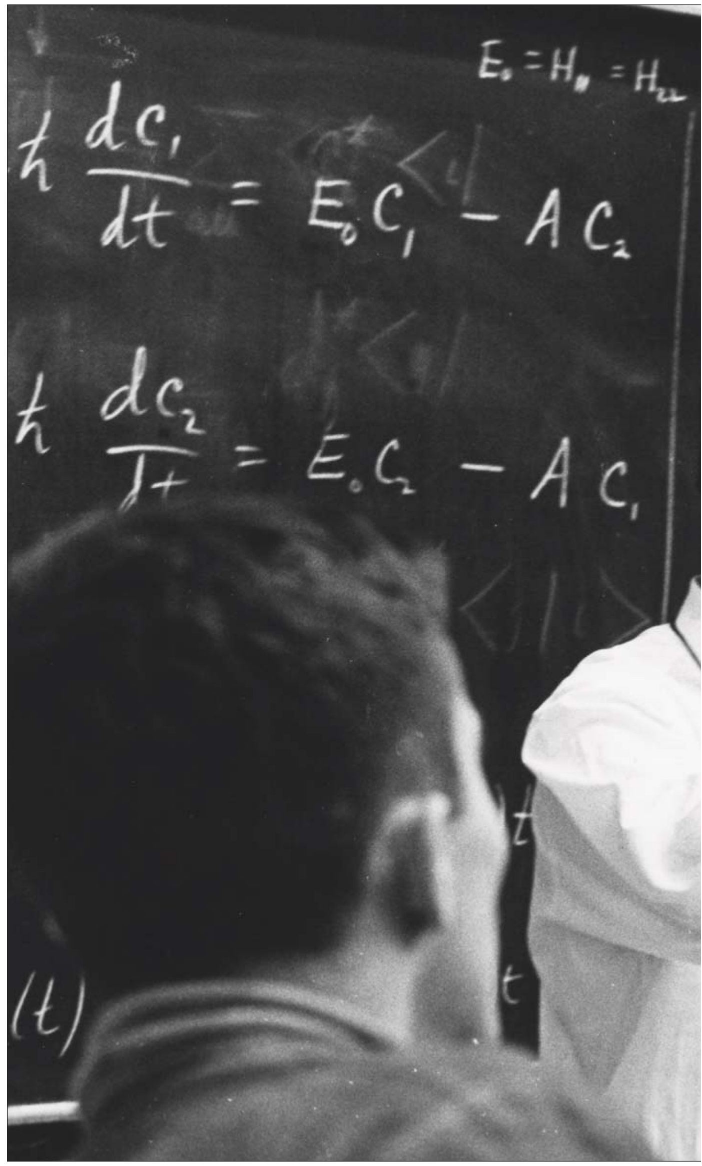
Reprinted from *Physics World*

David Kaiser, “Turning physicists into quantum mechanics,”
Physics World (May 2007): 28-33

Turning physicists into

Einstein, Bohr and the other pioneers of quantum mechanics loved to debate its strange philosophical implications with their students. **David Kaiser** thinks he knows why this approach to teaching the subject largely vanished from university curricula after the Second World War



Quantum computing, quantum encryption and quantum teleportation: today's physics journals sound more like *Star Trek* than ever. Based on the weird and counterintuitive features of quantum mechanics, these concepts have been brought to fruition in recent years by theorists and experimentalists alike. Indeed, these ideas are now leaving physics laboratories and being used by industry to make real products. Who knows what revolutions await in computation and communications from these budding breakthroughs?

But as they move from theory to application, these developments have rekindled for many physicists an interest in some long-standing questions about quantum mechanics – interpretive, philosophical questions that, on the face of it, seem light-years away from the grubby worlds of engineering and manufacturing. Can something be in two places at once? Can an object influence another more quickly than the time it takes light to travel between the two? Is it really impossible – as the uncertainty principle suggests – to fix the properties of a quantum-mechanical object such as its position and momentum at the same time?

