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Physics 201: Modern Physics

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Introduction

Following the spirit of the new curriculum, it was decided to convert the Modern Physics course, Physics 201, into a course with a COLL200 attribute. The course covered the basics of relativity and quantum mechanics, and typically has 50-60 students. It was desired to include a substantial discussion of the historical and social significance of the material.

Jamie Leach is a history major who took the course in the Fall of 2014, and he wrote these files with the support of the Physics Department and the Center for the Liberal Arts during the summer of 2015. Students were assigned, every week, to read these documents and write a half-page response on the material. Every Friday, the instructor would also discuss the material.

The reaction was extremely positive, and students were much more interested in the course material as a result. There was one additional lecture on the "nature of physical reality" that is not included here. The materials will be used in future semesters of the course.

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December, 2015

Contents

The Michelson-Morley Experiment(s)

Early Experimentation:

By the 1870s, the luminiferous ether was an accepted feature of contemporary physics. Double slit experiments early in the 1800s had demonstrated that light is wave-like, suggesting that it must propagate through some medium. Physicists disagreed on the exact nature of the ether: some thought of it as a fluid, while others thought it behaved like an elastic solid, for example. The consensus was that the ether was necessary to explain the propagation of light and would provide a rest frame for the universe. Newton himself had argued that a single correct coordinate system for space and time existed, and the idea was taken for granted by many physicists. The most significant disagreement among physicists was whether the ether was entirely stationary (the ether drift hypothesis) or was dragged along with the Earth, either partially or completely (the ether drag hypothesis). By the 1880s, the ether drift model was more widely accepted.

Michelson's original experiment of 1881 was designed to measure the velocity of the Earth against the stationary ether's rest frame. Testing the existence of the ether did not make much sense in his context, as there was little reason to doubt its existence. All earlier tests had found no relationship to the first order of v/c. A relationship corresponding to v^2/c^2 was possible, but this required incredibly precise measurement. Michelson accomplished this with his new invention, the interferometer, which was probably his largest source of fame during his lifetime. The 1881 experiment found no change in light's velocity, which Michelson attributed to ether drag.

Few other physicists paid attention to this first experiment. Those who did focused on the ingenuity of the interferometer rather than the actual results. One person who did pay attention was Hendrik Lorentz, who pointed out that Michelson had miscalculated one of the light beams' paths. This, along with a desire for still greater precision, convinced Michelson to repeat his experiment. Around this time he began collaborating with Edward Morley, whose chemistry lab provided him with high quality equipment. In 1886, the two repeated the famous Fizeau Experiment, comparing the velocity of light passing through water running in opposite directions. They found that light moves at the same velocity regardless of the water's motion, suggesting that the ether is not affected by moving matter. This contradicted the ether drag hypothesis and Michelson's 1881 results, which provided another reason to redo the experiment.

The Famous Experiment:

The Michelson-Morley Experiment of 1887 was specifically intended to resolve the ether drag question. The pair intended to perform several tests at different points in the year, to incorporate the effects of the Earth's rotation, but they never completed these later trials. This may have been due to their disappointment at early negative results or Michelson's excitement to move on to other projects to test his interferometer. The same year, Heinrich Hertz demonstrated the existence of electromagnetic waves, confirming Maxwell's electromagnetic theory and seeming to confirm the need for a medium for the waves. Michelson was concerned with interferometry's applications, while the broader community was more impressed with Hertz's results than with Michelson's; as a result, the Michelson-Morley Experiment did not immediately lead to the death or even the questioning of the ether model.

Once again, Lorentz was one of the few who noticed the experiment. He first identified the negative results as one of the major unsolved problems of contemporary physics and derived the length contraction formula and Lorentz transformation in order to explain it. Lord Kelvin also directly referred to the experiment in a speech in 1900 (the source of his famous "two dark clouds" quote), further spreading awareness. By this point, experiments had contradicted both the ether drift and ether drift theories. Michelson, Morley, and a new collaborator, Dayton C. Miller, continued experimenting in different situations and with greater and greater precision, while theorists formulated alternate ideas. Lorentz contraction was one example of this; unlike Einstein, he attributed contraction to changes in molecular-scale forces due to motion through a stationary ether and continued to believe in absolute measurements of time and space (the Lorentz transformation of *t* being only a mathematical formality). Conversely, Henri Poincaré argued against absolute space and time, questioned the necessity of the ether, and theorized the equivalence of all inertial reference frames (even referring to this as "the Principle of Relativity"). Poincaré came very close to Einsteinian relativity, but did not develop it fully.

From Ether to Relativity:

Despite these early contributions from Lorentz and Poincaré, Albert Einstein is correctly identified as the founder of special relativity. His 1905 paper was not immediately noticed, as he was only 26 years old and had no prior reputation. Two early supporters were Max Planck, who developed relativistic dynamics, and Hermann Minkowski, who formulated relativity in terms of four-dimensional spacetime and thus made Einstein's theory more comprehensible (Einstein was initially hostile to this mathematical modeling, but later accepted it as essential to general relativity). Although Einstein did not draw a direct connection to the Michelson-Morley Experiment in 1905, others soon did, and relativity's supporters quickly realized its importance in explaining the ether's contradictions. Not everyone was enthusiastic about relativity: William F. Magie was indignant that relativity had succeeded in explaining a single result while the ether could explain everything except that one result. Others mixed different components of the ether and relativity models, leading to confusion over which interpretation meant what.

Among the opponents of relativity were Michelson, Morley, and Miller, who continued interferometry experiments up through the 1920s. They applied various conditions to test the velocity of light, such as magnetic fields, high-altitude trials (guessing that ether drag may be weaker higher up), and vertical beams of light (designed to test the Earth's rotational rather than translational motion). All tests returned negative results. The most significant tipping point in favor of relativity came in 1919, when a solar eclipse provided strong evidence of general relativity. Rather than accepting Einstein's ideas, these results encouraged Michelson and Miller to continue experimentation at even higher altitudes. That said, they were not blindly dogmatic or reactionary: they were honest about their many negative results and their work was taken seriously by contemporaries. The final blow to the ether probably came in 1930, when an automated interferometer capable of incredible precision found no effect of ether wind. Michelson died the next year, having still not fully embraced relativity.

Key Ideas:

- The shift from the ether to special relativity did not simply happen as a result of the passage of time. Throughout the narrative above, specific individuals consciously made efforts to spread awareness of what they considered important to their colleagues. The advance of science was pushed along by the likes of Lorentz, Kelvin, and Minkowski. This is not to suggest that changes in scientific thought are simply the result of elites telling their peers what to think. It simply demonstrates that individuals have an active role in forging a scientific consensus.
- Almost 20 years passed between the famous 1887 experiment and the publication of special relativity, and it was even longer before that theory was widely accepted. The Michelson-Morley Experiment is sometimes characterized as beginning a "crisis" in physics, but this does not capture how long it took for its results to be resolved. The physicists who knew about the experiment recognized it as a problem, but its results did not immediately plunge physics into chaos. The ether theory was able to continue basically unchallenged for many years afterward.
- 19th century physics was characterized by the consolidation of different fields: electricity and magnetism were combined, then electromagnetism and optics; the kinetic theory of gases and modern thermodynamics connected different phenomena to classical mechanics. Eventually it was hoped that all of physics would be subsumed into a single field, based either in mechanics or electromagnetism. The ether seemed to be the final step in this realization, and therefore its formulation was a crowning feature of 19th century physics. Abandoning the ether, for many, intuitively seemed like a step backward away from the resolution of the field. It is easy to call physicists who refused to shift to relativity "stubborn" or even "stupid," but it is important to understand how important the ether was to their worldview.
- In 1907, Michelson became the first American to win the Nobel Prize in physics. The prize was awarded for the spectrometer's advances in precision measurement rather than his actual experiment. In the 19th century, America was mostly peripheral to the physics world, which was concentrated in Western Europe. In the 1920s, America's influence began to grow, to the point where the country dominated physics in the 1950s and 1960s. Michelson's Nobel Prize can be considered an early step in this decades-long process.
- Historians have debated whether Einstein knew about or was influenced by the Michelson-Morley Experiment, closely analyzing his writings and searching out new or obscure sources. This may seem like a minor detail to obsess over, but it carries heavy implications about the relationship between experiment and theory. If Einstein based special relativity on the experiment, it is easy to draw a clear line of cause and effect and claim that this is how science works—new experiments inspire new theories. However, if Einstein did not know about the Michelson-Morley Experiment, this entire narrative must be reevaluated. Today, it seems fair to say that Einstein probably knew about the experiment and was affected by it, but that it was not the single determining influence on relativity. Trying to reduce Einstein's formulation of special relativity as a simple

reaction to one event misses out on the rich complexity of his theoretical influences.

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Time Travel

Relativity and Culture:

It is difficult to choose a single event as beginning popular interest in time travel, but the best candidate is probably H. G. Wells’ publication of *The Time Machine* in 1895. In this story, a time traveler explains that time is simply a fourth dimension that can be traversed just like any spatial dimension. Of course, this is not correct, but it firmly established the idea of the fourth dimension in popular culture. Earlier mathematicians had explored the possibility of a hypothetical fourth dimension being either spatial or temporal, and philosophers had speculated as to why humans experience exactly three spatial dimensions, but these discussions did not enter public consciousness. Wells’ story, by contrast, was immediately popular, even receiving a positive review in *Nature*. It continues to serve as a basis for most time travel stories today.

In 1908, Hermann Minkowski formulated the four-dimensional model of spacetime to explain Einstein’s special relativity. It is important to remember that, in this model, space and time are not mathematically equivalent (spatial and temporal dimensions have different signs in the spacetime interval, for example). That said, Wells’ novel 13 years earlier proved to be surprisingly close to later scientific developments. It is unknown whether Minkowski or Einstein had read *The Time Machine* before publishing their theories.

However, for some, Wells’ work seemed to have unfortunate philosophical implications. If time was simply another dimension that one could travel along forward and backward, then it would appear that the past and the future exist in the same sense as the present does, right now. This echoes Parmenides’ concept of the block universe, in which all events in the universe--past, present, and future--exist simultaneously and unendingly. There is no possibility for free will, since everything is already determined. As mentioned above, Minkowski’s actual conception of time has been misunderstood in popular thought. His formulation of a useful mathematical model does not immediately imply a block universe. However, questions of free will have appeared in many time travel stories throughout the 20th century.

Key Ideas:

- Fiction both responds to developments in physics and shapes popular perception of science. It can make a theory easier to understand or put it in a more engaging context, but also, knowingly or unknowingly, distort the theory's intended meaning.

