already been observed, but disagrees somewhere else, you have made a great discovery. It is very nearly impossible, but not quite, to find any theory which agrees with experiments over the entire range in which all theories have been checked, and yet gives different consequences in some other range, even a theory whose different consequences do not turn out to agree with nature.[3]

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2. Two reviews are P. Pearle in *Open Systems and Measurement in Relativistic Quantum Field Theory*, H. P. Breuer, F. Petruccionne, eds., Springer, Berlin (1999), p. 195 and A. Bassi, G. C. Ghirardi, *Phys. Rep*. **379**, 257 (2003).
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Mermin replies: Rather than attempting a general definition of "real" and "abstract," I illustrated with examples what it means to reify an abstraction. Michael Nauenberg and Derek Walton insist on a definition, though Walton agrees with me that it's not easy to provide one. In their own definitions, Nauenberg assigns reality to phenomena or events that can be recorded by a device, and Walton says reality is that which can be observed. These can be compared with what I came up with toward the end of my essay, though I offered it as a sufficient condition for reality rather than a definition: "What impinges directly upon us is real." My warning against extending reality to the abstractions that help us impose coherence on our perceptions works almost as well if you replace "our perceptions" by "what the device records" or "what we observe."

In quoting my phrase that "spacetime is an abstract four-dimensional mathematical continuum of points that approximately represent phenomena," Nauenberg drops the rest of my sentence: "whose spatial and temporal extension we find it useful or necessary to ignore." Representing phenomena (or, if you prefer, the location of phenomena) by abstract geometric points is invariably an idealization of a state of affairs that in reality is not sharply defined. The fact that crude (on some scale) spatial or temporal distances can be recorded irreversibly by macroscopic instruments does not confer reality on the continuum of ideal points we use to represent such data.

Nauenberg remarks that interpretational problems in quantum physics usually come from attempts to impose views of reality learned from classical physics on the microscopic world. I would have said "sometimes." As Mark Alford critically notes, I also believe that even in classical contexts we should look more skeptically at some of our classical ideas of what is real.

I mentioned Werner Heisenberg's views on the acquisition of knowledge only in the context of whether wavefunction collapse is a real physical process, produced, for example, by Philip Pearle's randomly fluctuating field. Heisenberg believed, on the contrary, that "collapse" was merely our updating of information. Although Nauenberg dismisses Heisenberg's views as irrelevant to the question of what is real, he seems to agree with Heisenberg in declaring that wavefunction collapse is no more mysterious than the change in a probability distribution after an outcome is recorded.

Nauenberg's colleagues, Fred Kuttner and Bruce Rosenblum, come at me from quite a different direction, reading me as deploring books that honestly and interestingly present the strangeness of quantum physics. But I've even tried to write such a book myself. What I do deplore is making quantum mechanics sound more peculiar than it already is. Physicists can be as guilty of this as mystics.

In particular, separating the strangeness of the uninterpreted data from the strangeness of the formalism that accounts for those data is a subtle business. One of the things the pilot-wave interpretation of quantum mechanics does perfectly well is to provide a straightforwardly unweird explanation of two-slit particle diffraction: A wave goes through both slits and directs a real particle to the screen on the other side, guiding it through one slit or the other. So I do not agree with Kuttner and Rosenblum that the two-slit data, in and of themselves, boggle the mind, independent of one's perspective on the quantum theory. And I would say that what is usually called "the measurement problem"—the issue that Pearle addresses—is impossible to formulate without invoking the orthodox quantum formalism.

It's a pleasure to become reacquainted with my old friend Rodney Brooks after half a century. I'm glad he agrees that the field operators are mathematical tools, and I apologize for misconstruing his 50-year-old views. But I do think appealing to quantum field theory to solve the paradoxes of special relativity is using a sledgehammer to crack a walnut. Abandoning the reification of time does the job all by itself.

Leonardo Colletti wonders what I think about Galileo's condemnation by the church. I'm with Galileo. It was the church that was (and still is) guilty of reifying abstractions. I do not "agree with those who refuse to recognize any objective truth in physical theories," but I also think that Colletti's "mere calculational device" undervalues the beauty and power of the best abstractions physicists have come up with. A coordinate system fixed in the rotating Earth, with real—to use a dangerous term—centrifugal and Coriolis forces, is just fine for most terrestrial purposes. It's pretty poor for describing the solar system, and a disaster for cosmology.

What's important is not to succumb to the belief that the correct coordinate system is built into the nature of things, as the church did for one coordinate system, and as Colletti seems to favor for another. We should choose the one that best suits our purpose. In an only slightly different context, Galileo understood this very well. That's why we talk to this day of Galilean transformations.