These philosophical issues are not new. Perhaps the most famous physicist to agonize over the implications of quantum mechanics was Albert Einstein, who did not like the inherent randomness of the theory and dubbed the seeming ability of one particle to instantaneously influence another as "spooky action at a distance". But Niels Bohr also worried about such questions; so too did Werner Heisenberg and Erwin Schrödinger. In fact, most of the architects of quantum theory, toiling away during the 1910s and 1920s, thought that quantum mechanics – our description of matter and forces at the atomic scale – demanded new ways of thinking.

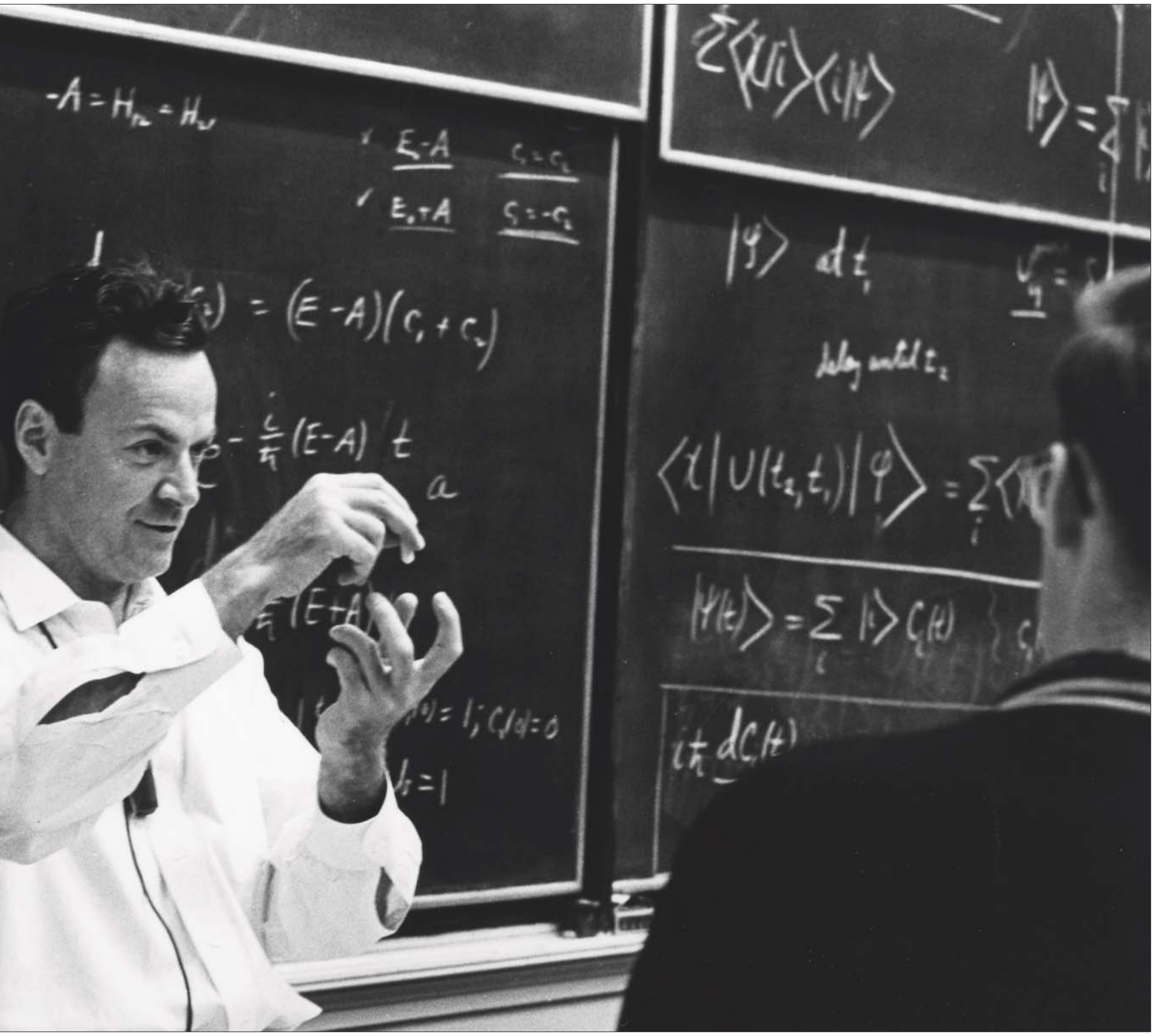
Yet these complex puzzles largely disappeared from view during the mid-20th century, despite Einstein's hope that some means might be found to regain a deterministic description of nature. They had not been solved – as lively discussions in recent books like Seth Lloyd's *Programming the Universe* make plain – but were simply sidestepped. Why was this?

