able inference [though not in itself a logically watertight one (*1*)] that no such mechanism of "realization" has come into play by that level.

Even a decade ago, considerable skepticism existed about the prospect of ever observing quantum superpositions involving more than a few "elementary" particles. However, in the last 5 years progress in this direction has been spectacular, ranging from traditional Young's slits experiments conducted with C_{70} molecules (~1300 "elementary" particles) to SQUID experiments in which the two superposed states involved $\sim 10^{10}$ electrons behaving differently (*1*). Thus, the experiments are beginning to impose nontrivial constraints on hypotheses of class (c). If in the future these constraints grow tighter and tighter, we may find that at the end of the day we have no alternative but to live with option (b).

References and Notes

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10.1126/science.1109541

VIEWPOINT

From Pedigree Cats to Fluffy-Bunnies

Jacob Dunningham, Alexander Rau, Keith Burnett*

We consider two distinct classes of quantum mechanical entanglement. The first "pedigree" class consists of delicate highly entangled states, which hold great potential for use in future quantum technologies. By focusing on Schrödinger cat states, we demonstrate not only the possibilities these states hold but also the difficulties they present. The second "fluffy-bunny" class is made up of robust states that arise naturally as a result of measurements and interactions between particles. This class of entanglement may be responsible for the classical-like world we see around us.

The nature of quantum superposition states and how we can "see" them in our classical world continues to fascinate scientists. In recent years, this fascination has led to a new awareness of the potential uses of these states in science and technology. Their nature opens the door to a whole range of new types of precision measurements. They also have important implications for what the classical world around us can look like. In this Viewpoint, we illustrate the nature of entanglement by focusing on two types of quantum states that we call "pedigree cats" and "fluffy-bunnies" (*1*). We want to explain why these states are so fascinating and why the pedigree cats are so difficult to breed and keep alive. They can be thought of as highly entangled, highly vulnerable, and easily killed off. The type of quantum entanglement that is breeding all around us and is responsible for the way we see the world is the wild fluffy-bunny kind.

The idea of a cat state first came about as a consequence of a famous thought experiment of Schrödinger in 1935 (*2*). In it, he imagined that a cat was placed in a box along with a radioactive sample arranged so that if a decay occurred, a toxic gas would be released and the cat killed. Quantum mechanics tells us that at any time the nucleus involved is in a superposition of the decayed and original state. Because the fate of the cat is perfectly correlated with the state of the nucleus undergoing decay, we are forced to conclude that the cat must also be in a superposition state, this time of being alive and dead. This result does not sit comfortably with our experience of the world around us—we would expect the cat to be either alive or dead but not both—and continues to fascinate and provoke discussion. Cat states have now come to refer to any quantum superposition of macroscopically distinct states. Here we call them pedigree cats to emphasize their prized but delicate nature.

Cat states are interesting not only for the questions they raise about quantum mechanics but also for their potential use in new quantum technologies. An important example of this is their use in pushing the limits of precision measurements. Because measurement is a physical process, we would expect the accuracy we can achieve in any measurement to be governed by the laws of physics. For quantum states, the very act of measuring changes the state and so affects subsequent results. This process is known as back-action. We will focus our discussion on interferometry, which is the basis for a wide range of precision measurements. Ultimately the precision that can be achieved in any measurement is subject to Heisenberg's uncertainty principle, which states that the uncertainty in any pair of conjugate variables obeys an inverse relation. The more accurately one variable is measured, the less accurately the other can be known. This leads to a fundamental limit to how accurately quantum phases can be measured that scales as $\Delta\phi \sim 1/N$, where N is the total number of particles involved. In practice, however, measurements are limited by more practical effects. Interferometry schemes, for example, usually use a stream of photons or atoms and are, therefore, normally limited by shot noise, where the measurement accuracy scales as $N^{-1/2}$. This conventional bound to measurement accuracy is a consequence both of the discrete nature of particles and of independent-particle statistics. The fundamental quantum limit (*3*, *4*) can be reached, however, by taking advantage of "cooperation" between the particles in entangled states. There are a number of proposals for how this might be achieved, and an excellent review of them is given by Giovannetti *et al.* (*5*). We will focus here on how entangled states, i.e., pedigree cats, open the door to this possibility.