Topics for Illustrating Time Travel and Relativity:

- Wells' time machine would not work because it remains stationary. As soon as it begins to move backwards through time, it would collide with itself from a moment ago.
- If the Klingons fire a missile that travels faster than light, it will hit its target before it was launched.
- Dirac's formulation of electrons as extended bodies resulted in a third-order differential equation that suggested the possibility of pre-acceleration: an electron subject to external forces will begin accelerating a tiny fraction of a billionth of a second before the pulse reaches it, seeming to violate causality. This also suggests the possibility of using the electron's radiation to send signals faster than light.
- Feynman observed that positrons moving forward in time are equivalent to electrons moving backward in time.
- Gödel theorized that, in a rigid, uniformly rotating universe, there is a certain critical distance from the axis of rotation where the future light cone at one point tips over into the past light cone at an adjacent point. Traveling at this critical distance in the opposite direction of rotation would allow the traveler to move backwards in time without ever exceeding the speed of light. This is impossible in our universe, as it is not rotating as Gödel described.
    - A similar effect can be achieved by Tipler's infinitely-long rotating cylinder, which also tips over light cones until past and future overlap.
- Time travel via stable wormholes would require large Casimir plates to create a region of negative energy density around a rotating black hole.
- Time travel paradoxes: there are many possible examples (many variations on the grandfather paradox), but one of the most interesting is Heinlein's "All You

Zombies," in which a single individual is both father and mother to himself/herself.

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Einstein as a Celebrity

The Eclipse Expedition:

Einstein's primary paper on general relativity was published in 1915, but did not become accepted among physicists for several years, as direct experimental confirmation was not available. An eclipse in May of 1919 would present the opportunity to test the theory, by measuring the angular displacement of stars close to the sun compared with non-eclipse photographs, but it seemed unlikely at first that any tests would be carried out. During World War I, deep resentment between Britain and Germany obstructed scientific cooperation between the two countries. This resentment was widespread among intellectuals and scientists in addition to the population at large: the British elite saw the German "Huns" as inhumane and opposed to culture, while Germans were upset by these attacks on their nation. With a few exceptions, such as Einstein himself, most of the leading German and English scientists of the 1910s participated in public campaigns condemning the other side, even going so far as to suggest excluding Germany from the international scientific community. In this climate, it seemed impossible that Britain would bother using its resources to test the ideas of a German theoretician. Another chance at testing general relativity would not come about for several more years.

The eventual British-led eclipse expedition was the work of Arthur Stanley Eddington, an astronomer well-known for his work determining stellar structure. Eddington was a Quaker who objected to the violence of the war and the dehumanization of Germans. During and after the war, English Quakers had travelled to Germany to provide material aid to the suffering country and reaffirm the common brotherhood of humanity. Eddington, who identified with Einstein's pacifism and antimilitarism, saw the eclipse test as a Quaker mission within the scientific community, creating new bonds between Britain and Germany and restoring the international spirit of astronomy. He argued continually for relativity's importance among fellow astronomers. Many objected that gravitational deflection and optical refraction would be indistinguishable and that the expedition to the eclipse's path (which crossed Africa and South America) would be an expensive waste of time. However, Einstein's explanation of Mercury's precession intrigued enough astronomers that Eddington was able to win support and carry out the plan.

The expedition consisted of two observational teams: Eddington lead a group to Principe off the coast of West Africa, while another went to Sobral, Brazil. Despite some bad weather, the Principe group was able to get enough plates to confirm a deflection. The Sobral group showed a smaller deflection, but their photographs were of much worse quality. A last-minute auxiliary camera in Sobral ended up getting the best results out of the entire expedition. After analysis, Eddington decided on a mean deflection of 1.64”, in comparison with the prediction of 1.75”. A rumor has persisted that Eddington discarded or ignored the worse results in his excitement to confirm general relativity, but this is not substantiated. He was honest about the poor quality of some of the photos and described the expedition as a tentative initial test. In the November 6, 1919 presentation of the results by the Royal Astronomical Society, Eddington claimed that he had confirmed Einstein’s prediction (though not necessarily his theory) and called for further testing. The astronomers present generally agreed that Einstein’s quantitative predictions held but that his explanation was still open to questioning.

The public reaction was much stronger. *The Times* issue of November 7 famously proclaimed a “revolution in science,” and other newspapers made similar claims over the next days and weeks. The press portrayed relativity as one of the greatest achievements in human thought and claimed that Einstein had knocked Euclid and Newton off their pedestals. This popular obsession with relativity was partly the result of the dramatic eclipse test, but also of the nature of the theory. Unlike quantum theory, which never became such a fixture in popular thought, relativity took simple, everyday concepts and rearranged them in seemingly paradoxical ways. Although non-scientists could not understand the mathematics behind general relativity, they latched onto ideas such as length contraction, extra dimensions, a finite universe, and the curvature of space (if not the curvature of spacetime) that seemed to belong in *Alice in Wonderland* rather than the usually inaccessible world of physics. This degree of public engagement is rare in the history of science; similar examples include Darwinian evolution or Freudian psychoanalysis.

Einstein's Fame:

A distinction should be drawn between the fame of relativity, which was well-established by the 1919 headlines, and the fame of Einstein, which developed more slowly. This was especially important in America, where the concept of the individual celebrity was strongest. Before Einstein's first visit to the U.S., in 1921, public feelings toward relativity were more fearful and distrustful than elsewhere. This was a time when Americans were more interested in stability and continuity than new ideas of the universe: in the aftermath of the Russian Revolution and among widespread labor unrest at home, Americans were not willing to accept another "revolution" that would upset the established order. The *New York Times* went so far as to proclaim that Bolshevism was invading science. Furthermore, Americans were struck by the difficulty in understanding general relativity: a common claim was that "only twelve people in the world understood it." The idea of obscure science that only an elite few could understand seemed to undermine the American ideal of common-sense democracy. The general sense was that an elite few (probably all foreigners) had the power to rearrange space and time or even destroy gravity.

These feelings quickly passed once Einstein arrived in America. His first trip in April 1921 was actually part of a campaign to raise support for Zionism. His party, consisting of several prominent Jewish intellectuals (including Chaim Weizmann, a biochemist who later became the first President of Israel), received a warm welcome from New York's Jewish community. While this excitement was directed toward the group as a whole, the mainstream press interpreted it as a "hero's welcome" for Einstein. This initial reception helped to remove much of the fear surrounding the mysterious physicist, as anyone receiving a hero's welcome had to be worth welcoming. In addition, Einstein's personality was well-received in America. The press expected a pompous, aloof European intellectual who looked down on America's lack of culture. Instead, Einstein was modest, witty, and informal. America first saw Einstein in pictures revealing his ill-fitting clothes, charming smile, and habit of smoking pipes. Unexpectedly, Einstein's reception and personality resonated with Americans and paved the way for his celebrity status.

Later Legacy:

Instead of fading out as a fad, Einstein has remained a fixture in the public consciousness since the initial media storm of 1921. He has acquired an almost religious connotation as a secular saint embodying the abstract concepts of genius and reason. The press exaggerated his distance from common people, emphasizing that his theories were incomprehensible to the average person and creating a mythology around the physicist. He happened to become famous at the moment when the mass media was coming into being, giving the world easy access to pictures and quotes revealing his unconventional personality. Although Einstein never particularly enjoyed his media attention, he accepted it and maintained friendly relations with the public. Public opposition to Einstein has been scarce, mostly coming from anti-Semites who rejected him on principle rather than because of his theories or personality. This anti-Semitism was most famous in Nazi Germany, although undercurrents of it persisted in America and elsewhere.

One important shift in Einstein's legacy came in the aftermath of World War II, which reinforced the connection between science and destructive weaponry in popular thought. In particular, nuclear weapons, as the symbol of science-gone-too-far, became connected with Einstein and his mass-energy equivalence formula (see *Time* cover in bibliography under Baker). Einstein himself was largely unconnected with the bomb's development and did not realize the possibility of nuclear weapons when he first published his 1905 papers. Nevertheless, the misconception of Einstein as the creator of the nuclear bomb transformed his image into that of a tragic figure, pushing for international peace while unintentionally paving the way for horrible destruction. During the Cold War and after, the public perception of science changed: instead of representing humanity's progress and betterment, science was now a double-edged sword that, if not controlled, could bring disaster to a society unprepared for its consequences.

Influence on the Arts:

Over the first several decades of the twentieth century, contemporaneously with the development of modern physics, widespread experimentation flourished in art, literature, and poetry. It is possible to draw a connection with these modernist artists and Einstein, although this should not be overstated. It would not be fair to claim that relativity was the cause of this experimental mood, as it had already begun before 1919 and Einstein's widespread fame. However, direct references to both Einstein and modern physics makes it tempting to find parallels between contemporary shifts in art and science.

Some modernists drew connections between their work and Einstein's. One prominent example is William Carlos Williams' 1921 poem "St. Francis Einstein of the Daffodils" portrays the physicist as a rebellious liberator bringing new life to a dead world of old-fashioned knowledge. The poem reflects a general mood that advances in physics had opened up new possibilities for intellectual exploration in other areas. A similar mood is found in Archibald MacLeish's "Einstein," published in 1926, which follows the physicist's efforts to break free from conventional modes of thought and obtain a truer understanding of the universe. In a sense, Einstein provided validation and inspiration to these poets: they were following in his footsteps by breaking down conventional barriers in order to reveal deeper truths. In a world transformed by modern physics, modern artists felt compelled to keep up and adapt.

Other modernists incorporated relativistic concepts into the form of their works. The Cubist painter Pablo Picasso, who spent time with scientifically-educated peers and thus may have been exposed to relativity early on, broke with the tradition of linear perspective that had long been central to Western Art. He instead portrayed the same subject from multiple perspectives simultaneously or overlapped drawings of the same subject at different points in time. This does not directly imply an influence from Einstein, his confusion of the separation between space and time reflects relativistic ideas. Similarly, authors experimented in telling the same story from multiple perspectives (such as Virginia Woolf's *The Waves* or James Joyce's *Ulysses*) or out of chronological order (such as William Faulkner's *The Sound and the Fury*). These techniques were not new to the modernists, but they became more prominent and disjointed in this period. Instead of different perspectives being used to reinforce a single master narrative, writers in this period emphasized the lack of a complete picture—there was no preferred frame of reference. Some of these authors followed scientific developments and directly referred to relativity, but it is unlikely that most understood the mathematical details of the theories.

Relativity's relationship with philosophy and morality was often misunderstood in the 1920s. Many mistook the theory as implying moral relativism or suggesting that all viewpoints and opinions are equally valid. The philosopher José Ortega y Gasset enthusiastically incorporated relativity into his own philosophical system, perspectivism, arguing that non-Western perspectives are just as correct as Western ones and that other cultures should not be dismissed as barbaric or uncivilized. Regardless of how sympathetic we might be to this view, it has nothing to do with the actual theory of relativity. Others saw the moral ambiguity supposedly implied by Einstein less favorably: poets such as E. E. Cummings lamented the new direction of science, seeing it as dehumanizing, amoral, and undermining the mystery of religion. A more moderate position was that advances in physics were alright as wrong as they were not misunderstood and applied to ethics.

