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The Most Dangerous Possible German

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What trace of his earthly passage can a man of genius hope will remain after his death? For a great scientist, it is almost certainly a discovery that advances human understanding a step further from ignorance and confusion. To uncover some eternal truth that has been carefully concealed from ordinary sight by Nature or whatever gods there be, and to enjoy the lasting esteem accorded the world-altering thinkers—these are the motive forces behind the most serious and accomplished scientific lives. To one who opens new mental continents for further exploration, and exploitation, the supreme accolades rightly belong. Honor of this order is not a paltry thing.

Yet John Milton called the craving for fame "that last infirmity of noble mind"; and while such infirmity might easily be forgiven poets, who are notorious for their moral weakness, we have become accustomed to thinking of scientists as free of such all-too-human frailties. Like Aristotle's theoretical man in the *Nicomachean Ethics*, scientists are said to live for the unsurpassed pleasure of knowing the highest things in the universe, those that cannot be other than they are. This makes them godlike, so that they need nothing else—certainly not the glint of admiration or envy in other men's eyes.

And yet perfection is not to be expected even from the most high-minded among us. The man who loves knowing alone is a creature of fantasy, a chimera, an impossibility. He is bound to have other, competing loves, which adulterate the loftiest vocation, however dedicated to it he might be. He will love his wife and children, his country, his reputation. One hesitates even to call these lesser loves, let alone infidelities; most people value them above the work they happen to do to earn their living, and indeed to consider your job more important than your family will rightly mark you to your fellows as a sorry excuse for a human being.

But of course there are jobs and then there are callings, as there is the democratic understanding of life's responsibilities and there is the noble

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understanding of one's appointed task. When one has a true vocation, to fall short of its demands is unacceptable, even though it is unavoidable. The honest man punishes himself for such failures. His own standards are the law he obeys, and his conscience is the most exacting judge of his integrity. But if one happens to be a theoretical man yet also a man of honor, who needs the good opinion others have of him, a complication enters the picture. Then the most painful failure offends against those standards of one's own as well as against the public's sense of right and wrong. In that case it is exceedingly hard to remain an honest man; the temptation to lie both to yourself and to the populace is overwhelming, and it is deadly.

The physicist Werner Heisenberg (1901–1976) won himself a lasting name with a world-altering discovery so startling and influential that it has leaked into popular culture—albeit in a misconceived, bastardized form. Heisenberg's uncertainty principle is a pillar of quantum physics, and represents the titanic straining of human intelligence to explain phenomena that we really don't have words to describe. Heisenberg's achievement rivals Einstein's—although Einstein found the uncertainty principle to be worse than dubious, a gross violation of the cardinal rules governing scientific truth and an offense against God Himself. Yet for Heisenberg, as he said in *Physics and Philosophy* (1958), quantum theory—along with Newtonian mechanics, thermodynamics, and electrodynamics and special relativity—is one of the four conceptual systems of physics "that have already attained their final form."

Great honor is due such masterly theoreticians. But of course both Einstein's and Heisenberg's theories laid the groundwork for the most terrible weapons ever devised, and many have not forgiven the minds that opened the prospect of man-made Armageddon. Einstein in his innocence was disagreeably surprised when more worldly colleagues told him that such a thing as an atomic bomb was possible. No longer quite so innocent, Einstein wrote to President Roosevelt telling him of this possibility, and warning him that the Germans may already be working toward realizing it. The less-innocent Heisenberg was enlisted in the Nazi effort to build an atomic bomb, and his was the most formidable, and the most feared, intelligence to work on that project.

How Heisenberg came to terms with Hitler's regime, why he served its mania for annihilation when he had ample opportunity to find refuge in the civilized world, are questions that bedevil his reputation. The regard he showed for what he peculiarly called his "honor" when he was savaged in the Nazi press as a "white Jew" presents further matter for the inquiring moralist. And what he actually did to help or to hinder the bomb project remains the most vexed question there is for his biographers, not to say for the whole history of twentieth-century science. That Heisenberg's own accounts of his motives and actions spray in all directions does not make the historian's task an easy one. And the fierce emotions that attach to the memory of Nazi war-making inevitably color the search for the truth, which is not to say that hot feeling is necessarily an unreliable moral guide here.

The controversy surrounding Heisenberg's wartime role has been of sufficient public interest that it even begat a Tony Award–winning play, Michael Frayn's *Copenhagen* (1998). Publicity of this kind is not exactly the vessel of remembrance in which Heisenberg would have wished his reputation to be preserved. To be honored as the discoverer of the uncertainty principle would have been quite enough. But history made other plans for Heisenberg, and placed him in the defendant's dock, along with a multitude of his countrymen—where he does stand out among them, both for his intellect and the potential murderousness of his task.

One must say that he chose his fate, more freely and thoughtfully than many others who served Hitler's evil intent. Thus, a scientific career that would have been the object of awed—if largely uncomprehending—praise has become instead the subject of moral judgment. Ordinary men and women who would be utterly dumbfounded by the mathematical arcana of Heisenberg's signature matrix mechanics now deliberate the question of what kind of man he really was. And that question is an eminently fair one for ordinary people to ask.

Turmoil after the Great War

Werner Heisenberg was born in December 1901, to a well-schooled and prosperous family in Würzburg, Germany. His father, August, was then a respected teacher in a local *Gymnasium*, a university preparatory school for students aged ten to eighteen. Shortly after Werner's birth, August was made a *Privatdozent* or university lecturer, and later became Germany's sole professor of Byzantine philology and sole full professor of middle and modern Greek. Werner's mother, Annie, was the daughter of a scholar of Greek tragedies who directed a prestigious Munich *Gymnasium* that emphasized classics at the expense of science, and where young Werner, eager to impress, became a relentless striver and a paragon of schoolboy virtue.

He excelled in all subjects except physical education and German, and was the superstar in mathematics and physics, which stuck to Newtonian mechanics and ignored altogether Einstein's relativity and Max Planck's quanta. Werner played the cello and the piano, the latter well enough that he considered a career in music. Chess so consumed the youth that when he got to university his mentor told him to give up the game because it had become an addictive distraction from his work; he obeyed. Although not a natural athlete, he learned to ski with power and grace, and developed his endurance as a long-distance runner. One of his friends spoke of him as a *Willensmensch*, a man of will, and he did drive himself to be the best at whatever he did. He came to think so well of his own ability at ping pong, of all things, that years later, when he was a grown man in most respects, and a Japanese colleague beat him in a ferocious game, he refused to play him again. Losing brought out the worst in him, so he contrived to avoid losing.

The political world reached into his peaceable young life and grabbed him by the throat. When the Great War broke out, his forty-five-year-old father volunteered for combat. But trench warfare so horrified him that after a few months he requested more agreeable duty, which he was granted because of his age. Long afterward, Werner would write that his father had been wounded in battle, though this appears to be untrue. That the war was not the magnificent undertaking nationalist propaganda proclaimed it to be, and that his own father might be a coward, was hard to accept for the young patriot. Fortunately, the young man was not subjected to a more severe trial of his patriotism at that time; the war ended less than a month before his seventeenth birthday, when he would have been called up for duty.

Violent political disorder erupted in Germany upon its defeat and Kaiser Wilhelm's abdication, and Munich was the cynosure of socialist uprising. The Jewish intellectual Kurt Eisner proclaimed a Bavarian socialist republic days before the Armistice, but three months later he was gunned down in the street by an aristocrat who hated socialists, and especially Jewish socialists. Heisenberg joined his fellow liberal students in rejoicing at Eisner's assassination, but it was not the time and place for prolonged celebration. Gunplay became a regular feature of the Munich scene. Regimes did not last long and went down hard. The moderate socialists who succeeded Eisner's radical socialists were overthrown by another band of self-proclaimed soviet republicans, "coffeehouse anarchists" under the direction of an expressionist poet. His minions in the press taunted respectable liberal youth, to the point of revolt, with the promise that German culture would be extinguished as the moral universe was remade. But another Bolshevik faction overthrew the "pseudo-soviet republic" and replaced it with the real thing.

August Heisenberg—as a bourgeois, a likely candidate to be taken hostage—went into hiding from the very real Red terror. Economic collapse was inevitable, precipitated by the immense expense of a Red Army. The Heisenbergs were threatened with starvation, and one winter night Werner and a couple of his friends sneaked through the lines of the White Army (the anti-Communists) and the Red Army (the Bolsheviks) to return home with provender, which they bought from a farmer sympathetic to Mrs. Heisenberg. The boys nearly did not make it back.

Werner became a paramilitary recruit in the service of Berlin's socialist war minister, who was bent on eradicating the more extreme leftists. As David C. Cassidy writes in *Uncertainty: The Life and Science of Werner Heisenberg* (1992), the free corps units to which Heisenberg was attached "became a fertile breeding ground for right-wing extremism. Many infamous Nazi careers had their start in one of these units." Red terror gave way to White terror. Mass murder and reprisal constituted the rhythm of public life.

Heisenberg would recall his part in the turmoil as "a kind of adventure," though "why all this happened is no longer quite clear to me." One night he was ordered to stand watch over a Red prisoner until morning, when the man was to be tried in a kangaroo court and shot. After talking with the condemned man all night, Heisenberg was sure he was innocent and deserved to live, and the compassionate youth managed to convince his superiors to set this enemy free.

The adventure of civil war was a sobering one. Strenuous moral and political engagement, often more passionate than reasonable, proved a necessity for his German generation. "We therefore took the right to see for ourselves what in this world is valuable and what is worthless, and not to ask our parents and teachers about it," Heisenberg later said. Cassidy writes, "Werner the physicist would enter the apolitical, bourgeois world of the upper-middle-class academic, but Werner the man would perceive his place within it in terms derived from the emotional and ideological commitments espoused by what he and his friends were now calling a youth movement."

