The Physics of the Small and Large: What is the Bridge Between Them?

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We think of the laws of quantum mechanics (and of quantum field theory) as underlying our physical descriptions of small-scale phenomena, whereas large-scale physics is described by the use of classical fields. The mathematical descriptions that are used at these two scales are very different; yet they have several fundamental qualities in common. Each depends upon a time-evolution governed by partial differential equations, each of which provides a completely deterministic evolution that is both time-symmetrical and local. At the *quantum level* **U**, we have a *state-vector*, with a time-evolution governed by the Schrödinger equation—the most usual formulation of *unitary evolution*—whereas at the *classical level* **C**, we have classical *fields* governed by the equations of Maxwell(–Lorentz) for electrodynamics and those of Einstein's curved spacetime geometry for gravitational physics. The well-known *indeterminacy* of quantum theory is not part of either the quantum-level (**U**) or classical-level (**C**) equations. It comes in only when the "measurement" of a quantum system is made, which happens when a quantum-level process is magnified to the classical level. (A Geiger counter provides a good example: upon receiving a quantum particle, this device induces such a process of magnification, resulting in an audible classical-level "click".) In conventional treatments, this "measurement process" is described by a mathematical procedure completely different from either **U**'s Schrödinger equation or **C**'s classical field equations, and which shares none of the fundamental characteristics common to **U** and **C** just pointed out, being *non*-deterministic, time-*a*symmetrical, and *non*-local. The state-vector is taken, instead, to *jump* from one state to another, in a way that is *random*, the outcome being constrained only by *probability laws*. This "jumping" evolution **R** is referred to as *state-vector reduction* (or collapse of the wavefunction). The inconsistency of **R** with **U** is referred to as the *measurement paradox*.

The best known manifestations of the non-locality in **R** are EPR (Einstein–Podolsky–Rosen) phenomena, whereby pairs of particles emitted from a common source continue to behave as a single entity despite their being widely separated—by up to some 10 kilometres or more, according to careful experiments—until a measurement is performed on one or the other particle. The presence of this non-locality is made manifest in the violation of the famous *Bell inequalities*. These inequalities would have to be satisfied by the joint probabilities of the results of measurements performed on each member of a pair of particles if they were to behave as separate independent entities. Thus, in quantum mechanics, they are *not* separate independent entities, but behave as an integral "whole", right up until a measurement is performed on one or the other of them. Such a particle pair is described, quantum mechanically, as an *entangled state*—a concept first recognized by Schrödinger. The "quantum non-locality" comes about when the separate components of an entangled state are measured. There are two deep puzzles here. The first is the existence of the phenomenon itself; the second is a complementary puzzle: why does the system of particles in the universe not behave as an "entangled mess" instead of seeming to consist of essentially independent parts? In my opinion, the latter puzzle is another aspect of the measurement paradox. A measurement on one component of an EPR pair cuts it loose from its entanglement with the other component.

An even more fundamental feature of the quantum-level world is the *superposition principle*, which tells us that quantum state-vectors form a complex linear space: if Ψ and Φ are two allowable quantum states, then so is any (non-zero) complex linear combination $w\Psi+z\Phi$. The equally fundamental *linearity* of **U** tells us that the **U**-evolution of this combination maintains exactly this same form, as the linear combination of the individual **U**-evolutions of Ψ and Φ (where w and z are constant). This leads us directly to the *paradox of Schrödinger's cat* in which a belief in the universal validity of **U** leads us to have to accept that a *cat* could be put into a linear combination of being alive and dead! Schrödinger proposed this *thought experiment* in order to point out the limitations of his own equation (i.e. of **U**) when applied to a macroscopic object such as a cat. Put another way, this tells us that it makes no sense to take the ontological position that a state-vector evolving universally according to **U** can describe *reality*, where this "reality" refers to the evolving world that we perceive about us. Most philosophically minded modern quantum physicists would either follow Niels Bohr and deny any reality to the quantum state, or else take the "many-worlds" position in which the quantum state essentially *is* reality, but all outcomes of a quantum measurement (including our perceptions of these outcomes) "coexist" in parallel real worlds, all in quantum linear superposition. A practically minded physicist might, on the other hand, take a "pragmatic" viewpoint and not worry about these ontological issues at all—since no practical experiment could detect the interference effects needed to confirm the presence of macroscopic superpositions, such as that of a live with a dead cat. Opposed to all these is the class of viewpoints according to which **U** is but a superb *approximation* to a quantum-level reality, described by a yet-unknown physical theory; indeed, *all* of **U**, **C**, and **R** would, accordingly, be superb approximations at, respectively, the quantum level, the classical level, and the bridge between the two. This would include an *objectively real* version of **R**, that I refer to as **OR**.