If we were to split a single particle along the two paths of an interferometer, the state of the particle would be $|\Psi\rangle = \left(|1\rangle|0\rangle + e^{i\phi}|0\rangle|1\rangle\right)/\sqrt{2}$, where the first ket in each term represents the number of particles on one path and the second ket represents the number of particles on the other path. A particle on the second path acquires a phase shift ϕ relative to one on the first. Interferometry schemes generally use a stream of such single-particle states to make a measurement of ϕ. If instead we had a cat state of the form

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|N\rangle|0\rangle + |0\rangle|N\rangle\right) \qquad (1)$$

things would be quite different. The particles in this state are entangled because we cannot write the total state as a tensor product of the state of each of the particles. Another way of saying this is that if we know which way one of the particles goes, we know which way all of them go. This property makes these states very fragile—knowledge of the whereabouts of one particle blows the cover for all the others and destroys the superposition. However, this same property also makes the state very sensitive to phase shifts. In the case considered here, the phase shifts acquired

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by particles in the second path combine to give the state

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|N\rangle|0\rangle + e^{iN\phi}|0\rangle|N\rangle). \quad (2)$$

This gives an N-fold enhancement in phase sensitivity over the single-particle case. However, in order to be even-handed, we should compare the performance of each scheme when the same number of atoms are used. Repeating the single-particle scheme N times gives a phase resolution that scales as $N^{-1/2}$. However, using the cat state gives a phase resolution that scales as N^{-1}, which is the fundamental quantum limit. This possibility of gaining a $\sqrt{N}$ improvement in measurement resolution is one of the reasons that cats are so highly prized. This shows how phase information can be exquisitely encoded on a quantum state, and various schemes have been put forward for achieving this. However, the important challenge is to devise techniques for reading out the information. This read-out should be regarded not as a mere detail but rather as a fundamental part of the physical process.

The key question is, how can we determine the phase between the two terms in Eq. 2? This is closely related to the question of how we can determine that this is indeed a coherent superposition rather than a classical mixture. The standard way to check for coherences is to perform an interference experiment. We can think of this in terms of Young's slits. In this experiment, two slits etched on an otherwise opaque barrier are illuminated with plane waves of light (or matter). On the other side of the barrier, a screen is set up to detect the positions of the particles that have passed through the slits (Fig. 1). It is well known that an interference pattern is seen and that this is due to each particle passing through both slits and interfering with itself when the two paths are recombined on the screen. If we were to include devices, D_1 and D_2, that record which slit each particle passes through, no interference would be seen. It is only by recombining the paths and ensuring that there is no information that betrays which path a particle took that we can confirm the superposition. The state of the photon at the slits can be considered to be catlike in the sense that the particle is in a superposition of two macroscopically distinct locations. The principle of Young's slits interference can therefore be applied as a general technique for seeing signatures of much larger cats.

Cat states have been created in the laboratory for atoms (*6–8*) and for buckminsterfullerene molecules ("bucky balls") (*9*, *10*) in two distinct locations, and interference experiments of the Young's slits type have confirmed that a superposition was created. This suggests a possible route for reading out the precision phases encoded on states of the form of (*3*): By simply overlapping the components on a screen and imaging an interference pattern, the position of the fringes should reveal the phase shift. However, this only works if the cat consists of a single object, e.g., a bucky ball. For the other types of cats, composed of collections of particles, this approach is less successful, as we will now see.

Suppose we had a cat state in a superposition of all N particles passing through one slit and all N particles passing through the other. How do we confirm that we have this superposition? If we had a multiparticle detector that detected all N particles at once, the situation would be equivalent to having one big object, and we would see interference in the multiparticle detections. If, however, we simply applied the Young's slits scheme and detected particles one at a time, i.e., the way we are usually forced to by available detectors, no interference would be seen.

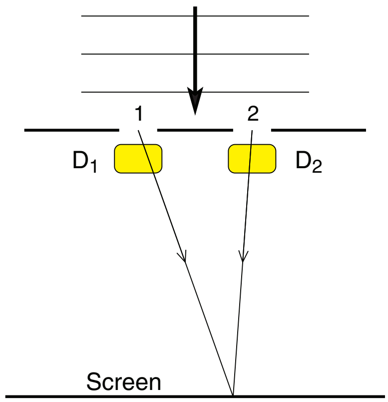

Fig. 1. Young's slits. Plane waves of particles are incident on a barrier with slits etched on it and are detected at a screen. Interference fringes are seen in the variation of intensity with position on the screen. If, however, detectors D_1 and D_2 record which slit each particle passes through, no interference is seen.

