Einstein's Clocks: The Place of Time

Peter Galison

Einstein, 1933: "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."[1] Solitude, Einstein argued, would be perfect for the young scientist engaged with philosophical and mathematical problems. His own youth, we are tempted to speculate, might be thought of this way, the Bern patent office where he had earned a living seeming no more than a distant oceanic lightship. Consistent with this picture of otherworldliness, we have enshrined Einstein as the philosopher-scientist who, unmindful of the noise from his office work, rethought the foundations of his discipline and toppled the Newtonian absolutes of space and time.

Einstein's removal of these philosophical absolutes was more than a contribution to relativity; it has become a symbol of the overthrow of one philosophical epoch for another. To physicists such as Henri Poincaré, Hendrik Lorentz, and Max Abraham, Einstein's special relativity was startling, almost incomprehensible, because it began with basic assumptions about the behavior of clocks, rulers, and bodies in force-free motion—it began, in short, by assuming what these senior physicists had hoped to prove with starting assumptions about the structure of the electron, the nature of forces, and the dynamics of the ether. Soon a generation of

Unless otherwise indicated, all translations are my own.

1. Albert Einstein, speech delivered at the Royal Albert Hall, London, 3 Oct. 1933, in *Einstein on Peace,* ed. Otto Nathan and Heinz Norden (New York, 1960), p. 238.

Critical Inquiry 26 (Winter 2000)
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physicists, including Werner Heisenberg and Niels Bohr, patterned its quantum epistemology around Einstein's quasi-operational definitions of space and time in terms of rulers and coordinated clocks. For the philosophers of the Vienna Circle, including Moritz Schlick, Rudolf Carnap, and Philipp Frank, Einstein's special relativity paper was also a turning point, an ever present banner to be flown for scientific philosophy.

For all these reasons, Einstein's 1905 "On the Electrodynamics of Moving Bodies" became the best-known physics paper of the twentieth century. Einstein's argument, as it is usually understood, departs so radically from the older, "practical" world of classical mechanics that the work has become a model of the revolutionary divide. Part philosophy and part physics, this rethinking of distant simultaneity has come to symbolize the irresolvable break of twentieth-century physics from that of the nineteenth. Recall the order of the argument. Einstein began with the claim that there was an asymmetry in the interpretation of Maxwell's equations, an asymmetry not present in the phenomena of nature (fig. 1). A magnet approaching a coil produces a current indistinguishable from the current generated when a coil approaches a magnet. In Einstein's view this was a single phenomenon (coil and magnet approach and produce a current in the coil). But in their usual interpretation Maxwell's equations gave two different explanations of what was happening, depending on whether the coil or the magnet was in motion with respect to an all-pervasive ether. When the coil moved, charge within it experienced a force due to the static magnetic field; when the magnet moved, the changing magnetic field produced an electric field that drove the charge around the stationary coil. Einstein's goal was to produce a symmetric account, one that did not distinguish between the explanation given in the frame of reference of the coil and that given in the frame of reference of the magnet. The problem, as Einstein diagnosed it, was that "insufficient consideration" had been paid to the circumstance that electrodynamics always depended on a view about *kinematics*, that is, about how clocks and rulers behaved in the absence of force.[2]

2. Einstein, "Zur Elektrodynamik bewegter Körper," *Annalen der Physik* 17 (1905): 892, hereafter abbreviated "ZE"; trans. Arthur I. Miller, under the title "On the Electrodynamics of Moving Bodies," appendix in *Albert Einstein's Special Theory of Relativity: Emergence (1905)*

