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Chapter 1

"Shut Up and Calculate"

It was very different, when the masters of the science sought immortality and power; such views, although futile, were grand: but now the scene had changed. The ambition of the inquirer seemed to limit itself to the annihilation of those visions on which my interest in science was chiefly founded. I was required to exchange chimeras of boundless grandeur for realities of little worth.

—Victor Frankenstein, character in Mary Shelley's *Frankenstein*

In the spring of 1974, a most unusual meeting took place. Two physicists—Fred Alan Wolf and Jack Sarfatti, who would soon become charter members of the Fundamental Fysiks Group—sat down with Werner Erhard in the lobby of the Ritz Hotel in Paris. Erhard, one of the leading exponents of the "human potential movement," was at the top of his game. His *est* workshops ("Erhard Seminars Training"), forerunner of today's self-help and personal-growth industry, had already grossed several million dollars and boosted Erhard to worldwide celebrity.[1] He had asked Wolf and Sarfatti to meet with him because he was fascinated by the way physicists attacked complicated and counterintuitive problems with rigor.[2]

The meeting did not get off to an auspicious start. Sarfatti felt restless, uninterested in the meeting; he had never heard of Erhard. Erhard's gaudy outfit, accessorized by a beautiful female admirer hanging on his sleeve, put Sarfatti off even more. Sarfatti asked what Erhard did. Erhard grinned and replied, "I make people happy." It was more than Sarfatti could take. Itching to leave, he said in a strong Brooklyn accent, "I think you're an asshole." As Sarfatti remembers it, Erhard rose from his chair—smile stretching from ear to ear—embraced Sarfatti right there in the hotel lobby, and said, "I am going to give you money." Without knowing it, Sarfatti had used one of the catchphrases associated with Erhard's sprawling self-help venture. Soon the money began to flow: thousands of dollars, all from this most eager new patron of quantum physics.[3]

Erhard was not the first to seek enlightenment from the strange subject of quantum theory. Even more than relativity—with its talk of shrinking meter 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 separated light-years apart retain telepathic links with one another. The seeming solidity of the world evaporates into a cloud of likelihoods. Long before Erhard, Wolf, or Sarfatti had arrived on the scene, the world's leading physicists had struggled to come to grips with quantum theory, to tease out just what it might mean. Many of their ideas sounded no less peculiar than the half-formed inklings that inspired Erhard on that fateful spring day.[4]

Quantum mechanics emerged over the first quarter of the twentieth century, honed primarily by Europeans working in the leading centers of theoretical physics: Göttingen, Munich, Copenhagen, Cambridge. Most of its creators—towering figures like Niels Bohr, Werner Heisenberg, and Erwin Schrödinger—famously argued that quantum mechanics was first and foremost a new way of thinking. Ideas that had guided scientists for centuries were to be cast aside. Bohr constantly spoke of the "general epistemological lesson" of the new quantum era. The disjuncture of cause from effect, Heisenberg's uncertainty principle, wave-particle duality—all required explicit, extended philosophical engagement, so these leaders proclaimed. They differed, often passionately, over which philosophical schools of thought might best clarify the new material. Some invoked the writings of eighteenth-century scholar Immanuel Kant; others quoted aphorisms from Hindu holy scriptures, or "Upanishads"; some even dabbled in Jungian depth-psychology. The subject's leading detractors, such as Albert Einstein, likewise agreed that quantum mechanics had to meet stringent philosophical tests. Mathematical self-consistency and agreement with experiments were important, but hardly sufficient.[5]

During this heady period, grown men argued into the night, trying to make sense of a series of puzzles and paradoxes. Names were called; tears were shed. At one point, an ailing Schrödinger sought refuge in bed while visiting Bohr's Institute for Theoretical Physics in Copenhagen. Unable to let a disputed matter of interpretation rest, Bohr hounded the poor Austrian at his bedside, repeating, "But surely Schrödinger, you must see . . ."[6]

That style of working on quantum mechanics faded fast after World War II. Especially in the United States, the war and its aftermath shaped how generations of new physicists were trained. Ultimately, the war changed what it meant to be a physicist. The Cold War completed the transformation, winnowing the range of acceptable topics and admissible approaches. Very quickly, philosophical inquiry or open-ended speculation of the kind that Bohr, Einstein, Heisenberg, and Schrödinger had considered a prerequisite for serious work on quantum theory got shunted aside. "Shut up and calculate" became the new rallying cry.[7]

Yet the Cold War consensus proved to be no more eternal than the prewar style had been. As the fortunes of physics plummeted in the late 1960s and early 1970s, sending academic physics departments into a tailspin, new intellectual possibilities opened up. Buoyed by cash from new patrons like Erhard, small clusters of physicists, including Wolf, Sarfatti, and their colleagues in the Fundamental Fysiks Group, labored to carve out a new identity for themselves and for the science they loved so much.

Back in the 1920s, sticking points seemed to abound in the new quantum theory. Every time physicists tried to make sense of their hard-won equations, new and bizarre challenges tumbled forth. One experiment captured the lion's share of peculiarities. It came to be known as the "double-slit experiment." Champions of quantum mechanics trotted it out time and again to sharpen their understanding of the issues involved.