Experimentalists have been much more sympathetic than theorists to my views on reification. They seem to be less enchanted by their abstractions. I'm glad Amin Dharamsi understood what I was trying to say, and would only add to his examples the simplest of all geometric abstractions—the single point—which plays a central role in my remarks on the reification of spacetime.

Alford finds spark chamber trajectories analogous to magnetic fields. I would have said they were analogous to Faraday's iron filings. He goes on to warn against letting quantum mechanics undermine our normal classical sense of reality. The doubts I raised about the reality of classical electromagnetic fields did come entirely from quantum electrodynamics. But my qualms about the reification of the spacetime continuum (which, to my surprise, nobody but Nauenberg objected to) are based entirely on classical physics, untainted by quantum weirdness.

It's a funny coincidence that Alford and Fletcher Goldin ask whether I believe atoms are real. I polished up my column during a three-month visit to Copenhagen, where I argued at some length with Aage Bohr, Ben Mottelson, and Ole Ulfbeck about their view[1] that all problems in the interpretation of quantum mechanics can be resolved by abandoning "the notion that matter is built of elementary constituents called atoms." I'm still not persuaded that their program makes sense, but I admire their willingness to reexamine even as apparently unassailable a reification as atoms.

Joseph Isler brings up the reification of the ether. The most important culprit caught by special relativity was the reification of time, but the ether is a spectacular example of a reification that most of us today agree was unwarranted, even without an explicit general definition of what it means to be real. The ether was surely making life harder than it had to be.

But as Isler notes, and as Alford remarks more generally, reifications can also have considerable heuristic power. If we denied ourselves all our reifications, creative thinking would become difficult, if not impossible. Evolution has hardwired us to reify. It's important to be aware of the habit, and be ready to consider questioning even our most successful reifications when they start getting us into serious trouble. "At last it came to me," said Einstein,[2] reminiscing about 1905, "that time was suspect." Wow!

I agree with Alexey Burov that paradoxes and contradictions are a rich source of inspiration. But nature is neither paradoxical nor contradictory. Paradoxes and contradictions arise from our defective understanding of nature. What I advocate is that in trying to improve that understanding we keep in mind, among the possible resolutions of an apparent paradox or contradiction, an unacknowledged and inappropriate reification of an abstraction.

I expressed a hope that readers would agree to a certain proposition. Sabine Hossenfelder takes my rhetorical flourish as an attempt to argue, fallaciously, for the truth of that proposition. That was not my intent any more than I intended, by calling attention to the agreement among most of us that the ether is not real, to establish thereby its unreality. Although Hossenfelder takes my column as a shallow, polemical dismissal of both philosophy of science and quantum foundations, I had viewed it as an amateurish attempt to contribute to both disciplines.

Pearle recalls that John Bell put me in my place in 1989 in Erice for trying to make a point similar to the one in my column. This surprises me. What I remember is trying unsuccessfully to defend my absent friend and colleague Kurt Gottfried, whose ideas on quantum foundations Bell had tried, in the nicest possible way, to demolish. I developed the views in my recent column a decade later. Conversations with friends in the quantum information community had resonated unexpectedly with some apparently unrelated efforts of mine to make Minkowski spacetime diagrams accessible to nonscientists.

On my part, I remember Bell at that same meeting strenuously encouraging Pearle to persist in his efforts to construct a dynamical theory of wavefunction collapse. "Don't be a sissy!" is what I heard him shout at Pearle, during a very noisy reception. I respect the skill and courage with which Pearle has persisted in these efforts for many decades. But my instincts tell me that he (and Ghirardi, Rimini, Weber, Roger Penrose, and even Tony Leggett) is barking up the wrong tree in seeking an explanation of the measurement problem in a breakdown of quantum mechanics. I wouldn't (and couldn't) discourage them from trying, and I'll be among the first to praise them should they find a squirrel.

For me, identifying the bad intellectual habits that induce us to think there is a quantum measurement problem is just as big a challenge (*pace* Nauenberg) and a lot more fun. Be that as it may, I agree with Pearle that Bell, who is one of my all-time scientific heroes as a thinker, writer, and public performer, would not have approved of my column. I wish he were here to denounce me.

Ironically in the present context, Bell and I did agree in Erice that the Fitzgerald contraction, contrary to prevailing opinion, was a real physical phenomenon. Although I'm still nervous about defining "real," I haven't changed my mind about that. No reasonable definition of reality could be expected to omit it.

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