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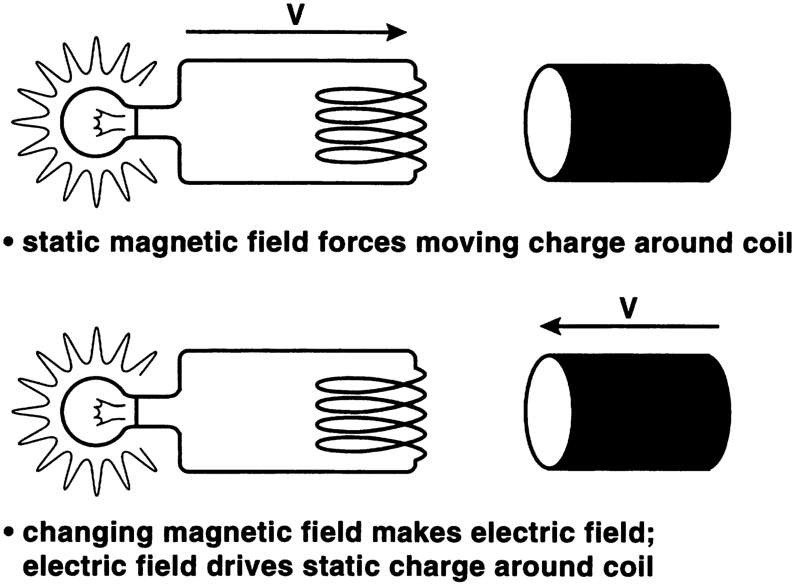

FIG. 1.—Coil and magnet.

A coordinate system was, by Einstein's lights, a system of rigid measuring rods embodying Euclidean geometry and describable with ordinary Cartesian coordinates. So far, so good. Then comes the surprising part, the reanalysis of *time* that contemporaries like Hermann Minkowski saw as the crux of Einstein's argument.[3] 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'" ("ZE," p. 893; "OE," p. 393).[4] For simultaneity *at a point,* there is

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and Early Interpretation (1905–1911) (Reading, Mass., 1981), p. 393, hereafter abbreviated "OE."

3. See Peter L. Galison, "Minkowski's Space-Time: From Visual Thinking to the Absolute World," *Historical Studies in the Physical Sciences* 10 (1979): 85–121.

4. We have all learned to read Einstein's papers in no small measure through the extensive work by Gerald Holton, *Thematic Origins of Scientific Thought: Kepler to Einstein* (Cambridge, Mass., 1973). I also find very helpful the more recent work by Abraham Pais, *Subtle Is the Lord* (Oxford, 1982), and Andrew Warwick, "On the Role of the FitzGerald-Lorentz Contraction Hypothesis in the Development of Joseph Larmor's Electronic Theory of Matter," *Archive for History of Exact Sciences* 43, no. 1 (1991): 29–91, "Cambridge Mathematics and Cavendish Physics: Cunningham, Campbell, and Einstein's Relativity, 1905–1911, Part I: The Uses of Theory," *Studies in the History and Philosphy of Science* 23 (Dec. 1992): 625–56, and "Cambridge Mathematics and Cavendish Physics: Cunningham, Campbell, and Einstein's Relativity, 1905–1911, Part II: Comparing Traditions in Cambridge Physics," *Studies in the History and Philosophy of Science* 24 (Mar. 1993): 1–25; Richard Staley, "On the

no problem: if an event located immediately next to my watch (say, the train engine arriving next to me) happens just when the small hand of the watch reaches the seven, then those two events are said to be simultaneous. The difficulty, Einstein insists, comes when we have to link events at a distance: what would it mean to say two *distant* events are simultaneous?

In order to address this question, Einstein advances, in a seemingly philosophical vein, a thought experiment infinitely far from the exigencies of instruments, much less the daily considerations of patent office life. How, Einstein asks, ought we to *coordinate* our 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" ("ZE," p. 893; "OE, p. 393; trans. mod.). Alas, Einstein notes, because light travels at a finite speed, this system is not independent of the observer with the central clock. Two events judged simultaneous with respect to one origin will not be simultaneous if the origin is moved. This epistemic straw man will not tell good time (figs. 2 and 3).

Young Einstein had a better system: let one observer at *A* send a light signal at noon to another at *B* a distance *d* away. *B* sets his clock to noon plus the time it takes a light signal to get to *B*, noon + d/c, where c is the speed of light. Continuing in this way, all other observers and their clocks are put in synchrony. With this system of coordination there is no special origin; there is no master clock. Here, so the account we have told ourselves goes, is the philosophical triumph of neo-Machian epistemic criticism over the fossilized absolutes of untouchable space and time. Einstein the philosopher-scientist has used thought experiments to vanquish unquestioned school dogma and a scientific-technical cadre too sophisticated to ask basic questions. But wait.

