Probing Spacetime Ontology with Quantum Mechanics

Kent A. Peacock

Department of Philosophy.
University of Lethbridge.

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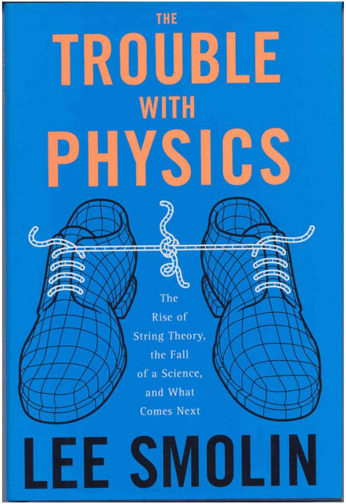
Is There Trouble With Physics?



- "Why, despite so much effort by thousands of the most talented and well-trained scientists, has fundamental physics made so little definitive progress in the last twenty-five years?"
- One would have to go back to the time of Lavoisier to find a twenty-five year period in which there have been fewer advances in *fundamental* understanding.

Smolin's Diagnosis

- There are pathologies in the *culture* of theoretical physics since WWII that militate against conceptual innovation.
- A *philosophical* analysis of time, space, causation, etc. is needed.
  - Carlo Rovelli, Bill Unruh, and others have made similar remarks.
- Perhaps we need to "despatialize" time.
  - I'll explore what this could mean.

So What Is Philosophy?

- It is a philosophical question as to what philosophy *is*.
- Question basic assumptions and definitions no matter how implicit or "obvious".
  - Everything is "on the table."
- Philosophers work in the tradition of Socrates, who argued it was his duty to be the "gadfly of society."
- Philosophers of physics would therefore be the "gadflies of physics."
- In philosophy mistakes are allowed and even encouraged, so long as they are interesting; whereas today's culture of science tends to discourage intellectual risk-taking.
- My hope today is to make some interesting mistakes!

Staticist Views About Time

- Weyl: "the objective world just *is*, it does not *happen*."
  - Relativity naturally indicates 4-dimensional picture of the world; relativity of simultaneity *seems* to imply there is no invariant way to distinguish past, present, and future.
- Gödel (in Rucker): Our persistent belief in the reality of change is due to a failure to *understand* spacetime structure.
- Barbour: "stillness reigns".

Dynamicist Views, or “Eppur si muove!”

- Aristotle:
  - Mocked the staticism of Parmenides and Melissus, and insisted that “nature is a principle of movement” (*Physics*).
  - Distinguished between time and motion: time is not motion itself, but a measure or number of motion.
- David Bohm:
  - “There is an unknown reality which can only be described as eternal flux or flow.”
  - “Movement is fundamental and time is an order which we derive. Movement is the fact with which we begin.”
  - The downside (Bohm): “Reality cannot be specified unambiguously.”
    - Accepting reality of motion could force us to accept limitations on rational describability, similar to those following from work of Heisenberg & Gödel.
    - Maybe the best we can do in order to defend the reality of change is to show that the notion that “it’s all there” is in conflict with (quantum) physics.

My Own Prejudices

- The world is *quantum all the way down*.
- This implies the ontological indeterminacy of regions of spacetime, likely including that region we style "the future."
  - This is mostly what I will argue for today.
- Quantum indeterminacy is in part a reflection of an inherent dynamism in the physical world; and thus—
- In contrast to Barbour, I believe that "movement reigns."

But Does Quantum Indeterminacy Imply Openness?

- Many authors take it as obvious that in a quantum universe particle trajectories are not exact. E.g., Paul Teller:

> *...on a prequantum conception, a particle always has an exact spacetime trajectory. As I am sure all readers know, conventional quantum mechanics already gives up on exact trajectories. The uncertainty relations for position and momentum require these never to receive simultaneous exact values in quantum descriptions of particles...(Teller 1995, p. 10)*

Wheeler: "No meaning for spacetime..."

- Misner, Wheeler, and Thorne reject not only the concept of spacetime trajectory, but classical spacetime itself:

> *The uncertainty principle... deprives one of any way whatsoever to predict... "the deterministic classical history of space evolving in time."* **No prediction of spacetime, therefore no meaning for spacetime**, *is the verdict of the quantum principle. That object which is central to all of classical general relativity, the four-dimensional spacetime geometry, simply does not exist, except in a classical approximation. (Misner, Thorne, & Wheeler, 1973, pp. 1182–1183).*

This is not a new idea...

- In 1924 (even before Heisenberg's Uncertainty Relations of 1927), Born argued that because of quantum discontinuities spacetime lost all meaning as an independent background for atomic processes (Beller 1983).
- However, by the late 1920s most physicists (including Heisenberg) had gone back to more conservative picture, with classical Minkowski background to quantum physics.
- This was reinforced by great successes of quantum electrodynamics & field theory in the 1940s and 1950s.
- Standard Model uses classical Minkowskian background, and many physicists are reluctant to move away from it.
- Hence despite intuitions of Born, Wheeler, et al., the closed future/block universe picture still lives.