A large part of the answer to that question, unexpected though it may be, is the huge impact on physics of the Second World War. The success of military projects, such as the development of the atomic bomb and radar, convinced influential policymakers that what they needed after the war was many more physicists to secure the peace. The hardening of the Cold War a few years later added new urgency. The massive training mission that ensued – bolstered in the US by tens of thousands of new federal fellowships in physics and allied fields – radically changed how physics was taught both in American universities and elsewhere.

Even though many new physics professors were hired, the ratio of students to staff ballooned in the US, with the pre-war ratio trebling by the mid-1950s and then widening further after that. During the boom years, the number of students studying physics rose faster than any other field in the US, peaking at about 15 000 graduate-level students in 1969. As class sizes grew, however, the philosophical aspects of quantum mechanics got squeezed out of the lecture hall. The goal of physics became to train "quantum mechanics": students were

David Kaiser is a historian and physicist at the Massachusetts Institute of Technology, US, e-mail dikaiser@mit.edu. He is currently writing a book entitled *American Physics and the Cold War Bubble*

quantum mechanics



Calculating minds Richard Feynman, shown here lecturing at the California Institute of Technology in 1963, was one of many physicists to sidestep the philosophical aspects of quantum mechanics when teaching the subject after the Second World War.

Archives, California Institute of Technology/Melanie Jackson Agency, LLC

to be less like otherworldly philosophers and more like engineers or mechanics of the atomic domain.

The focus on learning to calculate, unburdened by speculative philosophical concerns, certainly brought some good pay-offs. Students from this era successfully applied quantum theory to tackle nuclear forces, superconductivity and more. Indeed, the huge success of the Standard Model of particle physics is in large part based on our fundamental knowledge of the rules of quantum mechanics.

Yet by the early 1970s, the effects of economic recession, détente between the West and the Soviet Union, and immense cuts in defence and education spending led to a decline in student numbers, with physics plummeting faster than any other field. By the end of that decade, the number of physics students had halved from its post-war peak. As class sizes shrank, fundamental questions of quantum theory returned to the lecture room and textbooks, as my historical research has revealed. In surprising and often subtle ways, these changes in the student ranks shaped how US physicists grappled with quantum mechanics, with similar trends apparent in other countries too (see box on page 33).

Focusing on philosophy

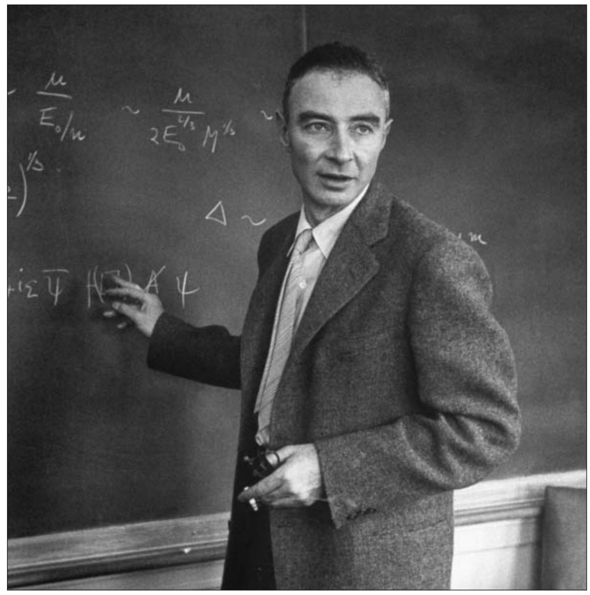
Even more than relativity – with its talk of shrinking metre sticks, slowing clocks and twins who age at different rates – quantum mechanics is a science of the bizarre. Particles tunnel through walls. Cats become trapped, half dead and half alive. Objects light-years apart retain telepathic links with one another. The seeming solidity of the world evaporates into a play of likelihoods.