But what is it that characterizes this notion of "level"? It is certainly not just a matter of distance. I referred, earlier, to the quantum-mechanical EPR effects stretching to at least 10 kilometres. It is my own strong opinion that in order to get a better idea of what kind of criterion to adopt, we must turn to that other great revolution in 20^{th} century physics: Einstein's general theory of relativity. There are many approaches to the question of *quantum gravity*, i.e. of forging a union between Einstein's general relativity and the principles of quantum mechanics, but almost all of these (and certainly all of the popular ones) would take the laws of quantum mechanics (or, more properly, of quantum *field* theory) to be sacrosanct. Accordingly, the term "quantum gravity" is generally taken to refer to a theory that is conventional as a quantum field theory, and which incorporates Einstein's theory only as a classical-level limit. However, I contend that there are strong reasons to believe that Nature's own "quantum gravity" must have features that are distinctly *non-standard* as a quantum field theory. Two of the most important of these reasons have to do with the nature of the *spacetime singularities* that classical general relativity tells us would have to be present within *black holes* and at the *Big Bang* origin of the universe—were it not for quantum effects. Specifically, one of these two reasons has to do with the ultimate (seeming) loss of unitarity (i.e. violation of **U**) in the final stage of Hawking's black-hole evaporation process; the other has to do with the gross time-asymmetry that we find in the structure of spacetime singularities. This time-asymmetry is fundamentally connected with the Second Law of Thermodynamics; indeed, the extraordinarily special nature of the Big Bang (to a greater precision than about 1 in $10^{10^{123}}$, in terms of phase-space volume) can be identified as the *source* of the Second Law. Arguments have been put forward, using inflationary cosmology, the anthropic principle, or both, which attempt to explain away this fantastic precision, but such arguments are not able come close to providing an explanation. I believe that these reasons give us very strong motivation for a belief that our sought-for "quantum gravity" must be a *time-asymmetric* theory, since black-hole "singularities of destruction" are *not* subject to the same enormous constraint, despite their being seemingly *time-reverses* of the Big Bang's "singularity of creation". The time-asymmetry can be related to the aforementioned time-asymmetry in the **R** process, so it seems to be reasonable to suppose that the appropriate quantum/gravity union that we seek should indeed incorporate such a proposed yet-unknown physical process **OR** to which **R** is such a good approximation.

There are other arguments which support this view, but which go much further in identifying the explicit criteria for defining the line which separates the quantum from the classical levels. The clearest of these involves an investigation of a fundamental tension between basic principles of quantum mechanics and those of general relativity: specifically, between **U** and Einstein's principle of general covariance (giving an instance of the so-called "problem of time" in quantum gravity). An inanimate version of Schrödinger's cat is considered, according to which an object is placed in a quantum superposition of two slightly different locations, each of which would be stationary on its own (and of the same energy). In standard **U**-quantum mechanics, the superposition would also be stationary. However, the Schrödinger notion of "stationarity" requires an operator "$\partial/\partial t$", the "stationary states" being its eigenstates. In a background curved spacetime geometry, describing a stationary gravitational field, we have a *Killing vector* $\boldsymbol{K}$, which plays the role of "$\partial/\partial t$". But if we need to be concerned with the gravitational field *of* the object itself, then we have two slightly different $\boldsymbol{K}$s, one for each of the two stationary spacetimes of the two different locations of the object, these having to be in quantum superposition. One might imagine that the appropriate "$\partial/\partial t$" operator, in terms of which the Schrödinger equation for the superposition is to be expressed should be some sort of *average* of the two $\boldsymbol{K}$s, but to form any such average would go against the spirit of the principle of general covariance. Such an "average" would involve a pointwise identification of the two spacetimes in superposition, which is inconsistent with general covariance. Strictly speaking, this would be "cheating"! One can, however, proceed by allowing this "cheat", provided that due account is taken of the *error* involved in doing so. This error can be estimated, at least in the Newtonian limit of small velocities and small gravitational fields, the resulting error measure being a quantity E_G, which turns out to be the *gravitational self-energy* of the *difference* between the mass distributions in the two locations of the object. These mass distributions are taken as *expectation values*, for the two individual stationary wavefunctions. The quantity E_G represents a fundamental "uncertainty" in Schrödinger's "$i\hbar\partial/\partial t$", so it corresponds to a fundamental uncertainty in the energy of the superposition. Comparing this with Heisenberg's time/energy uncertainty relation (as is applied to an unstable nucleus), we can estimate a *lifetime* of the order of $\hbar/E_G$, for the superposition to "decay" (effectively randomly) into one or other of the stable (stationary) components of which it is composed. Thus, **R** is effected spontaneously (without a conscious observer needing to be present to perceive the result). This indeed provides a plausible physical basis for an **OR** process.

But is the overall time scale plausible? The energy E_G is very tiny, for ordinary human-scale objects (such as a cat!), but so also is $\hbar$. In fact we find that the "decay times" seem very reasonable, giving no conflict with any experiment performed to date (confirming the expectations of standard quantum theory). On the other hand, for cat-scale objects in quantum superposition, reduction to one or the other component would be virtually instantaneous, thus removing Schrödinger's paradox. To test these ideas at the critical intermediate scale, there are difficult but feasible experiments that could be performed, such as to put a tiny crystal, about the size of a speck of dust, into a quantum superposition of two slightly differing locations, displaced one from the other by about a nuclear diameter, where it is anticipated that **OR** should then occur in about a tenth of second. A proposed experiment to test whether this is correct is being actively investigated by colleagues of mine in Oxford.

If such experiments were actually to confirm the predictions of this kind of **OR** proposal, this could provide pointers for a future unified mathematical theory that might supersede our present-day **U**/**R**/**C** hybrid. It is hard to see how this could be achieved without a major revolution, however, of the magnitude of conceptual change that we have already witnessed in gravitational theory, where Einstein's curved-spacetime replaced Newtonian forces. It is to be hoped that such a revolution would provide us with a more consistent ontology than does present-day quantum mechanics. This would also have practical advantages in the application of quantum ideas to subjects like biology—in which one does *not* have the clean distinction between a quantum system and its classical measuring apparatus that our present formalism requires. In my opinion, moreover, this revolution is needed if we are ever to make significant headway towards a genuine scientific understanding of the mysterious but very fundamental phenomenon of conscious mentality.

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