The Standard Argument

- Any way of partitioning the world into past, present, and a possibly open future must be in terms of a simultaneity relation.
- *The only physically significant kind of simultaneity is in terms of the time coordinate.*
- The time coordinate is frame-dependent; therefore, judgements of simultaneity in terms of time coordinate are frame-dependent and do not pick out sets of events in an invariant way.
- Only invariant structures (those that link the same sets of events regardless of their description in different frames of reference) can mark an objective or ontological distinction, such as that between past and future.
- Therefore, there is no way, in a relativistic universe, to mark an ontological distinction between past, present, and future; the past, present, and future are all equally real or equally unreal.

Requisites...

- A three-part argument is needed:
  1. We need a precise mathematical characterization of the notion of a closed future.
  2. We need a way of testing whether such a future is tenable in a quantum universe.
  3. If it turns out that it is not, then we need a response to the Standard Argument.
- General idea is to see if one can construct a quantum "no-go" theorem against the closed future.

From EPR to Bell

- Before 1910 Einstein realized that there was something funny about the statistics of light quanta; they were *too well* correlated for their own good!
- Einstein regarded quantum *Spukhaftefernwirkungen* as absurd, literally a threat to scientific rationality.
- EPR paper of 1935: in simple terms, argued that the *apparent* action at a distance of QM was due to the incompleteness of the theory; there had to be a fully local story explaining why particles are correlated the way that QM (successfully) predicts.
- Von Neumann (1930s) argues that "hidden variable" underpinnings of quantum statistics are mathematically impossible.
- Bohm (1952) proves him wrong, but Bohm's theory depends on nonlocal dynamics *via* the quantum potential.

- J. S. Bell (1964) wondered if *any* "completion" of QM had to be nonlocal.
- He studied spin correlations in a version of the EPR thought experiment devised by Bohm, and showed that if such correlations are determined by local hidden variables they have to obey certain inequalities.
- These inequalities are violated by QM.
- Physicists were in a "schizophrenic" (G. Fleming) state over this until about 1980, when experiments by Aspect *et al.* confirmed Bell's prediction.
- Meanwhile, mathematical work by Gleason (1957), Kochen and Specker (1967), showed that predictions of QM are in general inconsistent with Boolean underpinning of quantum statistics.
- Bell's Theorem is special case of generalized Bell-KS Theorem for spacelike separate entangled particles (Bub, Mermin).

What is Booleanity?

- This can be expressed informally in several equivalent ways:
  - To say that something has a Boolean property structure is to say that its properties obey set theory.
  - Every possible proposition about the properties of that thing has a definite truth value (even if one might not know them for practical reasons).
  - There is a logically consistent description of the whole of the thing.
  - Every possible experimental question we could ask about the thing already has an answer *before we ask it*.
  - The properties of the thing can be described by "urn" model (Pitowsky 1994).
    - Pitowsky showed that the Bell Inequalities were first discovered by George Boole in the 1850s, and were called by Boole "conditions of possible experience."
    - The Boole-Bell Inequalities are simply consistency conditions *given that* one examines a system *without altering its properties*.

So What is Non-Booleanity?

- Demopoulos (2004) emphasizes that descriptions of quantum systems are *incompletable* because the presumption of completability entails a mathematical contradiction.
- Anticipated by Schrödinger (1935):

  > *. . . if I wish to ascribe to the model [of a quantum mechanical oscillator] at each moment a definite (merely not known exactly to me) state, or (which is the same) to* **all** *determining parts definite (merely not known exactly to me) numerical values, then there is no supposition as to these numerical values* **to be imagined** *that would not conflict with some portion of quantum theoretical assertions.*

The Lump In the Carpet

- Fitting QM predictions to a Boolean substrate is like trying to smooth out a carpet cut from surface of sphere onto a flat floor.
  - There will be a lump!
  - You can move it around and even hide it under furniture, but you can't make it go away.
- It is not entirely accurate to call the "no-go" theorems "no hidden variable" theorems; more accurately, they are *no Boolean variable* theories.
  - Even more precisely, *not enough Boolean variable theorems*, since non-Boolean quantum systems can have Boolean subspaces defined by CSCO.

Bell-KS Theorem in Summary:

- QM in general disagrees with presumption that all experimentally answerable questions have yes/no answers before we ask them.
  - "Before" does not mean with respect to a time coordinate, but with respect to the invariant sequence of preparation and measurement operations taken on the system.

Logical Structure of No-Go Theorems

- We arrive at a paradox if we assume that a quantum system has a Boolean property structure.
- Bell's (1964) argument was a *modus tollens*: P implies Q, not-Q, therefore not-P.
- "For Whom Bell's Theorem Tolls" is therefore a double pun.
- No-go theorems are negative results; they show what cannot be the case, but they do not directly show us what must be the case.

Why Non-Booleanity?