During the 1920s and 1930s the architects of quantum mechanics – most of whom were European – tackled the deep philosophical implications of the subject in their classrooms and textbooks head on. No clean line separated calculation from interpretation. Theorists like Bohr, Heisenberg, Hermann Weyl, Max Born and Arnold Sommerfeld each paused within their textbooks to relate the latest discoveries in atomic physics to long-standing trends in philosophical inquiry, such as the extent to which we can ever gain trustworthy knowledge about the physical world (let alone unobservable entities), the role of language in shaping our concepts, or the active filtering of seemingly direct observations by our prior concepts such as space and time. Some invoked the philosophers Immanuel Kant or Ernst Mach; others even turned to Eastern mysticism and Jungian psychoanalysis to help interpret the latest physics research. But all agreed that the new physics demanded serious philosophical scrutiny.

Even in the US, where physicists tended to be more practically minded than those in Europe, it was generally felt that the philosophical implications of quantum mechanics needed to be examined. During the late 1920s and through the 1930s, young American physicists such as Edwin Kemble, Arthur Ruark and Henry Margenau paraded their philosophical convictions in the *Physical Review* and in their textbooks. Indeed, it became common for reviewers to compare and contrast the latest US quantum-mechanics textbooks based on their philosophical approaches.

Many of this pre-war generation's most influential teachers likewise focused on philosophical material in their classrooms. Emblematic was Robert Oppenheimer's popular course at the University of California at Berkeley. Graduate students routinely sat through his quantum-mechanics course more than once; one desperate student even went on a hunger strike until Oppenheimer relented and let her attend the class for a fourth time. Well into the late 1930s, Oppenheimer still introduced quantum mechanics as a "radical solution" to pressing philosophical issues that have their roots in physics.

On page after page of his lecture notes, Oppenheimer focused not only on the new formalism of quantum mechanics – centred on Schrödinger's wavefunction – but also on its physical interpretation, lavishing attention on the origins and meaning of probabilistic interpretations. Long before going through the first practical calculation with the new equations, he even indulged in Einstein-styled thought experiments to circumvent the uncertainty principle, each of which, Oppenheimer showed, was destined to fail.



Time Life Pictures

Strange thoughts Before the Second World War, physicists did not shy from the philosophical implications of quantum mechanics. J Robert Oppenheimer's famous course at the University of California at Berkeley emphasized hard questions of philosophy and interpretation alongside more practical calculations with the new formalism.

Oppenheimer was not alone. Lecture notes from other graduate-level courses on quantum mechanics in the 1930s reveal similar attention to matters of interpretation. Copies of "general" exams from the same period, which students had to pass if they wanted to do a PhD, survive from a dozen top-ranked physics departments across the US. Common to each of them are essay questions probing such thorny issues as how a wavepacket gets reduced from a superposition of possibilities to a single measured result. Others ask how the role of the observer differs between classical and quantum mechanics or press students to explain how the uncertainty principle challenges the nature of physical explanation.

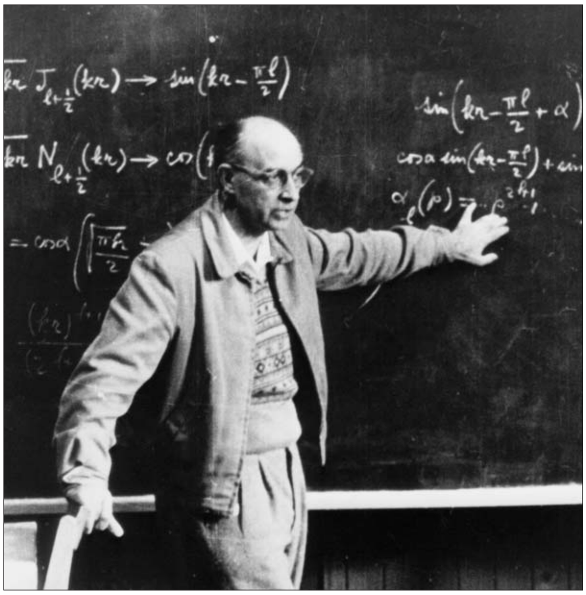
Enrolments and interpretation after the war

After the Second World War the unmistakable importance of nuclear and solid-state physics to the success of military projects like the atomic bomb pushed quantum mechanics to the forefront of US physics curricula. Formal courses in the subject became a requirement for graduate students across the country and, within a few years, nearly all undergraduate physics majors had to take classes in the subject as well. Topics from classical physics, such as acoustics, optics and thermodynamics, to which pre-war students had devoted most of their time, lost their prime role in the curriculum.