We can understand this because, although the detection on the screen cannot distinguish which path the particle took, we can in principle know which one it was. This is because, after the first detection, we could introduce detectors D_1 and D_2 to determine which path the second particle takes. Because all particles pass through the same slit, this also reveals the path that the first particle took. Interference is only seen if it is not possible, even in principle, to determine the particle's path (*11*) and, because it is possible here, no interference is seen. This same argument holds for subsequent measurements right up until the final one. The final detection will exhibit interference fringes because, after this detection, there is nothing left to reveal the path it took.

This result has been expressed elsewhere (*12*) in terms of correlation functions for the positions at which atoms are detected on the screen and, not surprisingly, only the Nth order correlation function reveals any difference between superposition states and mixtures.

In order to see cats, it seems that we not only need to recombine the elements of the superposition, but we also have to ensure that we wipe out any which-path information. This is the principle behind using probes to detect cats. We consider a state of the form of a cat entangled with a probe,

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|X_1\rangle|\uparrow\rangle + |X_2\rangle|\downarrow\rangle), \quad (3)$$

where $|X_1\rangle$ and $|X_2\rangle$ are states with the macroscopically distinct values X_1 and X_2 of some variable, e.g., position or momentum, and $|\rangle$ and $|\downarrow\rangle$ are the states of a single-particle probe, e.g., a photon that has different polarizations or passes through different slits. This has the same form as Schrödinger's original idea of a cat being dead and alive entangled with a nucleus that is decayed and not. If we now perform an interference experiment on the probe state, the probability of detecting a particle corresponding to a phase shift ϕ between the paths is $P_\phi = ½[1 + \Re(e^{i\phi}\langle X_1|X_2\rangle)]$. If the macroscopic states are orthogonal, i.e., $\langle X_1|X_2\rangle = 0$, then there is no interference. If, however, we could operate on state 3 in such a way as to make the macroscopic states indistinguishable, i.e., $\langle X_1|X_2\rangle = 1$, we get $P_\phi = 1 + \cos\phi$, and fringes are visible. This is the idea behind a number of cat schemes, including an experimental study of how superpositions of coherent states of light are affected by loss (*13*) and a theoretical proposal for how cats may be created in the motion of micromirrors (*14*).

In essence, this read-out scheme scarcely differs from the Young's slits scheme, because it involves single-particle interference with no which-path information. The state we are left with, $|X_0\rangle$, is no longer a cat, and our only evidence for the cat's former existence is the faintest murmur of a death cry. It would be nice to have a scheme that provides evidence for the cat without destroying it. One possibility for achieving this is to only "partially recombine" the components of the cat. By this we mean that we perform some operation on Eq. 3 to obtain a state of the form,

$$|\Psi\rangle = \frac{1}{\sqrt{2}}[(a|X_1\rangle + b|X_0\rangle)|\uparrow\rangle + (a|X_2\rangle + b|X_0\rangle)|\downarrow\rangle], \quad (4)$$

where $|a|^2 + |b|^2 = 1$ and, for weak recombination, $|b| \ll |a|$. In this case, we have partially wiped out the which-path information and, if we performed an interference experiment with the probe state, we would see fringes with reduced visibility $|b|^2$. The key point, however, is that, after detecting the probe, the state we are left with is $|\Psi\rangle = a(|X_1\rangle + |X_2\rangle)/\sqrt{2} + \sqrt{2}b|X_0\rangle$, i.e., $|\Psi\rangle \approx (|X_1\rangle + |X_2\rangle)/\sqrt{2}$, and so the macroscopic superposition is only slightly affected. In essence, so long as we can identify fringes with small visibilities, it is possible to find signatures of cats while only delicately changing them. This further emphasizes the important role that precision measurements play in quantum physics.

Although we have found a way to avoid destroying the cats, we are still drawn to the view that recombination (whether complete or partial) is necessary to see them (*15*). If this is true, there are some interesting philosophical consequences. In particular, if no operator exists that can recombine a certain type of cat, then we can never see that cat. For example, in Schrödinger's original experiment, when we open the box, what we see may indeed be a superposition of the cat being alive and dead. However, because there is no "Lazarus operator" that turns dead into alive, there can be no way of distinguishing this from a mixture. We are free to choose the interpretation we wish because there are no physical consequences of picking one in favor of the other. It is much more appealing to our instincts of the world around us to think of it as a mixture, and so this is how we generally interpret it.