Key Ideas:

- Based on the modern myth of Einstein, many aspects of his life and personality seem to contradict each other: he was approachable, yet his theories are beyond comprehension; he fought for peace while inadvertently aiding the war effort; he represents the triumph of reason, yet was often shown expressing himself on the violin. These contradictions are, in many cases, the result of misinterpretations of his theories or distortions by the popular media. They often reveal more about society's contradictory attitude toward science than the reality of Einstein's life.
- No other physicist in history, even Newton or Galileo, comes close to Einstein in terms of popular recognition. Part of Einstein's fame comes from the genuine importance of relativity to modern science, but he was helped by coincidences and lucky happenings such as the timing of the 1919 eclipse and his reception in America's Jewish community. Had events turned out differently, Einstein would certainly have remained a highly-respected physicist, but it is interesting to speculate whether he would have achieved legendary status without help from luck.
- Einstein entered the popular culture at the moment when the modern celebrity ideal was taking shape. In this sense he might be compared to figures such as

Charles Lindbergh or Charlie Chaplin. Earlier scientists such as Charles Darwin or Louis Pasteur had become well-known to laypeople, but did so without the mass exposure made possible by modern media. Later in the 20th century, scientists such as Carl Sagan or Stephen Hawking achieved celebrity status through the use of popular media, often acting as popularizers of science or explaining theories to a general audience. Einstein does not exactly belong to either group, marking a transition point in how physicists were viewed by society at large.

- The relationship between scientific advance and artistic experimentation is not a simple case of cause and effect. It is fair to say that the two existed in the same intellectual atmosphere of the early 20th century and that experimental artists were aware of relativity, even if they did not understand it. However, given how tempting it is to draw interesting connections between art and science, it is important to be cautious when direct evidence of a relationship is not available.

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Cosmology

The Great Debate:

While astronomy is one of the oldest of the physical sciences, cosmology (here referring to the scientific study of the universe's structure as a whole) developed mostly during the 20th century. The discipline was formed through the interactions of astronomers, astrophysicists, and nuclear physicists.

Astronomers in the 19th century struggled to explain the size and distance of nebulae, as well as their physical makeup. While there was no clear consensus in the early 20th century, the most popular theory was that each nebula was itself an "island universe" of comparable size to the Milky Way. This view was supported by evidence such as stars being visible in some nebulae using precise telescopes and the similarities between solar and nebular spectra. Evidence against the theory included rapid changes in the behavior of some nebulae, which seemed impossible for clusters of stars of the Milky Way's size. (Today we understand that some of the objects being observed were nebulae and others were galaxies, but astronomers at the time seemed to believe that they all must have been one or the other.)

In 1918, the astronomer Harlow Shapley introduced an alternate model of the universe. He calculated the diameter of the galaxy at 300,000 light years (about ten times as large as contemporary estimates and about 50% larger than the modern value), placed the Earth far from the center of the galaxy, and concluded that there were no significantly-sized objects outside the Milky Way. Based on his calculated size and contemporary data on the apparent rotational speed of another galaxy, the outer edges of this galaxy would move faster than the speed of light, rendering the island universe theory absurd. The island universes were either star clusters within our own galaxy or a nebulous cloud outside it. While Shapley was wrong about this, his estimate of the galaxy's size and the Earth's position within it were the most accurate of his time.

In 1920, the National Academy of Sciences chose "The Scale of the Universe" as its next lecture topic and decided to structure it as a debate between two opposing views. Shapley was one obvious choice, but he also agreed in the hope that the event's publicity would help him win the directorship of the Harvard Observatory. Heber Curtis represented the island universe theory. The lecture has since become known as the Great Debate, or the Shapley-Curtis Debate, and it helped undermine confidence in the island universe theory. While both parties were correct on some points and wrong on others, Curtis was a much more experienced public speaker and was generally regarded as the "winner" of the debate.

A resolution to the debate came in 1923, when Edwin Hubble discovered a Cepheid (a star that varies periodically in brightness) in the Andromeda nebula and used it to calculate its distance at over 900,000 light years. Even using Shapley's large galaxy, it was clear that Andromeda was incredibly far from the Milky Way. Most astronomers quickly agreed that the new discovery supported the island universe hypothesis, which became the new consensus.

Expansion of the Universe:

In 1917, Einstein attempted to use general relativity to model the structure of the universe as a whole. He assumed a bounded universe of static size and introduced the cosmological constant (Λ) that served to counteract gravity and keep the universe in a state of equilibrium. Another solution to the general relativity field equations was found by Dutch astronomer Willem de Sitter the same year, again assuming a static universe. De Sitter's model predicted a redshift of distant galaxies proportionate to their distance—not because the galaxies were receding, but as an intrinsic feature of spacetime. These were the only two solutions possible if one assumed a static, bounded universe, and neither was sufficient to explain astronomical observations: Einstein's solution did not account for the observed redshifts in other galaxies, while de Sitter's only seemed to work for a low-density universe.

In 1929, Hubble discovered a linear relationship between a galaxy's distance and its spectral redshift. While he was cautious about interpreting this as evidence for actual movement away from the Earth (he referred to other galaxies' "apparent velocities"), given the difficulties with static models, astronomers quickly accepted this as evidence for an expanding universe. This was theoretically grounded in a paper by Georges Lemaître, which proposed that the curvature of the universe increased with time.

The Big Bang and Steady-State Models:

By the early 1930s, astronomers agreed that the universe was indeed expanding. However, this does not necessarily mean that the universe has a finite age or began from a single source. Lemaître's original paper suggested a static universe as described by Einstein that somehow was thrown out of equilibrium and began expansion. This was a popular view for many years, as it avoided problems of causality associated with the beginning of the universe. However, in 1931 Lemaître changed his view and speculated that the universe began with a single quantum of energy, a "primeval atom" that split apart and began expansion. While this was more speculation than theorizing, Lemaître is sometimes considered the originator of the Big Bang theory.

The Big Bang in its modern form was developed by the Russian-American physicist George Gamow. Gamow was involved in the new field of nuclear physics and wanted to explain the presence of heavy elements in the universe. In his 1948 collaborative paper with Ralph Alpher, Gamow formulated the early universe, created in a nuclear explosion, as a hot neutron gas where the conditions were extreme enough to allow the fusion of all heavy elements. The paper also predicted the existence of detectable cosmic radio waves from this Big Bang. Although the heavy elements are now explained by stellar synthesis, Gamow's work was important in establishing the connection between nuclear physics and cosmology.

1948 also the publication of a rival cosmological theory proposed by Fred Hoyle, Hermann Bondi, and Thomas Gold, known as the Steady-State universe. In this theory, the universe does not have a finite age and its structure does not change with time. Matter is spontaneously created throughout the universe at a rate that keeps the total density of the universe constant. This avoids questions of the beginning or end of the universe (the heat death implied by the second law of thermodynamics). One way to summarize the differences between the two ideas is that the Big Bang conserves the content of the universe but allows its structure to vary with time, while the Steady-State universe has a constant structure but variable content.

Between 1948 and 1965, there was no consensus as to which of the two theories was correct. Without observational data, physicists chose between the two on philosophical or aesthetic grounds. Some preferred the Steady-State theory for its simplicity and testable predictions, while others objected to its disregard for energy conservation and lack of any explanation for matter creation. These considerations are important for the philosophical dimension of cosmology discussed below. However, in the early 1960s, advances in radio cosmology began providing evidence in favor of the Big Bang. Penzias and Wilson’s 1965 discovery of the cosmic microwave background (CMB) radiation, predicted by Gamow in 1948, finally shifted consensus away from the Steady-State.

Cosmology and Philosophy:

The Steady-State/Big Bang disagreement of the 1950s provided a background for discussions on the nature of science and the philosophical position of the new cosmology. Put simply, the lack of observable evidence for either theory before the discovery of CMB convinced many that cosmology was more philosophical speculation than physical science. It occupied a vague middle ground between the two, unwilling to commit to either physics or metaphysics. William McCrea argued that, given the expansion of the universe and the limit of the speed of light, it was impossible to gather enough data to make meaningful statements about the universe as a whole. One could use known physical laws to make predictions, but he argued it that was absurd to claim that locally-proved laws can be transferred to the entire universe. In response, William Davidson admitted that these observations were difficulties, but claimed they were not insurmountable. Finding evidence for cosmological theories would be difficult, but that was no reason to throw out the entire subject and declare it unscientific. Davidson was vindicated by the discovery of the CMB, an event which prompted McCrea to take back his earlier criticism.

The debate between Big Bang and Steady-State theories evolved alongside changes in general attitudes toward the philosophy of science. From the 1920s through the 1950s, the philosophy of science was dominated by the school of logical positivism, which claimed that all knowledge should be built on a base of verified experimental fact. Speculation, intuition, and appeals to aesthetics had no place in science; all theories should be based solely on the observable facts available. Many critics of cosmology, especially astronomers used to relying primarily on observational data, drew on positivist thought when they criticized it as philosophical speculation. However, as the century continued, logical positivism came under increasing attack. Critics claimed that it was naive to accept all observations without reservation and that it science must ultimately rest on metaphysical assumptions.

One of the leading philosophers in the new school of thought was Karl Popper, who formulated a new way to demarcate the line between science and non-science. In Popper's view, the ultimate measure of a theory was whether it allowed for falsifiable tests of its validity. The distinction between positivistic verificationism and Popperian falsificationism is subtle but important: no theory can be proven beyond doubt by experiment (as the positivists seemed to claim), but they can certainly be proven wrong; therefore, the strongest scientific theories present many opportunities to be proven wrong but pass them all. For example, Popper considered Freudian psychoanalysis to be pseudoscience because none of Freud's claims can be decisively falsified by experiment. Popper's focus on falsifiability was appealing to Steady-State theorists, as their model presented more opportunities to be falsified. Ironically, the tests that were performed ultimately favored the Big Bang theory.

Cosmology, Religion, and Ideology:

Unsurprisingly, questions about the beginning of the universe risk blurring the lines between physics and theology. One early example of this came in the 19th century, after the formulation of thermodynamics. Some physicists argued that, if the second law of thermodynamics applies to the entire universe, eventually entropy would reach a maximum and the universe would end in a heat death of thermal equilibrium. Going further, they argued that the universe must have a finite age, since maximum entropy had not yet been reached; if the universe was infinitely old, it would have already achieved heat death (as above, critics objected that it was unwise to try applying physical laws to the entire universe). Although these 19th century physicists were careful about letting religion affect their ideas, generally the more religious thinkers accepted the entropic argument while materialists (such as Marx and Engels) and atheists believed in an infinite or regenerating universe. By the early 20th century, physicists generally accepted that this argument was more metaphysical than scientific and ignored it.

Interactions between theology and physical cosmology continued into the 20th century, however. Most physicists were careful to separate science and religion completely (Lemaître, despite being a priest, disliked literal readings of the Bible and did not believe his finite universe suggested a Creator), but connections still emerged. Fred Hoyle, one of the most vocal Steady-State advocates, ran a BBC radio program on astronomy and wrote a book promoting popular understanding of science. In addition to presenting the Steady-State model is a positive light, Hoyle used these platforms to attack both Christianity and Marxist materialism. He immediately became a controversial figure, criticized by other astronomers for going beyond science into his own personal opinion and feared by the Christian establishment. Although the connection was tenuous, the Steady-State theory became known as the more atheistic of the two models.