But how was one to teach quantum mechanics? By the late 1940s few traces of the earlier pedagogical approaches remained. Faced with runaway enrolments, most physicists in the US recrafted the subject of quantum mechanics, accentuating those elements that allowed students to be taught as quickly as possible, while

At a Glance: Teaching quantum mechanics

- Quantum mechanics is a theory with many philosophical ramifications that pioneers like Bohr, Heisenberg and Oppenheimer delighted in discussing in the classroom and in their textbooks
- After the Second World War, many physicists abandoned this approach to teaching the subject – instead the goal was to train students to calculate with the theory, unburdened by speculative, philosophical concerns
- New research suggests that this change of approach was driven by the demand for more physicists: large classes simply proved to be unsuitable venues for deep philosophical discussions
- The focus on learning to calculate, however, brought many pay-offs, including the Standard Model of particle physics
- As quantum computing and communications becomes reality, the philosophical aspects of quantum mechanics are coming back into fashion



AIP Emilio Segrè Visual Archives

No more musing The need to teach physics to increasing numbers of students after the Second World War changed the way that quantum mechanics was taught. Physicists like Enrico Fermi, shown here, eschewed interpretive material, focusing instead on the nuts and bolts of calculating.

quietly dropping the last vestiges of qualitative, interpretive musings that had occupied so much classroom time before the war.

Several explanations for this shift might be offered. Perhaps the field had simply matured and the conundrums that had stumped the interwar generation had been solved satisfactorily with the passage of time. Not so: most of the interpretive problems that had emerged in the 1920s remained puzzling after the war and indeed are still not fully explained today. Perhaps the war (along with postwar defence funding) had turned practitioners into pragmatists; projects like radar and the atomic bomb required a hands-on approach to calculations in a way that interwar theorizing had not. Or perhaps the teaching of quantum mechanics had changed because physicists knew that more and more students would end up in industrial and government labs, where philosophical niceties were not so important.

While these explanations may in part be true, it turns out that the biggest influence on the teaching of quantum mechanics after the war was class size. When one looks at post-war quantum-mechanics courses or compares US textbooks on the topic with those from other countries, as I have done, it becomes clear that lecturers who had small classes taught quantum mechanics very differently from those who were faced with very big class sizes.

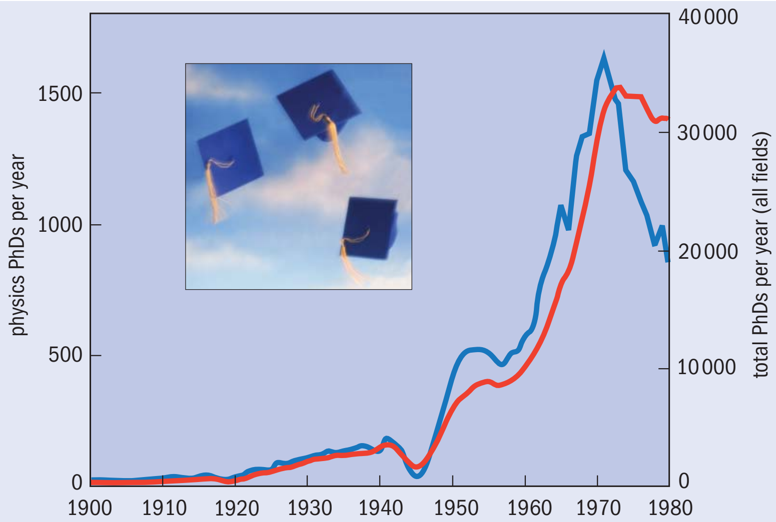
I have been able to track down about a dozen sets of lecture notes from quantum-mechanics courses aimed at first-year graduate students in the 1950s and early 1960s, at the height of the enrolment boom. Several of these sets derive from some of the discipline's most celebrated teachers, such as Enrico Fermi, Hans Bethe and Richard Feynman. Although these notes are from different universities, they ought to be quite similar to each other: each had the same level of technical difficulty; each purported to cover the same basic material; and several relied on the same textbooks. Yet they vary hugely – not in terms of equations derived or applications analysed, but in the amount of attention devoted to interpretive or philosophical issues.

