

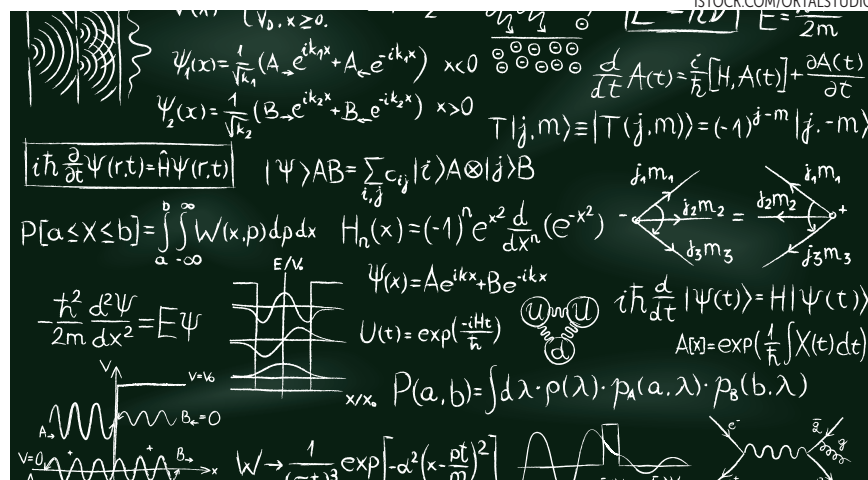
Commentary

Teaching quantum concepts

Quantum mechanics is one of the pillars of modern physics. Although quantum computing seems to grab the headlines, quantum mechanics lies at the heart of a vast array of fields, including modern electronics and modern medicine—not to mention all of chemistry. But it is also a notoriously obtuse subject in many ways. In fact, there's no clear consensus on what represents the bare-minimum competency in quantum mechanics, and there is even less consensus on the best formalism to use.

Classical mechanics can be understood entirely within the context of the conservation of momentum and energy. That is, we can derive the basic rules of classical mechanics, such as Newton's laws, from those conservation laws. But what is the equivalent foundation of quantum mechanics? The answer to that question—whether it is probability, discreteness, nonclassical correlation, or something else—has ramifications for how it is taught, for how it is communicated to the public, and even for how it is communicated to other physicists.

It's easy to fall down a rabbit hole when attempting to convey quantum ideas to an audience for the first time. Analogies only go so far in the quantum world, since it is so far removed from our everyday experience. For example, I have found that some people have difficulty even grasping the notion of discrete energy levels, let alone understanding the notoriously murky subject of entanglement. And yet



both of those ideas are important enough that they *should* be understood by more people.

Consider climate change, for example. It is an existential problem for humanity, and it is attributable to a basic quantum mechanical phenomenon. As someone who works in quantum information, I suppose it's fair to say that quantum mechanics colors the way I view the world. But there's no denying that the only reason the atmosphere retains any heat at all is that carbon-based compounds absorb and reemit IR radiation while oxygen and nitrogen molecules, which constitute the majority of the atmosphere, do not. That's a purely quantum mechanical effect. In fact, it is arguably one of the two critical physical processes behind climate change (the other being the biosphere's conversion of the Sun's broad spectrum of energy to IR).

When you teach about quantum mechanics, a lot depends on the audience itself. Some ideas are inevitably simplified or wholly abandoned in certain settings. The climate change course I taught in the fall of 2021 was open to all majors, so in addition to physics majors, I had students from history, English, criminal justice, peace and justice studies, environmental science, and politics. Concurrently, I also taught a standard modern-physics course, which covered special relativity and quantum mechanics, to second-year

physics majors. It introduced students to concepts such as spin and entanglement. Although entanglement may have a role in photosynthesis,¹ which is a key component of the global carbon cycle, it's tangential to the main point that I was trying to convey in my climate change course, so I never discussed it in that setting.

The importance of quantum mechanics outside of certain specialties is not limited to climate science, of course. With the rise of quantum computing and quantum information, there is a growing need for computer science and mathematics courses to introduce basic quantum concepts. In a computer science setting, it's much easier to introduce basic quantum concepts by using linear algebra than, say, a strict calculus-based formalism that emphasizes differential equations. In fact, I tend to find that the algebraic approach is easier even with physics majors.