Conversely, the Big Bang theory of the 1950s developed connections with Christianity. Gamow sent a copy of his 1948 paper to Pope Pius XII, who publicly endorsed the theory as empirical proof of a higher Creator: if the universe began, then something (God) must have caused the beginning to take place. Pius was unusually well-educated in science for a pope, aiming to reconcile Christianity with the empirical sciences using logical reasoning. Some physicists, such as Lemaître, were unhappy with his intervention, arguing that evidence-based science could have no influence on theological conclusions and vice versa. Even so, some believed, like their 19th century counterparts, that a universe of finite age supported the existence of God.

A third opinion dominated in the communist world, which rejected cosmology altogether. As mentioned above, Engels had opposed the entropic argument for the universe's age: similarly to Pius XII, he believed that a finite universe needed a Creator, which contradicted his dialectical materialism and atheism. This opinion persisted among Marxists up through the 1950s. The pope's public support of the Big Bang certainly did not make any communists more willing to accept it. Theorists in the Soviet Union and China went farther and rejected both the Big Bang and Steady-State models as metaphysical dreaming, similar to the idealism that Marx himself had originally rejected.

This position began to change once the CMB shifted cosmology away from philosophical speculation and solidly into the empirical sciences.

Key Ideas:

- Physical cosmology was created through the interactions of different scientific fields. What originally seemed like the domain of pure astronomy incorporated elements of theoretical relativity and new developments in nuclear physics to provide a more accurate description of the universe. These different disciplines, in addition to studying different subjects, employed different methodologies: astronomy is highly observational, whereas nuclear physics employs a mix of theory and experimentation. These methodological differences can be seen in different fields' attitudes toward proposed theories. While the older astronomy establishment tended to dislike the highly theoretical models that emerged after World War II, physicists such as Gamow or Bondi favored a mix of observational evidence and theoretical elegance.
- The historical narrative above is dominated by two disagreements in cosmology: the Great Debate of the 1920s and the Big Bang/Steady-State debate of the 1950s. The presence of these large-scale disagreements in the cosmological community are evidence that physical cosmology was, at the time, still a new field of science. However, differences between the debates are worth highlighting. The Great Debate was mostly contained within the astronomical community and concerned how to interpret the data already available. The cosmological debate of the 1950s involved several different parties and discussed how to form a theoretical model in the absence of sufficient data. Based on these differences, it is unsurprising that the later disagreement witnessed more interaction with religious and political schools outside of physics.
- Although philosophers in the mid-20th century became more open to reconsidering the relationship between evidence and theory, it is worth emphasizing that experimentation and empiricism continued to have a central role in cosmology. The discovery of the cosmic microwave background is a good example of this: while physicists were comfortable discussing a theory's

simplicity or aesthetic appeal, the CMB provided direct evidence for the Big Bang and ended the discussion quickly. In any discussion on the philosophy of science, the bottom line is that observations should agree with theory.

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Quantum Theory before World War I

Fin de Siècle Physics:

It is sometimes casually claimed that physicists at the end of the 19^{th} century believed they were approaching the end of their discipline and that there was nothing left for them to discover. While there may be a few who believed this (as a student, Max Planck was discouraged from pursuing physics because its basic structure was already in place), the 1890s in particular were an important period of discovery that foreshadowed the advances of 20^{th} century physics.

The most famous event of the decade was Wilhelm Röntgen's discovery of x-rays in 1895. Both physicists and the general public were fascinated by the unexplained rays, which seemed to behave differently from both visible light and cathode rays. Röntgen himself suggested that they might be longitudinal ether vibrations (as opposed to the transverse vibrations of regular electromagnetic waves). The matter was not settled until the early 1910s, when evidence such as crystal diffraction showed that x-rays are simply high frequency EM waves. Inspired by Röntgen, Henri Becquerel began investigating other sources of rays and discovered what he called "uranium rays." Later, Marie Curie showed that these rays emit from compounds other than uranium and renamed the phenomenon "radioactivity." These discoveries inspired others to seek out new varieties of rays, most of which do not actually exist. Black light, N-rays, and magnetic rays were all considered as possibilities. The existence of cosmic rays was also doubted until they were observed in the 1910s.

The 1890s also saw important progress in knowledge of the electron. Early electron theories, such as proposed by Hendrik Lorentz and Joseph, thought of the electron as the physical manifestation of the ether and the fundamental constituent of matter. Such a worldview would unite all known areas of physics under the common basis of electromagnetism and the ether. Pieter Zeeman's 1896 discovery of the influence of a magnetic field on light (the Zeeman Effect) established more definite physical characteristics of the theoretical electron, such as its negative charge and high ratio of charge to mass. The next year, J. J. Thomson demonstrated that cathode rays are composed of negatively charged particles with a constant charge/mass ratio. These two lines of research, theoretical and experimental, were pursued separately, but by 1900 they established the electron as a negative particle of small mass that was either the sole fundamental particle or one of several.

Planck and Quantum Theory:

During the 19^{th} century, Max Planck's main interest was in thermodynamics. In particular, he saw the second law of thermodynamics as a fundamental feature of nature rather than a statistical trend. In contrast to Ludwig Boltzmann, whose statistical mechanics predicted that the entropy of a system could occasionally decrease, Planck took as a first principle the fact that entropy increase was a strictly unidirectional process. In 1899, he derived Wilhelm Wien's blackbody radiation distribution from this assumption, which seemed to agree with experiment. When it was discovered that the Wien distribution was incorrect for long wavelengths, Planck slightly modified his derivation and came up with the famous Planck distribution in 1900. While the new results matched observations very closely, he saw this derivation as unsatisfactory, as it was more mathematical guessing to fit the facts rather than an explanatory theory. Later that year, he announced that his distribution only made sense if the total energy of the blackbody was divided into several finite portions of energy $\varepsilon=hf$.

Historians have debated exactly what Planck thought of his work in 1900. Some have argued that he did not think his equation had any definite physical meaning and that it was only a temporary mathematical construction. Others believe that he recognized that his work implied energy discontinuity but was unwilling to accept this result fully. In any case, it is clear that Planck took a conservative, cautious approach to physics and that he did not see his distribution as particularly revolutionary. He did not move forward exploring the implications of energy discontinuity or the new constant h; instead, he spent much of the next decade fleshing out the dynamics of special relativity.

It is also worth noting that the so-called "ultraviolet catastrophe" played little role in Planck's theorizing. Using the classical equipartition theorem (which states that the energy of a system will spread evenly across all degrees of freedom) results in the Rayleigh-Jeans distribution of blackbody radiation. Unlike the Wien distribution, this law broke down at short (ultraviolet) wavelengths, where it gave infinite energy. Eventually, Lorentz proved that his ether-based electromagnetic theory necessarily led to the incorrect Rayleigh-Jeans distribution. This was the context of the ultraviolet catastrophe: there was no way to explain the blackbody distribution if physical reality reduced to a fundamentally electromagnetic basis. For Planck, with his worldview instead based in thermodynamics, the Rayleigh-Jeans distribution was less important.

Einstein and Quantum Theory:

The first of Einstein's 1905 papers is usually referred to as "the photoelectric effect paper," but this does not convey its extent or how thoroughly it departed from contemporary ideas. Einstein began his paper by noticing the inelegant contrast between discrete matter and the continuous electromagnetic field, and aimed to resolve it by suggesting that light is composed of corpuscles rather than waves. This contradicted years of evidence in favor of wavelike light, but Einstein pointed out that the wave theory inevitably led to incorrect results for the blackbody problem. He derived an expression for the entropy of blackbody radiation and noted that it had the same mathematical form as the entropy of an ideal gas. By analogy, Einstein reasoned that, as gases are composed of discrete molecules, blackbody radiation is quantized in packets of energy $E=hf$. He then suggested using the photoelectric effect to test the implications of this new model of light, predicting the effects of varying the light's frequency. These predictions were confirmed by Robert Millikan in 1914 (although Millikan refused to accept the theoretical basis of Einstein's work).

Although Einstein mentioned Planck's distribution formula, he made few direct references to Planck in the 1905 paper. In fact, Einstein probably believed in 1905 that he and Planck were working from different theoretical bases that contradicted each other. In a 1906 paper, Einstein reconsidered his and Planck's ideas and concluded that Planck's assumptions in creating his distribution also imply the existence of light quanta.

Early Growth of the Quantum Theory:

In the early 1900s, blackbody radiation was a specialized branch of physics that concerned few physicists. Because of this, quantum theory made little impact until it was applied to other subjects. In 1907, Einstein extended his ideas into solid-state physics by using quantized energy to explain irregularities in the specific heats of different elements. This was a much more mainstream field and introduced new physicists to quanta, while also suggesting quantum theory's eventual use in atomic structure and chemistry. Another important step came in 1908, when a lecture by Lorentz demonstrated that classical electromagnetism would only lead to the incorrect Rayleigh-Jeans distribution (as mentioned above), convincing his followers that Planck's distribution was the only way forward.

The specific heat problem introduced quantum theory to German physicist Walther Nernst, who became convinced of its importance and played an important part in its general acceptance. Nernst convinced the philanthropist Ernest Solvay to hold a conference on the new quantum theory summing up its relationship to radiation and gas theory. The Solvay Conference, held in November 1911 in Brussels, brought together Lorentz, Planck, Curie, Einstein, Rutherford, and other leading physicists in a discussion on quantum theory's progress thus far. The meeting did not lead to any new breakthroughs or insights (a fact which annoyed Einstein), but helped focus attention on the breadth of problems related to quantum theory. It also transformed quantum theory into a community project recognized by the mainstream of physics and gave the sense that it was a revolutionary departure from older physics. Many historians have argued that the concept of "modern physics" was created at the Solvay Conference.

Key Ideas:

- A large portion of this week's historical narrative is focused on misconceptions and confusions about the early history of quantum theory: late 19th century physics was not stagnant, Planck did not begin a scientific revolution, and exactly what he and Einstein thought at given times is not entirely clear. This is understandable, as a lot of the work done before 1920 became obsolete after fuller quantum mechanical theories took shape. It feels less pressing to understand exactly how these theorists understood their physics. Also, many of the exciting aspects of quantum theory (the uncertainty principle, the Bohr-Einstein debates, nuclear fission) came later; compared to them, blackbody radiation is less glamorous. Because of this, historical research in this area is less robust than that of relativity or later quantum theory.
- One of the key ideas made obsolete by quantum theory was the electromagnetic worldview (or "electron theory," in Lorentz's terms), which appears occasionally in the history above. As mentioned on the first week, the late 19th century saw physicists trying to unify the entirety of nature under a single physical framework. The electromagnetic worldview, usually associated with Hendrik Lorentz and Joseph Larmor, aimed to explain all the different areas of mechanics using electromagnetic waves and the ether. In this view, electrons were discrete manifestations of the continuous ether; thus, if electrons were the only fundamental particle, there would be no physical reality except for the electromagnetic ether. This simple, elegant formulation of nature is tempting; it might be compared to more recent unified theories that attempt to unite the four fundamental interactions. As time went on, however, it became clear that natural phenomena required quantum as well as electromagnetic explanations.