Bohr and Heisenberg, for example, featured it in some of their earliest expositions of quantum mechanics.[8] Critics likewise saw much of value in the experiment, goading their colleagues to admit how preposterous their explanations sounded. Schrödinger—caught between the warring camps, with his own uneasy relationship to the equations he had produced—recognized the pedagogical value of the double-slit experiment for clarifying many of the core mysteries of quantum mechanics, and featured it prominently in lectures during the 1930s.[9] Since that time, generations of physicists have followed Schrödinger's lead. In fact, readers of the trade magazine *Physics World* recently voted the double-slit experiment the single most beautiful experiment of all time. In their view, it edged out heavyweight contenders from Galileo to Newton, and even a classic dating from ancient Alexandria, all of which also made the top ten.[10]

In an essay for Einstein's seventieth birthday, published in the late 1940s, Bohr used the double-slit experiment as the leitmotiv of his decades-long debate with Einstein.[11] Years earlier, Einstein had helped to launch the quantum revolution, introducing several crucial concepts. In fact, the Nobel Prize committee cited only his contributions to quantum theory when granting his award in 1921, remaining mum on relativity. Then, in one of the delicious ironies of the history of science, Einstein reversed course and turned his back on his own creation. (The irony was not lost on Einstein. "After all," he wrote to Schrödinger, "many a young whore turns into an old praying sister, and many a young revolutionary becomes an old reactionary.") He brandished the double-slit experiment in private correspondence to drive home his criticisms as early as April 1926, and in more public settings the following year.[12]

Fearing that their friendly squabbles over quantum theory had become too ethereal or detached from the real world over the years, Bohr worked with an artist to make his position more concrete when preparing his essay for Einstein's birthday. The resulting images had the look and feel of engineering diagrams, all bulky bolts and heavy planks. In Bohr's reconstruction, the double-slit experiment centered around an apparatus like the one in Figure 1.1, a thick wall with two slits hollowed out. A sliding

latch was installed in front of one of the slits, so that physicists could choose whether to leave that slit open or shut. Behind the wall stood a recording screen—it could be photographic film or some other means of detection—bolted securely in place.

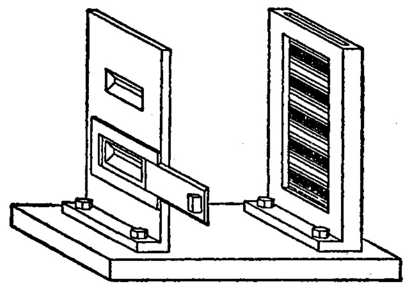

FIGURE 1.1. Niels Bohr's depiction of the double-slit apparatus. (Cropped from Bohr [1949], 219. Reproduced with permission of Open Court Publishing Company, a division of Carus Publishing Company.)

Einstein and Bohr each knew well what would happen if they shined a light on the wall when both slits were open. Bohr included a picture in his birthday essay. (Fig. 1.2.) If the light source were far enough away, the light waves would approach the wall-with-slits in a simple configuration that physicists call a "plane wave," with all the crests and troughs lined up neatly in rows. Most of the light from the source would be blocked by the wall. The light that passed through the narrow slits would fan out in a new pattern, arcing in semicircular waves toward the recording screen. The crests and troughs of the two curving light waves, emanating from the open slits, would no longer be lined up with each other. In some locations along the recording screen, the crest from one wave

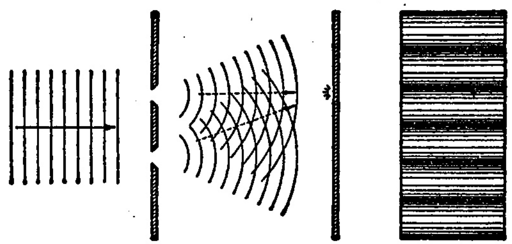

FIGURE 1.2. The double-slit apparatus and interference pattern. (Cropped from Bohr [1949], 216. Reproduced with permission of Open Court Publishing Company, a division of Carus Publishing Company.)

would arrive in step with the crest from the other, adding up to make a bright spot on the photographic film. In other locations, however, the crest from one wave would arrive with the trough of the other. At those spots, the light waves from each slit would cancel each other out, leaving no mark on the film. And so it would go as one moved down the recording screen: alternating light and dark bands known as an "interference pattern."

Bohr pressed on. One of the biggest surprises in quantum physics was that the same quintessential interference pattern arose when one fired tiny particles, such as electrons, at a wall with two slits. Each particle seemed to behave like a tiny billiard ball when released from the source on one side of the room and detected at the screen on the other side. Yet upon shooting tens, hundreds, or thousands of electrons at the twice-slitted wall, the locations at which each tiny electron was detected matched the wavelike interference pattern. That would never happen with ordinary billiard balls. When thrown at a wall with two slits, the balls would cluster in two clumps, one behind each of the open slits. The billiard balls would never arrange themselves in the alternating interference pattern. Even more strange, physicists could choose to shoot a thousand electrons at the wall one at a time, an hour apart. After all the electrons had made their way through the apparatus, the pattern of light and dark patches on the recording screen—marking where each individual electron had arrived, one at a time—would appear just as if physicists had sent light waves to interfere. (Fig. 1.3.)

