Chapter 1

SYNCHRONY

TRUE TIME WOULD never be revealed by mere clocks—of this Newton was sure. Even a master clockmaker's finest work would offer only pale reflections of the higher, absolute time that belonged not to our human world, but to the "sensorium of God." Tides, planets, moons—everything in the Universe that moved or changed—did so, Newton believed, against the universal background of a single, constantly flowing river of time. In Einstein's electrotechnical world, there was no place for such a "universally audible tick-tock" that we can call time, no way to define time meaningfully except in reference to a definite system of linked clocks. Time flows at different rates for one clock-system in motion with respect to another: two events simultaneous for a clock observer at rest are not simultaneous for one in motion. "Times" replace "time." With that shock, the sure foundation of Newtonian physics cracked; Einstein knew it. Late in life, he interrupted his autobiographical notes to apostrophize Sir Isaac with intense intimacy, as if the intervening centuries had vanished; reflecting on the absolutes of space and time that his theory of relativity had shattered, Einstein wrote: "Newton, forgive me ['Newton, verzeih' mir']; you found the only way which, in your age, was just about possible for a man of highest thought—and creative power."[1]

At the heart of this radical upheaval in the conception of time lay an extraordinary yet easily stated idea that has remained dead-center in physics, philosophy, and technology ever since: *To talk about time, about simultaneity at a distance, you have to synchronize your clocks. And if you want to synchronize two clocks, you have to start* *with one, flash a signal to the other, and adjust for the time that the flash takes to arrive.* What could be simpler? Yet with this procedural definition of time, the last piece of the relativity puzzle fell into place, changing physics forever.

This book is about that clock-coordinating procedure. Simple as it seems, our subject, the coordination of clocks, is at once lofty abstraction and industrial concreteness. The materialization of simultaneity suffused a turn-of-the-century world very different from ours. It was a world where the highest reaches of theoretical physics stood hard by a fierce modern ambition to lay time-bearing cables over the whole of the planet to choreograph trains and complete maps. It was a world where engineers, philosophers, and physicists rubbed shoulders; where the mayor of New York City discoursed on the conventionality of time, where the Emperor of Brazil waited by the ocean's edge for the telegraphic arrival of European time; and where two of the century's leading scientists, Albert Einstein and Henri Poincaré, put simultaneity at the crossroads of physics, philosophy, and technology.

Einstein's Times

For its enduring echoes, Einstein's 1905 article on special relativity, "On the Electrodynamics of Moving Bodies," became the best-known physics paper of the twentieth century, and his dismantling of absolute time is its crowning feature. Einstein's argument, as usually understood, departs so radically from the older, "practical" world of classical mechanics that the paper has become a model of revolutionary thought, seen as fundamentally detached from a material, intuitive relation to the world. Part philosophy and part physics, Einstein's rethinking of simultaneity has come to stand for the irresolvable break between modern physics and all earlier framings of time and space.

Einstein began his relativity paper with the claim that there was an asymmetry in the then-current interpretation of electrodynamics, an asymmetry not present in the phenomena of nature. Almost all physicists around 1905 accepted the idea that light waves—like water waves or sound waves—must be waves *in* something. In the case of light waves (or the oscillating electric and magnetic fields that constituted light), that something was the all-pervasive *ether.* Most late-nineteenth-century physicists considered the ether to be one of the great ideas of their era, and they hoped that once properly understood, intuited, and mathematized, the ether would lead science to a unified picture of phenomena from heat and light to magnetism and electricity. Yet it was the ether that gave rise to the asymmetry that Einstein rejected.[2]

In physicists' usual interpretation, Einstein wrote, a moving magnet approaching a coil at rest in the ether produces a current indistinguishable from the current generated when a moving coil approaches a magnet at rest in the ether. But the ether itself could not be observed, so in Einstein's view there was but a single observable phenomenon: coil and magnet approach, producing a current in the coil (as evidenced by the lighting of a lamp). But in its then-current interpretation, electrodynamics (the theory that included Maxwell's equations—describing the behavior of electric and magnetic fields—and a force law that predicted how a charged particle would move in these fields) gave two different explanations of what was happening. Everything depended on whether the coil or the magnet was in motion with respect to the ether. If the coil moved and the magnet remained still in the ether, Maxwell's equations indicated that the electricity in the coil experienced a force as the electricity traversed the magnetic field. That force drove the electricity around the coil lighting the lamp. If the magnet moved (and coil stayed still), the explanation changed. As the magnet approached the coil, the magnetic field near the coil grew stronger. This changing magnetic field (according to Maxwell's equations) produced an electric field that drove the electricity around the stationary coil and lit the lamp. So the standard account gave *two* explanations depending on whether one viewed the scene from the point of view of the magnet or the point of view of the coil.

As Einstein reframed the problem there was *one* single phenomenon: coil and magnet approached each other, lighting the lamp. As far as he was concerned, *one* observable phenomenon demanded *one* explanation. Einstein's goal was to produce that single account, one that did not refer to the ether at all, but instead depicted the two frames of reference, one moving with the coil and one with the magnet, as offering no more than two perspectives on the same phenomenon. At stake, according to Einstein, was a founding principle of physics: relativity.

Almost three hundred years earlier, Galileo had similarly questioned frames of reference. Picturing an observer in a closed ship's cabin, borne smoothly across the seas, Galileo reasoned that no mechanical experiment conducted in a below-deck laboratory would reveal the motion of the ship: fish would swim in a bowl just as they would were the bowl back on land; drops would not deviate from their straight drip to the floor. There simply was no way to use any part of mechanics to tell whether a room was "really" at rest or "really" moving. This, Galileo insisted, was a basic feature of the mechanics of falling bodies that he had helped create.

Building on this traditional use of the relativity principle in mechanics, Einstein in his 1905 paper raised relativity to a principle, asserting that physical processes are independent of the uniformly moving frame of reference in which they take place. Einstein wanted the relativity principle to include not only the mechanics of drops dripping, balls bouncing, and springs springing but also the myriad effects of electricity, magnetism, and light.

