Are Our Best Physical Theories (Probably and/or Approximately) True?

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There is good reason to suppose that our best physical theories are false: In addition to its own internal problems, the standard formulation of quantum mechanics is logically incompatible with special relativity. I will also argue that we have no concrete idea what it means to claim that these theories are approximately true.

1. Introduction. Quantum mechanics and special relativity are the two cornerstones of modern physics. Together they provide the most accurate empirical predictions we have ever had. But are they true, probably true, or probably approximately true as descriptions of the physical world? There is good reason to answer the first two parts of this question with no. And answering the third part will require some care.

The standard von Neumann-Dirac collapse formulation of quantum mechanics is logically inconsistent on a strict, uncharitable reading; and it is inconsistent with special relativity in a perfectly straightforward sense. Moreover, it is unclear how to get a consistent description of the physical world out of the two theories, and the various alternative proposals for how one might get started on this project suggest radically different physical worlds. Consequently, we have good reason to suppose that the standard formulation of quantum mechanics and special relativity considered together are false, and it is impossible now to say how they might be taken to be approximately true.

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Note that the argument here that our best physical theories are false is not a pessimistic induction on our past failures to produce the right physical theory. Rather, we have good reason to believe that our best current physical theories are false on the basis of their internal structure and their relationship to each other.

Insofar as scientific knowledge is our best empirical knowledge, and physical theories are a paradigm of scientific knowledge, we should expect to learn something about the fundamental nature of our best empirical knowledge by considering the cognitive status of our best physical theories.

2. The Standard Formulation of Quantum Mechanics. The standard collapse formulation of quantum mechanics, which is still the one presented in most textbooks, was first described by P. A. M. Dirac and John von Neumann in the early 1930s. This theory was an attempt to unify the earlier theoretical work of Heisenberg and Schrödinger and the interpretational insights of Max Born. The standard formulation of quantum mechanics can be summarized as follows:

1. Representation of states: The state of a physical system S is represented by an element $|\psi\rangle_S$ of unit length in a Hilbert space $\mathcal{H}$.
2. Representation of observables: Every physical observable O is represented by a Hermitian operator $\hat{O}$ on the Hilbert space, and every Hermitian operator on the Hilbert space corresponds to some complete observable.
3. Interpretation of states: A system S has a determinate value for observable O if and only if it is in an eigenstate of O: that is, S has a determinate value for O if and only if $\hat{O}|\psi\rangle_S = \lambda|\psi\rangle_S$, where $\hat{O}$ is the Hermitian operator corresponding to O, $|\psi\rangle_S$ is the vector representing the state of S, and the eigenvalue λ is a real number. In this case, one would with certainty get the result λ if one measured O of S.
4. Laws of motion:

   I. Linear dynamics: if no measurement is made of a physical system, it will evolve in a deterministic, linear way: if the state of S is given by $|\psi(t_0)\rangle_S$ at time t_0, then its state at a time t_1 will be given by $\hat{U}(t_0, t_1)|\psi(t_0)\rangle_S$, where $\hat{U}$ is a unitary operator on $\mathcal{H}$ that depends on the energy properties of S.

   II. Nonlinear collapse dynamics: if a measurement is made of the system S, it will instantaneously and nonlinearly jump to an eigenstate of the observable being measured (a state where the system has a determinate value of the property being measured). If the initial state is given by $|\psi\rangle_S$ and $|\chi\rangle_S$ is an eigenstate of O, then the probability of S collapsing to $|\chi\rangle_S$ is equal to $|\langle\psi|\chi\rangle|^2$. That is, if a measurement is made, then the system instantaneously and randomly jumps from the initial superposition to an eigenstate of the observable being measured

$$\psi = \sum_k c_k \, |\psi_k\rangle \longrightarrow |\psi_j\rangle \tag{1}$$

where $|c_j|^2$ is the probability of ending up in the eigenstate $|\psi_j\rangle$.

The standard eigenvalue-eigenstate link (rule three) and the collapse dynamics (part II of rule four) follow from Born's statistical interpretation of quantum-mechanical states and state completeness (the claim that the standard quantum-mechanical state of a system provides a complete physical description of the system).