Physicists had managed to conduct laboratory demonstrations of the effect as early as 1927.[13] Einstein pressed his colleagues at an informal conference that year to explain: what did the waving? Certainly not the electrons themselves, at least not without straining credulity. Each had been fired one at a time, so no two electrons could have interacted with each other (say, by repelling each other with their electric charge). Each had been detected as a tiny particle; none showed up at the recording screen as a washed-out wave. The distance between the slits was much larger than the electrons themselves, so it hardly made sense to think that an electron passed through both slits at the same time and inter-

FIGURE 1.3. Three snapshots of the detection of individual photons after they have passed through a barrier with slits. The photographs show results after 1/30 of a second (*left*), 1 second (*middle*), and 100 seconds (*right*). Each photon, or quantum of light, gets detected as an individual particle, and yet the pattern that builds up over time reveals wavelike interference. (Courtesy Robert Austin and Lyman Page, Princeton University.)

fered with itself on the other side. Einstein clearly enjoyed watching his colleagues squirm. Like two giddy schoolboys, Einstein and a close friend passed notes back and forth while one defender of quantum theory after another tried to fend off Einstein's challenges. "Don't laugh!" his friend scribbled. Einstein's prescient reply: "I laugh *only* at the naiveté [of the proponents of quantum theory]. Who knows who will be laughing in the coming years."[14]

Einstein's sparring partners were laughing soon enough. Bohr, Heisenberg, and their colleagues cobbled together an interpretation of what was happening in the double-slit experiment. Every quantum system, they reasoned, had an associated "wavefunction," which they labeled with the Greek letter, Ψ (pronounced "psi"). The values that the wavefunction assumed in different locations, and the way those values changed over time, were governed by a new equation first introduced by Schrödinger in 1926. Schrödinger's equation was similar in mathematical form to well-known equations that described wave behavior, such as water waves on the ocean. Max Born—Einstein's friend and Heisenberg's mentor—advanced an interpretation that same year that Ψ was related to probability. In particular, the probability for detecting a quantum object at a particular time and place was given, in Born's account, by the absolute square of the associated wavefunction: Probability = $|\Psi|^2$. In the double-slit experiment, according to this interpretation, the electron's wavefunction spread out like a wave and went through both slits, leading to the characteristic interference pattern.[15]

So were the electrons behaving like particles or waves? The answer—which brought a smile to Niels Bohr's face every time he walked a new audience through the experiment—was "all of the above." Einstein was less amused. "The Heisenberg-Bohr tranquilizing philosophy—or religion?—is so delicately contrived," he complained in a letter to Schrödinger in May 1928, that "for the time being, it provides a gentle pillow for the true believer from which he cannot very easily be aroused. So let him lie there. But"—he left no doubt—"this religion has so damned little effect on me."[16]

Heisenberg and Bohr had more tricks up their sleeves; they weren't finished with the double slit yet. They considered modifying the apparatus, to be able to measure through which slit an individual electron passed. Despite all the talk of wavefunctions, after all, each electron was emitted and detected like a tiny particle; surely each electron must have passed through one slit or the other, just like ordinary billiard balls would do. That notion could be tested, they explained, by placing some other tiny particles behind one of the slits. If an electron passed through that slit en route to the recording screen, then some of the test particles would get scattered, like pins tossed about by a bowling ball, signaling the electron's passage through the slit. If, on the other hand, none of the test particles were scattered, then the electron must have passed through the other slit.

It sounded simple enough. And it would have worked, too, but for one catch, known as Heisenberg's uncertainty principle. Soon after Schrödinger and Born worked out the basic rules for manipulating Ψ, Heisenberg demonstrated that the new equations behaved in some

unexpected ways, totally unlike the usual physics of particles or waves. Certain pairs of quantities, such as position and momentum or energy and time, could never be specified with unlimited precision at a single instant. The more precisely a quantum object's position was specified, the less precisely its momentum could be, and vice versa. According to Heisenberg, in other words, we can never know exactly where an object is and where it is going at the same time.[17]

During lectures at the University of Chicago in 1929, in one of his earliest deployments of the uncertainty principle, Heisenberg demonstrated why the slit detector could not work as advertised. To yield a reliable measurement of whether an electron passed through a particular slit, the test particles would have to be clumped tightly behind that slit. The uncertainty in their position, in other words, would have to be much smaller than the distance between the two slits. That small uncertainty in position, in turn, would correspond to a large uncertainty in their momentum. The incoming electron thus would careen into a collection of test particles that already had some large uncertainty in their momentum; this would translate into a correspondingly large uncertainty in the electron's momentum following the collision. Heisenberg needed just a few lines of algebra to show that the collision would jostle the electron's path just enough to smear out the sharp peaks and valleys of the interference pattern. In fact, if every electron could be measured to pass through one slit or the other, the resulting detection pattern would revert to two broad peaks, one behind each slit; all wavelike interference would vanish. On the other hand, reducing the uncertainty in the electron's momentum after scattering, to retain the interference pattern, could only be done by increasing the uncertainty of the test particles' position—by such an amount that no one would know whether they had been clumped behind one slit, the other, or both.[18]