A clear pattern emerges. Courses in the smallest departments, which had the smallest enrolments, consistently devoted considerably more time to the puzzles and paradoxes of quantum mechanics than those for the large-enrolment classes. When one determines the proportion of space these discussions take up in the surviving notes, it turns out that professors with small classes (where the average class size was 13) included five times more material on interpretive or philosophical issues than those with large classes (where the average class size was nearly 40). However, there was no correlation between class size and where graduates of these departments took jobs, be it academia, industry or government.

The small-enrolment classes in this sample, just like the large ones, were each taught by veterans of the wartime projects, so the war cannot be the whole explanation. The small classes were likewise taught by recipients of defence-department largesse, also like the large classes. For example, Lothar Nordheim, a physicist who had played a leading role at the Oak Ridge laboratory in Tennessee as part of the Manhattan project, taught relatively small classes at Duke University in North Carolina in the late 1940s, where he insisted that his students focus intensely on the bizarre, surprising and qualitative aspects of quantum mechanics. His very first lecture addressed questions such as what it means for a theory to only predict the probabilities of various outcomes or how that can affect causality. Nordheim took similar care when introducing the uncertainty principle, pressing his students to think about the consequences of never being able to measure certain quantities, like where a particle is and where it is going, at the same time.

However, this pedagogical approach did not scale to larger classrooms. Back-and-forth discussion was quite difficult to sustain in classes of 40 or more students; deep discussions of interpretation were ill-suited for auditorium-sized lecture halls. "With these subjects [such as uncertainty, complementarity and causality] lecturing is of little avail," complained a frustrated Edward Gerjuoy in 1956 – a physics professor at the University of Pittsburgh who had passed through Oppenheimer's course at Berkeley before the war. "The

Faced with runaway enrolments, most physicists in the US recrafted quantum mechanics so that students could be taught as quickly as possible, while quietly dropping the qualitative, interpretive musings



Rise and fall The number of PhDs granted by US institutions between 1900 and 1980 in physics (blue) and in all fields (red). Physics numbers rocketed after the Second World War, outpacing the growth in every other field. By the early 1970s, however, they had crashed harder than any other field. (Based on data from the US National Science Foundation)

baffled student hardly knows what to write down, and what notes he does take are almost certain to horrify the instructor." The message was clear: it was better to stick with other types of material, such as how to perform various coordinate transformations, diagonalize matrices or execute series expansions.

Fermi, for example, devoted just two pages of his 1954 lecture notes at the University of Chicago to the uncertainty principle – supplying a loose derivation based on finite wavepackets, but no qualitative discussion – while spending twice as long on the niceties of Laguerre polynomials as part of his derivation of the wavefunction of an electron in a hydrogen atom. At Cornell University, Bethe noted dismissively in his notes for a 1956 class that trying to circumvent the uncertainty principle was as foolish, and as wasteful, as chasing perpetual-motion machines, so he and his students would spend their time learning to calculate.

As for Feynman, he admonished his students at the California Institute of Technology that interpretive issues were all "in the nature of philosophical questions [and] not necessary for the further development of physics". These large-enrolment classes were by no means poorly executed. On the contrary, the lecture notes reveal the clarity and attention to detail that earned these leading physicists their well-deserved reputations. Yet for every additional example that Fermi, Bethe, Feynman and the others marched through at the blackboard – how to approximate the effects of an electric field on the energy levels of a hydrogen atom, or how to calculate the likelihood that two particles would scatter – they spent correspondingly less time encouraging their students to think hard about what all those fancy equations really said about the world.