Let's go back to Einstein's train. You will recall that he wants to know what we mean by the arrival of a train in a station at seven o'clock. I have long followed Einstein himself in reading these remarks about trains and simultaneity as an instance of Einstein posing a question normally posed only "in early childhood," a matter that he, peculiarly, was still asking when he "was already grown up."[5] Such riddles about time and space appear, on this reading, to be so elementary, so basic, that they lay below the conscious awareness of the physics community. But was it, in fact, below the threshold of thought? Was no one else in 1904–5 in fact asking

Histories of Relativity: The Propagation and Elaboration of Relativity Theory in Participant Histories in Germany, 1905–11," *Isis* 89 (June 1998): 263–99; and Albrecht Fölsing, *Albert Einstein: A Biography,* trans. Ewald Osers (New York, 1997), p. 155.

5. Quoted in *Helle-Zeit-dunkle Zeit: In Memoriam Albert Einstein,* ed. Carl Seelig (Zurich, 1956), p. 71; trans. in *The Quotable Einstein,* ed. Alice Calaprice (Princeton, N.J., 1996), p. 182.

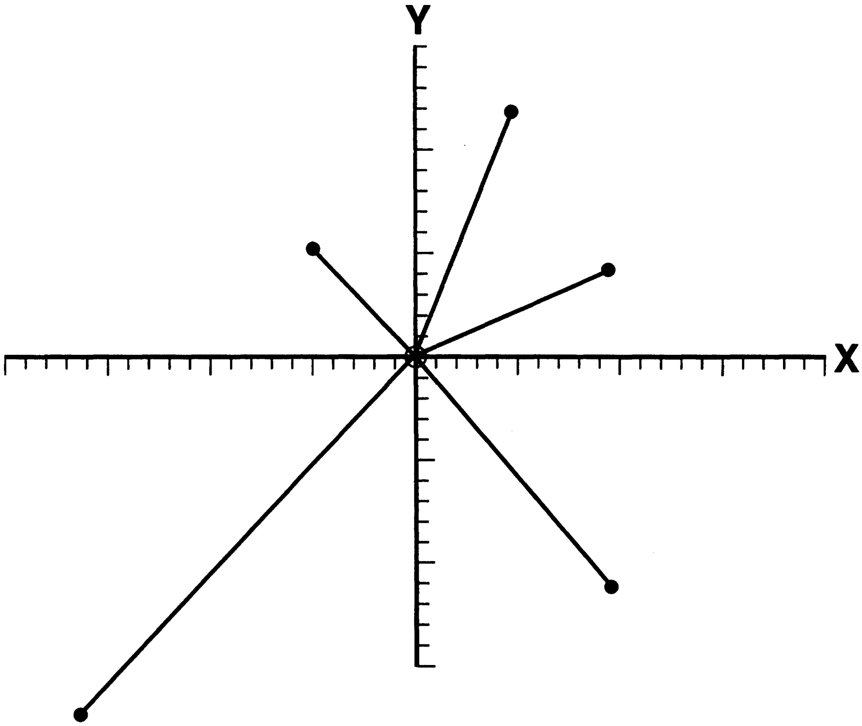

FIG. 2.—Central clock coordination.