To Bohr, the paradox of the slit detector exemplified a more general feature of quantum mechanics. Ask a "particle-like" question—"through which slit did the particle pass?"—and you will always receive a particle-like answer ("slit A" or "slit B"). Ask a "wavelike" question—"how does Ψ behave in the region between the slits and the detectors?"—and you will always receive a wavelike response ("in a state interference, crests canceling troughs in some places and amplifying crests in others"). Bohr coined the term "complementarity" for his emerging philosophy. Explanation in the quantum realm, he maintained, required the constant juxtaposition of statements that were themselves mutually exclusive, the particle "yin" always paired with the wavelike "yang." (In 1947, when the king of Denmark anointed Bohr with the prestigious Order of the Elephant, Bohr needed to produce a family coat of arms for display in the Frederiksborg Castle near Copenhagen. He placed the classical Chinese yin-yang symbol at its center.) Einstein had little patience for this kind of talk. The goal of physics, he maintained his entire life, was to determine how the world works on its own, independent of the questions we happen to ask of it. Writing to Schrödinger, Einstein mocked Bohr's increasingly oracular outbursts as those of a "a ridiculous little Talmudic philosopher."[19]

Einstein had other bones to pick. Max Born had suggested—and nearly all quantum physicists came to agree—that the square of the wavefunction yielded a probability. But neither Born nor anyone else had succeeded in pressing beyond mere probabilities. For Einstein, this seemed an intolerable shortcoming. He made a few false starts of his own, at one point jotting a rushed note to Born to announce that he had found an interpretation of Ψ that did not resort to probabilities; but each of these efforts fell short of the mark. In the meantime, Einstein only accorded quantum mechanics what he called "transitory significance," despite his many contributions to the subject. "I still believe in the possibility of giving a model of reality," he explained in a lecture at Oxford in 1933, "a theory, that is to say, which shall represent events themselves and not merely the probability of their occurrence."[20] Writing to Born, he was even more direct. "Quantum mechanics is certainly imposing," he began. "But an inner voice tells me that it is not yet the real thing. The theory says a lot, but does not really bring us any closer to the secret of the 'old one.' I, at any rate, am convinced that *He* is not playing at dice." Einstein had no beef with the logical self-consistency or the empirical successes of quantum mechanics. In the right hands, he acknowledged,

Schrödinger's equation and Born's interpretation of Ψ could produce stunningly accurate descriptions of the overall outcomes of large collections of events, such as where, on average, thousands of electrons that had been fired at a barrier would be detected. But the quantum formalism could never reconstruct those aggregate results on a case-by-case basis; it could never explain why the electron in experimental run 867 happened to pass through one slit rather than the other and wind up at a particular location.[21]

Einstein's frustrations reached the boiling point in the summer of 1935. He exchanged a series of letters that summer with Erwin Schrödinger, each egging the other on with his discontent over the direction quantum physics had taken. Building on suggestions from Einstein, Schrödinger crystallized their position with a thought experiment that came to be known as "Schrödinger's cat." In what he called a "ludicrous example," Schrödinger pushed the problem of only being able to calculate probabilities to the extreme. Imagine a cat, Schrödinger instructed readers of his resulting article, "enclosed in a steel chamber, together with the following infernal machine": a small source of radioactive material next to a Geiger counter, which would be able to detect any radioactive decays. Rigged up to the Geiger counter would be a hammer. Should the Geiger counter detect even a single radioactive decay, it would release the hammer, which would strike a bottle of poison, killing the cat. Suppose, Schrödinger continued, that the radioactive material had a probability of one-half to decay within an hour. The best that quantum mechanics could say was that after one hour had elapsed, the cat locked inside the box would be in the strangest of conditions: "in equal measure, the living and the dead cat are (*sit venia verbo* [pardon the expression]) blended or smeared out." Neither dead nor alive, the cat would be in some weird quantum mixture of half-dead-and-half-alive, a condition with no analogue in ordinary experience. But, Schrödinger and Einstein emphasized, no one had ever seen a cat in such a horrid state. Surely, they were convinced, there must be more to physics than mere probabilities.[22]

Bohr, in contrast, delighted in the new probabilistic framework, reaching back to his undergraduate studies of Kant and Kierkegaard to craft a new quantum worldview. Heisenberg, too, found ample fodder for philosophizing in the turn to probabilities. The son of a classicist, Heisenberg enlisted ancient concepts of being and becoming, or "potentia," from the likes of Plato and Aristotle. Puzzling through the uncertainty principle, he liked to recall later in life, had sent him scrambling for his copy of Plato's *Timaeus*. (To Heisenberg's close friend and collaborator Wolfgang Pauli, such claims smacked of mere posturing. Pauli declared in a letter to Bohr that Heisenberg was in fact "very unphilosophical.")[23] Indeed, Bohr, Heisenberg, Pauli, and their colleagues like Max Born became convinced that their new quantum theory ushered in an entirely new philosophical age. Bohr announced at every opportunity that his "either-or" interpretation of the quantum realm, complementarity, was a "general epistemological lesson," to be applied liberally across the entire gamut of human learning, from biology and psychology to anthropology. Typical example: according to Bohr, we can either experience the free flow of our own thoughts, or observe ourselves in the process of thinking, but not both at the same time. Soon after the onset of the Cold War, Max Born was moved to liken capitalism and communism to particle and wave, destined for a quantumlike complementarity.[24]