My goal is neither to sow nostalgia for the philosophically engaged style of teaching, nor to condemn the pragmatic approach

Perhaps without realizing it, they were teaching a particular style in those bloated classrooms. Day in and day out, they inculcated a pragmatism quite different from the approach fostered in many American classrooms before the war, and in a handful of small classes after it. Little wonder, then, that so many US physicists preferred to ignore the interpretative issues of quantum mechanics and focus instead on its application to nuclear and solid-state physics, from which so much new physics emerged.

Textbook trends

As enrolments continued to climb after the war, textbooks on quantum mechanics written by US physicists also began to change. Where once reviewers had evaluated textbooks (in part) on their specific philosophical stance, now they routinely praised the newest offerings for "avoiding philosophical discussion" and for omitting "philosophically tainted questions" that distracted from the business of calculating. Enough with the "musty atavistic to-do about position and momentum", declared Herman Feshbach of the Massachusetts Institute of Technology in a review of the French physicist Albert Messiah's fat and philosophy-laden textbook, which was translated into English in 1961.

Between the late 1940s and 1980, physicists working in the US published a total of 33 textbooks on quantum mechanics for first-year graduate students, such as Leonard Schiff's *Quantum Mechanics*, while a further 20 books appeared for undergraduates. Although these books varied greatly in the methods they adopted and the examples they analysed – some clung to Schrödinger's approach, while others adopted Paul Dirac's state-vector formalism – from the vantage point of managing large enrolments, the books began to look quite similar. They now routinely included hundreds of problems and exercises – an order of magnitude greater than the number usually found in the pre-war US textbooks.

What was interesting was that the nature and not just the number of problems changed. For example, the first quantum-mechanics textbook to be published in the US – written by Edward Condon and Philip Morse in 1929 – contained 16 exercises, fully a quarter of which called on students to go beyond the equations and discuss their calculations in words. By the early 1950s, however, these qualitative, short-answer questions began to disappear from US textbooks, hovering at about the 10% mark while American physics classrooms underwent their exponential bulge. Only after enrolments plummeted in the early 1970s did a new kind of textbook begin to appear, featuring interpretive essay questions in nearly half of its problems.

In 1974, for example, Robert Eisberg of the University of California at Santa Barbara and Robert Resnick from the Rensselaer Polytechnic Institute in New York published their 700-page *Quantum Physics of Atoms, Molecules, Solids, Nuclei, and Particles*. Graduate-level enrolments in physics were by then 40% lower than their late 1960s highs and their book reflected some of these changing classroom dynamics. Although there were hundreds of quantitative problems, Eisberg and Resnick also included long lists of "discussion questions", each of which called for an explanatory (rather than algebraic) response on topics such as the nature of black-body radiation, particle tunnelling and the conceptual difficulties associated with a point electron.

Two years later, the enrolment curve having bottomed out, a similar book appeared by Michael Morrison, Thomas Estle and Neal Lane from Rice University in Texas. *Quantum States of Atoms, Molecules, and Solids* featured a majority (over 55%) of essay-type questions.

Quantum mechanics in Europe

Having proved their worth to the military during the Second World War, the demand for physicists in the US surged dramatically in the early 1950s. As university class sizes grew, however, the philosophical implications of quantum mechanics, which had once dominated the teaching of the subject, were increasingly being sidelined in packed-out lecture halls. But as every student of statistics knows, correlation alone does not imply causation. So can we really be sure that classroom size is linked to how quantum mechanics was taught?

Interestingly, physicists in countries that faced little enrolment pressure after the war tended to write textbooks on quantum mechanics that were quite different from those of their American colleagues. Books by authors in Germany, where enrolments stagnated after the war, still emphasized the close ties to philosophy that earlier German books had heralded. Werner Heisenberg's associate Wolfgang Finkelnburg, for example, included a long section on "achievements, limitations, and philosophical significance of quantum mechanics" in his 1948 textbook, culminating in a detailed discussion of the philosopher Immanuel Kant's ideas about the nature of knowledge. Textbooks by French authors similarly focused on philosophy, often incurring dismissive reviews in US journals for their "excessive" and "overdone" treatments of interpretive material.