"A Path to the Central Order"

In 1919 younger schoolmates of Heisenberg's looked to the impressive older youth for guidance, and asked him to head their *Pfadfinder* (Pathfinders) group, the German offshoot of the English Boy Scouts. *Gruppe Heisenberg*, the troop he led, would share the general Pathfinder revulsion against what they saw as the older generation's decadence, which brought down the monarchy. But they also shared its antipathy to the socialist scheme to democratize elite schools like theirs and thus to eviscerate German high culture.

In *Physics and Beyond: Encounters and Conversations* (1971), Heisenberg's intellectual autobiography—which, in the manner of his model Thucydides, took liberties with the actual facts—he recalls in detail impassioned youthful arguments about political and metaphysical questions, and the need he and his friends had for definitive answers. At a large and obstreperous Pathfinder gathering at Prunn Castle, where the contentious discussion flying from every direction only enhanced Heisenberg's confusion about what he really believed, a violinist

> struck up the first great D minor chords of Bach's Chaconne. All at once, and with utter certainty, I had found my link with the center. The moonlit Altmühl Valley below would have been reason enough for a romantic transfiguration; but that was not it. The clear phrases of the Chaconne touched me like a cool wind, breaking through the mist and revealing the towering structures beyond. There had always been a path to the central order in the language of music, in philosophy and in religion, today no less than in Plato's day and in Bach's. That I now knew from my own experience.

There was a transcendent wisdom available to persons who needed it even in those soul-racking times.

Young Heisenberg tried to live his life so as to be worthy of this descent of grace. While a university student in 1920 and 1921, Heisenberg took part in the *Volkshochschule* movement of adult education for the working class. In his astronomy class, he led hundreds of his students away from the city lights and into the dark fields at night to look at the stars. He also taught German opera with a woman who sang arias to his piano accompaniment. Cassidy rather snidely attributes Heisenberg's eager solicitude to his guilt at having taken part in crushing the Munich Soviet. It is just as likely that he acted out of an overfull heart that chimed nicely with perfectly decent political prudence.

Mostly, however, prudence directed Heisenberg to stay clear of politics. The ethos of the *Neudeutsche Pfadfinder* (New German Pathfinders), which grew out of the Prunn Castle congregation, led Heisenberg to exalt physics, nature, and music, and elevated him far above the political muck and muddle, which became ever more sordid and disordered as the decade wore on. In 1923 Heisenberg wrote to a Pathfinder comrade, "I never thought that I could interest myself in politics, because it seemed to me to be a pure money-business." The money-business angle of German politics would soon be the least of its moral disqualifications.

Meanwhile, Heisenberg and his friends reveled in the glories of German culture. He filled his boys so full of Goethe's poetry that they would recite it at length by heart as they sat around the campfire on their weekend outings to the countryside. The group was renowned for its music-making; everyone played an instrument, and the best of them would join Heisenberg in a chamber ensemble where he played the piano with expert flair. And they did not neglect their physical culture, favoring a game that Wagner's Siegfried would have enjoyed had he found suitable playmates, in which a competitor on one team would hurl a javelin and a player on the other team would try to catch it. It was Heisenberg's preferred sort of exercise. Some character-building Teutonic forms of sport never found their way to the playing fields of Eton.

The New Pathfinders adopted a morally charged vocabulary intended to represent an order of chivalric nobility: Their bywords, Cassidy avers, were *Gemeinschaft* (community), *Führer* (leader), and *Reich* (empire). These words sounded almost innocent on their lips. The Third Reich they imagined "bore a striking resemblance to the Christian concept of the coming kingdom of God, where all Christian believers will live together in peace and harmony under one God-given savior." What would become of the Jews and other unbelievers was better left unclear.

The Heisenberg group was a breeding ground for clergymen and theologians. Its more worldly members would become secular academics or scientists. The outfit did produce one banker, and in Heisenberg's eyes this anomaly was a disgrace. Later commentators would mete out the disgrace differently.

Cassidy summarizes the disparity between the charges of Heisenberg's most severe critics and his understanding of his own moral constitution:

> To Heisenberg himself his actions and motives largely coincided with the lofty ideals of duty and responsibility that he, as an exemplary Pathfinder leader, had internalized during his fundamental formative experiences in the youth movement; to others, viewing his responses to the Third Reich, he was so infused with the volkish politics of the New Pathfinders that he capitulated all too easily to a brutal, antiscientific, antihuman dictatorial regime with which he sympathized.

Heisenberg, for his part, would remember his participation in the youth movement as "the most beautiful days of my life."

The Core Model

Perfervid conversations about science with his friends formed an integral portion of that youthful beauty. In *Physics and Beyond*, Heisenberg recalls roving with his mates in the hills above a lake on a beautiful spring morning:

> It was here that I had my first conversation about that world of atoms which was to play so important a part in my subsequent life. To explain why a group of young nature lovers, enraptured by the glorious spring landscape, should have engaged in such conversations in the first place, I ought perhaps to point out that the cocoon in which home and school protect the young in more peaceful periods had burst open in the confusion of the times, and that, by way of a substitute, we had discovered a new sense of freedom and did not think twice about offering views on even such subjects as called for much more basic information than any of us possessed.

Youth in that world which had come undone had to explain the world from first principles, and nothing was more fundamental to such explanation than atomic theory. Heisenberg was thus introduced by a friend to Plato's *Timaeus*, and his curiosity about how the material world was put together took off from there.

The conceptual beauty of theoretical physics would become Heisenberg's consuming passion as he leapt from discovery to revelation in his early and middle twenties. He had entered the University of Munich in 1920 intending to study mathematics, but a meeting with the faculty panjandrum did not go well: When Heisenberg told the distinguished professor that he had recently read Hermann Weyl's *Space—Time—Matter*, a technical consideration of relativity, the eminence dismissed him with the valediction, "In that case you are completely lost to mathematics."

Mathematics' loss was physics' bounty. Professor Arnold Sommerfeld, a sometime mathematician who became a force in quantum physics as an associate of the Danish master Niels Bohr, was delighted with Heisenberg's knowledge of Weyl and with his general demeanor, and accepted him straightaway into his research seminar for doctoral candidates. At that time, German universities had no general education requirements like those for American undergraduates; for the doctorate, only three years' residence capped by a thesis and oral examination were needed, and Sommerfeld threw the recent *Gymnasium* graduate directly into deep water.

A year later the student rewrote his teacher's formula for the Zeeman effect, a phenomenon of light spectra that at the time had not yet been fully explained. When chemicals emit light, they do so at predictable sets of frequencies based on their atomic composition. Thus, when the light beam of a glowing chemical is split using a prism, it will appear as a black bar interrupted by several distinct bright lines of different colors, known as spectral lines. But under the presence of a magnetic field, these solid lines will split into several narrower bands.

The atom's daunting smallness necessitates ingenuity in examining it experimentally. One cannot of course peer into the atom itself, and one can deduce its structure "only by bombarding it with high-speed particles, or by observing what goes into it, what comes out of it, and how it interacts with other atoms and with electric and magnetic fields," as Cassidy succinctly describes the art in his 2009 book *Beyond Uncertainty: Heisenberg, Quantum Physics, and the Bomb*. (This book is a revised version of *Uncertainty*, accommodating the release of information previously classified about the atomic bomb project, while condensing the earlier book to accommodate the general reader likely overmatched by its detail.)

Sommerfeld had subjected the observed spectra to an elegant mathematical arrangement that he called "an atomic music of the spheres, a harmonizing of whole number relationships." But he confessed that his beautiful ordering could not account for crucial data regarding the division of certain quantum energy states, or the way a gas emitted by an atom changed from one type of the Zeeman effect to another when the magnetic field was intensified. Heisenberg's revised explanation accounted nicely for the renegade data, but only by defying the textbook definition of quantum theory as Bohr and Sommerfeld had proclaimed it.

Under the reigning theory, electron orbits possessed discrete, indivisible units of energy that could be represented only by whole integers. But Heisenberg replaced the integers with forbidden half-integers—1/2, 3/2, 5/2, and so forth—and produced a model that fit the observed facts. In Heisenberg's theory, the half-integers arose because the outer electrons of an atom were each able to share a half-unit of their momentum with the atomic core (the nucleus and the closely orbiting inner electrons). Sommerfeld balked, for, as Cassidy writes, "Half-integer numbers simply had no physical meaning or place in quantum theory." But in the end Sommerfeld accepted the model, with all its brilliant perversity.

Although this theory, which would become known as the "core model," would eventually be replaced, it was a crucial conceptual leap—the current model still uses half-integer energies, but explains them as arising not from shared momentum but from an electron's spin. Cassidy offers lavish praise for Heisenberg's core model, which "displayed his incredible intuition, his ability to achieve a breakthrough when others could not, and his audacity in achieving success in physics even at the expense of accepted methods." When Heisenberg published the model in an article in the most prestigious journal of quantum physics, he had just turned twenty.

A Walk in the Woods

In 1922, Heisenberg met Niels Bohr, who had broken the tacit postwar quarantine of German science by the international community, and had come to Göttingen to deliver a series of seven lectures on atomic quantum theory—an intellectual feast that came to be known as the Bohr Festival. Heisenberg stood up after one lecture and pointedly questioned Bohr's presentation, in violation of the academic protocol of that time and place, according to which a student did not publicly contradict a professor. Bohr was both startled and impressed—he had heard of the young man's core model, which he emphatically rejected as fundamentally unsound—and he asked Heisenberg to join him for a walk through the Hain Mountain woods. In *Physics and Beyond*, Heisenberg declares that his "real scientific career only began that afternoon."