- Non-Booleanity is formally a consequence of the fact that quantum mechanical observables come in non-commuting conjugate pairs (Bub):
  - $[\hat{A}, \hat{B}] = i\hbar\hat{C}$.
- But "who ordered *that*?"
  - Why do some observables not commute?
  - Why does Planck's constant of action have the observed value it has (6.626×10^{-27}erg.sec)?
- A suggestion:
  - Obervables (Hermitian operators) correspond to rotations in Hilbert Space;
  - Finite rotations do not in general commute;
  - $\therefore$ *perhaps all rotations in Hilbert Space are finite.*
  - The quantum of action would reflect the existence of a (dimensionless) quantum of phase, which might have the value it has for purely *mathematical* reasons.

Phase Quantization and Quantum Gravity

- The notion that all rotations are finite is consistent with DSR and quantum gravitational theories in which spacetime is discrete.
- But which comes first?
  - Are rotations finite because spacetime is discrete?
  - Or is spacetime discrete because rotations (when better understood) are finite?
- Stay tuned!

Is the Block Universe a No-Go?

- How can we characterize notion of closed future precisely?
  - Proposal: *a region of spacetime is ontologically closed only if it has a Boolean property structure*.
  - Captures intuitive notion (Weyl) that it's "all there," a given.
  - Mathematically, block universe interpretation implies that the region inside the forward cone of any event is a continuous manifold of real numbers, differentiable to at least order 2 (to support Maxwell's Equations); such structures are Boolean.

Example: Wheeler's Delayed Choice Experiment

- Wheeler proposed an interferometer extending several billion ly, with the light from a distant quasar bent around a gravitational lens.
- A measurement choice in an Earthly lab seems to determine which path some photons took even though they were emitted billions of years ago.
- This can be set up as a Bell-KS experiment, which will demonstrate correlations that will violate the assumption that the photons had definite trajectories.
- Well-verified set-ups like this show that the *past* is to some degree non-Boolean!

Could We Save President Kennedy?

- Delayed-choice seems to suggest that there could be paradoxical situations in which we could change the known past.
- No; we could not deflect a bullet and save a certain president because we know we did not.
- The only events we can change in the past are among those we do not know about now!
- Analogous to double-slit experiment in which knowing which slit the particle goes through wipes out interference (and thereby wipes out non-Boolean effect).

Advanced Choice Experiment?

- Could there be an *advanced* choice experiment, along the following lines?
  - There is good reason to take the idea of advanced (time-reversed) influences seriously.
  - We need to define some sort of interferometer in which correlations in the here-and-now are a function of interference between retarded and advanced influences.
  - One would almost certainly find that the correlations would violate the assumption that the emitters of the advanced potentials in the future had a Boolean property structure.
  - This ought to be doable!
    - In fact, J. D. Franson (early 1990s) may have already done this, but I am not sure if his work has been interpreted this way.

A Quantum Definition of Time?

- Non-Booleanity will have a measure similar to other measures of quantum mechanical uncertainty.
- The degree of openness of a region of spacetime (past or future) is a quantitative matter.
- To compute degree of uncertainty of region of spacetime (its ontological "gappiness") would require a theory of quantum gravity that tells us how to count the *states of space*.
- Reasonable guess is that the future has a much greater measure of uncertainty (non-Booleanity) than the past.
- Proposal: *time is the direction in which the measure of non-Booleanity varies*.

What About the Standard Argument?

- The notion of ontological distinctions between regions of spacetime seems to violate the relativity of simultaneity.
- We need a more general conception of simultaneity, conceived of as equivalence relation on events.
- *Simul* (Latin) has two meanings:
  - At the same time.
  - In joint process.
- Only in a universe with absolute time does it makes sense to equate these two conceptions.
- The fact that we still insist that physical changes (such as state reduction) have to be linked to the *time coordinate* just shows how hard it is to get away from the Newtonian picture.

- In a relativistic universe distant events could be in joint process (and thus simultaneous in the broader sense) even if they are not at the same time in some coordinate system; e.g., particle localizations in entangled system.
- Proper quantities such as action, phase, can form natural basis for invariant simultaneity relations which give us tools to discuss ontological distinctions between regions of spacetime.

Does This Despatialize Time?

- I'm not sure, but it certainly makes time a lot *less* like a spatial coordinate, in the following sense:
- *Space* is characterized by joint or co-existence, or perhaps "concurrence."
  - Concurrence is definable not in terms of time coordinate, but in terms of dynamical properties of matter.
- Bell-KS Theorems show that not all possibles can be *compossible*, to use Leibniz's term.
- Space is constructed out of states that are compossible.
- Time is defined as an ordering of states that *cannot* coexist or be compossible.
- In some cases it may be possible to define a time or time-like parameter that labels the succession of possible spaces, but this is *not* absolute time!

A Richer Universe?

- The classical picture is one of maximal compossibility: roughly, what is not compulsory is forbidden.
- On the quantum view there is less restriction on what is possible in general but not everything that is possible is compossible.
- That makes for a more interesting universe, in my view!