Einstein would have none of it. "This epistemology-soaked orgy ought to come to an end," he wrote to a colleague at one point. Setting aside the wider speculations in which the quantum theorists indulged so freely—traipsing from natural sciences to social sciences, religion, politics, and beyond—Einstein still harbored deep reservations about their interpretation of the physics. Their embrace of probabilities was especially troubling. Such a probabilistic description might well be useful, Einstein granted, but it was hardly fundamental. "My own opinion," he confided to a correspondent late in 1939—nearly fifteen years after the breakthroughs by Heisenberg, Schrödinger, Bohr, and Born—was that "we will return to the task to describe real phänomena in space and time (not only probabilities for possible experiment)." By that time, most of the younger generation had stopped worrying about Einstein's quibbles. Yet others, closer in age to Einstein (such as Schrödinger), came to share Einstein's dissatisfaction with quantum mechanics. All agreed that mysteries like the double-slit experiment demanded serious philosophical attention. The fate of physics depended on it.[25]

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The creators of quantum mechanics formed a tight-knit community. At its center, roughly a dozen physicists occupied what sociologists would call a "core set." Surrounding the core, only a few dozen more published on the topic anywhere in the world during the critical period of the mid-1920s. The main players knew each other well. They continually crossed paths at Bohr's institute in Copenhagen, Born's center in Göttingen, or the informal conferences sponsored by the industrialist-turned-philanthropist Ernest Solvay. Quantum physicists criss-crossed Europe by rail, dropping by for visits that lasted days, weeks, or months. "Kramers was here for eight days," Born wrote to Einstein in typical fashion in July 1925, "and Ehrenfest. . . . Last week Kaptiza from Cambridge was here, and Joffé from Leningrad." "If it is agreeable to you," Schrödinger wrote to Einstein a few years later, "I would be glad to come over sometime to talk" more in person about Bohr's latest ideas.[26] When not in the same town, they kept up their conversations by letter, tens of thousands of which have survived. Over the years, scholars have dutifully inventoried, archived, microfilmed, and translated these letters, subjecting them to the kind of line-by-line scrutiny once reserved for Scripture. The letters reveal just how earnestly the early quantum physicists worked to interpret their new formalism, day in and day out. Clustered in small, informal groups, they struggled to put flesh on the new equations, to wrap their heads around how the world could possibly *work* that way.[27] (Fig. 1.4.)

The same philosophical impulse shaped their earliest pedagogical writings. Some textbooks included entire chapters with titles like "Quantum mechanics and philosophy." Other textbook authors paused within their expositions to pronounce the death of the Kantian "thing-in-itself," or to weigh the consequences of Heisenberg's uncertainty principle for scientists' age-old quest for objectivity.[28] The young American physicists who learned quantum mechanics at the feet of the European masters

FIGURE 1.4. Niels Bohr and Albert Einstein deep in conversation about the mysteries of quantum mechanics while visiting the house of a mutual friend in 1930. (Photographs by Paul Ehrenfest, courtesy Emilio Segrè Visual Archives, American Institute of Physics.)

likewise agreed that the material demanded philosophical attention. They often broke with their teachers' preferred philosophies—American instructors turned most often to the homegrown philosophy of Harvard physicist Percy Bridgman, rather than the rarefied heights of Plato, Kant, or Kierkegaard. But they, too, demanded that their students sit with the quantum weirdness during the 1920s and 1930s and hone their own philosophical response. General examinations from across the country, required for graduate students to advance to candidacy for a PhD, routinely pressed students to compose essays about wave-particle duality, the double-slit experiment, and related matters. Throughout the 1930s, reviewers held the latest American textbooks on quantum mechanics accountable for their philosophical orientation and exposition.[29]

The landscape changed sharply after World War II. In the early 1950s, Einstein—having moved to the United States twenty years earlier, fleeing fascism in Europe—surveyed the scene with despair. The problem was no longer his colleagues' "tranquilizing philosophy"; it was their ardent lack of interest in philosophy altogether.[30] Graduate students at Caltech were caught equally off guard. Having dutifully pored over reports from their predecessors about what to expect on the general examination, the new generation felt cheated. One complained that all the effort he had "invested in analysis of paradoxes and queer logical points was of no use

in the exam." Others recorded how their questions had avoided matters of interpretation altogether, focusing instead upon a narrow set of stock problems. (Forget about philosophy and just give the "usual spiel," came one student's advice to those who would take the examination after him.) Essay questions disappeared from graduate students' written exams across the country, replaced by a coterie of standard problems to calculate. Textbook reviewers in the United States began to praise books on quantum mechanics that "avoided philosophical discussion" or omitted "philosophically tainted questions." Enough with the "musty atavistic to-do about position and momentum," stormed MIT's Herman Feshbach in 1962.[31]

Much had changed. The hateful policies of Mussolini and Hitler had chased scores of intellectuals out of Europe. Nearly a hundred physicists and mathematicians followed Einstein's lead and resettled in the United States during the 1930s. Born and Schrödinger rode out the war in Edinburgh and Dublin, respectively, while a few—including, most famously, Heisenberg—remained behind in the Nazi Reich. By the close of the 1930s, quantum physicists had been scattered across the globe, their days of riding the rails in pursuit of further banter gone forever.[32]