- It is easy to pinpoint 1905 as the beginning of relativity, but finding the exact beginning of quantum theory is not as simple. Although 1900 is the most common date given, physicists did not realize that Planck's work constituted a definite break with classical theories until several years later. The shift from classical to modern physics did not happen all at once, but was a more gradual process as different physicists added individual components to quantum theory and realized that their work was a complete departure from 19th century traditions. This is one reason why the Solvay Conference is important: despite not seeing any new scientific breakthroughs, it helps convince its participants that significant historical changes were happening.
- A wide range of phenomena require quantum theory to understand fully, including radioactivity, the blackbody distribution, the photoelectric effect, specific heats, and atomic structure. Part of the difficulty in constructing a unified quantum theory was recognizing that all these problems share underlying features. Thus, many of the important steps in early quantum theory involved physicists crossing between different problems and drawing connections between them. This is most apparent in Einstein's work with photons and in the Solvay Conference. After this event, progress towards quantum mechanics moved much more smoothly as physicists recognized the need for a unified approach to quantum phenomena.
- A few weeks ago, I argued that the 1919 confirmation of general relativity saw unprecedented media attention to a discovery in physics. This is not entirely true, as Röntgen's discovery of x-rays also began a media frenzy that was unusual for the time. That said, the scale of relativity's impact was much greater than that of x-rays. In addition, Einstein became a worldwide celebrity along with his theory, while Röntgen remained relatively unknown outside the world of physics.

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Bohr and the German Physics Community

The Bohr Atom:

Niels Bohr's early work concerned the application of Lorentzian electron theory to metals and conductance. While completing his dissertation on the subject in 1911, he became convinced that existing theories were insufficient and that a new model, probably based in the new quantum hypothesis, was needed. He travelled to England in order to work with J. J. Thomson, the established authority on electrons and atomic theory. Disappointed with Thomson's lack of interest in his ideas, Bohr was instead inspired by Ernest Rutherford, recently returned from the Solvay Conference. Returning to Copenhagen, Bohr abandoned his earlier work and set out to improve Rutherford's atomic model by using quantum theory to stabilize electron orbits. While working on this problem, a colleague casually asked him how it related to the Balmer formula for hydrogen spectra. Unexpectedly, Bohr realized he could explain both atomic stability and hydrogen's spectral lines through the same model. His key insight was that the orbital frequency of the election (ω) was not equal to the frequency of the emitted spectral lines (f), as was commonly assumed.

Bohr's model of 1913 was criticized for its strange theoretical assumptions (how does the electron "know" which energy levels are stationary states?), but its incredible agreement with observations made it difficult to argue against, and most critics chose to accept the model. Further progress was slowed by World War I, but important contributions were made, especially by Arnold Sommerfeld. Sommerfeld explored the possibility of elliptical electron orbits (which seemed to be allowed by the theory), introduced special relativity into the Bohr model, and used these to explain fine structure splitting. While Bohr understood his model as a preliminary step before a fuller understanding of quantum mechanics could be achieved, he and Sommerfeld were incredibly successful at explaining various phenomena under a single framework.

Physics and International Politics:

The 1920s were a difficult time for Germany. After its defeat in 1918 and transition from a German Empire to the new Weimar Republic, Germany faced an economic slump, food shortages, political unrest, and massive inflation that did not stabilize for several years. Despite many challenges, these years were incredibly productive for German physicists and saw some of the most important advances of modern physics.

The international situation made cooperation with non-German physicists difficult. International organizations such as the new International Research Council (IRC) restricted membership to Allied countries, only accepting neutral countries (such as Denmark) in 1922 and Germany in 1925. German physicists were largely excluded from international conferences until the late 1920s and German-language publications often went untranslated. On top of this, Germany's economic situation further impeded cooperation: with rampant inflation, it was difficult for Germans to import the latest foreign publications or travel abroad in order to keep up to date with current research elsewhere.

This divide between German and Allied physicists was never total (Einstein was accepted by both communities, and Bohr, as a neutral Dane, was more respected in the West than his German colleagues), but it harmed physics as a whole. German and Danish physicists formed a mostly self-contained community where important ideas from the English- and French-speaking world (such as de Broglie's matter waves) had little impact until the international situation improved toward the middle of the 1920s. The rest of this week will cover these self-contained advancements in the German community, which focused on energy transitions in the hydrogen atom and produced the first version of quantum mechanics in 1925. Next week will follow advancements outside of this community, which tended to give more emphasis to the wave-particle duality and led to Schrodinger's version of quantum mechanics in 1926.

Physics and Weimar Culture:

German culture in the 1920s was hostile to the physics community. During the war, scientists had enjoyed public status and prestige as an important component of the militarized society. After the defeat, much of the German public saw science as the cause of the disastrous war and subsequent crisis. There was a general feeling that German culture had lost its soul as rational science had replaced the music and poetry of the past.

Interest in artistic icons such as Goethe and Mozart increased at the expense of interest in physics. This zeitgeist was expressed in Oswald Spengler's best-selling book *The Decline of the West*, which claimed that science only had value relative to its particular culture and that physics needed to abandon "outdated" concepts like strict causality and determinism in order to keep up with the times. These anti-rational streams of thought had long been a feature of German culture (for example, in the 19th century Romantic Movement), but they resurged dramatically in the atmosphere of crisis after World War I.

While a few physicists (most notably Planck and Einstein) responded to this hostile environment by reasserting the value of classical physics and defending the discipline from criticism, many German scientists seemed to capitulate to these views in their public addresses. Physicists tended to highlight connections between physics and philosophy while downplaying their association with technology. They admitted that physics' power to describe abstract ideas like the human spirit was limited and portrayed physics research as being for its own sake, rather than utilitarian usage. Most significantly, physicists began arguing that concepts like strict determinism and cause and effect might have to be abandoned, in line with Spengler's analysis.

Exactly why German physicists acted this way is not entirely settled. In 1971, the historian of science Paul Forman made the controversial argument that physicists basically capitulated to the 1920s culture and accepted the need for acausality; thus, when the probabilistic nature of quantum mechanics was discovered, German physicists were generally willing to accept it quickly. In other words, forces outside of science shaped the direction that quantum physics took in a direct cause-and-effect relationship. Other historians have challenged this view as focusing too much on external rather than internal motivations away from causality. For example, John Hendry has argued that physicists were already considering abandoning concepts like determinism and strict conservation of energy before the cultural backlash; in this view, internal rather than external forces pushed physicists toward acausality.

Heisenberg's Quantum Mechanics:

Regardless of the degree to which Forman was correct, by the mid-1920s there was an atmosphere of crisis both in the physics community and German culture at large.

While the Bohr model was very useful through the 1910s, its deficiencies could no longer be ignored: it offered no explanation for the intensity or polarization of light emitted in transitions and could not be used at all in describing atoms larger than hydrogen or chemical bonds. The most pressing issue was fine structure splitting due to the anomalous Zeeman effect, which would not be fully explained until the discovery of electron spin.

In early 1924, Bohr, his assistant Hans Kramers, and the American John Slater published a paper outlining what has become known as BKS theory. Although Compton scattering had been discovered in 1923, demonstrating that photons behave like particles, Bohr was committed to the wave theory, and formulated BKS theory as a final effort to explain energy transitions without light particles. The theory attributes the frequencies of light emitted during a transition to virtual charges oscillating with the required frequency and intensity. However, without photons to induce transitions, the theory abandoned strict cause and effect and energy conservation in order to preserve the wave theory. BKS theory enjoyed popularity for a few months, until experimental evidence demonstrated that transitions strictly obey energy conservation.

At this point, when all existing theories had been shown to be imperfect, Heisenberg arrived at the key breakthrough which led to the resolution of quantum theory. Everything discussed so far in this history is often called the “old quantum theory,” while Heisenberg’s advances of 1925 truly began “quantum mechanics.” Inspired by BKS theory, Heisenberg chose to do away with any description of electron orbits or positions and instead focus solely on observable quantities. His work, along with additions from Max Born and Pascual Jordan, is usually called matrix mechanics to distinguish it from Schrodinger’s wave-based quantum mechanics. The final theory expressed the probabilities of transitions between stationary states in a matrix consisting of the amplitudes of the terms of a Fourier series that describes an electron’s periodic motion. This formulation was highly abstract and relied on obscure matrix calculus, but it described hydrogen satisfactorily. With the addition of electron spin, discovered the same year, matrix mechanics provided the most powerful description of quantum phenomena yet. While Schrodinger’s version of quantum mechanics is the more widely-used formulation, Heisenberg’s work is one of the key turning points in the history of quantum theory.

Key Ideas:

- The controversy around the Forman thesis demonstrates the difference between internalist and externalist histories of science. Forman’s argument was radically externalist, in the sense that the entire course of quantum theory was determined by factors outside the physics community. Hendry’s position is more moderate: while he accepts that factors from society at large may have influenced physicists, he argues that the primary reason physicists moved away from causality was that physical evidence pointed in that direction. Resolving this tension between external and internal explanations is one of the key tasks of historians of science.
- Another example of an externalist explanation comes in the influence that international relations had on physics. The fact that German and French physics were largely cut off during the early 1920s meant that de Broglie’s hypothesis had a delayed reception in the mainstream physics community. Had external social conditions been different, Bohr and Heisenberg may have realized the importance of wave-particle duality earlier and developed their ideas differently. The aftermath of WWI was not the only factor that shaped the course of quantum mechanics, but I would argue that evidence indicates that it is one of several important factors.
- Relativity, as we have seen, was almost entirely the work of a single individual, whereas quantum mechanics was formed through the interactions of many physicists. The advances discussed this week were facilitated by personal correspondences and visits to other universities. The primary centers of research were Copenhagen, where Bohr and Kramers worked, Munich, where Sommerfeld was chair of the physics department, and Göttingen, where Born served as a mentor for Heisenberg, Pauli, and Jordan. These physicists frequently travelled between these universities and collaborated on papers. The dynamics of how relativity and quantum theory spread and developed followed distinct patterns of social interaction, with quantum developments being helped by the existing university structure.

- Beginning in the 1920s, many of the most important advances in quantum theory were made by very young physicists: Heisenberg, Pauli, Dirac, and Jordan were all in their 20s during this period. Older physicists continued to play an important role, often as facilitators of cooperation in addition to researchers. Famous theorists of the previous generation, such as Bohr and Born, helped their students by spreading awareness of their theories and arguing for their importance. Their existing prestige and credibility helped establish Heisenberg and Pauli in the physics community. Others, such as Planck, moved farther away from involvement in research, acting as elder statesmen facilitating university research at a higher level.

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De Broglie and Schrödinger

Waves and Particles:

Although Einstein had certainly established his reputation as a leading physicists by the 1920s, his particle theory of light outlined in 1905 took many years to be taken seriously. The wave description of light had been a central feature of classical physics since the early 1800s and could be demonstrated using a simple double-slit setup. Even when Einstein's photoelectric predictions were confirmed with reasonable accuracy, most experimentalists were unwilling to accept the underlying explanation of wave-particle duality: Millikan, who performed the decisive experiments confirming the photoelectric equation in the mid-1910s, claimed that the mathematical relationship had been inarguably confirmed but argued just as strongly that the underlying explanation of light quanta could not be accepted.