In the Thucydides-like dialogue, Bohr does most of the talking, and instructs Heisenberg in the disconcerting "stability of matter"—the fact that "even after a host of changes due to external influences, an iron atom will always remain an iron atom, with exactly the same properties as before." This defies the principles of classical mechanics, "according to which all effects have precisely determined causes, and according to which the present state of a phenomenon or process is fully determined by the one that immediately preceded it." Bohr goes on:

> We know from the stability of matter that Newtonian physics does not apply to the interior of the atom; at best it can occasionally offer us a guideline. It follows that there can be no descriptive account of the structure of the atom; all such accounts must necessarily be based on classical concepts which, as we saw, no longer apply. You see that anyone trying to develop such a theory is really trying the impossible. For we intend to say something about the structure of the atom but lack a language in which we can make ourselves understood....
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> We must be clear that when it comes to atoms, language can be used only as in poetry. The poet, too, is not nearly so concerned with describing facts as with creating images and establishing mental connections.

The perplexed and anxious Heisenberg asks what happens then to the scientific scruple for exactitude, and to the idea of scientific progress. It is clear to him that Bohr does not consider electrons inside atoms to be "things" in the way that classical physics thought of things, with "position, velocity, energy and extension." Clarity about the impossibility of clarity seems to be as far as the quantum physicist's mind can reach. Without the necessary language, Heisenberg frets, "How can we ever hope to understand atoms?" Bohr hesitantly replies that understanding may come eventually. "But in the process we may have to learn what the word 'understanding' really means."

This dialogue dramatizes the confusion, amounting to consternation in Heisenberg's case, of the finest minds in physics as they tried to subdue the refractory quantum world and reduce it to reasonable terms. Bohr is serene in his incomprehension, where Heisenberg is feverish with distress. Under Bohr's tutelage he would grow into the acceptance of mystery that is part of the modern physicist's wisdom. (He would also learn far more in due course about the strange and shattering *in*stability of radioactive matter.) Heisenberg would write to his father in 1923, "I realize ever more that Bohr is the only person who, in the philosophical sense, understands something of physics." The most fruitful collaboration in quantum physics would grow out of this walk through the woods.

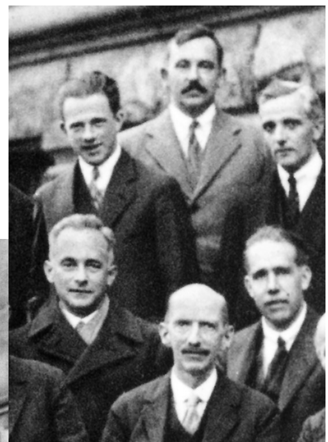
Struggling for Mastery

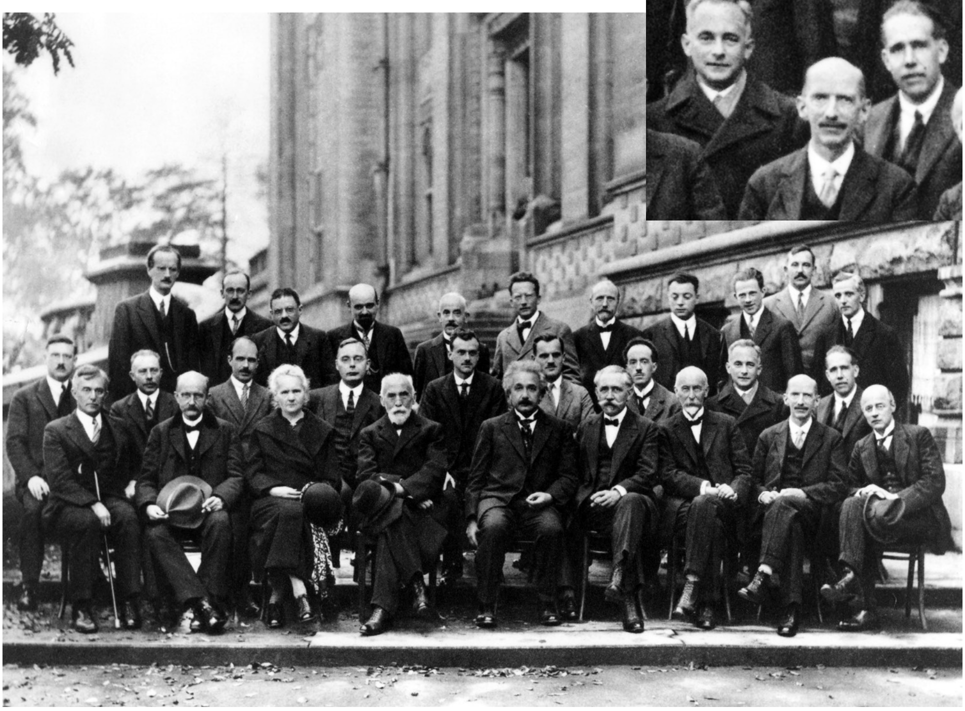
In good time, Heisenberg would join Bohr in Copenhagen. But first he spent a semester in Göttingen studying with Max Born and working as his assistant. Born and Heisenberg joined forces, as Cassidy writes, "in an effort to push detailed planetary models of the atom to their limits and [to compare] the results with the observed stabilities and properties of simple atoms." The hope was that electrons could be shown to orbit the nucleus as planets orbit the sun—that the laws of matter operated in exactly the same way for the smallest objects in the universe as for some of the largest.

But the theorizing got complicated, for a planet's orbit is determined not only by its gravitational attraction to the sun but also by its much smaller attractions to all the other planets, which Newton had called "perturbations." Born deployed the mathematically fiendish perturbation theory developed by nineteenth-century astronomers in his atomic model. But a further complication arose from the fact that electrons repel each other almost as forcibly as the positively charged nucleus attracts them.

The Göttingen quantum theorists struggled. The Copenhagen rivals floundered. The planetary model was a bust. In 1923, Born averred in a review article "that not only new assumptions in the usual sense of physical hypotheses will be necessary, but the entire system of concepts of physics must be rebuilt from the ground up." Born coined the term "quantum mechanics" for the new system that physics needed, which would operate strictly on its own terms, unencumbered by memories of Newtonian order.

In the midst of his quantum work, however, Heisenberg returned to studying with Sommerfeld in order to write his doctoral thesis on hydrodynamics—specifically, what happens when smoothly flowing fluid, like the water in a placid river, turns turbulent. Sommerfeld thought this would be a safer topic than anything quantum, as the faculty member who specialized in experimental physics took a dim view of what went on inside the atom. The thesis was published in the exclusive *Annalen der Physik*, edited by that experimental authority.





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At age twenty-five, Werner Heisenberg was the youngest attendee of the 1927 Solvay Conference. Inset: Heisenberg is at left top; Max Born is at left bottom; Niels Bohr is at right bottom.

The same professor, though, gave Heisenberg a failing grade on his oral exam when the uncharacteristically flustered genius could not adequately explain the resolving power of a telescope or microscope or the workings of a storage battery. Sommerfeld for his part gave Heisenberg the very highest mark, based on both the dissertation and the *viva voce*, but the aggregate score was the equivalent of a gentleman's C. Heisenberg was disconsolate. Competition for the very few German university teaching positions in physics was cutthroat, and at a time of trillion-fold inflation, general economic hardship, and political bombardiering, prospects looked bleak. He wondered if he had any future in physics.

Shortly after, he abruptly left a party in his honor, that very night hauling off to Göttingen, where he would work under Born on his habilitation thesis, a requirement for a post-doctoral degree, which would qualify him to become a university lecturer. New experimental evidence had further complicated the already forbidding Zeeman effect and pretty well discredited his core model, which had encountered stiff theoretical resistance to begin with. But with his mathematical cunning, Heisenberg was able to reconcile the core model with the intrusive data by, as Cassidy explains, "converting the continuous 'classical' energies of observed spectroscopic lines into discontinuous quantum jumps between states." This quick, brilliant work earned Heisenberg his habilitation and increased his professional stature—although his ad hoc patch too was eventually made obsolete, in part by Heisenberg's own subsequent advances.

Heisenberg sent his habilitation thesis to Bohr, who invited him to Copenhagen for a visit in March 1924. The two men talked daily for hours, leaving the core model alone at first, and instead resuming the conversation on fundamental principles that they had started on the Hain Mountain. To his father, who was skeptical about the professional usefulness of Heisenberg's philosophizing turn of mind, he enthused discreetly about the budding intellectual rapport with his new mentor: "We have always talked about the most general questions and have picked apart their philosophical foundations (I see you scornfully smiling here, Papa)."

But in time they focused on Heisenberg's recent work, and the upshot of these discussions was that Heisenberg got serious about making good the deficiencies in his general knowledge of physics, and spent his spare hours poring over the textbooks in Bohr's library. The brilliant young man to whom accomplishment in the most abstruse science had always come easy realized how much harder he would have to work in order to attain mastery like Bohr's.

The Death of Orbital Paths

After finishing his thesis and his visit with Bohr, Heisenberg turned to studying the vexing problem of wave–particle dualism. In the 1860s, James Clerk Maxwell had shown visible light to be an electromagnetic wave. As Cassidy puts it, "only a wave could display such well studied effects as interference, diffraction, and dispersion, such as occur when light is bent through a glass prism or sunlight is split into the colors of a brilliant sunset." But in 1905, attempting to explain the photoelectric effect, Einstein had offered "the revolutionary hypothesis that light also behaves as a stream of particles, or light quanta." And in 1922, Arthur H. Compton had experimentally verified Einstein's hypothesis: Light quanta and free electrons collide and rebound "like billiard balls, rather than like a wave washing over a stone."