Unlike climate change, quantum computing and quantum information don't represent existential crises, but they do have the potential to greatly affect humanity. Yet they are built around a handful of extremely counterintuitive ideas. Getting people to understand those ideas for the first time often requires a creative approach that sometimes sacrifices rigor in favor of a certain level of conceptual understanding. The fact is that we live in a highly complex world, and not every-

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one can be an expert in everything. So we have to find some way to convey those complex ideas in a manner that doesn't require years of study but that is effective enough to allow for sound judgments to be made both at the personal level and at the policy level.

Unfortunately, there is no simple, one-size-fits-all method. It would certainly help matters if people were introduced to quantum concepts at multiple points through a variety of techniques during their K–12 education, but that would require changing standards and increasing the number of teachers who have been exposed to those ideas.

Several initiatives are working to introduce more quantum mechanical topics into K–12 and undergraduate curricula. This past summer I participated in the Quantum Undergraduate Education and Scientific Training (QUEST) workshop. As the name suggests, it was aimed at quantum information science education at the undergraduate level, and several of the participants were from computer science and mathematics departments. Currently I am cofacilitating a faculty online learning community that is taking a deeper dive into some of the themes discussed at the workshop. A related initiative is the National Q-12 Education Partnership. The program, spearheaded by the White House Office of Science and Technology Policy and NSF, is compiling resources for use in the classroom. The general public and policymakers represent an entirely different cohort from those of either QUEST or the Q-12 partnership, which will necessitate yet another approach.

So what have nearly two decades of teaching quantum concepts taught me? They have taught me to be creative and to try multiple approaches. They have taught me that sometimes rigor must be sacrificed in service to the bigger picture. And much to the chagrin of family and friends at holidays and weddings, they have taught me to be annoyingly persistent. But there are few things I would rather do than talk about physics. What about you?

Reference

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LETTERS

Subtle historical connections between Magritte and Einstein

In the recent letter “Einsteinian subtleties in Magritte’s *Time Transfixed*” (PHYSICS TODAY, April 2021, page 10), the author, Robert Fleck, candidly admits that “there is no evidence that [René] Magritte intended to represent . . . Einsteinian ideas in his painting” (shown below). The temptation to dismiss the whole piece as a purely subjective and arbitrary association is rather strong, but there are perhaps tenuous links that might save it from scorn.

The word *durée* in the French title of the painting, *La durée poignardée*, would have had for Magritte and his contemporaries the unmistakable association to the French philosopher Henri Bergson. Before World War I, Bergson was something of a superstar: His lectures were attended by large crowds, and just about everybody knew the buzzword *durée*.

Bergson’s *durée* is not time but rather something else: What his philosophy emphasized is that personally experienced time (*la durée*) is totally different from objective time. “Bergson sees spatialization as the hallmark of the inauthentic, mechanized time of science,” wrote a commentator,¹ and that idea

seems to fit Magritte’s picture rather well.

A mirror mechanically sends back inverted images but does not turn back time: “Reading the picture” spatially from left to right, the spectator notes that the reflection of the second candleholder is missing in the otherwise realistic representation. The locomotive, another mechanical device, irreversibly transmutes the internal energy of coal into external movement. The original thoughts that Bergson developed at length were badly damaged when Einstein’s special theory of relativity became known. To say that they were stabbed (*poignardées*) could be an eloquent image.

Jimena Canales recently published a book about a confrontation between Bergson and Einstein² that took place in April 1922. Later that year Bergson published the monograph *Durée et simultanéité* (*Duration and Simultaneity*) about Einstein’s theory. The book, if not the historical meeting, is something that Magritte might have known about. So perhaps there is a roundabout way to connect more convincingly the picture and Einstein.

Magritte commented on the association to Bergson in a letter he wrote decades after he had finished the painting and given it the title *La durée poignardée*: “You think of Bergson and Proust when you look at this painting,” he said. However, he had already discussed the title in an earlier letter he sent to his friend Marcel Mariën sometime around the painting’s production. A pen-and-ink sketch of the painting occupies the upper part of the sheet, and on the last line of text below it, Magritte asks his friend if he would like to “meditate” about it.

For avid readers of popular-science articles, trains and clocks have become suggestive of Einstein’s



TIME TRANSFIXED, by René Magritte, oil on canvas (1938), Art Institute of Chicago. (Image from Peter Barritt/Alamy Stock Photo.)