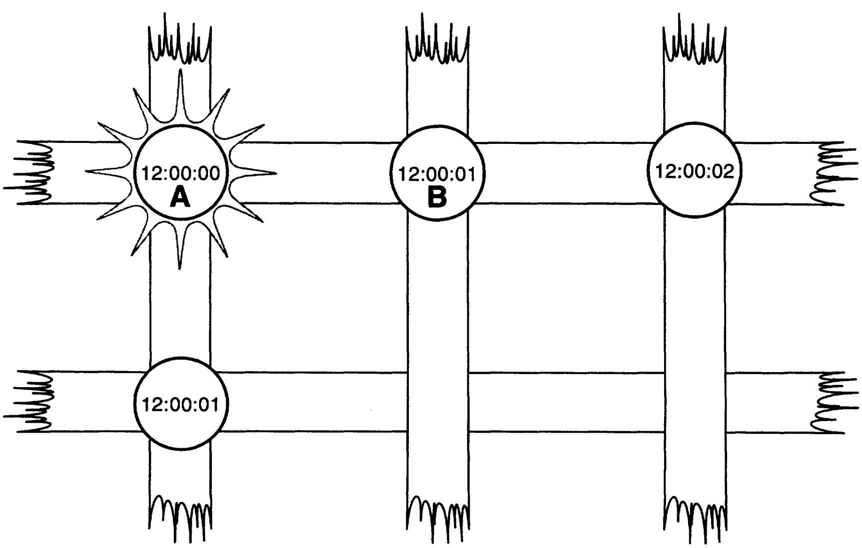

FIG. 3.—Einstein's clock coordination.

FIG. 4.—Bern train station circa 1860–65. Burgerbibliothek Bern, negative 12572.

what it meant for a distant observer to know that a train was pulling into a station at seven o'clock? Was the idea of defining distant simultaneity such a philosophical reach?

This summer I was standing in a northern European train station, absentmindedly staring at the turn-of-the-century clocks that lined the platform. They all read the same to the minute. Curious. Good clocks. But then I noticed that, as far as I could see, even the staccato motion of their second hands was in synchrony. These clocks were not simply running well, I thought, these clocks are coordinated. Einstein must have seen such coordinated clocks while he was grappling with his 1905 paper, trying to understand the meaning of distant simultaneity (fig. 4).

Already in the 1830s and 1840s Charles Wheatstone and Alexander Bain, both in England, and soon thereafter Mathias Hipp in Württemberg and a myriad of other inventors began constructing electrical distribution systems to bind distant clocks to a single central clock, called, variously, the *horloge-mère,* the *Primäre Normaluhr,* and the master clock (figs. 5 and 6).[6] In Germany Leipzig was the site of one of the first such electrically distributed time systems, followed by Frankfurt in 1859; Hipp (then director of a telegraph workshop) launched the Swiss effort at the Federal Palace in Bern, where a hundred clock faces began marching together in 1890 (fig. 7). Geneva, Basel, Neuchâtel, and Zurich followed in quick succession, each with its own clock coordination system, and railroad lines—where clock coordination was vital—were soon rigged in Switzerland for coordinated time.[7]

Without coordinated times, cities, towns, and villages functioned on their own times, marking an individuality that remained unimportant before the railroad. In England during the 1830s London time led Reading time by four minutes, marched seven minutes and thirty seconds in advance of Cirencester, and chimed fourteen minutes before Bridgewater. If you wanted to display time on the front of a major building, you needed more than one clock. The Isle Tower in Geneva boasted three: the big clockface in the center showed Geneva time (about 10:13), the face on the left showed the Paris-based time used all along the track of the Paris-Lyon-Méditerranée railroad company (9:58), and the right-hand clock boasted Bern time—a handsome five minutes in advance (10:18) (fig. 8). A few years later standardization entered the picture (fig. 9) but proceeded line by line—every railroad company defined its own proper time and did so ceremoniously. In London

> each morning an Admiralty messenger carried a watch bearing the correct time to the guard on the down Irish Mail leaving Euston for Holyhead. On arrival at Holyhead the time was passed on to officials on the Kingstown boat who carried it over to Dublin. On the return mail to Euston the watch was carried back to the Admiralty messenger at Euston once more.[8]

6. Remotely set clocks were discussed by, among others, Charles Wheatstone and William Cooke, the Scottish clockmaker Alexander Bain, and the American inventor Samuel F. B. Morse. For Wheatstone, Cooke, and Morse, clock coordination came out of their work on telegraphy. See Kenneth F. Welch, *Time Measurement: An Introductory History* (Newton Abbot, 1972), pp. 71–72.