We have seen that cat states are very useful but temperamental. They prove difficult to observe, and their form means they are fragile with superpositions that are destroyed by the slightest dissipation (*16–19*). There are also other highly prized pedigree species that form the general class of highly entangled states and, like cats, are well worth studying because of the possibilities they afford in measurement schemes (*5*) and other quantum technologies. Partly because of their fragility and partly because they prove difficult to observe, these pedigree states are not familiar to our everyday experience of the world. What we see instead is a whole different class of states that we call fluffy-bunnies. These are the robust entanglements that arise as a result of measurements and interactions between particles.

The idea of fluffy-bunnies developed from theoretical work undertaken to study the interference fringes that are seen when two Bose-Einstein condensates spatially overlap (*20*). If these condensates are both initially in number states, they contain no quantum phase information, and we would not expect any interference. This is seen from $\Delta N \Delta\phi \sim 1$: If $\Delta N \to 0$, $\Delta\phi \to \infty$. However, a careful analysis of the measurement process reveals the surprising result that interference fringes are in fact seen.

This can be understood because each detection of an atom entangles the two condensates due to the fact that we do not know which condensate the atom came from. This entanglement induces a relative phase between the condensates, which serves to reinforce the probability of certain positions for the next atom detected, and the process continues by a feedback mechanism. An interference pattern builds up on the screen, and the condensates develop a well-defined relative phase. The condensates are now in a fluffy-bunny state: They have acquired a relative observable, which is robust, i.e., it hardly changes with subsequent detections and so is, in a sense, classical. The width of the relative phase distribution scales as $N^{-1/2}$ for the number of atoms detected and so gives us an understanding of the conventional measurement bound for nonpedigree states.

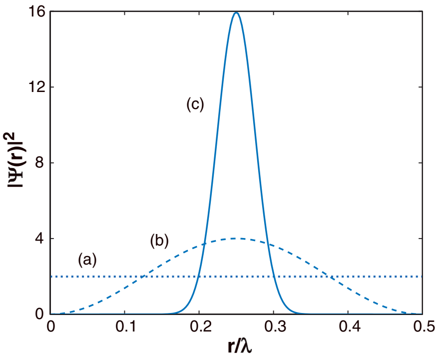

Fig. 2. Relative position probability distribution for an initially delocalized pair of particles after (a) 0, (b) 1, and (c) 20 photons have been scattered from them and detected. The relative position of the particles is plotted in units of the wavelength, λ, of the photons. We see that the relative localization becomes better defined as more detections are made.

These fluffy-bunnies are fascinating and reveal how classical-like variables can emerge from quantum systems. In the case considered here, only relative phases exist; the absolute phase of each condensate remains undefined throughout the process. Furthermore, these phases are transitive so that if we have a collection of condensates and know the phase of each of them relative to any one of them, then we know the relative phase of any pair of condensates. This means that the classical nature of fluffy-bunny entanglements enables us to define a consistent phase standard for Bose-Einstein condensates (*21*). This concept of transitivity is ingrained in our classical perception of the world but is not obvious in quantum mechanics, where measurements generally change the system.

Fluffy-bunnies can be applied equally well to any pair of conjugate variables. For example, they can be used to understand how objects localize in position space—an issue central to the boundary between quantum and classical physics. An analysis has been carried out for light scattering from a pair of particles that are intially smeared out over space, e.g., the particles are each initially in momentum eigenstates (*22*). A sequence of measurements of the scattered photons entangles the two particles, leading to robust semiclassical states of well-defined relative position. This can be seen by considering a system of two particles in momentum eigenstates with relative momentum p, i.e., $|\Psi\rangle = |p\rangle$. After scattering a photon from these particles and detecting the angle at which it is scattered, the state of the particles is

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left[\left|p + \frac{\Delta}{2}\right\rangle + e^{i\phi}\left|p - \frac{\Delta}{2}\right\rangle\right], \quad (5)$$

where Δ is the momentum kick imparted by the photon and ϕ is a phase shift that depends on the angle at which the photon is detected. We see that the measurement has broadened the relative momentum distribution of the particles. Because the system remains in a pure state, Heisenberg's uncertainty relation tells us that this must be accompanied by a reduction in the relative position distribution. This process continues by feedback, and Fig. 2 shows the relative position distribution of the particles after (a) 0, (b) 1, and (c) 20 scattering events. The initially delocalized particles become progressively more localized as more measurements are made, and these relative positions are robust because subsequent measurements do not change their mean value. In this sense, we can think of them as classical variables and can see why fluffy-bunnies describe a world that is much more familiar to our everyday experience. As was the case for the phase of condensates, these localizations are transitive (*23*) and so form a consistent coordinate space. The absolute positions of the particles remain undefined throughout the procedure, which draws us toward the interesting conclusion that relative observables are fundamental in our world.