The early 1920s saw renewed interest in light quanta. First, Einstein received the 1921 Nobel Prize specifically for his work on the photoelectric effect, lending some extra prestige to the wave-particle theory. Also important was Arthur Compton's 1923 discovery of Compton scattering, attributing definite momentum to light. Even with this demonstration of particle behavior, some theorists held out for several years. The German community discussed previously was especially hostile to any wave-particle model of light, leading to the BKS theory's sacrifice of strict energy conservation in favor of wavelike light. By 1924, the community as a whole had yet to reach agreement on the wave-particle problem.

De Broglie's Thesis:

Louis de Broglie began his research career by assisting his older brother Maurice with data analysis. In 1921, the older de Broglie presented his work on X-ray diffusion and concluded that radiation must be absorbed or emitted from atoms in finite quanta. Although this did not resolve the issue to the community as a whole, it convinced Louis of the importance of the wave-particle model. Revisiting Einstein's 1905 paper, de Broglie's early publications claimed that light quanta have mass and thus travel at slightly less than *c*. He theorized "light molecules" or agglomerations whose interactions would explain interference. However, his most important step, made in his dissertation in late 1924, was an attempt to link special relativity with quantum theory and produced the equation $mc^2=hf_0$. This suggests that all massive particles (including light, in this model) have a characteristic frequency f_0 in their rest frame. Although he was vague as to the specific meaning of this frequency, he was confident that matter waves had physical significance: they could explain the energy levels of the Bohr atom and predicted electron interference as a falsifiable test. The dissertation extended wave-particle duality beyond disagreements on the nature of light and first suggested a more fundamental unity between light and matter.

Einstein was the first to argue for de Broglie's significance. In 1924, Einstein was collaborating with the equally-unknown Satyendra Nath Bose on quantum gas theory and establishing Bose-Einstein statistics. Working out the specifics of Bose's new method of counting particles, Einstein found that the number of particles within a partial volume would fluctuate according to similar laws of radiation fluctuation. This suggested interference between particles and thus a wave-particle duality. At this point, Einstein received an advance copy of de Broglie's thesis from Paul Langevin, one of the thesis' judges. Einstein realized its importance to his statistical methods and began arguing its significance to his colleagues. Schrödinger, Born, and most other physicists heard about de Broglie through Einstein.

However, even with Einstein's help, matter waves had little influence in Copenhagen and Göttingen. This was partly due to continuing poor relations between France and Germany and the difficulty of translating discoveries in physics across the gap. Also important was the influential Bohr's aversion to any theory on wave-particle duality. De Broglie's poor understanding of spectroscopy (the most significant problem for German physicists) and some condescending remarks about Sommerfeld and Heisenberg certainly did not help his reputation. Although Heisenberg was likely at least aware of de Broglie's thesis when he first formulated quantum mechanics, it is unlikely that he was influenced by the idea.

Schrödinger's Equation:

Schrödinger, however, was an outsider to the mainstream German physics community. An Austrian working in Switzerland, he was known as a loner and did not align himself with any school of thought within quantum theory, working on a variety of problems over time. Like Einstein, he was working on gas theory in 1925 and thus came to appreciate de Broglie's significance. In particular, de Broglie's use of matter waves to model hydrogen's energy levels shared a mathematical similarity to an earlier theory of Schrödinger's from 1922: using Hermann Weyl's work on general relativity, Schrödinger concluded that, if an electron carries an associated four-vector (derived from Weyl's theory) as it orbits an atom, the value of this vector will be multiplied by an integer value every time it completes a revolution. With some modifications, this bears similarity to de Broglie's condition of electrons as standing waves. By 1925, Schrödinger had abandoned this work on atomic modeling; after Einstein introduced him to de Broglie's ideas, he returned to the hydrogen atom to describe it using matter waves.

After failing to construct a working relativistic wave equation (now known as the Klein-Gordon equation), Schrödinger published his work in several papers that appeared early in 1926. These provided several derivations of his equation (the most famous being an extension of Hamilton's analogy between mechanical and optical motion to quantum theory) and demonstrated its power at solving existing quantum problems. In his original interpretation, Schrödinger considered the square of the wave function to be a measure of charge density distributed over space. At this point, there was nothing probabilistic about the Schrödinger equation.

Almost as important as the equation itself was Schrödinger's rigorous proof that his and Heisenberg's versions of quantum mechanics are mathematically equivalent (Schrödinger later claimed that he had been aware of Heisenberg's work while developing his equation but was unaffected by it). Immediately after Schrödinger's publication, the physics community was split over whether to accept matrix or wave mechanics—both gave the correct answers, but their forms were so different that establishing a connection between them was difficult. With the demonstration that both were equally legitimate, the community was free to choose the version it preferred. Schrödinger's equation quickly became the more popular: it relied on a well-known mathematical basis (rather than the obscure matrix calculus), making calculations simpler, and it was easier to visualize electrons as waves rather than as abstract matrices. Despite some animosity between Schrödinger and the Copenhagen/Göttingen physicists, the community as a whole accepted wave-particle duality and moved on. With a mathematical basis established, the next step in developing quantum mechanics was interpreting exactly what the wavefunction meant and what it implied. This led to the construction of the Copenhagen interpretation beginning around 1927.

Key Ideas:

- As was the case with matrix mechanics (see last week's summary), Schrödinger's wave mechanics was the product of communication and collaboration between physicists. However, collaboration took a different form in the two theories: in the matrix mechanics case, cooperation took place within the existing structure of the universities and was facilitated by formal research groups and semesters abroad. The key physicists who developed wave mechanics were more spread out (as far as India, in Bose's case), and communicated through unofficial channels such as private letters. In both cases, sharing ideas was necessary to the development of quantum mechanics.
- Between these two communities developing quantum mechanics, we can see both hostility and cooperation. Heisenberg was initially upset that Schrödinger's method had become the standard despite being published later. Both thought that other was emphasizing the wrong fundamental principle in their derivation (Heisenberg focused on observable quantities; Schrödinger focused on created a visualizable model). However, both groups made important contributions to the fully realized quantum mechanics. While Schrödinger's mathematical notation became accepted, the former developers of matrix mechanics provided the theoretical interpretations used today (Born's probability density, Heisenberg's uncertainty principle, and Bohr's complementarity). In this sense, quantum mechanics was the product of a single, unified community of physicists.
- De Broglie was an exception among physicists in many ways: he was French at a time when Germany (and to a lesser extent England) dominated the sciences, he was originally trained as a historian, and he was an aristocrat. Louis and several of

his siblings expressed interest in science in their youth: Maurice, as mentioned, worked on x-ray experimentation, while their sister Pauline became interested in geology and archaeology. This went against the wishes of their relatives, who wanted the youths to take more traditional aristocratic professions such as diplomacy or banking. This unusual status between social classes meant that Louis' place within the scientific community was uncertain; when he, like Einstein, objected to the Copenhagen interpretation and indeterminism, de Broglie's criticisms carried less weight and were easier to ignore.

- Since its publication, de Broglie's 1924 thesis has been celebrated to the point of developing a mythology around it. Calling it "the most important thesis of the 20th century" is certainly appropriate, but the anecdotes surrounding it can be questioned. I have found no evidence that it really was the shortest physics thesis ever written; at roughly 70 pages, it does not seem likely. The story of Langevin giving the thesis to Einstein for judgment is probably true, but many sources leave it out entirely as if it never happened. These anecdotes surrounding the thesis should at least be taken with a grain of salt.

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The Manhattan Project

Physics in America:

Although Germany, England, and Denmark were the biggest centers of physics research for the first three decades of the 20th century, the United States' physics program expanded rapidly beginning in the 1920s. As industry grew and demand for technically-educated professionals increased, more and more young people received undergraduate and graduate degrees. Philanthropic organizations (especially the Rockefeller and Guggenheim Foundations), a uniquely American phenomenon, funded young students' research and allowed them to visit the famous laboratories of Europe. On the other hand, European physicists increasingly visited the United States on lecture tours, to see the products of American research, or to take positions at one of the country's many universities (European universities typically had small physics departments and few opportunities for new professors). These Europeans were struck by the vitality of the young American program and the cultural differences between the continents: American physicists tended to be more focused on industry and applied science, and were comfortable interacting with the media or commercializing their work; on the other hand, American research teams were less hierarchical and tended to ignore conventional boundaries between disciplines. The philosophical questions introduced by quantum mechanics did not interest Americans, who were willing to accept the new theory's utility and move on.

A key change in the relationship between American and European physics came in early 1933, when Adolf Hitler took power in Germany. Soon afterwards, he expelled Jewish academics from German universities, immediately affecting roughly a quarter of the German theoretical physics community. Over the next several years, many others in Germany and its neighbors resigned their posts, either out of fear or in protest. The British and American communities quickly condemned Hitler's actions and organized to provide the displaced physicists with new university positions in safe countries. Although many (such as Schrödinger and Born) chose to relocate to Great Britain, the majority moved to the United States. Ultimately, Einstein, Fermi, Bethe, Paul Debye, James Franck, Alfred Landé, Emilio Segré, Eugene Wigner, Otto Frisch, Otto Stern, Leo

Szilard, Edward Teller, and many others ended up at American universities. Those who chose to stay within the Nazi Reich out of loyalty to their country included Planck, Heisenberg, and Max von Laue. Although the German physics program was not crippled by the migration, the country lost its preeminent position in theoretical physics.

Production of the Bomb:

The story of the American project to develop nuclear weapons in the broader context of World War II is probably well-known to many students, so this summary will give a very general overview of some key details.

Early on, the primary motivation for the program was to develop a bomb before the Nazis could (ironically, serious espionage into the progress of German nuclear research did not begin until 1945, by which time their bomb research had been abandoned). Fearing the danger of a German bomb, the Hungarian-born physicist Leo Szilard drafted a letter to President Roosevelt urging the U.S. to invest its resources into nuclear research. Einstein signed the letter, hoping his fame would lend credibility to the proposal; an earlier meeting between the lesser-known Enrico Fermi and the Navy had come to nothing. Roosevelt approved, but the project stalled until the 1941 attack on Pearl Harbor. The Manhattan Project was put under Army command, with General Leslie Groves directing the project and drawing on the military's massive financial resources. The project eventually consisted of sites in Oak Ridge, Tennessee, where raw uranium was separated into depleted ^{238}U and enriched ^{235}U, which could be used in a fission bomb; Hanford, Washington, where the depleted uranium was converted to plutonium by inducing beta decay inside a nuclear reactor; and Los Alamos, New Mexico, where leading physicists worked on the uranium and plutonium bombs' designs under J. Robert Oppenheimer.

By the early 1940s, the theoretical possibility of a nuclear bomb was well-known among physicists in many countries. Physicists in the Manhattan Project had to deal with technical problems, such as the design of the bomb's triggering mechanism or whether an airplane could handle the bomb's weight. The key issue, which proved insurmountable for the non-American nuclear programs, was separating the uranium isotopes. The three methods eventually used were diffusion (in which uranium hexafluoride gas is pumped through a series of hundreds of mesh barriers which the lighter 235 isotope crosses more quickly), thermal diffusion (consisting of a heated tube placed inside a cooled tube; the uranium gas is placed in the space between, where the lighter isotope diffuses toward the hot pipe and then rises to the top of the chamber), and the calutron (in which uranium is magnetically accelerated in a semicircle, with the 235 isotope moving in a slightly tighter radius and then captured separately). None of these processes were particularly efficient, and they acted as the bottleneck of the project until sufficient enriched uranium was produced by mid-1945.