While the standard formulation of quantum mechanics has proven remarkably successful in explaining counterintuitive quantum phenomena and in making accurate statistical predictions, the quantum measurement problem threatens the theory with inconsistency. The collapse dynamics is supposed to tell us what happens when a measurement is made and the deterministic dynamics is supposed to tell us what happens the rest of the time. If we suppose that measuring devices are ordinary physical systems interacting in their usual deterministic way (and why wouldn't they be), then we get a straightforward logical contradiction between the states predicted by the two dynamical laws.

The problem can be seen by considering a simple experiment where one measures the x-spin of a system S. Suppose that we build an x-spin measuring device M so that if S starts in a determinately x-spin up state and M starts in a ready-to-make-a-measurement state, the x-spin of S is undisturbed by M and M ends up reporting that the measurement result was *up* and that if S starts in an x-spin down eigenstate and M starts in a ready-to-make-a-measurement state, the x-spin of S is undisturbed and M ends up reporting that the measurement result was *down*. That is, suppose that M has the following two dispositions:

(A) $|\text{ready}\rangle_M|\downarrow\rangle_S \rightarrow |\text{up}\rangle_M|\downarrow\rangle_S$

and

(B) $|\text{ready}\rangle_M|\downarrow\rangle_S \rightarrow |\text{down}\rangle_M|\downarrow\rangle_S$

Now suppose that M measures the x-spin of S when it is initially in an eigenstate of z-spin, a superposition of x-spin up and x-spin down eigenstates, and suppose that the interaction between the two systems is described by the linear dynamics. Here the composite system $M + S$ begins in the state

$$\text{ready}\rangle_M 1/\sqrt{2}(|\uparrow\rangle_S + \ \downarrow\rangle_S) = 1/\sqrt{2}(|\text{ready}\rangle_M |\uparrow\rangle_S + |\text{ready}\rangle_M |\downarrow\rangle_S) \quad (2)$$

Since the time-dependent Schrödinger dynamics is linear and since our measuring device has dispositions (A) and (B) above, the composite system will evolve to the state (i) $1/\sqrt{2}(|\text{up}\rangle_M |\uparrow\rangle_S + |\text{down}\rangle_M |\downarrow\rangle_S)$ which is a superposition of M recording x-spin up and S being x-spin up and M recording x-spin down and S being x-spin down (because the dynamics is linear, one can figure out what happens to each term of the initial linear superposition individually, then take the linear superposition of the results as the final state). The problem is that if one takes this to be a complete and accurate description of the post-measurement state, then one cannot say that M recorded a determinate result; or more precisely, one cannot say that M recorded *up* and one cannot say that M recorded *down*. In order to take the quantum-mechanical state as complete and accurate and to account for the repeatability of measurements, one must suppose that the post-measurement state is either (ii) $|\text{up}\rangle_M|\uparrow\rangle_S$ or (iii) $|\text{down}\rangle_M|\downarrow\rangle_S$, and here these states are each incompatible with the linear dynamics. So, given the standard interpretation of quantum-mechanical states, there must be a different dynamical law for measurement processes.

In the standard formulation of quantum mechanics it is the collapse dynamics that gets one from a state like (i) where there is no determinate measurement record to one like (ii) or (iii) where there is a determinate measurement record. The problem is that the standard theory does not tell us what constitutes a measurement, so there is no consistent prescription for when to apply the linear dynamics and when to apply the collapse dynamics. And there are always experiments that might at least in principle distinguish between states predicted by the linear dynamics, states like (i), and states predicted by the collapse dynamics, states like (ii) or (iii). Perhaps there is something special about measuring devices, something that causes them to behave in a radically different way from other systems. But until one says exactly what it is that distinguishes measuring devices from other physical systems, one cannot claim to have a complete and consistent physical theory. So the standard formulation of quantum mechanics is logically inconsistent if one supposes that measuring devices are physical systems like any other, and it is incomplete in an empirically significant way if one supposes that they are somehow different.