7. For discussions of the extensive work on clock coordination before 1900, see, for example, the series of articles by A. Favarger, "L'Électricité et ses applications à la chronométrie," *Journal suisse d'horlogerie* 9 (Sept. 1884–June 1885), esp. pp. 153–58; Favarger, "Les Horloges électriques," in *Histoire de la pendulerie neuchâteloise,* ed. Alfred Chapuis (Paris, 1917), pp. 399–420; Friedrich Anton Leopold Ambronn, *Handbuch der astronomischen Instrumentenkunde,* 2 vols. (Berlin, 1899), esp. 1:183–87. On the expansion of the Bern network, see Gesellschaft für elektrische Uhren in Bern, *Jahresberichte* (1890–1910), Stadtarchiv Bern.

8. Philip S. Bagwell, *The Transport Revolution from 1770* (London, 1974), p. 125; quoted in Wolfgang Schivelbusch, *The Railway Journey: Trains and Travel in the Nineteenth Century,* trans. Anselm Hollo (New York, 1980), pp. 48–50.

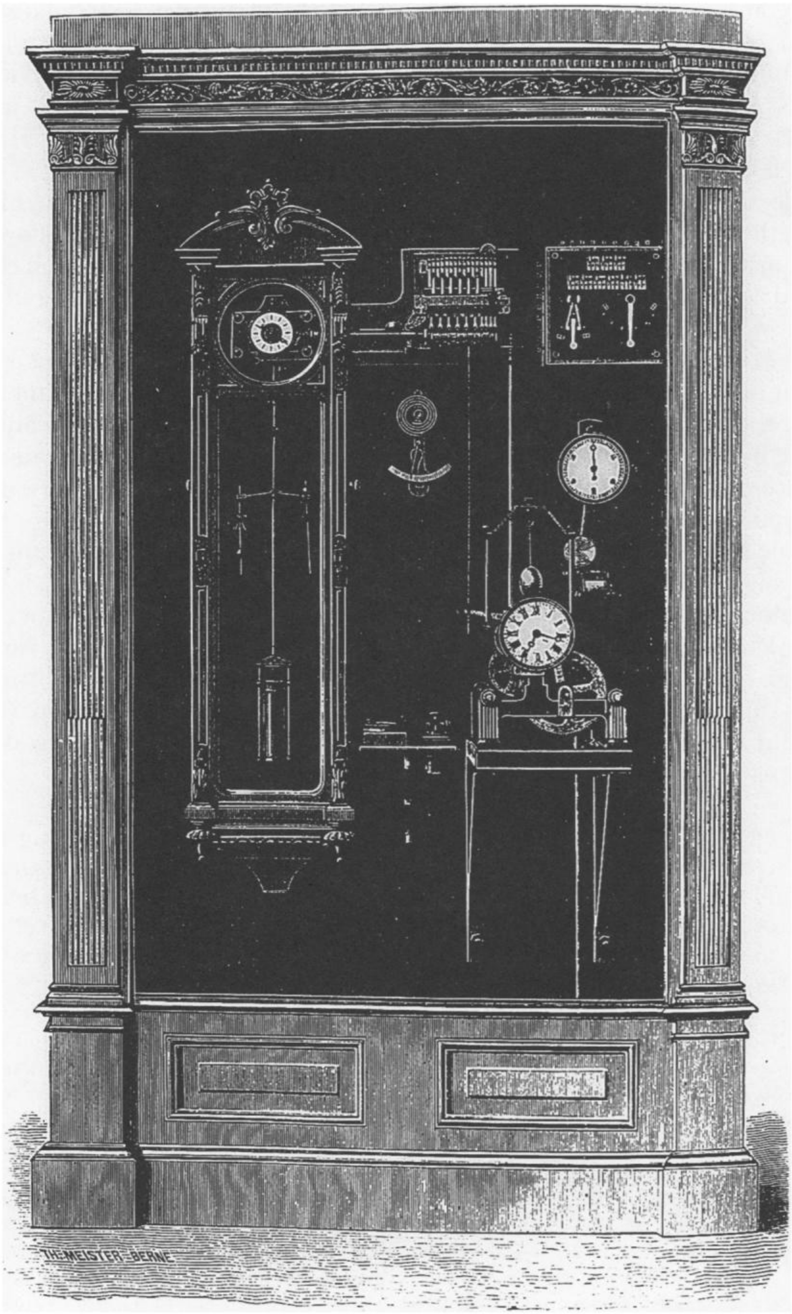

FIG. 5.—L'Horloge-mère, Neuchâtel. From A. Favarger, *L'Électricité et ses applications à la chronométrie* (Neuchâtel, 1924), p. 414.