This relativity postulate ("no way to tell which unaccelerated reference frame was 'truly' at rest") gave rise to an additional assumption that proved even more surprising. Einstein noted that experiments did not show light traveling at any speed other than 300,000 kilometers per second. He then *postulated* that this was always so. Light, Einstein said, always travels by us at the same measured speed—300,000 kilometers per second—*no matter how fast the light source is traveling*. This was certainly not how everyday objects behaved. A train approaches and the conductor throws a mailbag forward toward a station; it goes without saying that someone standing on the station platform sees the bag approach at the speed of the train *plus* the speed at which the conductor habitually hurls mail. Einstein insisted that light was different: stand, your lantern raised, at a fixed distance from me and I see the light travel by me at 300,000 kilometers per second. Hurtle toward me on a train, even one moving at 150,000 kilometers per second (half the speed of light), and I still see the light from your lantern go by me at 300,000 kilometers per second. According to Einstein's second postulate, the speed of the source does not matter to the velocity of light.

Both of these postulates would have seemed reasonable (at least in part) to Einstein's contemporaries. In the science of mechanics, not only had the principle of relativity been around since Galileo, but for some years Poincaré (among others) had also analyzed the relativity principle's problems and prospects in electrodynamics.[3] If light, moreover, was nothing but an excitation of waves in a rigid, all-pervasive ether, then in the frame of reference in which the ether was at rest, it was plausible to assume that the speed of light would not depend on the speed of the light source. After all, for reasonable source speeds, the speed of sound does not depend on the velocity of the source: once a sound wave is started, it moves through air at a fixed speed.

But how could Einstein's two postulates be reconciled? Suppose in the ether rest frame a light was shining. To an observer *moving* with respect to the ether, wouldn't the light appear to travel either faster or slower than normal, depending on whether the moving observer was approaching or retreating from the light? And if a difference in the velocity of light was observable, then wouldn't that violate the principle of relativity, since that observation would indicate whether one was truly moving with respect to the ether? Yet no such difference could be measured. Even precise optical experiments failed to detect the slightest hint of motion through the ether.

Einstein's diagnosis: "insufficient consideration" had been paid to the most fundamental concepts of physics. He claimed that if these basic concepts were properly understood, the apparent contradiction between the relativity and the light principles would vanish. Einstein proposed, therefore, to begin at the very beginning of physical reasoning, asking, What is length? What is time? And especially: What is simultaneity? Everyone knew that the physics of electromagnetism and optics depended on making measurements of time, length, and simultaneity, but as far as Einstein was concerned, physicists had not paid enough critical attention to the basic procedures by which these fundamental quantities were determined. How could rulers and clocks yield unambiguous space and time coordinates for the phenomena of the world? In Einstein's judgment, the predominant view that physicists should concern themselves first with the complex forces that held matter together had it backward. Instead, *kinematics* had to come first, that is, how clocks and rulers behaved in constant, force-free motion. Only then could the problem of *dynamics* (for example, how electrons behaved in the presence of electrical and magnetic forces) be usefully addressed.

Einstein believed that physicists would only find consistency by sorting out the measurements of space and time. To make spatial measurements, a coordinate system is needed—by Einstein's lights, a system of ordinary rigid measuring rods. For example: this point is two feet along the x-axis, three along the y, and fourteen up the z-axis. So far, so good. Then came the surprising part, the reanalysis of *time* that contemporaries like the mathematician and mathematical physicist Hermann Minkowski saw as the crux of Einstein's argument.[4] As Einstein put it: "We have to take into account that all our judgments in which time plays a role are always judgments of *simultaneous events*. If, for instance, I say, 'That train arrives here at 7 o’clock,’ I mean something like this: ‘The pointing of the small hand of my watch to 7 and the arrival of the train are simultaneous events’.”[5] For simultaneity *at one point*, there is no problem: if an event located in the immediate vicinity of my watch (say, the train engine pulling up beside me) occurs just when the small hand of the watch reaches the seven, then those two events are obviously simultaneous. The difficulty, Einstein insisted, comes when we have to link events separated in space. What does it mean to say two *distant* events are simultaneous? How do I compare the reading of my watch *here* to a train’s arrival at another station *there* at 7 o’clock?

For Newton the question of time held an absolute component; time was not and could not be merely a question of “common” clocks. From the instant Einstein demanded a *procedure* in order to give meaning to the term “simultaneous,” he split from the doctrine of absolute time. In an apparently philosophical register, Einstein established this defining procedure through a *thought experiment* that has long seemed far from the play of laboratories and industry. How, Einstein asked, should we synchronize our distant clocks? “We could in principle content ourselves to time events by using a clock-bearing observer located at the origin of the coordinate system, who coordinates the arrival of the light signal originating from the event to be timed . . . with the hands of his clock.”[6] Alas, Einstein noted, because light travels at a finite speed, this procedure is not independent of the place of the central clock. Suppose I stand next to A and far from B; you stand exactly halfway between A and B:

A—me——you————B

Both A and B flash light signals to me, and both arrive in front of my nose at the same moment. Can I conclude that they were sent at the same time? Of course not. It is obvious that B’s signal had a much longer way to travel to me than A’s signal, and yet they arrived at the same time. So B’s signal must have been launched before A’s.