There is perhaps good reason to suppose that the collapse dynamics is to blame for the measurement problem, and it has always been viewed with some suspicion. As Wolfgang Pauli argued, for a particle initially in a superposition of different locations "it is not reasonable to invent a causal mechanism according to which 'looking' fixes the position" (Pauli 1971, 222). Pauli concluded that the collapse dynamics cannot describe a real physical process. (Pauli seems to have taken the collapse dynamics to describe a non-physical aspect of nature, perhaps something involving the evolution of mental states. While it is unclear exactly what he had in mind, what he said to Max Born in this 1954 letter suggests some sort of mind-body dualism and is consistent with David Albert and Barry Loewer's single-mind and many-minds formulations of quantum mechanics.)

Einstein certainly held the collapse dynamics to be philosophically objectionable, but he also had straightforward physical worries concerning the relationship between the standard formulation of quantum mechanics and relativity. As early as 1927, Einstein complained that the collapse dynamics and the essential use of configuration space to represent the states of entangled systems in quantum mechanics implied, to his mind, "a contradiction with the postulate of relativity" (Instituts Solvay 1928, 256). Einstein was certainly right to worry about the compatibility of the standard theory and relativity.

But it is easier to complain about the collapse dynamics than it is to explain how to get by without it. Given the standard interpretation of quantum-mechanical states, which is still held by the overwhelming majority of physicists, it is the collapse dynamics that explains how measurements yield determinate measurement records at all. It is also the collapse dynamics that explains correlations between the results of repeated measurements on a single system. And, more generally, it is the collapse dynamics that provides the statistical predictions that make quantum mechanics an empirically successful theory in the first place.

To be sure, there are other formulations of quantum mechanics. Many of these have been cooked up with the specific aim of resolving the quantum measurement problem. Detailed descriptions of these theories can be found elsewhere (see, for example, Albert 1992 and Barrett 1999), but there are three features of alternative formulations of quantum mechanics that are worth noting for the philosophical purposes at hand.

First, alternative formulations of quantum mechanics typically suggest radically different metaphysical commitments concerning the nature of the physical world. Some formulations are deterministic (Bohm's theory), others are stochastic (GRW and other collapse theories); some have a rich ontology of physical properties (the standard collapse theory), others explain all phenomena by appeal to the determinate value of a single physical quantity (Bohm's theory, GRW, and some modal theories); some make it impossible to specify diachronic identity conditions for physical objects (the bare theory, DeWitt's splitting worlds theory, and Bell's Everett (?) theory); some require that the physical world be thought of as being constituted by many universes (DeWitt's splitting worlds theory and Barrett's many-threads interpretation of Everett); some suggest that there are typically no simple, determinate matters of fact concerning classical physical properties (the bare theory, relational quantum mechanics, correlations without correlata, and the relative-fact interpretation of Everett); and some seem to require a commitment to a strong form of mind-body dualism (Albert and Loewer's many-minds theory). (See Albert 1992, Barrett 1999, Bub 1997, Dickson 1998, and Rovelli 1997 for surveys and descriptions of these formulations of quantum mechanics.)

Second, alternative formulations of quantum mechanics provide striking examples of empirical underdetermination. Here we have radically different theories in terms of the fundamental structure of the physical worlds they describe, yet distinguishing the theories from each other from their empirical predictions ranges from being very difficult to being in principle impossible. (While some collapse theories, like GRW, make slightly non-standard empirical predictions, many no-collapse theories, like Bohm's theory and Albert and Loewer's many minds theory, are empirically indistinguishable from each other.)

Finally, and this is the point that we will turn to next, most non-standard formulations of quantum mechanics are, like the standard collapse theory, logically incompatible with the constraints of special relativity. And it is those theories that might most readily be translated into forms that are compatible with relativity (the bare theory, relational quantum mechanics, relative-fact interpretations of Everett, and Albert and Loewer's many-minds theory) that seem to require the most outlandish metaphysical commitments. This has led some philosophers of physics to take seriously the possibility that relativity might be given up as being descriptive of the fundamental spacial-temporal structure of the physical world. (Tim Maudlin, David Albert, and Craig Callender are among those who have considered this possibility. See Albert 2000 for a description of various ways that one might understand the relationship between quantum mechanics and relativity and the status of relativity. See also Bacciagalluppi 2001 for a recent discussion of the relationship between many-worlds formulations and special relativity.) But most physicists would presumably be unwilling to entertain giving up relativity.

It is easy to show the incompatibility of the standard collapse formulation of quantum mechanics and special relativity. The incompatibility of most other formulations of quantum mechanics and special relativity can also be shown by closely analogous arguments to the one that follows.