The new world that these émigrés found, meanwhile, was changing fast under their feet. With memories of fascism still fresh, dozens of them joined the Allied war effort, alongside their new American and British colleagues. During the war, physicists all over the world—but especially in the United States—received a crash course in "gadgetry," their new shorthand for the special flavor of research and development conducted side by side with engineers and military planners. Radar, the proximity fuse, solid-fuel rockets, and especially the atomic bomb project ripped academic physicists from their ivory towers and thrust them into a grubby world of grease and pumps, gauges and lathes. The round-the-clock pressure to produce working gadgets in time to impact the course of the war left little leisure for philosophizing. Physicists learned to put their heads down, ignore philosophical tangents, and wring numbers from their equations as quickly as possible. When Edward Teller lectured on quantum mechanics at Los Alamos—the central scientific laboratory of the atomic bomb project—for the gaggle of students and lab hands whose education had been interrupted by the war, he raced through the interpretive material so quickly that he replaced the fabled double slit with a *single* slit on the blackboard, from which the crucial interference pattern would never arise! Here, in stark relief, was the new face of war-forged pragmatism.[33]

The wartime relationships continued unabated after the war, especially as the Cold War with the Soviet Union hardened into a fact of life in the late 1940s. Defense agencies swamped the previous sources of funding for physics, keeping physicists' attention tethered close to the demands of national security. Only a small minority spent the bulk of their time working on weapons after the war. Yet across the United States, from bustling research universities to tiny liberal-arts colleges, nearly all academic physicists became enrolled in a massive Cold War project: to produce more physicists, at an ever-increasing rate, to ensure that the nation's supply of technical workers was trained and ready should the Cold War ever turn hot. Leading policymakers freely equated the country's population of physicists with a "standing army." In the course of a single speech in 1951, for example, a top member of the Atomic Energy Commission managed to describe physicists as a "war commodity," a "tool of war," and a "major war asset," to be "stockpiled" and "rationed." Analysts at the Bureau of Labor Statistics agreed. "If the research in physics which is vital to the nation's survival is to continue and grow," they asserted in a 1952 report, "national policy must be concerned not only with keeping the young men already in the field at work but also with insuring a continuing supply of new graduates."[34] Adding fuel to the fire, a series of reports published in the mid-1950s, which had been bankrolled secretly by the Central Intelligence Agency, seemed to suggest that the Soviet Union was training new scientists and engineers even more quickly than the United States. Coming at a propitious moment politically—one was published just two weeks after the Soviets' surprise launch of the first Sputnik satellite, in October 1957—these reports helped shake loose another billion dollars from Congress (more than $7 billion in 2010 dollars) to support graduate training in "defense" fields like science and engineering.[35]

The Cold War imperative for scientific "manpower" had immediate effects on enrollments. Backed by expansive fellowship programs and special draft deferments, classrooms in American physics departments bulged faster than any other field. Nearly all fields were growing exponentially after World War II, thanks to a backlog of veterans returning to the nation's campuses, supported by programs like the GI Bill. Yet physics outpaced them all, its graduate-level enrollments doubling nearly twice as quickly as all other fields combined. By the outbreak of fighting in the Korean War, American physics departments were producing three times as many PhDs per year as the prewar highs—a number that would only climb higher, by another factor of three, after Sputnik.[36]

The astronomical growth had an immediate effect on teaching. Enrollments in stock courses for graduate students, such as introductory quantum mechanics, swelled to more than 100 students in physics departments from MIT to Berkeley. Such classroom numbers, Berkeley's department chair exclaimed to his dean, were "a disgrace and should not be tolerated at any respectable university."[37] Despite a frenzy of faculty hiring, student-to-faculty ratios ballooned in physics departments across the country. Professors routinely complained that the bloated enrollments trampled out any sense of the prewar "intimacy" between faculty and students. Students agreed. "The classes are so large that there is little or no individual contact between student and teacher," complained one graduate student in Harvard's department after the war.[38]

Faced with such runaway growth, physics professors across the country revamped their teaching style. They began to accentuate those elements that could lend themselves to high-throughput pedagogy, pumping record numbers of students through their courses. First to go was the discussion-based, qualitative, philosophical inquiry into what quantum mechanics *meant*. Staring out at the sea of faces in their stadium-seating classrooms, many instructors felt they had little choice. (Fig. 1.5.) "With these subjects," explained one frustrated professor in 1956, "lecturing is of little avail." He had in mind once-central topics like the meaning of the uncertainty principle, Bohr's complementarity, and the consequences for causality of the probabilistic turn. "The baffled student hardly knows what to write down, and what notes he does take are almost certain to horrify the instructor, who perspicaciously usually resolutely refuses to question his students on these topics." And so, this commentator concluded with regret, when it came to "the philosophical issues raised by quantum mechanics . . . the student never has a chance to gauge their depth." A few years later, another critic weighed in. A lion of the interwar era who had emigrated from Europe to the United States, he accused his American colleagues of confusing what was "easy to teach"—the "technical mathematical aspects" of quantum mechanics, which could be chopped up and parceled out on problem sets and exams—with the conceptual, interpretive material that students needed most.[39]