On the other hand, physicists who faced similar enrolment pressures to their US colleagues tended to write textbooks that looked like their American counterparts, too. In the UK, for example, where the number of students taking physics peaked in the 1960s before falling sharply soon after, textbooks on quantum mechanics by physicists working in Britain, such as Franz Mandl's *Quantum Mechanics*, contained just as small a proportion of interpretive or short-answer problems as the US textbooks did.

The same pattern was true in the Soviet Union. The disappearance of philosophy from Soviet textbooks cannot be explained away entirely by authors' fears of meddling from Communist Party apparatchiks, who might have punished physicists for straying from the official "dialectical materialist" doctrine. After all, Stalin had an intense desire for nuclear weapons, and thus refrained from interfering with physicists on ideological grounds after the war in the way he did with biologists. Moreover, at least some of the Soviet textbooks from the earlier era – when ideological tests were strongly in effect, but before enrolment pressures took off – placed heavy emphasis on philosophical material.

Thus the pattern seems clear. Where enrolment pressures loomed largest, physicists on both sides of the Iron Curtain drilled their students to "turn the crank" and work through more and more quantitative problems, rather than spend their time philosophizing.

The authors had concluded that what worked best with the new, smaller classes was a series of multi-part problems, each with a lengthy introduction to lay out the scope and motivation for the materials to come. Problem after problem pressed students to "discuss", "explain" or "justify your conclusions".

Undergraduate textbooks followed the same trajectory. Books published between 1969 and 1978 had, on average, twice as many short-answer problems as those in books from the period 1959 to 1968, correlating with the sudden drop-off in enrolments. For example, when *Principles of Modern Physics* by Anthony French appeared in 1958 it contained 79 problems, less than 9% of which called on students to interpret the material in words. Two decades later, however, French published *An Introduction to Quantum Physics* with Edwin F Taylor that bulged with 244 problems, almost a third of which were interpretative in nature. The enrolment bubble having burst, faint echoes of philosophical engagement thus crept back into American physics classrooms.

Boom and bust again

Enrolment patterns in the US in more recent times have repeated the previous rise and fall, with a huge surge in physics enrolments in the 1980s, driven largely by the defence build-up of the Reagan administration, followed by a sharp decline once the Cold War ended. Perhaps this pattern is why research and teaching on philosophically juicy topics like quantum computing, quantum encryption and quantum entanglement, which force physicists to address many questions at the core of quantum mechanics, only began to take off in the late 1990s. Despite these issues having been around for 70 years or more, many physicists and their students are again debating how best to interpret superposition, probabilities and entanglement, as quantum weirdness gets hardwired in a new generation of devices.

There has never been just one best way to teach quantum mechanics. My goal is neither to sow nostalgia for the philosophically engaged style of Oppenheimer and Nordheim, nor to condemn the pragmatic approach of Fermi, Bethe and Feynman. It is rather to highlight the choices that physicists must always make when stepping into the classroom. Choices of topics to discuss and problems to assign reflect deeper decisions about the ideal type of physicist one seeks to train. Should the new generation be philosophically attuned, concerned with minute details of conceptual interpretation? Or should physicists hone their ability to calculate, pushing Heisenberg's and Schrödinger's equations into the service of ever more elaborate problems to solve and phenomena to analyse? Competing ideals have flourished under different pedagogical conditions.

Strangely enough, many of the philosophical issues surrounding quantum mechanics are today being used to entice potential students into physics. As quantum computing and quantum communication become a commercial reality, tomorrow's students may find themselves routinely grappling with the same philosophical questions that challenged their forebears almost a century ago.

More about: Teaching quantum mechanics

D Kaiser 2002 Cold War requisitions, scientific manpower, and the production of American physicists after World War II *Historical Studies in the Physical and Biological Sciences* **33** 131–159

D Kaiser 2004 The postwar suburbanization of American physics *American Quarterly* **56** 851–888

D J Kevles 1995 *The Physicists: The History of a Scientific Community in Modern America* 3rd edn (Harvard University Press, Cambridge, MA)

S W Leslie 1993 *The Cold War and American Science* (Columbia University Press, New York)

S Lloyd 2006 *Programming the Universe: A Quantum Computer Scientist Takes on the Universe* (Jonathan Cape, London)