3. Special Relativity and Its Incompatibility with Quantum Mechanics. Following Einstein, special relativity is usually presented as two physical principles, the principle of relativity and the principle of the constancy of the speed of light, followed by a derivation of the Lorentz transformations and a description of some of their physical consequences.

The principle of relativity says that the same physical laws will be valid for all inertial (unaccelerated) frames of reference. The principle of the constancy of the speed of light says that light is always propagated in empty space with a speed c which is independent of the relative state of motion of the emitting body (Einstein 1905).

Einstein noted that while these two principles may at first appear to be mutually contradictory, they can be satisfied if the relationship between coordinate systems in different inertial frames (the unprimed inertial frame and the primed inertial frame moving at velocity v along the x-axis relative to the unprimed frame) is given by the Lorentz transformations:

$$x' = \frac{x - vt}{\sqrt{1 - \left(\frac{v^2}{c^2}\right)}}$$

$$y' = y$$

$$z' = z$$

$$t' = \frac{t - \left(\frac{vx}{c^2}\right)}{\sqrt{1 - \left(\frac{v^2}{c^2}\right)}}$$

where c is the speed of light in vacuum.

These transformations can be thought of as the simplest relations between inertial coordinate systems that would allow two observers (unprimed and primed) initially at the source of a spherically propagating flash of light to describe the flash as a spherically symmetric wave propagating at the speed of light away from each observer in her own intertial frame. The point of *simplest* here is that the Lorentz transformations do not follow from the principle of relativity and the constancy of the speed of light alone, but also require a small handful of plausible symmetry assumptions.

The following are almost invariably mentioned in textbook presentations as consequences of the Lorentz transformations (together with standard physical assumptions). The mass m of a physical object depends on its velocity v

$$m = \frac{m_0}{\sqrt{1 - \left(\frac{v^2}{c^2}\right)}}$$

where m_0 is its rest mass and c is the speed of light in vacuum. It follows that the mass increase of the object is given by

$$m - m_0 = \frac{E_k}{c^2}$$

And it follows from this that mass and energy are related to each other by the expression $E = mc^2$. It also follows that c is a limiting speed for objects with a positive rest mass. And it is almost always mentioned in standard textbook presentations of special relativity that a rapidly traveling twin would age more slowly than her sedentary brother.

The Lorentz transformations and the principle of relativity entail something else concerning the temporal relationships between events that is perhaps less familiar: Space-like separated events (events that cannot be signaled between luminally) have no canonical temporal order. More specifically, if events E and F are space-like separated, then there will be an inertial frame E where an observer **E** would take E to occur first and another inertial frame F where an observer **F** would take F to occur first. And from this it follows, by the principle of relativity as typically understood, that there can be no physical matter of fact concerning the temporal order of the two events.

That special relativity predicts that there is generally no physical matter of fact concerning the temporal order of events provides a straightforward way of showing the incompatibility of the standard formulation of quantum mechanics and relativity.

Consider an electron e^- and two boxes E and F equipped with alarm clocks. The clocks are synchronized, the alarm on clock E is set to noon on 1 January 2050, and the alarm on clock F is set to noon plus one minute on the same date. The electron is put into a superposition of being in each box. An observer Fred then carefully carries box F far from Earth (further than one light-minute away); and another observer Elle carefully positions box E near Earth. Fred and Elle are each instructed to look for the electron in their box when the alarm on their clock rings.

Suppose that the initial state of the electron (in any inertial frame!) before either observer makes a measurement to locate it is

$$\frac{1}{\sqrt{2}}(|\text{Earth}\rangle_{e^-} + |\text{Far Away}\rangle_{e^-}$$

Now suppose that the standard formulation of quantum mechanics is right and that the collapse dynamics describes the time-evolution of quantum-mechanical states whenever there is a measurement interaction. What is the physical state of the electron when Fred measures it?

Since the measurement events are space-like separated, there will be an inertial frame $\mathcal{E}$ where Elle makes her measurement first. In this case, Elle's measurement caused a collapse, and the state of the electron when Fred makes his measurement is either (1) $|\text{Earth}\rangle_e$ or (2) $|\text{Far Away}\rangle_e$ with probability 1/2 in each case.