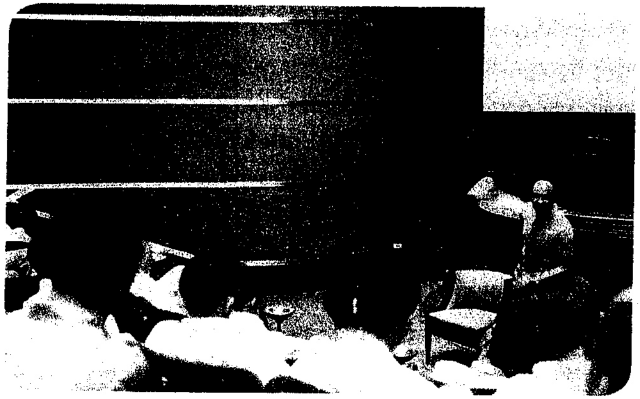

FIGURE 1.5. Enrico Fermi lecturing to physics graduate students in the early 1950s. (Photograph by Samuel Goudsmit, courtesy Emilio Segrè Visual Archives, Goudsmit Collection, American Institute of Physics.)

The few traces that remain from the nation's physics classrooms bear these observations out. Comparing lecture notes from graduate-level courses on quantum mechanics from across the country, each dating from the 1950s, reveals a stark pattern. An increase by a factor of three in enrollments correlated with a decrease by a factor of five in the

proportion of time spent on interpretive or philosophical material. In short, the larger the class, the less time spent talking through the big issues at the heart of quantum mechanics. Textbooks followed a similar trend. As physics enrollments continued to climb well into the 1960s, the proportion of essay questions plummeted to around 10 percent of all problems embedded in new textbooks. Faced with skyrocketing enrollments, no one had time to grade such verbiage. What students and faculty needed, opined a Berkeley physics professor in 1965, were more textbooks like Leonard Schiff's successful *Quantum Mechanics*. The Berkeley physicist had used the first edition, from 1949, as a student, and he looked back on it fondly. "The book kept me sufficiently busy to prevent pseudo-philosophical speculations about the True Meaning of quantum mechanics"—just the ticket for the new classroom realities. He urged the publisher to bring out a new edition of Schiff's book. By trimming what had already been paltry discussion of interpretive matters, the new edition could be larded even more fully with tough calculations, to keep the new generation busy. (The publisher brought out the new edition in 1968 to widespread acclaim from reviewers; it sold well.)[40] Countries that had similar physics enrollment patterns—major Cold War players like the United Kingdom and the Soviet Union—produced remarkably similar textbooks. Other European countries, like France, West Germany, and Austria, spent much more time rebuilding after the war and did not experience the same bulge in physics classrooms. Physicists in those countries continued to write textbooks in the prewar fashion, featuring long excursions into philosophy and stuffed with juicy essay questions.[41]

The enrollment-driven pragmatism, so stark in American physics departments after World War II, was anything but a "dumbing down." The second and third editions of Schiff's acclaimed textbook, for example, contained homework problems—aimed at entry-level graduate students—that would have stumped leading physicists only a decade or two earlier. The quarter century during which this Cold War style reigned witnessed an extraordinary buildup of calculating skill. All the same, an intellectual trade-off slipped by unnoticed, with wide-ranging implications. For every additional calculation of baroque complexity that physics students tackled during the 1950s and 1960s, they spent correspondingly less time puzzling through what all those fancy equations meant—what they implied about the world of electrons and atoms. The fundamental strangeness of quantum reality had been leeched out.

Not everyone in the United States adopted the mantra of "shut up and calculate" after the war. But the few groups that tried to retain the prewar style rapidly became exceptions that proved the rule. Throughout the hot summer months of 1954, for example, about a dozen physicists gathered in New York City to discuss the foundations of quantum mechanics. Even as most of their colleagues were too busy rewriting their lecture notes, editing their textbooks, and revising their examinations to drop nearly any mention of such interpretive material, this group pressed on, unconvinced that all was well with the central pillar of modern physics.[42]

More than a fascination with quantum mysteries brought these physicists together. Most shared the same politics as well. The group had been convened by Hans Freistadt, a native of Vienna who had fought in the U.S. Army during World War II. By the early 1950s he was an instructor at the sleepy Newark College of Engineering in New Jersey, the latest stop in his wanderings following his dramatic testimony before the Joint Congressional Committee on Atomic Energy back in 1949. Yes, he had confirmed, he was a member of the Communist Party, and yes, he continued, he had indeed received one of the first fellowships from the Atomic Energy Commission (AEC) to pursue graduate studies in physics. His studies had concerned strictly unclassified material. All the same, the headline-grabbing revelation, and the political firestorm that ensued, nearly ended the AEC fellowship program.[43]

Joining Freistadt to ponder quantum mysteries in the 1954 discussion group was Byron Darling. Until recently a tenured professor of physics at Ohio State University, Darling found himself out of work after testifying before the House Un-American Activities Committee (HUAC) during its March 1953 investigation of "Communist methods of infiltration" of the educational system. The committee had accused Darling of past membership in the Party; he pleaded the Fifth Amendment. Although he had signed his university's anti-Communist loyalty oath, had answered every question put to him by the university's investigating committee, and had stated categorically that he was not nor had ever been a member of the Communist Party, Ohio State dismissed him for failing to answer all of HUAC's questions. He left Columbus for New York City, where he passed the time during the summer of 1954 talking about possible alternatives to quantum theory with Freistadt and company, before taking up a new post at the University of Laval in Quebec.[44]