The pedigree and fluffy-bunny classes of states offer a fascinating insight into quantum physics. Delicate pedigree entanglements give us a fleeting glimpse of the quantum world and hint at the phenomenal potential for new technologies it contains. Their fragile nature, however, means that they do not describe the world we see every day. This role is left to fluffy-bunnies—the wild and hardy states that breed all around us. There is a lot more to be understood about these different classes of states, not least the profound implications that quantum measurement has on the way we see the world and the rich potential it keeps largely hidden from our view.

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10.1126/science.1109545

REVIEW

Time and the Quantum: Erasing the Past and Impacting the Future

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The quantum eraser effect of Scully and Drühl dramatically underscores the difference between our classical conceptions of time and how quantum processes can unfold in time. Such eyebrow-raising features of time in quantum mechanics have been labeled "the fallacy of delayed choice and quantum eraser" on the one hand and described "as one of the most intriguing effects in quantum mechanics" on the other. In the present paper, we discuss how the availability or erasure of information generated in the past can affect how we interpret data in the present. The quantum eraser concept has been studied and extended in many different experiments and scenarios, for example, the entanglement quantum eraser, the kaon quantum eraser, and the use of quantum eraser entanglement to improve microscopic resolution.

The "classical" notion of time was summed up by Newton: "…absolute and mathematical time, of itself, and from its own nature, flows equally without relation to anything external." In the present article, we go beyond our classical experience by presenting counterintuitive features of time as it evolves in certain experiments in quantum mechanics. To illustrate this point, an excellent example is the delayed-choice quantum eraser, proposed by Marlan O. Scully and Kai Drühl (*1*), which was described as an idea that "shook the physics community" when it was first published in 1982 (*2*). They analyzed a photon correlation experiment designed to probe the extent to which information accessible to an observer and its erasure affects measured results. The Scully-Drühl quantum eraser idea as it was described in *Newsweek* tells the story well (*3*), and Fig. 1 is an adaptation of their account of this fascinating effect.

In his book *The Fabric of the Cosmos* (*4*), Brian Greene sums up beautifully the counterintuitive outcome of the experimental realizations of the Scully-Drühl quantum eraser (p. 149):

> *These experiments are a magnificent affront to our conventional notions of space and time. Something that takes place long after and far away from something else nevertheless is vital to our description of that something else. By any classical-common sense-reckoning, that's, well, crazy. Of course, that's the point: classical reckoning is the wrong kind of reckoning to use in a quantum universe …. For a few days after I learned of these experiments, I remember feeling elated. I felt I'd been given a glimpse into a veiled side of reality. Common experience—mundane, ordinary, day-to-day activities—suddenly seemed part of a classical charade, hiding the true nature of our quantum world. The world of the everyday suddenly seemed nothing but an inverted magic act, lulling its audience into believing in the usual, familiar conceptions of space and time, while the astonishing truth of quantum reality lay carefully guarded by nature's sleights of hand.*

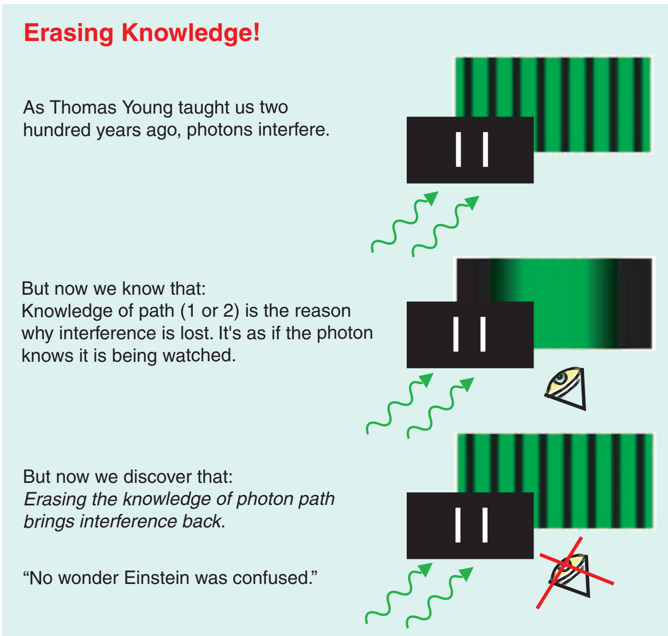

Fig. 1. Schematics for the Young's double-slit experiment. The which-path information wipes out the interference pattern. The interference pattern can be restored by erasing the which-path information.

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