Suppose I stubbornly insist that A and B *must* have launched their signals simultaneously; after all, I got the two signals at the same moment. Immediately I run into trouble, as you can bear witness: if you were standing exactly halfway between A and B, then you would have received B's light before A's. To avoid ambiguity, Einstein did not want to make the simultaneity of the two events "A sends light" and "B sends light" depend on where the receiver hap-

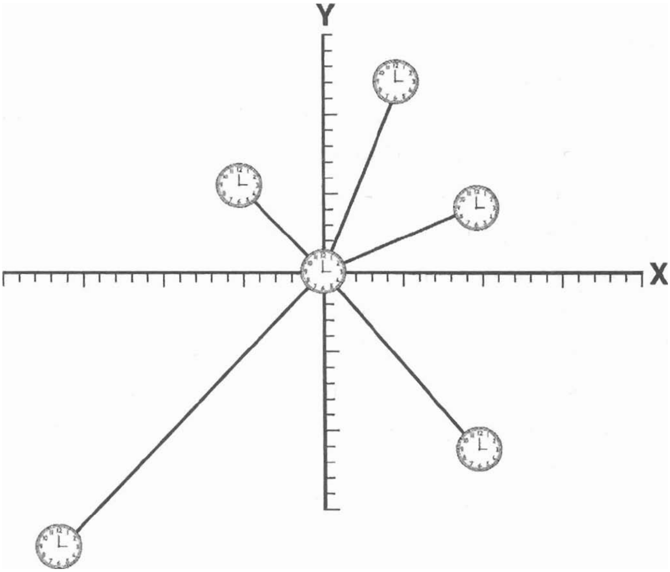

Figure 1.1 Central Clock Coordination. *In his 1905 paper on special relativity, Einstein introduced—and rejected—a scheme of clock coordination in which the central clock sent a signal to all other clocks; these secondary clocks set their times when the signal arrived. For example, if the central clock sent its time signal at 3:00 P.M., each secondary clock synchronized its hands to that same 3:00 P.M. when the pulse arrived. Einstein's objection: the secondary clocks were at different distances from the center so close clocks would be set by the arriving signal before distant ones. This made the simultaneity of two clocks depend (unacceptably to Einstein) on the arbitrary circumstance of where the time-setting "central" clock happened to be.*

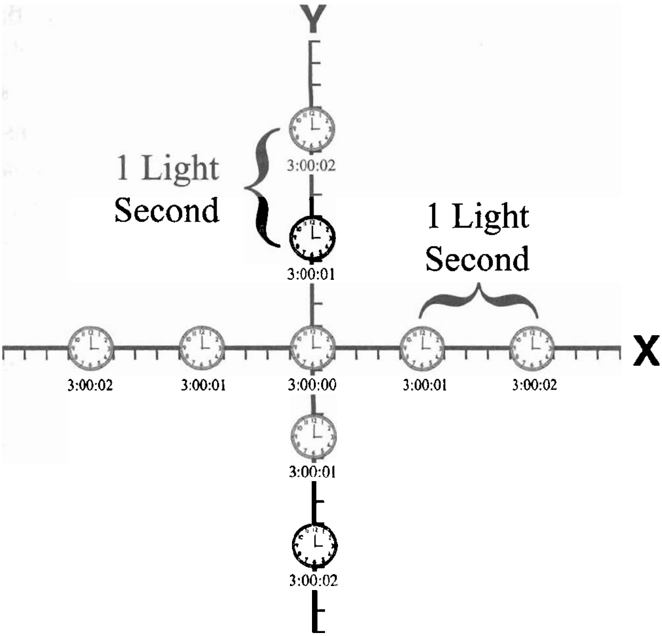

Figure 1.2 Einstein's Clock Coordination. *Einstein argued that a better and nonarbitrary solution to the simultaneity question was this: set clocks not to the time that the signal was launched, but to the time of the initial clock* plus *the time it took for the signal to travel the distance from the initial clock to the clock being synchronized. Specifically, he advocated sending a round-trip signal from the initial clock to the distant clock and then setting the distant clock to the initial clock's time* plus *half the round-trip time. In this way the location of the "central" clock made no difference–one could start the procedure at any point and unambiguously fix simultaneity.*

pens to be standing. As a procedure for defining simultaneity, "simultaneous receipt of signals by me" is a disaster, an epistemic straw man who cannot tell a consistent story.

Having knocked the straw out of this straw man, young Einstein proposed a better system: let one observer at the origin A send a light signal when his clock says 12:00 to B at a distance *d* from A;

the light signal reflects off B and returns to A. Einstein has B set her clock to noon plus half the round-trip time. A two-second round-trip? Then Einstein has B set her clock to noon plus one second when she gets the signal. Assuming that light travels just as fast in one direction as the other, Einstein's scheme amounts to having B set her clock to noon plus the distance between the two clocks divided by the speed of light. The speed of light is 300,000 kilometers per second. So if B is 600,000 kilometers from A when B receives the light signal, she sets her clock to 12:00:02, noon plus two seconds. If B were 900,000 kilometers away from A, B would set her clock to 12:00:03 when she gets the signal. Continuing in this way, A, B, and anyone else participating in this coordination exercise can all agree that their clocks are synchronized. If we now move the origin, it makes no difference: every clock is already set to take into account the time it takes for a light signal to arrive at the clock's location. Einstein liked this: no privileged "master clock," and an unambiguous definition of simultaneity.

With the clock coordination protocol in hand, Einstein had cracked his problem. By relentlessly applying the simple procedure of coordination and his two starting principles, he could show that two events that were simultaneous in one frame of reference were not simultaneous in another. Consider: the length measurement of a moving object always depends on making simultaneous position measurements of two points (if you want the length of a moving bus, it behooves you to measure the position of the front and back at the same time). Because the determination of length requires the simultaneous measurements of front and back, the relativity of simultaneity led to a relativity of lengths—my frame of reference will measure a meter stick moving by me as less than a meter long.