Nearly all the other members of Freistadt's discussion group shared a clear leftist orientation. Some had even left tenure-track jobs in the United States to work overseas for a few years, returning just in time to join the discussions in New York that summer. Freistadt's seminar produced two publications, both written by him. The first, published in the Marxist cultural magazine *Science and Society* before the sessions began, was filled with predictable talk of the "doctrinaire" thinking shown by "modern scientists in capitalist countries," whose "positivist obscurantism" had landed quantum theory in its current state of "crisis." The other, a technical review article on a variant of quantum mechanics, was published as a supplement to an Italian physics journal and promptly forgotten for the next twenty years. Fired from jobs or castigated in the media for their alleged political activities, the group members' politics and their unpopular research interests each marked them as clearly outside the discipline's mainstream. In that climate, they could find little traction for their work.[45]

Twenty years later, another informal discussion group convened, likewise bent on exploring the big metaphysical questions raised by quantum mechanics. Like Freistadt's group, the Fundamental Fysiks Group, established in Berkeley in the spring of 1975, was peopled with physicists on the margins. Yet for all the similarities, the two groups left rather different footprints. Where Freistadt's group toiled in obscurity, members of the Fundamental Fysiks Group became media darlings, publishing a series of best-selling books and leaving a genuine imprint on physics research and curricula throughout the country.

The divergence in outcomes for the two discussion groups, otherwise so similar in makeup and structure, illuminates how quickly conditions had changed for physicists by the early 1970s. Politics had thwarted the career trajectories of most members of the Fundamental Fysiks Group, but not the personal politics of red-baiting as in Freistadt's day. Rather, they were caught at the wrong place at the wrong time, bystanders of a systematic political upheaval that rocked the physics profession from top to bottom. Freistadt's circle had labored on the fringes of boom times for American physicists. By the time members of the Fundamental Fysiks Group found each other, the boom times had turned to bust.

When trouble came for physicists, it came fast. All too quickly, the assumptions that had driven the enrollment boom broke down. As tensions with the Soviets cooled and resources dried up, military patrons and congressional leaders revisited long-standing priorities. No longer did calls ring out to produce scientific "manpower" at all costs. The Pentagon's return on decades of investment in open-ended basic research—which had justified, and paid for, nearly all graduate training in physics—struck a new generation of analysts as rather lackluster. Years into the slog of the Vietnam War, meanwhile, antiwar protesters grew more brazen, taking over campus buildings and planting pipe bombs, all part of a campaign to force the Pentagon out of the higher-education business. (Physics laboratories provided some of their favorite targets, potent symbols of the "mutual embrace" between academic scientists and military paymasters.) Caught between hardnosed Pentagon accountants on the one hand and raised-fist radicals on the other, physics had nowhere to go but down.[46]

Nearly every field suffered cutbacks in the realigned political and budgetary landscape, but none more than physics. Since World War II, the discipline had become more reliant than any other on federal funding. When trouble hit, physicists' enrollments plummeted faster and deeper than any other field: down fully one-third from their peak in just five years, falling to one-half by decade's end. (Fig. 1.6.) Demand disappeared even more quickly. Records from the Placement Service of the American Institute of Physics tell the grim tale. The service had

arranged job interviews between prospective employers and physics students since the early 1950s. As late as the mid-1960s, the service had registered more employers than students looking for jobs. By 1968, the balance had tipped: 989 applicants registered, with only 253 jobs on offer. And then the bottom fell out. In 1971, the Placement Service registered 1053 applicants competing for just 53 jobs.[47]

Into that state of wreckage trod the young physicists who would form the Fundamental Fysiks Group. Like it or not, they would not follow physics careers like the ones their teachers had enjoyed. The ways and means of being a physicist came unmoored in a way they hadn't been for two generations. No longer would the attitude of "shut up and calculate" hold sway unchecked. Sitting around the large conference table at the Lawrence Berkeley Laboratory, with few other demands on their time, they sought to recapture the sense of excitement, wonder, and mystery that had attracted them to physics in the first place, just as it had animated the founders of quantum mechanics. They might not have enjoyed secure employment, but they fervently believed one thing: physics could be fun again.

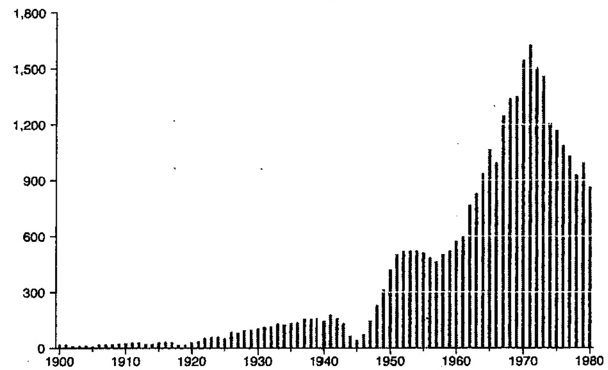

FIGURE 1.6. Number of physics PhDs granted in the United States, 1900–1980. (Illustration by Alex Wellerstein, based on data from the American Institute of Physics and the National Science Foundation.)