David Lindley, in *Uncertainty: Einstein, Heisenberg, Bohr, and the Struggle for the Soul of Science* (2007), describes an Einstein nonplussed and almost disoriented by the idea of light quanta:

> Classical waves always behaved smoothly, gradually, seamlessly. Light quanta, if such things there were, necessarily came and went abruptly, without apparent reason or cause. Here is the root of a problem that was to plague Einstein for the rest of his life. He believed in the reality of light quanta sooner than anyone else, but he rebelled more strenuously than anyone else against the implication that light quanta inevitably bring spontaneity and probability into physics.

The discontinuous and unpredictable behavior of the quantum world, in which electrons bounded as though willfully from orbit to orbit, upended classical ideas of order that the hardly classical Einstein cleaved to with his might.

Bohr for his part also showed a conservative streak and favored the time-honored wave description. This cautious stance, however, was succeeded by an audacious one: He eliminated light quanta but preserved the possibility of light's particle-like behavior, imagining "virtual oscillators" in the atom, electrons as balls that waved back and forth on springs and produced light waves with some of the same characteristics as the particle model. The whole apparatus was a convenient fiction that everyone knew better than to believe as fact, and the theory did not have a long shelf life. But while it lasted it blatantly violated the laws of causality and conservation of energy and matter, introducing "the radical idea that individual events may not be absolutely determined but only predicted as statistical probabilities," Cassidy writes. Einstein wrote to Max Born that renouncing these fundamental laws of physics was abomination, and if Bohr's theory were generally accepted then he "would rather be a shoemaker or an employee in a gambling casino than a physicist." Heisenberg would later make use of this renunciation of conventional reason in devising his uncertainty principle.

But first would come the discovery—or invention—of quantum mechanics. The oscillator model was Heisenberg's launching point. For although the oscillators were purely fictitious, the frequencies and intensities of the light waves they ostensibly emitted and absorbed were real and measurable. So Heisenberg focused on these and left the invisible atom to fend for itself.

Lindley tersely encapsulates Heisenberg's new method: "Worry less about what atoms *are*. Think more about what they *do*." Ever since the quantum model that Bohr and Sommerfeld had collaborated on, theory began with speculation about electron motion and proceeded to deduction of spectroscopic frequencies. In Lindley's summary, "Heisenberg turned this logic exactly backward. The characteristic frequencies would be the basic elements of his atomic physics, and the motion of electrons would be expressed only indirectly." As Heisenberg, in the throes of theorizing, wrote to his colleague and friend Wolfgang Pauli, "My entire meager efforts go toward killing off and suitably replacing the concept of the [electrons'] orbital paths that one cannot observe." What one could see was now of primary importance when trying to describe the infinitesimal and unseen.

To express the observations mathematically, Heisenberg made a path-breaking stumble onto the truth. Cassidy explains:

> When, for example, an electron makes a double jump—first to the next lower state, then to the state below that one—the two emitted frequencies must add together to produce the frequency that is actually observed. One can obtain this addition of frequencies by multiplying together the expressions for the virtual oscillators corresponding to each of the two jumps. Heisenberg found that, mathematically, if the two frequencies do add together, then the two amplitudes do not simply multiply together but are subjected to a new and strange multiplication rule involving all of the possible intermediate states—just in case the electron takes a circuitous route in getting from one place to another....
>
> But Heisenberg had no idea what this multiplication rule actually represented.

Two months later, when Born looked over Heisenberg's 1925 paper "On a Quantum-theoretical Reinterpretation of Kinematic and Mechanical Relations," he noticed that Heisenberg's multiplication rule was congruent with the rule in linear algebra for multiplying two matrices, or tables of numbers. And yet the mathematics for quantum expressions was strange enough in certain respects to seem impossible. Born and Paul Dirac would subsequently demonstrate that multiplying the matrix for an electron's position with the matrix for its momentum is not a commutative transaction—that is, as Lindley puts it, "x times y was not necessarily the same as y times x." The rules for classical physics and standard math patently, grotesquely, eerily, did not apply. The quantum reality was growing curiouser and curiouser, like the fantastic world Alice found in Wonderland.

Can Nature Be Absurd?

Founded on recondite algebra accessible only to expert mathematicians, Heisenberg's "matrix mechanics" was reputedly brilliant but widely unintelligible. So Erwin Schrödinger's rival "wave mechanics" of 1926 won an immediate following. The differential calculus at the core of his theory was simplicity itself compared to matrix algebra, and ordinary workaday physicists embraced the new system because they could understand it. Even Sommerfeld spoke of Schrödinger's having "come to our rescue." Schrödinger for his part grandly saw himself as the savior of "the *soul* of the old system" of mechanics, as he put it in his 1933 Nobel Prize lecture. Lindley explains the appeal of this conservative novelty: "Schrödinger insisted that a particle was not a tiny billiard ball but a tightly gathered packet of waves that created the illusion of a discrete object. Everything, fundamentally, came down to waves." Quantum jumps, those inexplicable discontinuities that appalled the traditionalists, were eliminated. Atomic reality was made smooth and agreeable again.

Heisenberg wasn't having it. Having come down from Copenhagen to Munich in July 1926 to hear Schrödinger lecture, he peppered the unacceptable new authority with objections. Certain experimental results—the photoelectric effect and Compton scattering—could not be explained by wave mechanics; they showed that light came not in waves but in discrete quanta. Moreover, Schrödinger's waves were not in fact directly observable, unlike the quantities in Heisenberg's matrix mechanics. Heisenberg's mathematics might be abstruse to the point of apparent absurdity, but he had the indisputable physical facts on his side. As Lindley writes, "Wave mechanics promoted a veiled quantity to theoretical primacy, and this was not, Heisenberg profoundly believed, the right way to construct quantum mechanics."

A complication arose. Schrödinger's theory and Heisenberg's only appeared to contradict each other. Paradoxically, they in fact agreed. Schrödinger and Wolfgang Pauli, independently of each other, discovered the mathematical equivalence of wave mechanics and matrix mechanics, and this evidently confirmed the truth of both theories. Lindley again: "In a nutshell, Schrödinger's waves can be used to calculate numbers that obey matrix algebra, while matrix algebra, applied to the appropriate quantities, can be made to yield Schrödinger's equation." Describing their theories in mere words provoked irreconcilable differences; employing the true language of physics, mathematics, proved that actually they both had it right. Words have their unquestionable importance, however, even for theoretical physicists, so Heisenberg and Schrödinger remained at odds, and the disputation continued. Heisenberg wrote to Pauli in no uncertain terms about his antipathy for Schrödinger's system: "The more I think about [it] the more repulsive I find it…to me, it's crap…but excuse this heresy and speak of it no more."

From deeper consideration of wave mechanics and matrix mechanics, a revolutionary insight emerged: that both waves and matrix elements signified not definite quantities but rather probabilities. As Lindley tells the tale, Max Born thought over the collision of two particles in Schrödinger's system, and saw that

> the waves corresponding to the rebounding particles spread out something like ripples on a pond, which by Schrödinger's interpretation would seem to mean that the particles themselves had become smeared out in all directions. That made no sense.…A particle had to *be* somewhere; it couldn't disperse uniformly throughout space. The end result of a collision had to amount to two distinct particles moving off in well-defined directions.

The waves rippling out in all directions, he reasoned, must denote not the positions of actual particles but rather the probability that the particles may be found in a particular place: strong wave, greater likelihood; weak wave, lesser likelihood. In *Physics and Philosophy*, Heisenberg describes the ontological peculiarity of this probability wave: "It was not a three-dimensional wave like elastic or radio waves, but a wave in the many-dimensional configuration space, and therefore a rather abstract mathematical quantity."

The bizarrerie of the results that quantum physicists were compelled to accept caused immense dissatisfaction. Einstein for his part refused even to accept them. Clarity, coherence, order, elegance: all the qualities Einstein demanded of a master theory he found lacking in quantum mechanics. In late 1926 he wrote to Born, in a famous (and variously rendered) letter, that quantum mechanics transgressed against the earthly manifestation of divine will as physicists had always understood it. Einstein's God had a mind too harmonious to conceive of so queer a reality as that promoted by Heisenberg and his crew. "The theory delivers a lot but hardly brings us closer to the secret of the Old One. I for one am convinced that *He* does not throw dice." Even those who had to allow that He does worked themselves up into a state. As Heisenberg writes,

> I remember discussions with Bohr which went through many hours till very late at night and ended almost in despair; and when at the end of the discussion I went alone for a walk in the neighboring park I repeated to myself again and again the question: Can nature possibly be as absurd as it seemed to us in these atomic experiments?

Heisenberg came to the conclusion that indeed it can, and as a consequence his name has been enrolled among the ranks of the most honored scientists.

Uncertainty—Either, Or, and Both

The uncertainty principle made its debut in 1927, with the paper "On the Perceptual Content of Quantum-Theoretical Kinematics and Mechanics," and an article in a German popular science magazine, titled "On the Fundamental Principles of 'Quantum Mechanics.'" Heisenberg offers a version of the principle in *Physics and Philosophy*, explaining how he proposed a definitive answer to the question of how absurd nature can be:

> Instead of asking: How can one in the known mathematical scheme express a given experimental situation? the other question was put: Is it true, perhaps, that only such experimental situations can arise in nature as can be expressed in the mathematical formalism? The assumption that this was actually true led to limitations in the use of those concepts that had been the basis of classical physics since Newton. One could speak of the position and of the velocity of an electron as in Newtonian mechanics and one could observe and measure these quantities. But one could not fix both quantities simultaneously with an arbitrarily high accuracy.