Astonishing in and of itself, this relativity of times and lengths led to many other consequences, some more immediate than others. Because speed is defined as distance covered in a certain time, combining the motion of objects had to be reconsidered in Einstein's theory. A person running in a train at a speed of 1/2 the speed of light (with respect to the train) while the train barreled along at 3/4 the speed of light would, in Newtonian physics, be moving relative to the ground at 1 1/4 times the speed of light. But by rigorously following the definition of time and simultaneity, Einstein showed that the actual combined speed would be less than that—indeed *always* less than the speed of light no matter what the speed of the train or the runner in the train. Nor was that all: Einstein could explain previously puzzling optical experiments and make new predictions about the motion of electrons. Finally, Einstein's starting assumptions about light speed and relativity, coupled with his clock coordination scheme, helped show that there weren't really *two different* explanations of the coil, magnet, and lamp but just one: a magnetic field in one frame was an electric field in another. The difference was one of perspective—the view from different frames of reference. And all without a whiff of ether. A short time later, Einstein was to use relativity to produce that most famous of all scientific equations, $E = mc^2$. With consequences that at first seemed restricted to the most sensitive of barely possible experiments to the utter transformation of the military-political domain forty years later, Einstein had found mass and energy to be interchangeable.

Much lies behind Einstein's relativity besides the coordination of clocks. Without exaggeration, one could say that the collective mastery of electricity and magnetism was *the* great accomplishment of nineteenth-century physical science. Theoretically, Cambridge physicist James Clerk Maxwell had produced a theory that showed light to be nothing other than electric waves and so unified electrodynamics and optics. Practically, dynamos had brought electric lighting to cities, electric trams had altered cityscapes, and telegraphs had transformed markets, news, and warfare. By the century's end physicists were making precision measurements of light—staggeringly accurate attempts to detect the elusive ether; they were refining work in electricity and magnetism to dissect the behavior of the newly accepted electron. All this led many of the leading physicists (not just Einstein and Poincaré) to consider the problem of an electrodynamics of moving bodies to be one of the most difficult, fundamental, and acute problems on the scientific agenda.[7]

By Einstein's own account, the recognition that synchronizing clocks was necessary to define simultaneity was the final conceptual step that let him conclude his long hunt, and *that*—time coordination—is the subject of this book. Indeed, Einstein judged the alteration of time in relativity theory to be that theory's most striking feature. But his assessment did not immediately carry the day, even among those who counted themselves as Einstein's backers. Some embraced relativity after experiments on the deflection of electrons seemed to lend it support. There were those who used the theory only when physicists and mathematicians had reworked it into more familiar terms that did not put so much stress on the relativity of time. Through tense meetings, exchanges of letters, articles and responses, by 1910 a growing number of Einstein's colleagues were pointing to the revision of the time concept as the salient feature. In the years that followed, it became canonical for both philosophers and physicists to hail clock synchronization as a triumph in both disciplines, a beacon of modern thought.

Younger physicists, including Werner Heisenberg, began in the 1920s to pattern the new quantum physics on what they took to be Einstein's tough stance against concepts (like absolute time) that referred to nothing observable. In particular, Heisenberg admired Einstein's insistence that simultaneity refer exclusively to clocks coordinated by a definite and observable procedure. Heisenberg and his colleagues pressed their insistence on observability hard: if you want to speak about the position of an electron, show the procedure by which that position can be observed. If you want to say something about its momentum, then display the experiment that will measure it. Most dramatically, if even in principle you could

Of course not everyone admired the relativity of time. Some lampooned it, others tried to rescue physics from it. But very broadly by the 1920s, both physicists and philosophers recognized that Einstein's question, What is time? set a standard for scientific concepts that demanded something more finite, more humanly accessible than Newton's metaphysical, absolute time. Einstein himself suggested that he had drawn an effective philosophical sword against absolute time from the eighteenth-century critical work of David Hume, who had forcefully argued that the statement "A causes B" meant nothing more than the regular sequence, A then B. Key for Einstein, too, was the Viennese physicist-philosopher-psychologist Ernst Mach's work lambasting concepts disconnected from perception. Among Mach's (sometimes excessive) roundup of idle abstractions, none figured as a greater offender than Newton's "medieval" notions of absolute space and absolute time. Einstein also studied time through the microscope of other scientists' inquiries, among them those of Hendrik A. Lorentz and Poincaré. Each of these lines of philosophical reasoning—and others that we will encounter—form part of our story of time and timepieces. Yet a purely intellectual history leaves Einstein hovering in a cloud of abstractions: the philosopher-scientist brandishing thought experiments against the dusty Newtonian dogma of absolute time. Einstein confounding a contemporary scientific-technical cadre too sophisticated to ask basic questions about time and simultaneity. But is this cerebral account sufficient?

A Critical Opalescence

Certainly Einstein and Poincaré often looked back on their work as if it originated entirely outside the material world. In this respect, it is useful to reflect on a speech Einstein delivered in early October 1933 to a massive rally organized to aid refugees and displaced scholars. Scientists, politicians, and the public jammed London's

Royal Albert Hall. Hostile demonstrators threatened to stir things up; a thousand students came to serve as protective "stewards." Einstein warned of the imminence of war, of the hatred and violence looming over Europe. He urged the world to resist the drive toward slavery and oppression, and pleaded with governments to halt the impending economic collapse. Then, suddenly, the political thread of Einstein's speech snapped. There was a sudden pulling back from worldly crisis, as if the calamity of current events had stretched him beyond his limits. In a different register he began to reflect on solitude, creativity, and quiet, on moments he had spent lost in abstract thought surrounded only by the productive monotony of the countryside. "There are certain occupations, even in modern society, which entail living in isolation and do not require great physical or intellectual effort. Such occupations as the service of lighthouses and lightships come to mind."[11]

Solitude was perfect for a young scientist engaged with philosophical and mathematical problems, Einstein insisted. His own youth, we are tempted to speculate, might be thought of this way: we might read the Bern patent office where *he* had earned a living as no more than such a distant oceanic lightship. Consistent with Einstein's garden of otherworldly contemplation, we have enshrined Einstein as *the* philosopher-scientist who ignored the clutter of the patent office and the chatter of the hallway to rethink the foundations of his discipline, to topple the Newtonian absolutes of space and time. Newton to Einstein: it is easy enough to represent this transformation of physics as a confrontation of theories floating above the world of machines, inventions, and patents. Einstein himself contributed to this image, emphasizing in many places the role of pure thought in the production of relativity: "[T]he essential in the being of a man of my type lies precisely in *what* he thinks and *how* he thinks, not in what he does or suffers."[12]