But since the measurement events are space-like separated, there will also be an inertial frame $\mathcal{F}$ where Fred is the first to look for the electron. In this case the state of the electron when Fred makes his measurement is (3) $\frac{1}{\sqrt{2}}(|\text{Earth}\rangle_e + |\text{Far Away}\rangle_e)$ since Elle has not yet interacted with the electron.

States (1), (2), and (3) are mutually exclusive. On the standard interpretation of quantum-mechanical states, state (1) describes an electron that is determinately in the box on Earth, state (2) describes an electron that is determinately in the far-away box, and state (3) describes an electron that has no determinate position whatsoever. And again, there are experiments that would in principle empirically distinguish between state (1) or (2) and state (3).

Since the standard formulation of quantum mechanics requires mutually incompatible states for different inertial frames, it is flatly inconsistent with the principle of relativity. So quantum mechanics and special relativity taken together are logically inconsistent.

Since the standard formulation of quantum mechanics had problems even before we considered its relationship with special relativity, a natural reaction would be to blame quantum mechanics for the inconsistency. The problem here presumably lies not with the standard linear quantum dynamics. The linear dynamics can be translated into a form that is compatible with the constraints of relativity in the context of a relativistic quantum field theory. One might consequently naturally suppose that the fault lies with the collapse dynamics.

While one might have thought that the quantum measurement problem would be resolved by finding a satisfactory prescription for when collapses occur, no formulation of mechanics that predicts collapse events like the one described in the story above can be compatible with the constraints imposed by relativity. And one cannot simply give up the collapse dynamics because this is what predicts the standard quantum statistics; and again, that is what makes quantum mechanics worth taking seriously in the first place. Indeed, without the collapse dynamics we lose the standard explanation for how one gets determinate measurement records at all. And even in a relativisitic quantum field theory one should want to explain how we get determinate measurement records distributed with the standard quantum statistics.

One might, of course, try non-standard explanations for how we get determinate measurement records distributed with the standard quantum statistics. One approach is to find a form of the collapse dynamics that is compatible with relativity, but these invariably suggest exotic structures for the physical world (Albert and Aharonov 1980, 1981 and Fleming 1988) and perhaps are untimately still incomparible with the constraints imposed by relativity (Malament 1996). Or one might get rid of the collapse dynamics altogether. There are several no-collapse formulations of quantum mechanics around. But most no-collapse theories are also incompatible with relativity, it is extremely difficult to see how to get compatibility, and the different fixes being considered suggest very different sorts of physical worlds. Those no-collapse theories that are most readily made compatible with relativity purchase this virtue at a high price (consider the bare theory, Albert and Loewer's many minds theory, relative-fact interpretations of quantum mechanics, and relational quantum mechanics). Indeed, it can be argued that at least some of these theories fail to make any empirical predictions whatsoever when taken as descriptions of the physical world (consider the bare theory, relative-fact interpretations of Everett, and relational quantum mechanics) (Barrett 1999).

The upshot is that a commitment to relativity makes resolving the quantum measurement problem all the more difficult and introduces a breadth of possibilities that make it all the more difficult to know what one is claiming when one claims that our current best physical theories are approximately true as a descriptions of the physical world. This last point is just that if wildly different proposals are all taken seriously, it is impossible to take seriously any of them to be approximately true.

4. Probable Truth and Approximate Truth. Insofar as inconsistent theories cannot be true, we know that the standard collapse formulation of quantum mechanics and special relativity taken together are false.

If our two best physical theories taken together are neither true nor probably true, then perhaps they are probably approximately true. This seems safe enough, but, given the discussion so far, it is not at all clear what it means. The safe optimism here is purchased at the cost of being hopelessly vague.

Part of the puzzle is to explain the sense in which mutually contradictory descriptions of the world might each be approximately true. Of course, a logical contradiction insofar as it is logically false is as far from the truth as possible. Our current best physical theories do not describe any possible world whatsoever, so in this sense, they are not even in the ballpark of accurately describing the actual physical world.

Perhaps then our theories are approximately true in the sense that it would take only a minor change in the statement of the theories to get from our current inconsistent description of the physical world to a true description. But in the case of quantum mechanics and relativity we have no concrete idea concerning what it means to claim that we are within a minor descriptive change of the truth since we do not know what this descriptive change might be.