Heisenberg demonstrates this proposition with what he calls an "ideal experiment"—an imaginary one—in which a researcher in the laboratory attempts to measure precisely the momentum (mass times velocity) and position of an electron using a high-resolution gamma-ray microscope, such as has never been invented.

> It has been said that the atom consists of a nucleus and electrons moving around the nucleus; it has also been stated that the concept of an electronic orbit is doubtful. One could argue that it should at least in principle be possible to observe the electron in its orbit. One should simply look at the atom through a microscope of a very high resolving power, then one would see the electron moving it its orbit. Such a high resolving power could to be sure not be obtained by a microscope using ordinary light, since the inaccuracy of the measurement of the position can never be smaller than the wave length of the light. But a microscope using γ-rays with a wave length smaller than the size of the atom would do.

The small wavelength of the gamma-rays permits an accurate measurement of the electron's position. However, the rays' smaller length compared to visible light also means that they carry more energy, so that when they strike the observed electron they will deflect it, thus confounding the measurement of the electron's momentum. One can of course sharpen the momentum measurement and lessen the electron's deflection by using a microscope with light of larger wave length, but that will necessarily blur the position measurement.

Cassidy quotes three momentous conclusions that Heisenberg drew from this thought experiment:

> The more precisely we determine the position, the more imprecise is the determination of momentum in this instant, and vice versa.

> The above-mentioned boundary of precision, as determined by nature, has the important consequence that in a certain sense the law of causality becomes invalid.

> In the strict formulation of the causal law—if we know the present, we can calculate the future—it is not the conclusion that is wrong but the premise.

The uncertainty principle demolished the fundamentals of causality and perfect determinism as promulgated in the late eighteenth century by the theoretician Pierre-Simon Laplace, who declared in an ebullition of Enlightenment hopefulness that if one could know the position and momentum of all the objects in the universe, and all the forces acting on those objects, one could predict everything that would ever happen thereafter. Heisenberg showed that even for a single particle the present is as incalculable, unknowable, and mysterious as the future.

And there were uncertainties even about what uncertainty means—the word itself and the conception it describes. As Lindley points out, the very English word whose significance has expanded as the uncertainty principle has insinuated itself into common parlance translates three different German words, not exactly synonymous, in Heisenberg's breakthrough paper. There is *Ungenauigkeit* or "inexactness," which refers to the imprecision of experimental measurements. But there is also *Unbestimmtheit* or "indeterminacy," which refers to theoretical ambiguity, and specifically to the assertion that quantum mechanical laws are generally only probabilistic. And then there is *Unsicherheit* or "uncertainty," which makes its appearance only in the endnote, and which Heisenberg introduces there at Bohr's behest. As Cassidy observes, "Today, we often speak of the uncertainty principle, while referring to the indeterminacy of quantum events."

Bohr was disputing and refining Heisenberg's discovery even while his paper was in press, once reducing his protégé to tears and provoking a cutting retort not soon forgiven. In the end the senior partner had the decisive say in determining the direction that quantum theory was to take. Cassidy writes,

> Bohr informed the author of what became the uncertainty principle that the principle arose, not from the recoil of the electron under bombardment by a light quantum, but from the scattering of the waves making up the light quantum into the aperture of the microscope's objective lens—an essential limitation on the resolving power of any microscope. Not only was the finite aperture of this lens essential to the analysis, Bohr argued, but most important, the analysis required a wave interpretation of the scattered light quantum.

The ultimate uncertainty, Bohr professed, could be discerned in the dual nature of light and matter, which showed themselves to be both wave and particle in any experiment. And so most everything was uncertain all at once, and nothing was more certain than that: What Bohr called complementarity became the home truth of quantum theory, in which apparently contradictory terms were true at the same time. In Cassidy's words,

> Together, uncertainty and complementarity, along with the probability interpretation of the wave function, represented the interpretive

> culmination of quantum mechanics, the basis for comprehending the dualities of waves and particles, wave functions and matrices, atoms and laboratories, continuity and discontinuity, causal and acausal descriptions, researchers and their experiments—the foundations of the Copenhagen interpretation of quantum mechanics.

Heisenberg kicked at his elder's insistence that the young man's theory was flawed and incomplete, but in the end he conceded the rightness of complementarity.

The Golden Age and the Dark

In 1927 Heisenberg's achievement was recognized just as he had long hoped, and he was called—the German verb *berufen* registers the vocational solemnity of the honor—to the professorial chair of the Institute for Theoretical Physics at the University of Leipzig. At twenty-five years old, he became the youngest full professor in Germany. Quantum colleagues were taking over choice academic positions in Germany, Switzerland, and Denmark. The subsequent five years, Heisenberg would write in *Physics and Beyond*, were "so wonderful that we often spoke of them as the golden age of atomic physics." Students came in droves to German physics, and particularly to Leipzig physics. Edward Teller was a doctoral student of Heisenberg's, and J. Robert Oppenheimer attended some of his lectures. Heisenberg was a towering peak among eminences.

In 1929 he traveled to the United States on a lecture tour, speaking at M.I.T., the University of Chicago, and Caltech; he would revise the Chicago lectures for publication as *The Physical Principles of the Quantum Theory*, which became the canonical textbook of the Copenhagen interpretation, and which Cassidy argues gave Bohr too much credit at Heisenberg's own expense. Japan and India were also on his itinerary; the vigorous alpine hiker tested his powers in the Himalayas.

And his innovative theoretical work did not flag. With Wolfgang Pauli, Paul Dirac, and Pascual Jordan, he prepared the groundwork for relativistic quantum field theory, which sought to conjoin quantum mechanics and relativity. Moreover, seizing upon the discovery of the neutron by James Chadwick in 1932, Heisenberg produced a nuclear quantum mechanics whose influence has resounded down the decades. Cassidy eulogizes the achievement:

> Heisenberg had opened the door to the entire nucleus. His proton-neutron model set in motion the field of contemporary nuclear structure

> studies, and it stimulated the branch of quantum theory that focused on two new forces of nature within the nucleus—the strong, or nuclear, force that holds nuclei together, and the weak force that holds together protons and neutrons.

Heisenberg was awarded the Nobel Prize in Physics for 1932.

Of course, the darkness closed in on the golden age in 1933: That January, German president Paul von Hindenburg appointed Hitler the nation's chancellor, and in short order Nazism became the one true—the one permissible—faith. Einstein, a visiting professor in the United States, chose civilization over barbarism, announced that he would not return to Germany, and called on other governments to join forces against the Nazi regime. When the gray eminences Max Planck and Max von Laue entreated him not to rile the powers with his intemperate public animadversions, Einstein shot back a declaration of principle:

> I do not share your view that the scientist should observe silence in political matters, i.e., human affairs in the broader sense.... Does not such restraint signify a lack of responsibility? Where would we be had men like Giordano Bruno, Spinoza, Voltaire, and Humboldt thought and behaved in such a fashion? I do not regret one word of what I have said and am of the belief that my actions have served mankind.

Heisenberg for his part saw things differently. In *Heisenberg and the Nazi Atomic Bomb Project: A Study in German Culture* (1998), Paul Lawrence Rose, Heisenberg's fiercest critic, cites a letter Heisenberg wrote to Max Born in June 1933:

> ...in spite of some nasty things that have been happening here within the workings of science itself, I know that among those in charge in the new political situation, there are men for whose sake it is worth sticking it out. Certainly in the course of time the splendid things will separate from the hateful.

Cassidy notes that the Jewish Born had been ousted from his professorship in Göttingen and had decamped to his summer home in Italy, intending to make the move permanent; it is unlikely he found Heisenberg's sunniness convincing. Heisenberg maintained this fulsome even-handedness in writing of the regime in October 1933, "Much that is good is now also being tried, and one should recognize good intentions." The Good Intentions Paving Company, to borrow a phrase from Saul Bellow, was laying down roadway at a ferocious clip, over anybody who stood in its path.

Jews were of course singled out for special attention from the start. There was no place for Jewish academics. The schools and universities were overcrowded, the authorities averred in April 1933, so Jewish students were dismissed, in order to give their Aryan classmates the safe space they needed to flourish. And Jewish professors were dealt with through the law for the "restitution" of the civil service, which consigned non-Aryan civil servants to an abrupt early retirement. Many of the finest minds in Germany followed Einstein's example and cleared out. Reasonable, sensitive, meliorist, Heisenberg was no anti-Semite and he tried to preserve the integrity of his calling, at least at first. He tried to coax Born, who by then had accepted a position at the University of Cambridge, not to burn his bridges, to leave open the possibility of returning to Germany; one should be hopeful that the Reich would relent and welcome him and his wandering brethren back. But then the regime only increased its savagery. And in due course the wrath of the state was turned on Heisenberg.

Man of "Honor"

In April 1937, Heisenberg married Elisabeth Schumacher. In July, when they arrived in Munich—she expecting twins and he anticipating his appointment as Sommerfeld's successor in the physics chair—the newspaper *Das Schwarze Korps* (*The Black Corps*), official organ of the SS, featured a long denunciation of theoretical physics and its principal German exponent, Heisenberg:

> The victory of racial anti-Semitism is to be considered only a partial war.... For it is not the racial Jew in himself who is a threat to us, but rather the spirit that he spreads. And if the carrier of this spirit is not a Jew but a German, then he should be considered doubly worthy of being combated as the racial Jew, who cannot hide the origin of his spirit. Common slang has coined a phrase for such bacteria carriers, the "white Jew."