The picture we so often see is of an Einstein otherworldly, oracular, communing with the spirits of physics; Einstein pronouncing on the freedom of God in the creation of the Universe; Einstein shucking off patent applications as so much busywork between him and the philosophy of nature; Einstein summoning a world of pure thought experiments featuring imaginary clocks and fantastical trains. Roland Barthes explored this imagined persona in his "Brain of Einstein," where the scientist appears as nothing but his cerebrum, an icon of thought itself, at once magician and machine without body, psychology, or social existence.[13]

Barthes would have known that among those scientists imagined to float above the material world was Henri Poincaré, the extraordinary French mathematician, philosopher, and physicist who produced, quite independently of Einstein, a detailed mathematical physics incorporating the relativity principle. In elegantly worded essays, Poincaré offered these results to the wider cultured world, at the same time probing the limits and accomplishments of both modern and classical physics. Like Einstein, Poincaré presented himself as a mind unbound. In one of the most famous accounts ever written by a scientist of his own creative work, Poincaré recounted his steps toward a theory of a new set of functions that were important for several domains of mathematics:

> For fifteen days I strove to prove there could not be any functions like those I [had in mind]. I was then very ignorant; every day I seated myself at my work table, stayed an hour or two, tried a great number of combinations and reached no results. One evening, contrary to my custom, I drank black coffee and could not sleep. Ideas rose in crowds; I felt them collide until pairs interlocked, so to speak, making a stable combination. . . . I had only to write out the results which took but a few hours.[14]

Not just in his account of his newly invented functions, but throughout his remarkable philosophical and popular essays, Poincaré dissected physics and philosophy by way of metaphorical worlds detached from the here and now, suspending imaginary scientists in idealized alternate universes: "Suppose a man were translated to a planet, the sky of which was constantly covered with a thick curtain of clouds, so that he could never see the other stars. On that planet he would live as if it were isolated in space. But he would notice that it revolves. . . ."[15] Poincaré's space traveler might exhibit the rotation by showing that the planet bulged around its equator, or by demonstrating that a free-swinging pendulum gradually rotates. As always, Poincaré here used an invented world to make a real philosophical-physical point.

It certainly is possible—even productive—to read Einstein and Poincaré as if they were abstract philosophers whose goal was to enforce philosophical distinctions by fabricating hypothetical worlds rich in imaginative metaphors. Poincaré (it might be thought) had in mind such a world when he spoke of such wildly varying temperatures that objects altered their lengths dramatically as one moved up or down. Poincaré and Einstein's attacks on Newton's absolute simultaneity could be taken to be just such metaphorical musings, ones that employed imaginary trains, fantastical clocks, and abstract telegraphs.

Let's return to Einstein's central inquiry. Invoking what may seem a quaintly metaphorical thought experiment, Einstein wanted to know what was meant by the arrival of a train in a station at 7 o'clock. I have long read this as an instance of Einstein asking a question that (as Einstein put it) was normally posed "only in early childhood," a matter that he, peculiarly, was still asking when he was "already grown up."[16] Was this the naïveté of the isolated genius? Such riddles about time and space appear, on this reading, to be so elementary as to lie below the conscious awareness of professional scientists. But was the problem of simultaneity, in fact, below the threshold of mature thought? Was no one else in 1904–1905 *in fact* asking what it meant for an observer here to say that a distant observer was watching a train arrive at 7 o'clock? Was the idea of defining distant simultaneity through the exchange of electric signals a purely philosophical construct removed from the turn-of-the-century world?

Relativity was certainly far from my mind when, not long ago, I was standing in a northern European train station, absentmindedly staring at the elegant clocks that lined the platform. They all read the same to the minute. Curious. Good clocks. Then I noticed that, as far as I could see, even the staccato motion of their second hands clicked in synchrony. These clocks are not just running well, I thought; these clocks are coordinated. Einstein must also have had coordinated clocks in view while he was grappling with his 1905 paper, trying to understand the meaning of distant simultaneity. Indeed, across the street from his Bern patent office was the old train station, sporting a spectacular display of clocks coordinated within the station, along the tracks, and on its facade.

The origins of coordinated clocks, like much in our technological past, remains obscure. Which of the many parts of a technological system does one count as its defining feature: the use of electricity? the branching of many clocks? the continuous control of the distant clocks? However one reckons, already by the 1830s and 1840s Britain's Charles Wheatstone and Alexander Bain, and soon thereafter Switzerland's Mathias Hipp and a myriad of other European and American inventors, began constructing electrical distribution systems to bind numerous far-flung clocks to a single central clock, called in their respective languages the "*horloge-mère*" [mother clock], "*Primäre Normaluhr*" [primary standard clock], and the "master clock."[17] In Germany, Leipzig was the first city to install electrically distributed time systems, followed by Frankfurt in 1859; Hipp (then director of a telegraph workshop) launched the Swiss effort in the Federal Palace in Bern, where a hundred clock faces began marching together in 1890. Clock coordination quickly embraced Geneva, Basel, Neuchâtel, and Zurich, alongside their railways.[18]

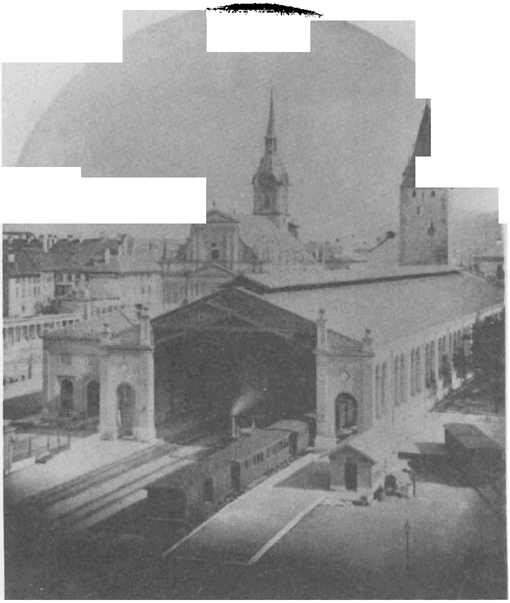

Figure 1.3 ***Bern Train Station (circa 1860—65)*** *One of the first buildings in Bern to be provided with the new coordinated clocks. Two clocks are (barely) visible just over the oval arches on the open side of the station.* SOURCE: COPYRIGHT BÜRGERBIBLIOTHEK BERN, NEG. 12572.

