if the complex neuron firing patterns in our brains have anything to do with consciousness, then decoherence in the brain will prevent us from perceiving weird superpositions.

As mentioned above, we perceive only those aspects of the world that are most robust against decoherence. Decoherence therefore selects what Zurek has termed a "pointer basis", basically the familiar quantities of classical physics, as special. Since all our observations are transmitted through neurons from our sensory organs, the fact that neurons decohere so fast makes them the ultimate pointer basis. As Zeh has stressed, this justifies using the textbook wave function collapse postulate as a useful "shut-up-and-calculate" recipe: compute probabilities as if the wave function collapses when we observe the object. Strictly speaking, we constantly keep entering

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*Although the processes of measurement and decoherence may appear different, there is a symmetry between the object-subject and object-environment interactions, involving the lack of information about the object (entropy): loosely speaking, the entropy of an object decreases while you look at it and increases while you don't. Decoherence is essentially a measurement that you don't know the outcome of.

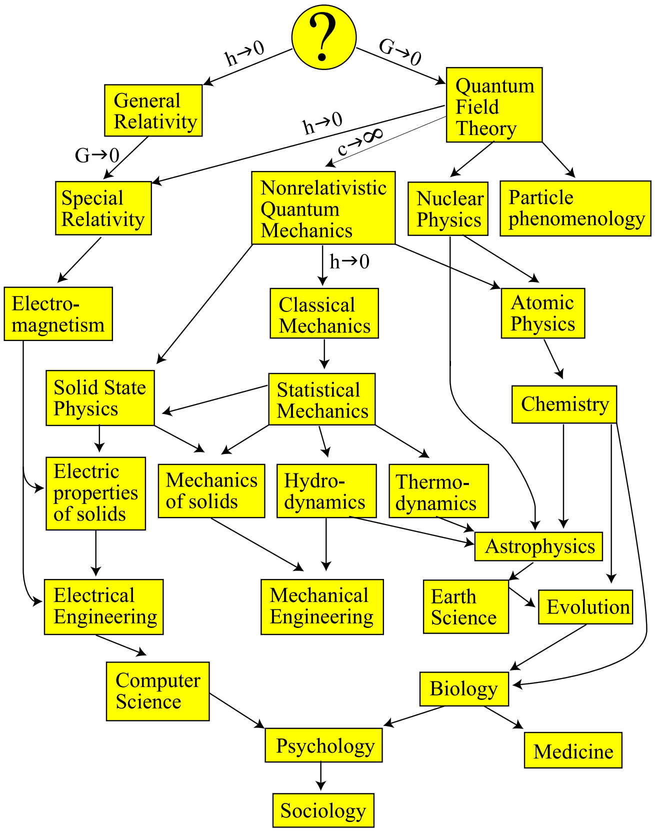

FIG. 4. Theories can be crudely organized into a family tree where each might, at least in principle, be derivable from more fundamental ones above it. For example, classical mechanics can be obtained from special relativity in the approximation that the speed of light c is infinite, and hydrodynamics with its concepts such as density and pressure can be derived from statistical mechanics. However, these cases where the arrows are well understood form a minority. Although chemistry in principle should be derivable from quantum mechanics, the properties of some molecules are so complicated to compute in practice that a more empirical approach is taken. Deriving biology from chemistry or psychology from biology would be even more hopeless in practice.

into superpositions of different mental states, but decoherence prevents us from noticing this — subjectively, we (all superposed versions of us) just perceive this as the slight randomness that disturbed Einstein so much.

A basic question of course remains: can quantum mechanics be understood in terms of some deeper underlying principle? How come the quantum?

LOOKING AHEAD

After 100 years of the quantum, let us take a step back and make some general remarks about what may lie ahead. Although basic issues about ontology and the ultimate nature of reality often crop up in discussions about how to interpret quantum mechanics, this is probably just a piece in a larger puzzle. As illustrated in Figure 4, theories can be crudely organized in a family tree where each might, at least in principle, be derivable from more fundamental ones above it.

All these theories have two components: mathematical equations and words that explain how they are connected to what we observe. Quantum mechanics as usually presented in textbooks has both components: some equations as well as three fundamental postulates written out in plain English. At each level in the hierarchy of theories, new concepts (*e.g.*, protons, atoms, cells, organisms, cultures) are introduced because they are convenient, capturing the essence of what is going on without recourse to the more fundamental theory above it. It is important to remember, however, that it is we humans who introduce these concepts and the words for them: in principle, everything could have been derived from the fundamental theory at the top of the tree, although such an extreme reductionist approach would of course be useless in practice. Crudely speaking, the ratio of equations to words decreases as we move down the tree, dropping near zero for highly applied fields such as medicine and sociology. In contrast, theories near the top are highly mathematical, and physicists are still struggling to understand the concepts, if any, in terms of which we can understand them.

The Holy Grail of physics is to find what is jocularly referred to as a "Theory of Everything", or TOE, from which all else can be derived. If such a theory exists at all, it should replace the big question mark at the top of the theory tree. Everybody knows that something is missing here, since we lack a consistent theory unifying gravity with quantum mechanics. To avoid the problem of infinite regress, where each set of concepts is explained in terms of more fundamental ones that in turn must be explained, a TOE would probably have to contain no concepts at all. In other words, it would have to be a purely mathematical theory, with no explanations or "postulates" as in quantum textbooks (recall that mathematicians are perfectly capable of — and often pride themselves of — studying abstract mathematical structures that lack any intrinsic meaning or connection with physical concepts). Rather, an infinitely intelligent mathematician should be able to derive the entire theory tree from these equations alone, by deriving the properties of the Universe that they describe, the properties of its inhabitants and their perceptions of the world.

The first 100 years of the quantum have provided powerful new technologies and answered many questions. However, physics has raised new questions just as important as those outstanding at the time of Maxwell's inaugural speech; questions regarding both quantum gravity and the ultimate nature of reality. If history is anything to go by, the coming century should be full of exciting surprises.

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