Community and Secrecy:

Physicists were used to the open, collaborative, largely apolitical atmosphere of the research universities and had trouble adjusting to work at Los Alamos. Beginning in the late 1930s, nuclear physicists had to compromise between sharing their advancements and keeping German competitors in the dark. Szilard and Fermi continued submitting papers to journals in order to establish precedence, but asked that they not be published. Conversely, McMillan and Abelson publically announced their discovery of neptunium, drawing heavy criticism from James Chadwick for potentially compromising the war effort. By the time Groves and the military took control of the Manhattan project, these questions were out of the scientists hands and secrecy was strictly enforced.

Working secretly was especially difficult for Leo Szilard. In addition to the scientists' isolation from the outside world, individual departments within Los Alamos were often cut off from one another. For Szilard, this was a serious impediment to scientific work, which requires cross-pollination between different ideas and thought processes. He tried bringing up his patents on the fission reactor as leverage for greater freedom; Groves, interpreting this as insubordination or espionage, ordered him put under surveillance (these fears of spying, of course, were groundless; Szilard had fled Europe to escape the Nazis). Other Europeans, unused to the American focus on utility and the current need for secrecy, were made uncomfortable by the guarded fence surrounding their workplace. Most were able to get by, reasoning that their restricted freedom was a necessary sacrifice for the war effort.

The community at Los Alamos found ways to adapt to its new environment. A social life of weekend dormitory parties, hiking trips, sports, and theater performances developed as physicists found ways to use their leisure time under security restrictions. The project involved, in some capacity, most of the famous physicists of the day outside Germany, but the great majority were young up-and-coming physicists (probably most famously Richard Feynman). The average age at Los Alamos was 25. Although Oppenheimer was greatly respected as the project's leader who had gathered such a large and diverse community together, even he struggled with the intense and restrictive conditions: he dealt with moral and religious questions which would later become famous, while his wife Kitty turned to heavy drinking.

Physics and Ethics:

There was no universal opinion on the morality of the bomb shared by all physicists. Early in the project, the threat of Germany was sufficient motivation for most to turn to weapons research. After the war ended in Europe in the spring of 1945, many theoreticians began to question the value of their work. Szilard, who had earlier been enthusiastic about the bomb, began arguing during the summer that it should remain secret instead of being used. Ernest Lawrence, born an American citizen, saw no problem with providing his country with tools to support it. Edward Teller, who went on to lay the groundwork for thermonuclear weapons, avoided questions of ethics altogether, arguing that scientists had no business trying to make policy decisions. Oppenheimer's reflections on the destruction made possible by the bomb are famous, and he dealt with guilt for the rest of his life.

One of the most fully-formed positions on the bomb was that of Niels Bohr, who was only marginally involved in the project itself. He foresaw that, inevitably, other countries would develop their own nuclear weapons, leading to the possibility of an arms race. Instead, Bohr urged a cosmopolitan policy of willingly sharing the bomb among different countries. This, he argued, would end war by making war impossible. Nations would be forced to work together in order to avoid mutual destruction, possibly even leading to the end of the nation-state as an entity and the beginning of world government.

To the government representatives who heard this plan, the idea of handing over military secrets to enemies was absurd.

Of course, the ultimate decision to use the bomb was made not by scientists but by politicians. By July, 1945, Japan's industrial capacity had been destroyed and the country was considering surrender. However, the U.S. demanded no less than unconditional surrender, which the Japanese refused to accept. This insistence on total surrender has been criticized, but it was motivated by the legacy of World War I: the confusing, conditional surrender of Germany had allowed the country to rearm and begin World War II. President Truman also had to deal with Stalin, who was preparing to declare war on Japan and extend Soviet influence into East Asia as he had in Eastern Europe. The dilemma was thus between ending the war quickly with an invasion at the cost of human lives, or waiting until the Soviets entered the war and gained more bargaining power. Nuclear weapons provided a way out of this problem by shocking Japan into surrender before the Soviet Union could intervene. Soon after the bombing of Hiroshima and Nagasaki, the emperor sidestepped Japan's military leadership and agreed to surrender as long as he kept his imperial sovereignty. As a compromise, the office of emperor was allowed to remain in a purely ceremonial role as Japan transitioned to democracy.

Ultimately, nuclear weapons were not decisive for the war effort: had there been no Manhattan Project, the Allies still would have won. The question of whether Truman's decision was morally justifiable is more philosophical than historical, but there are a few considerations we can raise. Given the requirements of unconditional surrender, excluding the Soviets, and minimizing the loss of life (especially of American lives), using the bomb may have been Truman's only option. It is easy to think of what-if scenarios in which the U.S. negotiated a surrender or cooperated with the Soviet Union against Japan, but determining what would really have happened in those cases is impossible. Finally, it is important to remember that Truman's perspective in 1945 is different from ours today and that considerations or ideas that seem obvious to us may not have seemed possible to him.

Other Nuclear Projects:

The United States was not the only nation to pursue nuclear research during World War II. Great Britain collaborated with many future Los Alamos workers on early research, but was pushed out of development as the military took over and secrecy became essential. Russian physicists were very successful at developing thermonuclear weapons in the early 1950s, but they made little progress during the war. Japan was also far from completing a functional bomb, and whatever progress it achieved was destroyed in American bombing missions.

The most famous non-American nuclear program was that of Nazi Germany, in which Heisenberg served as lead theoretician. For the first two years of the war, the German and American programs made roughly equal progress in nuclear fission. Hitler's many victories throughout Europe convinced German physicists that the war would be quick and that there was no pressure to finish a bomb quickly before the war's end. By early 1942 the situation changed: The U.S. officially entered the war and decided to fully commit its resources to the Manhattan Project. Conversely, the Germans, after failing to decisively defeat the Soviet Union and realizing how difficult the war would become, decided not to waste resources on a project that probably would not see results in time for use during the war; instead, these resources were given to the German rocket program. Fission research continued, but without the necessary funds for large-scale uranium enrichment. Allied bombing also served as an impediment for German scientists that Los Alamos did not have to deal with. Although the threat of Germany motivated much of the Manhattan Project, that threat had largely disappeared before any physicists had arrived at Los Alamos.

Thermonuclear Weapons:

Edward Teller probably was not the first physicist to realize the possibility of building a thermonuclear bomb (also called the Super or the hydrogen bomb), but he is often called the father of the hydrogen bomb. As the Los Alamos lab was being organized in 1943, Hans Bethe was made head of the lab's Theoretical Division rather than Teller. Teller was upset by this, both because he found Bethe's leadership style difficult and because of personal disappointment, leading to longstanding hostility between the two. Oppenheimer resolved that Teller should work on a separate project in order to avoid conflict. While most physicists spent the war working on the uranium and plutonium designs, Teller developed an early model of a hydrogen fusion bomb ignited by a fission explosion. The general consensus during the war was that developing a theoretical Super would be useful, although there were no plans to actually build it.

Work continued after the war, but without the sense of urgency that guided the Manhattan Project. This changed in September, 1949, when the Soviet Union tested its first nuclear bomb. The U.S. was initially unsure how to respond to this. The General Advisory Committee to the Atomic Energy Commission, which included Oppenheimer, Fermi, and several other leading physicists, suggested increasing plutonium production but not pursuing the Super, viewing it as a massively destructive weapon with no practical military use. President Truman ignored this and authorized the bomb's development in early 1950. The largest technical problem this time was the huge amount of mathematical simulation needed to understand the hydrodynamics of the explosion; the first computer, the ENIAC, was designed to run these tests. Teller's original design was recognized as unfeasible and revised by the mathematician Stanislaw Ulam, leading to the successful Teller-Ulam design (the original used the concentric sphere model of the plutonium bomb and exploded too quickly; Ulam's revision allowed the thermonuclear reaction time to develop). Physicists at Los Alamos again designed the Super, which was first successfully tested in November of 1952, with a yield a thousand times that of the original Hiroshima bomb. Within a few years, the Soviet program had developed its own thermonuclear bomb.

Key Ideas:

- Internationalism has appeared before as an important scientific value, inspiring Arthur Eddington to lead the 1919 eclipse expedition in the aftermath of World War I. Similarly, many Manhattan Project scientists justified their work as allowing an eventual state of permanent peace and cooperation between nations. Major wars force scientists to confront these issues and consider their allegiance to their home country. I do not think it is fair either to say that scientists always stick to a belief in internationalism or that they are willing to jettison this virtue as soon as a war starts; rather, scientific values are dynamic entities whose meanings change over time and are interpreted differently by individual scientists.

- Government funding was a key factor to developments in physics before, during, and (as we shall see) after World War II. I think this observation is a strong argument in favor of externalist explanations for the history of science. Exactly why governments or philanthropes chose to give or withhold resources to specific scientific projects can be influenced by a wide range of political, social, economic, or cultural factors. To understand which physicists succeeded in advancing their field, it is necessary to consider the resources available to them; to understand their available resources it is necessary to look beyond science entirely into a wider historical context.
- The negative implications of nuclear weapons are obvious and are frequently discussed in relation to the Manhattan Project. However, the bomb's creators were aware of possible positive effects their work could bring beyond ending the war. Bohr's vision of world governance may seem naive, but his predictions of mutually assured destruction were remarkably far-sighted. Nuclear deterrence is an accepted concept in international relations theory, helping to explain why the U.S. never went to war against the Soviet Union or India against Pakistan.
- The story of European scientists fleeing persecution and joining the American war effort is deservedly famous and was an important factor in the Manhattan Project's success. However, it is worth remembering why these physicists chose to go to the United States. Years before World War II, and with only a little involvement by Europeans, American physics had grown tremendously and rivaled the leading communities in England and Germany. The migration of physicists to America was not only a cause of America's eventual dominance in the sciences, but also a result of it.
- Frequently, the course of nuclear research was controlled not by physicists but by the American or German militaries. This does not mean that scientists were powerless, however: Oppenheimer succeeded in negotiating with Groves for lower military presence at Los Alamos, and, as we have seen, Szilard found ways to resist the military's authority. After the war, the Los Alamos scientists enjoyed

new levels of public fame and prestige, which they used to argue for the importance of responsible nuclear energy usage and which gained them advisory positions in government agencies such as the Atomic Energy Commission. If we think of nuclear policy as a conflict between physicists and the government, both sides had tools they could use to influence the outcome in their favor.

- Like anything involving Nazis, a mythology has developed around the German nuclear project. Questions of the morality of the leading scientists are difficult to answer: for the most part, their motivations were the same as Allied scientists (patriotism and a desire to finish a bomb before the other side). However, the question of whether Heisenberg sabotaged the project through miscalculation is misplaced. Whatever Heisenberg's actions or motivations were, the fate of the German bomb was decided by a lack of government support rather than physicists' decisions.