Einstein, therefore, was not only surrounded by the technology of coordinated clocks, he was also in one of the great centers for the invention, production, and patenting of this burgeoning technology. Were any other major scientists whose concern was with basic physical laws of electromagnetism and the nature of philosophical time also in the midst of this vast effort to synchronize clocks? There certainly was at least one.

Some seven years before the twenty-six-year-old patent officer redefined simultaneity in his 1905 relativity paper, Henri Poincaré had advanced strikingly similar ideas. A cultured intellectual, Poincaré was widely acclaimed as one of the greatest of nineteenth-century mathematicians for his invention of a great part of topology,

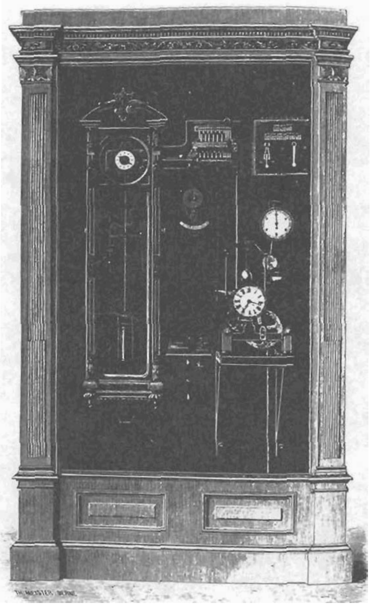

Figure 1.4 Neuchâtel Master Clock. *Beautifully decorated master clocks were objects of enormous value and civic pride. This one, in the center of the clockmaking region of Switzerland, received its time from an observatory and then launched its signals along telegraph lines.* SOURCE: FAVARGER, *L'ÉLECTRICITÉ* (1924), P. 414.

his celestial mechanics, his enormous contributions to the electrodynamics of moving bodies. Engineers lauded his writings on wireless telegraphy. The wider public devoured his best-selling books on the philosophy of conventionalism, science and values, and his defense of "science for science."

For our purposes, one of the most remarkable essays Poincaré published appeared in January 1898 in a philosophical journal, the *Review of Metaphysics and Morals*, under the title "The Measure of Time." There Poincaré blasted the popular view, espoused by the influential French philosopher Henri Bergson, that we have an

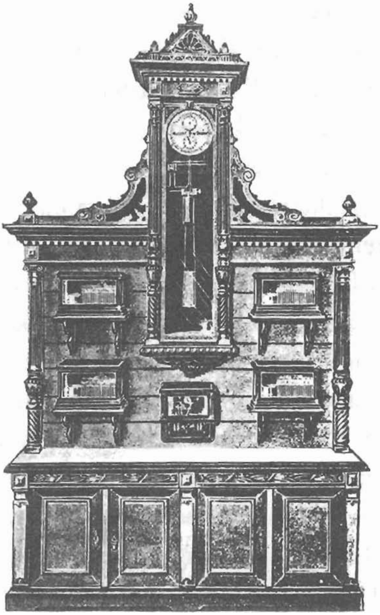

Figure 1.5 ***Berlin Master Clock.*** *This clock, residing at the Silesischer Bahnhof in Berlin, sent its time down the many tracks emanating from the station.*
SOURCE: *L'ÉLECTRICITÉ* (1924), P. 470.

intuitive understanding of time, simultaneity, and duration. Poincaré argued instead that simultaneity was irreducibly a *convention*, an agreement among people, a pact chosen not because it was inevitably in truth, but because it maximized human convenience. As such, simultaneity had to be *defined*, which one could do by reading clocks coordinated by the exchange of electromagnetic signals (either telegraph or light flashes). Like Einstein in 1905, Poincaré in 1898 contended that in making simultaneity a procedural concept, the time of transmission would have to be taken into account in any telegraphically communicated time signal.

Had Einstein seen Poincaré's paper of 1898 or a crucial subsequent one of 1900 before he wrote his 1905 paper? Possibly. While there is no definitive evidence one way or the other, it will, nonetheless, prove worthwhile to explore the question both narrowly and more widely. For as we will see, Einstein need not have read just those lines of Poincaré. Clock coordination appeared in the pages of philosophy journals, and even occasionally in physics publications. In fact, electromagnetic clock coordination was so fascinating to the late-nineteenth-century public that the subject came in for close discussion in one of Einstein's favorite childhood books on science.[19] In 1904–05, clock-coordinating cables were thick on the ground and under the seas. Synchronized timepieces were everywhere.

Just as commentators have grown used to interpreting Einstein's talk of trains, signals, and simultaneity as an extended metaphor, a literary-philosophical thought experiment, there is a similarly routine metaphorical reading of Poincaré's observations. Here too, supposedly, stands philosophical speculation, an anticipatory note to Einstein's special theory of relativity, a brilliant move by an author lacking the intellectual courage to pursue it to its logical, revolutionary end. So familiar is this story that it has become a commonplace to treat Poincaré's insight into coordinated time as if it were entirely isolated, a philosophical *aperçu* disconnected from his place in the world. But neither Poincaré nor Einstein was speaking in a vacuum about time.

