of quantum mechanics better than Feynman did. Presenting the new ideas takes somewhat longer than the material they replace, but not enormously so. Some time will be regained in courses that include an introduction to quantum entanglement and Einstein-Podolsky-Rosen, since circuitous arguments invoking Bell's inequality and the like, which can leave students quite confused, are replaced by a short, clear treatment of the essentials.

Although I can see the value of computer simulations of Schrödinger's equation, I think it is more effective to first introduce students to basic quantum dynamics, both unitary and stochastic, through the use of "toy models." I included various examples in *Consistent Quantum Theory*.[1] The properties of such models are easily worked out with a pencil on a small sheet of paper, like the back of an envelope. Working through them helps students master new concepts and get rid of certain misconceptions about quantum measurements.

The fact that students in my courses have been able to learn how to apply probabilities consistently to microscopic systems, in a way that disposes of numerous difficulties and conceptual paradoxes, suggests it might be worthwhile for other teachers to invest some time in learning post-Feynman ideas. The main difficulty is the absence of a textbook. I have used reference 1 as a supplement, though it is not ideal. It has no exercises, although a few are available on the corresponding website. I would be happy to hear from anyone skilled in textbook writing who wants to revise an older one or start something new.

In conclusion, I strongly favor every effort to improve students' understanding of quantum mechanics, and I consider the research reported by Singh and coauthors a valuable contribution to that end. However, if we want our students to genuinely understand quantum mechanics and not simply calculate things, I believe a much bigger step forward is possible by combining the efforts reported in the article with advances in quantum foundations.

Reference

1. R. B. Griffiths, *Consistent Quantum Theory*, Cambridge U. Press, New York (2002). Some chapters and a few exercises are available at http://quantum.phys.cmu.edu.

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In their article, Chandralekha Singh, Mario Belloni, and Wolfgang Christian focus exclusively on "functional understanding of quantum mechanics," which they claim "is quite distinct from the foundational issues alluded to by Feynman."

But are the foundational and the functional really so distinct? The work of other physics education researchers suggests not. For example, in a classic article, Alan Van Heuvelen discusses students' prevalent and frustrating use of "primitive formula-centered problem-solving strategies"[1] and suggests that physical, intuitive understanding developed through qualitative diagrams and models "must come before students start using math in problem solving. The equations become crutches that short-circuit attempts at understanding." Van Heuvelen also urges that "instead of thinking of [problems] as an effort to determine some unknown quantity, [teachers] might . . . encourage students to think of the problem statement as describing a physical process—a movie of a region of space during a short time interval or of an event at one instant of time." I suspect Singh, Belloni, and Christian would agree with this advice. They comment that such "qualitative understanding of quantum mechanics is much more challenging than facility with the technical aspects."

But isn't the main barrier to such intuitive, qualitative understanding the nature of quantum mechanics itself—at least, the version of the theory advocated by Niels Bohr, Werner Heisenberg, and virtually every textbook writer since? Why should we expect students to invest the time and energy necessary to, say, visualize the time-dependence of $|\psi|^2$ when we also preach the ambiguous and contradictory Copenhagen dogma that ψ does not represent anything physically real, yet still provides a complete description of physical reality? Why are we surprised that students are confused about, and don't take seriously, something that we assure them is, at best, some kind of algorithmic fantasy? Is there really any difference between "shut up and calculate" and "plug and chug"?

Why not teach them Bohmian mechanics—an alternative (deterministic) version of quantum theory in which particles are particles (and really exist, all the time) and the same dynamical laws apply whether anyone is looking or not?[2] About this alternative theory John S. Bell asked, "Why is [it] ignored in text books? Should it not be taught . . . as an antidote to the prevailing complacency? To show that vagueness, subjectivity, and indeterminism are not forced upon us by experimental facts, but by deliberate theoretical choice?"[3]

If we really want to help students understand quantum mechanics, the first step is to reject the confusion-spawning foundational vagueness, ambiguity, and philosophical absurdity of Copenhagen quantum theory, and adopt a clearer, more scientific, less fuzzy version. (See Sheldon Goldstein's two-part article "Quantum Theory Without Observers," PHYSICS TODAY, March 1998, page 42, and April 1998, page 38.) The first step, in short, is to present them with a theory that *can* be understood.

References

1. A. Van Heuvelen, *Am. J. Phys.* **59**, 891 (1991).
2. S. Goldstein, in *Stanford Encyclopedia of Philosophy,* http://plato.stanford.edu/entries/qm-bohm.
3. J. S. Bell, *Speakable and Unspeakable in Quantum Mechanics: Collected Papers on Quantum Philosophy*, Cambridge U. Press, New York (2004), p. 173.

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A quite different approach from the one presented by the authors of "Improving Students' Understanding of Quantum Mechanics" may be appropriate at least for some classes of students. It might be called the pragmatic approach, teaching students to deal with a wide variety of problems while minimizing philosophical discussion. I took this approach for several years while teaching a course for graduate engineers at Stanford.[1] The resulting course was surprisingly orthogonal to the traditional quantum course. Solving the Schrödinger equation became a minimal part of the subject; rather, tight-binding expansions allowed the student to use simple algebra to obtain a meaningful understanding of atoms, molecules, and solids. Transition rates and shake-off excitations provided understanding of a wide variety of phenomena.

I took the defensible stance that all of quantum mechanics is the direct consequence of a single assertion, wave–particle duality. The uncertainty principle and the Pauli principle are consequences, not independent conjectures. Quantum theory does not tell us that there will be a particle of spin ½ with the mass and charge of an electron, but it indicates how such a particle will behave if there is one. When the consequences seem puzzling, it is fair to say