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Big Science

The Roots of Big Science:

"Big Science" is a term used to describe trends toward larger-scale research in the natural sciences since the 1940s. During this period, budgets, research teams, machinery, and facilities grew to unprecedented sizes, often requiring cooperation between different institutions or nations. The most visible symbols of Big Science are particle accelerators, some of which are among the most expensive machines ever built, but all areas of physics (as well as space travel, astronomy, biology, etc.) experienced growth. Beyond the changes in scale, Big Science qualitatively transformed physics in important ways. The need for massive funding changed the relationship between physicists, the government, and the military, while the growing size of research teams and administrative structures changed what it meant to do physics on a day-to-day basis.

While Big Science is often associated with post-World War II trends in American government and military policy, traces of it can be seen in the 1930s, especially at Ernest Lawrence's laboratory at Berkeley. Lawrence was an aggressive and charismatic leader who ran a thriving research center in spite of the Great Depression. In order to create increasingly large cyclotrons, Lawrence had to mobilize large sums of money and workers to operate the machinery. He convinced the president and financial supporters of the University of California of the importance of his work, giving him access to state funding and private philanthropy (almost none of his money came from the federal government). Students, postdocs, and Works Progress Administration workers (displaced workers receiving aid under Roosevelt's New Deal) provided a practically unpaid labor pool. Lawrence's use of these resources allowed him to achieve projects on a much larger scale than his contemporaries and gave Berkeley a head start in particle accelerator research.

Lawrence is not just a useful archetype to think about early Big Science; his influence is concrete and traceable. Those who worked in his lab learned his successful leadership style and were able to bring it to other laboratories. Almost all early particle accelerators were constructed under the leadership of physicists from Berkeley. Many of the most important laboratories' directors, such as Wolfgang Panofsky at Stanford or

Robert Wilson at Fermilab, worked under Lawrence. In the mid-1980s, the new Jefferson Laboratory struggled to navigate politics and funding until a new director (and Lawrence Lab alum), Hermann Grunder, took over. One of the necessary ingredients of Big Science, mobilization of resources that physicists normally do not have to deal with, was provided in the style of Ernest Lawrence's leadership.

The Post-War Boom:

After World War II, federal funding for physics increased by a factor of twenty over fifteen years. The great majority of this was military funding from the Department of Defense or the Atomic Energy Commission (technically a civilian organization but practically oriented toward the military). The success of radar and nuclear weapons during the war convinced the American government that scientific research, even into seemingly theoretical or esoteric subjects, was key for national defense, and that investments today would pay off tomorrow. The Korean War beginning in 1950 led to another spending boom. In 1957, just when a recession seemed to threaten funding, the Soviet Union launched Sputnik; the U.S. responded by creating NASA and continued support for particle accelerators. The 1950s and early 1960s were a time of seemingly-unlimited funding and optimism among physicists, who enjoyed popular support and prestige. The U.S. spent about six times as much money per physicist as it did per chemist.

The early important sites of particle accelerator research were Brookhaven in Long Island, which built the 3 GeV Cosmotron in 1953 and the 30 GeV Alternating Gradient Synchrotron in 1960, and Berkeley, which dominated early cyclotron research and completed the 6.2 GeV Bevatron in 1954. Helped by the Sputnik boom, the Stanford Linear Accelerator Center (SLAC) was operational by 1966 and is still the world's largest linear accelerator. Despite its success, SLAC faced opposition from Congressional representatives who questioned its practical use, foreshadowing later trends in funding. The United States was unquestionably the leader in particle accelerators for two decades after World War II, but progress was made elsewhere. CERN (Conseil Européen pour la Recherche Nucléaire) was founded in 1954 as part of a broader movement toward European cooperation, particularly in order to rehabilitate German physicists back into the community after their long separation. Japan had made important progress in the 1930s, building the first non-American cyclotron, but the war's aftermath prevented the country from undertaking large-scale research for many years. The Soviet Union built successful accelerators, but generally did not match American progress.

Although physicists benefitted from this military spending, the source of their money understandably made many uncomfortable. Some objected to the politics of military support, while others simply wanted their independence back. Whether the military influenced the direction of physics research in this period is controversial and not entirely clear, but it is worth mentioning that important innovations such as atomic clocks and the laser have military applications and were funded in part by the military. Beginning in the mid-1960s, opposition to the Vietnam War increased criticism of the physics-military connection both within and outside of the scientific community. The connection effectively ended in 1969, when Congress passed the Mansfield Amendment restricting military funding to projects that are directly related to military applications. From then on, funding was no longer limitless and physicists' reputations were called into question by anti-war and anti-science movements.

Physics since the 1970s:

In this new environment, proposals had to compete for a limited pool of federal money. Although the National Science Foundation (NSF) had existed since 1950, it only took an important role in funding research beginning in the 1970s. Rather than university-controlled laboratories, which restricted access to outsiders, the government shifted toward more economical independent national laboratories. Planning for a "truly national laboratory" in the late 1960s resulted in the creation of Fermilab outside of Chicago, which in 1985 first produced a 1 TeV beam. Illinois was chosen as a location among many competitors due to its central location and, supposedly, in return for its Senator's support of President Johnson's civil rights legislation (although this rumor is unsubstantiated). This process of locations competing for federal funding was repeated with JLab and the planned Superconducting Super Collider (SSC).

The 1980s saw a brief increase in funding under the Reagan administration, which supported high-tech military applications such as the Strategic Defense Initiative (also called Star Wars). Reagan approved a plan to build the largest accelerator in the world, at 20 TeV and roughly $6 billion, and reclaim America's place as leader in high-energy physics from CERN. The SSC, planned to be built outside Dallas, was one of the most controversial physics projects in recent history. Criticism came from physicists, who resented the preferential treatment of high-energy physics in federal funding or viewed the massively expensive project as an abuse of taxpayers' trust. Criticism from Congress increased in the early 1990s, as costs increased and mismanagement was revealed; after the Cold War ended in 1991, physics research seemed less important to national defense. The project was finally cancelled in 1993.

This period also saw an increasing role for non-American particle accelerators. Japan established its own national laboratory, KEK (Ko Energy Butsurigaku Kenkyusho), in 1971, and has become an important center in high-energy research. By some measurements, CERN overtook the U.S. in particle accelerator research in the 1980s, publishing the majority of experimental high-energy papers and receiving more citations per paper. In 2008, CERN's Large Hadron Collider overtook Fermilab's Tevatron as the most powerful accelerator in the world, at an initial energy of 4 TeV and upgrades planned. Other major accelerators have been built in Vancouver, Novosibirsk, and Beijing.

Challenges of Big Science:

Historically, not all physicists have been satisfied with these new directions in scale and organization after World War II. Some from the older generation missed the days of small projects and thought that younger physicists lacked opportunities to show creativity or personal initiative when working among dozens of other researchers; loyalty and cooperation may become personality traits favored above individualism or intellectual freedom. Public attention typically focuses on the newest and biggest machines, rather than the physicists running them, calling into question whether physicists actually play the central role in physics anymore. Especially during the period of military support, Big Science has been criticized for compromising the independence of physics; on the other hand, given the huge scale and cost of modern accelerators, it can be difficult to imagine how particle physics could continue without government funding.

Regardless of how they feel about it, Big Science has presented new challenges and forced physicists to do their work differently. With only a handful of powerful accelerators, deciding which experiments should have access to valuable beam time is contentious; in addition to the merit of a proposal, laboratories have to weigh their cost, duration, and perhaps the established reputation of the researcher. With only limited opportunities to perform experiments, physicists have made efforts to get as much data as possible out of a single experimental trial; it is not unusual for analysis to continue for years after the data were obtained. The long time spans of experimentation and analysis can conflict with the established rhythm of the academic world: it is difficult to write a thesis on a tight schedule based on an experiment that lasts for years. As negotiating with governments and administrators for funding has become more important, physicists have had to split time between actually doing science and more mundane tasks. In large teams, attributing authorship for individual contributions is difficult. This problem only becomes more pronounced as accelerators and team sizes get bigger. In May 2015, a combined paper from the CMS and ATLAS teams at CERN set the record with over 5,000 authors; their names and institutions filled 24 out of the paper's 33 pages.

Key Ideas:

- Dissatisfaction with Big Science raises the question of whether it is possible, at this point, to change the system and remove constraints on the physics community. The argument against change is that Big Science is inevitable: it is impossible to return to a small-scale model of experimentation because new advances in particle physics require such large concentrations of energy. This is true, but it is important to be precise here: even if the scaling up of high-energy physics was inevitable, the specific configuration of the field that we call "Big Science" was not. The particular relationships between science, government, and military, as well as the relationships between individual physicists, have changed over time and will likely continue to change in the future. Focusing on inevitability shifts our attention away from this fluidity and locks us into a particular understanding of how physics is done.

- After World War II, the laboratory director emerged as an important position with specific responsibilities. The director must act as a mediator between the physics community and sources of funding. As time went on and this mediation became more demanding, their job became more specialized and further removed from actual lab work. Ernest Lawrence spent considerable time actually working with his cyclotrons, but lab directors in the 1970s or 1980s had a more administrative rather than experimental role.
- International values and national pride continue to be important conflicting themes throughout the 20th century. Since World War II, physicists from different countries (with the exception of the Soviet Union) have been happy to work together and share results. The animosity between former enemies in the aftermath of World War I has not been repeated. However, many physicists bring up national or local pride in justifying their projects, as each laboratory wants to be the first to make important discoveries. Funding for the SSC was justified as being necessary to keep the U.S. at the forefront of particle physics research. It seems unlikely that excessive nationalism will hinder research any time in the near future, but an undercurrent of competition between countries can be seen.
- Discussions of Big Science often focus on the largest and most expensive facilities that break records or discover new particles, but (maybe paradoxically) small- and medium-scale projects have also played an important role. An interesting example of this occurred at Berkeley in the late 1960s. Many physicists there were disappointed in the decision to build the new national lab in Illinois rather than California, as the famous Bevatron would now become obsolete. Instead of that happening, the Bevatron was physically connected to another machine, SuperHILAC (a heavy ion accelerator), and renamed Bevalac. This combination paved the way for a new area of research, relativistic heavy ion acceleration, at only a moderate price. The same sort of research is done today at Brookhaven's Relativistic Heavy Ion Collider (RHIC), completed in 2000. Even into the 1970s, it was possible to make advances in particle physics without spending billions of dollars.

- Funding for a new facility or experiment can be refused for many reasons. The decision not to provide funding may come from other physicists, who may judge the project to be scientifically unimportant or simply too expensive, or from non-scientists, who may or may not be educated about the physics they are judging. Being able to understand these reasons and play off them is an important skill for physicists seeking support. An example of the bargaining that accompanies government funding can be found in SLAC's planning in the early 1960s. Stanford's Professor Panofsky wanted the facility to be under the university's control, giving him greater freedom and control over research. The AEC threatened to cut off funding unless SLAC was made a national laboratory with access to non-Stanford physicists and control given to a national committee. As an eventual compromise, SLAC was made a national laboratory operated by Stanford, with Panofsky as its first director.

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