What, Poincaré asks, are the rules by which scientists judge simultaneity? What *is* simultaneity? His final, most forceful example turned on the determination of longitude. He began by noting that when sailors or geographers determine longitude, they must solve precisely the central problem of simultaneity that governed Poincaré's essay: they must, without being in Paris, calculate Parisian time.

Finding latitude is simple. If the north star is straight overhead, you are on the North Pole; if it is halfway to the horizon, you are at the latitude of Bordeaux; if it is on the horizon, you are at the latitude of Ecuador, on the equator. It does not matter at all what time you make latitude measurements—in any particular location the angle of the pole star is always the same. Finding the longitude difference between two points is famously more difficult: it requires two distant observers to make astronomical measurements *at the same time.* If the earth did not rotate, there would be no problem: you and I would both look up and check which stars were directly under the North Star (for example). By checking a map of the stars we could easily find our relative longitudes. But of course the earth does turn, so to fix longitude differences accurately we must be sure that we are measuring the position of the overhead stars (or sun or planets) at the same time. For example, suppose a map-making team in North America knew the time in Paris and saw that at the team's location the sun rose exactly six hours later than it had in the City of Light. Since the earth takes 24 hours to rotate, the team would know that it was somewhere along a longitude line 6/24 (one-fourth or equivalently 90 degrees) of the way around the world to the west of Paris. But how could the explorers know what time it was back in Paris?

As Poincaré says in his "Measure of Time," the roving cartographer could know Paris time simply by carrying a precision timekeeping device (chronometer) on the expedition, having set it to Paris time. But transporting chronometers led to problems both in principle and in practice. The explorer and his Parisian colleagues could observe an instantaneous celestial phenomenon (such as the emergence of a moon of Jupiter from behind the planet) from their two different locations and declare that their observations were simultaneous. But this seemingly simple procedure isn't. There were practical problems in using Jovian eclipses. Even as a matter of principle, as Poincaré noted, the time would need to be corrected because light from Jupiter travels over different paths to reach the two observation points. Or—and this is the method Poincaré pursues—the explorer could use an electric telegraph to exchange time-signals with Paris:

> It is clear first that the reception of the [telegraph] signal at Berlin, for instance, is after the sending of the same signal from Paris. This is the rule of cause and effect. . . . But how much after? In general, the duration of the transmission is neglected and the two events are regarded as simultaneous. But, to be rigorous, a little correction would still have to be made by a complicated calculation; in practice it is not made, because it would be well within the errors of observation; its theoretic necessity is none the less from our point of view, which is that of a rigorous definition.[20]

Direct intuitions about time, Poincaré concluded, are incompetent to settle questions of simultaneity. To believe so is to fall into illusion. Intuitions must be supplemented by rules of measurement: "No general rule, no rigorous rule; a multitude of little rules applicable to each particular case. These rules are not imposed upon us by themselves, and we might amuse ourselves in inventing others; but they could not be cast aside without greatly complicating the laws of physics, mechanics, and astronomy. We choose these rules, therefore, not because they are true, but because they are the most convenient."[21] All these concepts—simultaneity, time order, equal durations—were defined to make the expression of natural laws as simple as humanly possible. "In other words, all these rules, all these definitions are nothing but the fruit of an unconscious opportunism."[22] Time, according to Poincaré, is a *convention*—not absolute truth.

What time do the map makers make it out to be in Berlin when it is noon in Paris? What time is it down the line when the train pulls into Bern? In posing such questions, Poincaré and Einstein seem, at first glance, to be asking questions of stunning simplicity. As was their answer: two distant events are simultaneous if coordinated clocks at the two locations read the same—noon in Paris, noon in Berlin. Such judgments were inevitably *conventions* of procedure and rule: to ask about simultaneity was to ask how to coordinate clocks. Their proposal: Send an electromagnetic signal from one clock to the other, taking into account the time the signal takes to arrive (at approximately the speed of light). A simple idea of breathtaking consequences for concepts of space and time, for the new relativity theory, for modern physics, for the philosophy of conventionalism, for a world-covering network of electronic navigation, for our very model of secure scientific knowledge.

This is my quarry: how, at the turn of the century, was simultaneity actually produced? How did Poincaré and Einstein both come to think that simultaneity had to be defined in terms of a conventional procedure for coordinating clocks by electromagnetic signals? Addressing these questions demands far too wide a scope to be captured by a biographical approach, though there are, to be sure, too many biographies of Einstein and not enough of Poincaré. Nor is this book a history of philosophical ideas of time, a task that could easily take us back before Aristotle. It is not a comprehensive account of the intricate development of timepieces, even electric ones. And it is not a complete history of the many broadly shared concepts of nineteenth-century electrodynamics that Poincaré and Einstein appropriated as each struggled to reformulate the electrodynamics of moving bodies.

Instead, this is a slice through layers of physics, technology, and philosophy that cuts high and low, an exploration of synchronized clocks crisscrossing back and forth between the wiring of the oceans to marching Prussian armies. It reaches into the heartland of physics, through the philosophy of conventionalism, and back through relativistic physics. Take hold of a wire in the late-nineteenth-century telegraph system and begin to pull: it takes take you down and across the North Atlantic, up onto pebbled beaches of Newfoundland; it tracks from Europe into the Pacific and up into Haiphong Harbor; it slides along the ocean floor the length of West Africa. Follow the land-based wires and the iron and copper cables; they lead up into the Andes, through the backcountry of Senegal, and clear across North America from Massachusetts to San Francisco. Cables run along train lines, under oceans, and between the beachfront shacks of colonial explorers and the chiseled stone of great observatories.

But wires for time did not arrive on their own. They came with national ambitions, war, industry, science, and conquest. They were a visible sign of the coordination among nations in conventions about lengths, times, and electrical measures. Coordinating clocks in the nineteenth and twentieth centuries was never just about a little procedure of signal exchange. Poincaré was an administrator of this global network of electrical time, Einstein an expert at the central Swiss clearinghouse for the new electrotechnologies. Both were also riveted by the electrodynamics of moving bodies and fascinated by philosophical reflections on space and time. Understanding this world-embracing synchronization will take us some way toward understanding what is modern about modern physics and about how Einstein and Poincaré stood at crossing points of their respective modernities.