The purveyor of this closely reasoned magniloquence was Johannes Stark, a physics Nobel laureate and spokesman for the scientific cleanliness of the *Deutsche Physik* movement, which was fighting to reclaim control of the profession from the usurpers. The traditional experimentalists such as Stark and his fellow Nazi Nobelist Philipp Lenard loathed the theoretical physicists who had supplanted Newtonian good sense with outlandish speculation amounting to fantasy, the product of intellectual and moral deformity not to be countenanced by decent people. In *Heisenberg's War:*

The Secret History of the German Bomb (1993), Thomas Powers describes the deliberate backwardness in the name of racial purity: "'Jewish physics' joined 'Jewish art' and 'Jewish literature' in the National Socialist lexicon of modernist threats to traditional German values." As Lenard wrote in one of his volumes of collected lectures, "'German physics?' people will ask. I could have also said Aryan physics or physics of Nordic-natured persons, physics of the reality-founders, of the truth-seekers, physics of those who have founded natural research." The unreality, the unnaturalness, the untruth of the most innovative developments in modern physics were the objects of his fury.

With Einstein's removal to more congenial precincts, Heisenberg was the most egregious native representative of Jewish physics, and all the more to be condemned because he was an Aryan and a Christian—a race traitor. Cassidy enumerates Heisenberg's sins as presented by his inquisitor Stark:

> He had "smuggled" his article defending the teaching of relativity theory into a party newspaper; he had circulated a petition among physicists in order to influence wrongly a state agency [the Reich Education Ministry] and to silence his legitimate critics; he had refused to join his fellow Nobel Prize winners in the 1934 declaration of support for Hitler's presidency; and his appointment to the Leipzig chair in 1927 was clearly unearned, since he was obviously too young to have accomplished anything of value—a circumstance that "proved" that he had gotten the chair only because he was backed by the "white Jewish" establishment. In addition, Heisenberg had allegedly dismissed a "German" assistant in his institute in favor of the Jewish physicists [Felix] Bloch and [Guido] Beck; his institute continued to harbor an inordinate number of Jews and foreigners to the exclusion of "Germans"; and so on.

In this instance the old joke that academic politics are so vicious because the stakes are so small does not apply.

Sommerfeld, Heisenberg's Leipzig colleagues, and the Rector of the University of Munich protested to every available scientific and cultural authority, but the most heated protest to the Reich Education Ministry came from Heisenberg himself. He insisted that this insult to his personal honor be officially rebuked and rescinded, or he would resign his professorship. Heisenberg wrote to Sommerfeld of his distress:

> Now I actually see no other possibility than to ask for my dismissal if the defense of my honor is refused here. However, I would like to ask

> you for your advice in advance. You know that it would be very painful for me to leave Germany; I do not want to do it unless it must be absolutely so. However, I also have no desire to live here as a second-class person.

If he were to stay in Germany, only a first-class life would be acceptable; so he did what was necessary to secure such a life. His honor was unimpeachable, he asserted, and he demanded justice, as a loyal German. Of course had he been in fact an honorable man he would have welcomed such defamation from the likes of Stark. What Heisenberg called his honor was in fact nothing more than the good will of his masters.

As Cassidy explains Heisenberg's predicament, he was at best lukewarm toward the regime, he accepted Nazi authority by failing to leave Germany when he had abundant opportunity to do so, and in order to maintain his prestigious academic position he exposed himself to the need for morally lethal compromise. "So then because thou art lukewarm, and neither cold nor hot, I will spue thee out of my mouth," Christ declares his repugnance for trimmers and temporizers to St. John in Revelation 3:16; and by standing on his honor as good Nazis understood the word, Heisenberg proclaimed himself eligible for divine expectoration.

The cultural bureaucracy was slow to respond, so Heisenberg presumed upon a family connection to pursue his exoneration. Heisenberg's mother knew Heinrich Himmler's mother, both living in Munich, and Mrs. Heisenberg called on her to present her son's letter of petition to the SS leader. Himmler took the matter under advisement, and initiated an investigation into Heisenberg's case, which was directed by Reinhard Heydrich, head of the Gestapo and the *Sicherheitsdienst* (the SS intelligence agency). The Reich Education Ministry concluded its own investigation and cleared Heisenberg just as the SS probe was getting underway.

The SS inquiry was conducted with totalitarian punctilio, and lasted over eight months. Cassidy describes the ordeal: "Heisenberg had to endure long and exhausting interrogations; spies were planted in his classroom and throughout the institute; the Gestapo bugged his home." To tighten the screw another several turns, the SS brought a trumped-up charge of homosexuality against Heisenberg, a crime that meant certain internment in a concentration camp. This more serious charge was used as leverage to try to extract Heisenberg's confession to practicing Jewish physics. The dire situation consumed him; it was impossible to do any physics at all while he was plunged into this miasma. In the end, however, Heisenberg had his honor back. The SS reported that he was largely apolitical, except for being known to speak approvingly of the Hitler regime. Restoring his good name really meant soiling it past hope of cleansing.

The SS verdict evidently helped convince Heisenberg to remain in Germany. During the inquiry he had contacted Columbia University and been offered a position there, but once his exoneration came through he turned the opportunity down. He also rejected more than generous offers from Princeton and Chicago. When Heisenberg came to the United States for a month in the summer of 1939 to lecture on cosmic ray showers, his American colleagues, including German exiles, could not understand why he refused to emigrate, and many suspected that he was a Nazi at heart. Heisenberg would remember telling fellow scientists that he believed Germany would lose the inevitable war and that he wanted to remain there so he could take part in her reconstruction. Some others remember his predicting a Nazi triumph.

"The Most Dangerous Possible German"

In *Physics and Beyond*, Heisenberg recreates a conversation he had during that American trip with the Italian émigré Enrico Fermi, who would oversee the first controlled nuclear chain reaction in Chicago three years later. Pressing him on his reasons for staying in Germany, Fermi raised the question of whether Heisenberg would be willing to work on an atom bomb for Hitler:

> Once war is declared, both sides will perhaps do their utmost to hasten this development, and atomic physicists will be expected by their respective governments to devote all their energies to building the new weapons.

Heisenberg deflected Fermi's concern:

> But is emigration really the answer? In any case, I have the certain feeling that atomic developments will be rather slow however hard governments clamor for them; I believe that the war will be over long before the first atom bomb is built.

He went on to declare that he thought Hitler could not win the war he was planning, and that even though he himself fully expected defeat, Germany was his home as no other country could ever be and that was where he would always belong.

> I don't think I have much choice in the matter.... Every one of us is born into a certain environment, has a native language and specific

> thought patterns, and if he has not cut himself off from this environment very early in life, he will feel most at home and do his best work in that environment.

What Heisenberg suggests in this passage, wittingly or not, is that working on the atomic bomb for Germany's enemies would be morally no different from working on the bomb for Hitler. He recognized that Hitler was "irrational," but he had made his decision to serve him in whatever capacity the war would require.

Heisenberg had trained for several years as a reserve infantryman; he had been ready to go to war for the Sudetenland in 1938 before Neville Chamberlain had arranged for the peaceable cession of Czechoslovakia to Hitler. Nevertheless, when war was declared, he was most likely not surprised when he was summoned instead to work under the auspices of the *Heereswaffenamt* (Army Ordnance Office) on the project to determine how nuclear fission could be put to technological purpose.

Nuclear fission—ripping apart the nucleus of a heavy element such as uranium, with a convulsive eruption of energy—had been discovered just the year before, by Otto Hahn and Fritz Strassmann in Berlin. Hahn's esteemed colleague Lise Meitner, who could see that her conversion to Christianity would not erase the stigma of Jewish birth, had departed for Sweden shortly before the breakthrough; Hahn had helped provide for her in exile with the parting gift of a diamond ring. Meitner's physicist nephew Otto Frisch had joined her in Stockholm, and their own description of fission employed Niels Bohr's nuclear model. In Cassidy's words,

> Upon absorbing a stray neutron, the nucleus, viewed as a heavy liquid drop, would begin to vibrate so violently that it became unstable and eventually split into two smaller nuclei with the release of several neutrons and a lot of energy. Frisch told Bohr in Copenhagen of the discovery, and Bohr brought the news to America in January 1939. While Bohr and John Wheeler worked out a complete theory of nuclear fission in Princeton, a nuclear research team in Paris under Frédéric Joliot, the son-in-law of Marie Curie, confirmed in April that on average more neutrons were released per fission than were absorbed. A chain reaction could occur, releasing an enormous amount of energy in a very short time—in other words, an explosion.

While, in America, Einstein advised President Roosevelt of the German discovery and the German peril, in Germany word spread fast from physicists to the explosives experts at Army Ordnance. When war broke out, Germany alone had a military project with the destructive potential of nuclear fission in mind. This assemblage of nuclear scientists, most of them experimentalists, was called the *Uranverein*, or Uranium Club.

Erich Bagge, assistant to the chief army researcher, had been a doctoral student of Heisenberg's, and he enlisted his former professor as the outfit's primary theoretician. Heisenberg hurled himself full throttle into the war work, and soon was the regime's leading authority on nuclear fission, surveying the available literature and writing with uncanny speed a secret report that described the shattering possibilities the exceedingly rare isotope uranium-235 had as an explosive.