There is a more general point here that can perhaps be made by first distinguishing between forward and backward-looking notions of scientific progress. There are many concrete backward-looking notions of scientific progress that one might describe. Insofar as one can specify the content of our current physical theories, one can describe exactly how our current physical theories have succeeded where our past physical theories failed. This does not provide a single, canonical, backward-looking notion of progress; rather, it provides different backward-looking notions of progress for each theoretical virtue one might consider. One might praise Copernican astronomy for giving up the Ptolemaic earth-centered system, which certainly stood in the way of developing a universal mechanics, yet recognize that the empirical predictions of Copernican mechanics were not as accurate. Or one might concede various mechanistic explanatory virtues to Cartesian mechanics over Newtonian mechanics yet recognize the blatantly ad hoc nature of the former theory (especially after attempts to incorporate the successes of Newtonian mechanics into Cartesian mechanics). And it is worth noting here that only some of the ways in which one might compare our current best physical theories to their predecessors come in degrees and thus lend themselves to talk of approximation at all (It is difficult to assign a nearness-to-the-truth metric to even empirical predictions that can be expressed numerically. Exactly how much closer to the truth is a theory that predicts that neutrons decay with a half-life of about 12 minutes from one that predicts that neutrons are stable? And is this second theory closer or further from the truth than a theory that correctly predicts neutron decay but falsely predicts that protons decay with a half-life of 1,000,000 years?).

Just as there are many backward-looking notions of scientific progress, there are potentially many forward-looking notions of progress. But here we lack any concrete grounds for comparing our current theories against the truth. There are two reasons for this. While we do have a vague commitment that our future physical theories will somehow be better than our current physical theories, we do not now know *how* they will be better. If we did, we would immediately incorporate this insight into our current physical theories. And what makes matters epistemically worse is that, insofar as we expect surprising innovations in the construction of future theories (and we seem to have good inductive reason to expect this), we cannot now know even what the structure of the space of possible options for refining our current theories will prove to be. So we cannot now know even how we might judge our current theories to be mistaken given a better future understanding of the physical world. The upshot is that while one might claim that our false physical theories are nonetheless approximately true, this claim is hopelessly vague, and given the logic of inquiry, necessarily so.

Returning to the topic at hand, we know that the standard formulation of quantum mechanics together with special relativity is descriptively wrong, but we do not have any idea what the descriptive mistakes are. Since we do not know the specific relationship between our current best physical theories and the descriptive truth other than to know, as we do, that they are in fact false, we quite literally do not know what is being claimed when it is said that quantum mechanics and relativity are approximately true.

One might wonder why we are so insistent that our best physical theories be judged to be approximately true when, at least on this understanding, asserting their approximate truth conveys so little. In particular, asserting the approximate truth of our current best physical theories clearly does nothing to help us figure out what our future theories should be. Indeed, it is the other way around: In order to say anything concrete about even what one *might* mean when one claims that one's physical theories are approximately true, one must begin to construct the next generation of physical theories. In order to say how our current theories might differ from descriptive truth one must say how they might be improved, and this can only be done in the context of serious scientific inquiry into the nature of the next generation of best physical theories.

In the case of quantum mechanics and special relativity, we are just beginning to get some idea of the space of possible improvements, and the salient descriptive differences between those rival approaches that have been so far developed are vast. Moreover, none of those formulations of quantum mechanics that both resolve the quantum measurement problem and are compatible with relativity are particularly compelling. Insofar as one is dissatisfied with the current options for fixing our two best physical theories, and there is good reason to be dissatisfied, one will hold that we do not know now even the ways our current theories *might* be taken to be approximately true.

5. Epistemic Moral. We have good reason to suppose that quantum mechanics and special relativity, considered together, are false. And since we do not now know how we will fix them, we do not know how they are approximately true as descriptions of the physical world. Indeed, our only recourse in clarifying the claim that our best current physical theories are approximately true is to find theories that we take to be better descriptions of the world against which we can judge the merits of our current theories. If this is right, then explaining the precise content of our theoretical commitments and the epistemic status of our best physical theories is something that, if possible, can only be accomplished in the context of ongoing scientific inquiry.

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