Surely, we learn from the astonishing contrast between Newton's distant seventeenth- and Einstein and Poincaré's turn-of-the-twentieth century concepts of time. Their two conceptions stand as monuments to a clash between the early modern and the modern: on the one hand, space and time as modifications of the sensorium of God; on the other, space and time as given by rulers and clocks. But the distance between 1700 and 1900 should not eclipse the near at hand. It is the near at hand that interests me—the daily world of 1900 in which it became usual, and not just for Poincaré and Einstein, to see time, conventions, engineering, and physics as of a piece. For those decades it made perfect sense to mingle machines and metaphysics. A century later that propinquity of things and thoughts seems to have vanished.

Perhaps one reason for the difficulty we have in imagining science and technology so caught up with one another is that it has become habitual to divide history into separate scales: intellectual history for ideas that are or aim to be universal; social history for more localized classes, groups, and institutions; biography or microhistory for individuals and their immediate surround. In telling of the relation between the pure and applied, there are narratives that track abstract ideas down through laboratories to the machine-shop floor and into everyday life. There are also stories that run the other way, in which the daily workings of technology are slowly refined as they shed their materiality on the way up the ladder of abstraction until they reach theory—from the shop floor to the laboratory to the blackboard, and eventually to the arcane reaches of philosophy. Indeed, science often does function this way: from the purity of an etherial vapor, ideas may seem to condense into everyday matter; conversely, ideas seem to sublime from the solid, quotidean world into air.

But here neither picture will do. Philosophical and physical reflections did not *cause* the deployment of coordinated train and telegraph time. The technologies were not derivative versions of an abstract set of ideas. Nor did the vast networks of electro-coordinated clocks of the late nineteenth century cause or force the philosophers and physicists to adopt the new convention of simultaneity. No, the present narrative of coordinated time fits neither of these metaphors of progressive evaporation or condensation. Another image is needed.

Imagine an ocean covered by a confined atmosphere of water vapor. When this world is hot enough, the water evaporates; when the vapor cools, it condenses and rains down into the ocean. But if the pressure and heat are such that, as the water expands, the vapor is compressed, eventually the liquid and gas approach the same density. As that critical point nears, something quite extraordinary occurs. Water and vapor no longer remain stable; instead, all through this world, pockets of liquid and vapor begin to flash back and forth between the two phases, from vapor to liquid, from liquid to vapor—from tiny clusters of molecules to volumes nearly the size of the planet. At this critical point, light of different wavelengths begins reflecting off drops of different sizes—purple off smaller drops, red off larger ones. Soon, light is bouncing off at every possible wavelength. Every color of the visible spectrum is reflected as if from mother-of-pearl. Such wildly fluctuating phase changes reflect light with what is known as critical opalescence.

This is the metaphor we need for coordinated time. Once in a great while a scientific-technological shift occurs that cannot be understood in the cleanly separated domains of technology, science, or philosophy. The coordination of time in the half-century following 1860 simply does not sublime in a slow, even-paced process from the technological field upward into the more rarified realms of science and philosophy. Nor did ideas of time synchronization originate in a pure realm of thought and then condense into the objects and actions of machines and factories. In its fluctuations back and forth between the abstract and the concrete, in its variegated scales, time coordination emerges in the volatile phase changes of critical opalescence.

To dig into the records of almost any town in Europe or North America—indeed, far beyond both—reveals the struggle to coordinate time during these years of the late nineteenth century. There lie the yellowing data of railroad superintendents, navigators, and jewelers, but also of scientists, astronomers, engineers, and entrepreneurs. Time coordination was an affair for individual school buildings, wiring their classroom clocks to the principal's office, but also an issue for cities, train lines, and nations as they soldered alignment into their public clocks and often fought tooth-and-nail over how it should be done. Step back to the archives of central governments and the cast of characters grows wider and wilder: anarchists, democrats, internationalists, generals.

Amidst this cacophony of voices, this book aims to show how the synchronizing of clocks became a matter of coordinating not just procedures but also the languages of science and technology. The story of time coordination around 1900 is not one of a forward march of ever more precise clocks; it is a story in which physics, engineering, philosophy, colonialism, and commerce collided. At every moment, synchronizing clocks was both practical and ideal: gutta-percha insulator over ironclad copper wire *and* cosmic time. So variously construed was time regulation that it could serve in Germany as a stand-in for national unity, while in France at the same moment it embodied the Third Republic's rationalist institutionalization of the Revolution.

My aim is to pursue coordinated time through this critical opalescence, and in particular to set Henri Poincaré and Albert Einstein's revamped simultaneity in the thick of it. Entering the sites of time production and the lanes of its distribution will bring us repeatedly to two crucial locations in the binding of clocks that joined Einstein's and Poincaré's transcendent metaphors of clocks and maps to altogether literal places: the Paris Bureau of Longitude and the Bern Patent Office. Standing at those two exchanges, Poincaré and Einstein were witnesses, spokesmen, competitors, and coordinators of the cross-flows of coordinated time.

Order of Argument

Because the fate of coordinated time cannot be tracked from a nuclear group of railroad managers, inventors, or scientists in a simple widening circle, our story will switch scales back and forth between local and global narratives. I want to introduce Poincaré in chapter 2 ("Coal, Chaos, and Convention") in a way that may be somewhat unfamiliar. Who would guess from *Science and Hypothesis*, his best-selling book of 1902, that he had trained as a mining engineer and served as an inspector in the dangerous, hard-pressed coal mines of eastern France? Or that for decades he had helped run the Bureau des Longitudes in Paris, serving as its president in 1899 (and later in both 1909 and 1910)? Or that he co-edited and often published in a major journal on electrotechnology that ran