Heisenberg would presently rein in any undue hopes he might have excited of an easy path to an unbeatable weapon: U-235 had to be separated from the common U-238, and this exquisitely arduous process was beyond German means. Cassidy notes that Jewish physics would have been most helpful to the Nazi war effort here, which lost a prime opportunity for more efficient isotope separation thanks to racial policy. The pioneer of isotope separation by gaseous diffusion, Nobel laureate Gustav Hertz, had been disgraced and forced out of academic life because his uncle Heinrich Hertz, famous for discovering electromagnetic waves, had Jewish ancestry. Gaseous diffusion was therefore evidently unsuitable for *Deutsche Physik*, and the Nazis never thought to employ Gustav, who did civilian industrial work in Berlin during the war. The Allies would use gaseous diffusion to their advantage in the Manhattan Project. But then Jewish physics and Jewish physicists, including notable refugees from the Reich, figured prominently in the Allied A-bomb enterprise.

Heisenberg would have been more than welcome in the Allied project had he decided to emigrate; as things stood, however, he was believed "the most dangerous possible German in the field because of his brain power," as the British physicist James Chadwick, discoverer of the neutron, admonished American officials in the depths of wartime. Heisenberg's genius reputation eclipsed that of any one atomic scientist the Allies could pit against him. And his all-but-inhuman force of reason seemed to represent the chilling fury of a nation that thrilled at conquest and thrived on war.

Historian Thomas Powers sees sheer terror at Teutonic mind and character as the inspiration for the monumental Allied project to forestall devastation at German hands by developing an unprecedented weapon of annihilation of their own. "A single lurid fear brought the American decision to undertake the vast effort and expense required to build the atomic bomb—the fear that Hitler's Germany would do it first." This fear, he adds, was not unreasonable: "Nuclear fission had been discovered in Germany, Europe's only uranium mines were controlled by Germany, and in May 1940 German armies seized the world's only heavy-water plant, in Norway." A greater danger than civilization had ever known before was ever present. Even if the Allied armies managed to bring the enemy to its knees, atomic bombs dropped at the eleventh hour on London or Paris or Moscow could reverse the war's course in a moment, or at best make victory seem as ashen and sorrowful as defeat.

Little wonder then that the Americans contrived a plot to kidnap or kill Heisenberg while he was in Switzerland. Hans Bethe, Victor Weisskopf, and Oppenheimer discussed such possibilities as early as 1942. As Powers tells the story, the Office of Strategic Services, forerunner to the Central Intelligence Agency, dispatched an operative to Zurich in December 1944 to meet Heisenberg and to determine whether he ought to be eliminated.

Morris Berg, a recently retired catcher for the Boston Red Sox, Princeton-educated multilingual polymath, and one-man wrecking crew, attended a dinner party and enjoyed a long evening walk with Heisenberg. The plan was to find out what he knew about the progress of the German bomb project, to see if he was amenable to talk of defection, and to assassinate him if the Nazis seemed to be close to perfecting their weapon.

At the dinner party, Heisenberg, under pressure, claimed to know nothing about the wholesale murder of Jews in Holland and France—to general disbelief. He protested that he was a German but not a Nazi. He declared that Germany was the defender of European civilization against Soviet dominance. And he responded to the question of whether the war was lost for Germany, "It would have been so beautiful if we had won."*

This remark of Heisenberg's convinced Berg not to shoot him. If the mastermind of the bomb project was certain that his nation was going to lose the war, then the bomb must be nowhere near ready. The remark also contributed to Heisenberg's infamy, however: He had plainly been hoping, and working, for a German victory.

A Saboteur?

What then had this most fearsome intelligence behind the most fearsome enemy weapon been doing to make his homeland invincible? As little as

* This translation from German is Jeremy Bernstein's, in *Hitler's Uranium Club* (2001). He writes that the physicist Gregor Wentzel, in conversation with Heisenberg at the dinner, later repeated the line to others, including to some of Bernstein's colleagues. (Powers translates the German *schön* as "good" rather than "beautiful.")

possible, according to Thomas Powers. In 1941, Fritz Houtermans, a colleague and friend of Heisenberg's, gave the Jewish physicist Fritz Reiche, who was leaving Germany for America, a message for "the interested people" there. Twenty years later, Reiche recalled the message he had memorized and delivered to Princeton physicist Rudolf Ladenburg, his lifelong friend:

> We are trying here hard, including Heisenberg, to hinder the idea of making a bomb. But the pressure from above…Please say all this; that Heisenberg will not be able to withstand longer the pressure from the government to go very earnestly and seriously into the making of the bomb. And say to them, say they should accelerate, if they have already begun the thing…they should accelerate the thing.

Ladenburg arranged for Reiche to tell his tale to a gathering of a dozen scientists, including Hans Bethe, John von Neumann, and Ernest Wigner, who would work on the Manhattan Project; everyone listened intently. Days later Ladenburg responded to an overture from Lyman Briggs, head of the Uranium Committee, the Manhattan Project in embryo: "Heisenberg himself tries to delay the work as much as possible, fearing the catastrophic results of a success. But he cannot help fulfilling the orders given to him, and if the problem can be solved, it will be solved probably in the near future. So he gave the advice to us to hurry up if U.S.A. will not come too late." Briggs thanked Ladenburg and asked him to follow with any more information should he get it. After that, Powers laments, Reiche's message was swallowed by the bureaucratic maw and never heard from again.

Powers writes that the counterpart to "the official history of the war" is "a kind of shadow history—the real life that went on outside the committee rooms, where men struggled with conscience," and his project is Heisenberg's simultaneous moral and intellectual rehabilitation: Heisenberg has been maligned unjustly from different quarters not only for serving Hitler faithfully but also for failing to produce the bomb that Hitler expected of him. In fact, Powers argues, Heisenberg understood early on what was required to make the bomb, and he concealed his knowledge from his more eager colleagues and superiors. He was a nonpareil technical genius as advertised, a saboteur by silence, and a friend to the Allied cause. Hitler appalled him and he did all he could to prevent a Nazi victory. Emphasizing, not to say exaggerating, the difficulties of bomb manufacture to the military authorities, he sought to persuade the brass to abandon the unholy enterprise. Powers describes the strategy:

> If the scientists stressed the magnitude of the project, the uncertainty of the outcome, and above all the time it would take, then the military would find it difficult to go ahead. But if the scientists instead stressed the certainty that it could be done, the chance things might move quickly with all-out support, and above all the devastating power of the bomb itself, then the military would find it difficult to say no. At this point—but only at this point—the role of the scientists was potentially decisive.

And Heisenberg convinced himself that by talking with his old friend Niels Bohr in Nazi-occupied Copenhagen he might set in motion a plan to keep the Allies from building their own bomb to drop on Germany. As Powers writes, "he hoped to propose the possibility that Bohr might serve as an intermediary in arranging a secret agreement among German and American physicists to use their influence at this delicate moment to stress the difficulties of making a bomb, and thereby avoid its use during the war—*by either side*." Powers buttresses his contention with a quotation from Elisabeth Heisenberg's memoir of her husband, *Inner Exile* (1984):

> The truth was that Heisenberg saw himself confronted with the spectre of the atomic bomb, and he wanted to signal to Bohr that Germany neither would nor could build a bomb. That was his central motive. He hoped that the Americans, if Bohr could tell them this, would perhaps abandon their own incredibly expensive development. Yes, secretly he even hoped that his message could prevent the use of an atomic bomb on Germany one day. He was constantly tortured by this idea.... This vague hope was probably the strongest motive for his trip.

So according to Powers's account, in 1941 Heisenberg by turns prodded the Americans to speed along their bomb project and also tried to ensure that the Americans would forsake their project altogether. Historian Paul Lawrence Rose casts doubt generally on the postwar attempts by German physicists to claim that they were members in good standing of the anti-bomb resistance. Fritz Houtermans, for example, later claimed that he had tried to conceal from his Nazi overlords that a discovery he made was critically important to the bomb project—even though the paper he published on the discovery explicitly mentioned this significance. Rose also points out that Thomas Powers neglects to mention Fritz Reiche's expression of doubt after the war about Heisenberg's ostensible resistance: "I thought really it is so, that Heisenberg was strictly opposed to the whole thing. Obviously not. This was not so, I think." There are further difficulties with Powers's account, as we shall see.

The Copenhagen Meeting

By anyone's account, whatever Heisenberg's intentions might have been in going to see Bohr in September 1941, they exploded in his face. In *Physics and Beyond* he writes that as soon as he mentioned that it was in principle possible to build atomic bombs, "Niels became so horrified that he failed to take in the most important part of my report, namely, that an enormous technical effort was needed. Now this, to me, was so important precisely because it gave physicists the possibility of deciding whether or not the construction of atom bombs should be attempted." The very thought of nuclear weapons so unnerved Bohr that he shut down completely, and did not follow the rest of Heisenberg's remarks. Heisenberg allows that his old friend may have been so bitter at the German occupation of Denmark that he would not countenance talk of international comity among physicists.

Bohr would remember the conversation differently. In 1957 he wrote several drafts of a letter to Heisenberg that he never sent; they were placed in an archive to be sealed until 2012, but in 2002, as Michael Frayn's play *Copenhagen* excited a vortex of controversy about the two men's wartime meeting, a host of relevant documents were released. These appear in a 2005 scholarly collection, *Michael Frayn's* Copenhagen *in Debate*. In one draft, Bohr expresses amazement at how Heisenberg's memory had failed him in a 1957 letter Heisenberg sent to Robert Jungk, a historian who published portions of the letter in later editions of his book *Brighter than a Thousand Suns: A Personal History of the Atomic Scientists*. There Heisenberg claimed that he had opened his conversation with Bohr by asking "whether it was right for physicists to devote themselves in wartime to the uranium problem." Bohr offers this correction:

> Personally, I remember every word of our conversations, which took place on a background of extreme sorrow and tension for us here in Denmark.... [Y]ou and Weizsäcker expressed your definite conviction that Germany would win and that it was therefore quite foolish for us to maintain the hope of a different outcome of the war and to be reticent as regards all German offers of cooperation. I also remember quite clearly our conversation in my room at the Institute, where in vague terms you spoke in a manner that could only give me the firm impression that, under your leadership, everything was being done in Germany to develop atomic weapons and that you said that there was no need to talk about details since you were completely familiar with them and had spent the past two years working more or less exclusively on such preparations....That my silence and gravity, as you write

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> in the letter, could be taken as an expression of shock at your reports that it was possible to make an atomic bomb is a quite peculiar misunderstanding, which must be due to the great tension in your own mind.

Bohr goes on to state that if anything surprised him in Heisenberg's exposition, it was "that Germany was participating vigorously in a race to be the first with atomic weapons." In another draft Bohr observes that Heisenberg never offered any suggestion that he and his crew were taking pains to delay or to prevent the development of the bomb: "Without preparation, immediately you informed me that it was your conviction that the war, if it lasted sufficiently long, would be decided with atomic weapons, and I did not sense even the slightest hint that you and your friends were making efforts in another direction."

So Thomas Powers credulously gathers his impression of the Copenhagen meeting almost exclusively from Heisenberg's own version of events—for "Bohr never talked about it in public, much less put down an account on paper." Of course, Powers, whose book came out before these documents were released, could not have been aware of what Bohr did put down on paper to discredit Heisenberg's telling, and Powers's. But it is Bohr who deserves our trust. He had no reason to lie to himself or to anyone else about his war. A Danish patriot, half-Jewish, he was among the eight thousand Danish Jews clandestinely ferried to safety in Sweden one night in 1943 as a Nazi round-up was imminent. He made his way to Britain and thence to the United States, where he took part in the Manhattan Project. By contrast, it was Heisenberg's honor that, by *his* war, was being called into question from two opposing directions: as the loyal son of Germany and the physicist of genius who failed to produce the weapon that could have been his nation's salvation; and as the man of flawed conscience who ought to have removed himself from Germany and never deigned to serve the most vicious of tyrants.

Ignorance at Farm Hall

With Germany's defeat, in May 1945 Heisenberg fell into the hands of the Americans, then of the British. American law could produce no convincing reason to hold him longer than it did, but British law stipulated that anyone could be held for up to six months at the king's pleasure, so Heisenberg and nine of his fellow physicists were interned, quite commodiously, with free use of the tennis court and well-tuned grand piano, at Farm Hall, a manor and long-time Foreign Intelligence safe house fifteen miles outside Cambridge. The internees did not know that their conversations were being recorded; the transcripts were released in 1992 and are collected in *Hitler's Uranium Club: The Secret Recordings at Farm Hall* (2001), edited by Jeremy Bernstein, atomic physicist turned writer.

The most telling conversations were those after the physicists were told of the bombings of Hiroshima and Nagasaki. At first, they could not believe the news: They had been certain that the Allies had lagged far behind them in developing the A-bomb. Otto Hahn was despondent: In 1939 the discoverer of nuclear fission had believed he would commit suicide if his discovery ever led to a bomb, and the one saving thought he had now was that at least the Germans had not succeeded in their effort.

The Uranium Club members disputed the reasons for the Americans' success and their own failure. The scale of the American effort astonished and chastened them. Heisenberg said, "We wouldn't have had the moral courage to recommend to the government in the spring of 1942 that they should employ 120,000 men just for building the thing up." His idea of moral courage was in keeping with his odious notion of honor: To risk losing the favor of his superiors would have been an act of supreme daring. In an acerbic footnote, Bernstein comments, "What Heisenberg seemed most to have feared was that he would promise a weapon he couldn't deliver. That was his situation beginning in 1942."

The reason why Heisenberg failed to deliver became abundantly clear in the course of the discussion: The bomb-making fundamentals mystified him. At first he refused to believe the Allied bomb was in fact nuclear; he thought it a much-improved conventional bomb. His incredulity stemmed from his confused, almost laughable miscalculation of critical mass, the amount of uranium needed to make the bomb, which he believed to be thousands of times higher than it actually was. Hahn reminded Heisenberg that he once said a bomb of low critical mass was possible. Heisenberg replied, "I wouldn't like to commit myself for the moment," and that "I have never worked it out as I never believed one could get pure [uranium] '235.'" He proceeded to reel off a calculation for the chain reaction of the Hiroshima explosion, which the news reports said was equivalent to 20,000 tons of TNT. He reckoned there must have been "about a ton" of U-235—in fact, there was only 56 kilograms. Bernstein is all over Heisenberg's figures:

> The energy released in the Hiroshima explosion was caused by the fissioning of only a small part of [the 56 kilograms]—1 kilogram of ^{235}U—or about 2 percent of the material in the bomb. In Heisenberg's discussion this effect is ignored. Hence the obvious question is why,

> according to Heisenberg, is not the whole ton fissioned, which would have produced an explosion 1,000 times bigger than what was reported.... This problem does not seem to bother Heisenberg, which once again shows that at the time he had not really understood bomb physics.

A week later Heisenberg delivered a highly technical lecture to his fellow inmates on how the Hiroshima bomb must have worked. Thomas Powers believes the lecture, gotten up on a week's notice, to prove Heisenberg's incomparable genius. But he also claims that Heisenberg had known for years the facts about bomb-making that at last he disclosed to his associates. Heisenberg's lecture is of an order of difficulty that a mere layman (like this writer) cannot hope to penetrate.

Bernstein's expert eye, however, sees Heisenberg's grasp as seriously lacking: "The Germans had no comprehensive understanding of bomb physics. This goes way beyond Heisenberg's confusion about the value of the critical mass. Nearly everything Heisenberg says in this lecture misses essential points, and the comments of his colleagues are worse." And he finds Powers's presumption in adjudging the understanding of Heisenberg and his colleagues derisory: The idea that they "'really understood bomb physics' is so ludicrous that one wonders if Powers has any understanding at all of the physics contained in this lecture and the comments made during it. Moreover, the fantasy that Heisenberg understood how to make a bomb all along but kept 'the secret' to himself is equally absurd."

Powers believes that the exactitude and sweep of the lecture demonstrate Heisenberg's breathtaking mastery, which he had kept rigorously to himself until the right moment; Bernstein claims that Heisenberg never had any secret knowledge to conceal, that his manifest ignorance was proved when it came time to reveal what he knew.

Just Deserts

A free man in postwar Germany, an esteemed yet still suspect director of a Göttingen physics institute under British oversight, Heisenberg devoted much of his energy to defending his wartime conduct. The decision not to proceed with bomb development, he would declare, had come in 1942 from Albert Speer, the armaments minister. The disastrous Russian campaign made more urgent military needs the priority, and thereafter the German nuclear project was limited to reactor research for benign industrial use; the interesting possibilities of reactor-bred plutonium were not pursued. Heisenberg managed to suggest that it was his own emphasis on the technical difficulties of bomb manufacture that had dissuaded Speer from further action on that front.

Later Heisenberg would advertise the supreme competence of German bomb science, notably his own, in order to enhance his professions of moral excellence in not visiting such an enormity upon the world; that was strictly the enemy's responsibility. As Cassidy writes,

> …the more [the German scientists] were thought to have known about atomic bombs, the nobler they would seem to contemporaries for not having attempted to build them. He defended the obvious hero worship, the formation of a clique around himself, as a means of excluding "unscrupulous persons" from influence on the course of uranium research. Heisenberg's 1941 visit with Niels Bohr was now described as an effort to convey to the Allies that the Germans knew about the bomb but would not pursue it.

When Heisenberg called on Bohr in 1947, the Danish master refused to help his sometime protégé in his efforts to rehabilitate his good name. In Bohr's estimation, Heisenberg had the reputation he deserved. The relationship between the two men would thereafter be a fragile truce.

Some of Heisenberg's colleagues would remark that after the war Heisenberg labored under a cloud of relentless depression. Cassidy says that he worked right through it, if he could not manage to find his way out of it. He did all he could to restore the international esteem of German science; he voiced his support for the establishment of a European particle accelerator in Geneva, and was active in its governance; he presided over the Alexander von Humboldt Foundation, a government agency that sponsored foreign postdoctoral researchers in West Germany; he pressed for the relaxation of Allied Control Law 25, which until 1955 forbade any practical nuclear research in Germany; he opposed the 1955 NATO plan to equip the West German army with tactical nuclear weapons. In 1958 he announced a "world formula," or in Cassidy's words, "one simple set of equations for one unified field encompassing every form of matter and force." His sometime collaborator on the theory, Wolfgang Pauli, renounced and demolished it soon afterward. It was Heisenberg's last effort at a major theoretical statement. After he assumed the directorship of the Max Planck Institute in Munich later that year, becoming now principally an administrator, his horizons retracted sharply. In 1976 he died of kidney and gallbladder cancer.

Werner Heisenberg was a physicist of genius, but a failure at bomb-making, for which the civilized world may be grateful. He was a decent man in his personal relations, but the willing servant of a maniacal tyranny, for which civilized people are right to judge him severely. Apologists' efforts to turn his grave shortcomings into moral and intellectual triumphs flounder at every turn. It is only just to honor him for his feats of mind, and to dishonor him for employing his mental powers in immoral servitude to his nation's barbarism. And one can take comfort, as though in Providence, that this man of superb intellect was not any smarter than he was.