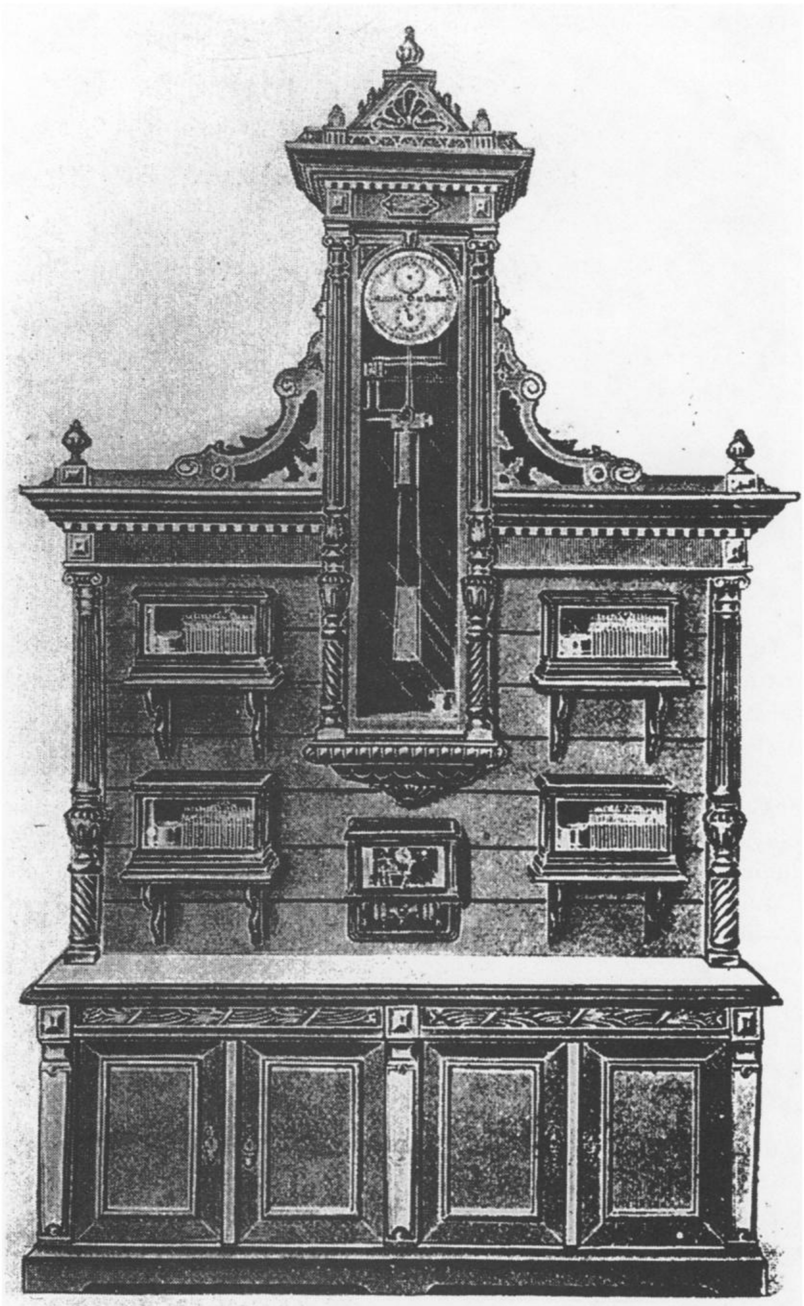

FIG. 6.—Normaluhr, Silesischer Bahnhof. From A. Favarger, *L'Électricité et ses applications à la chronométrie,* p. 470.

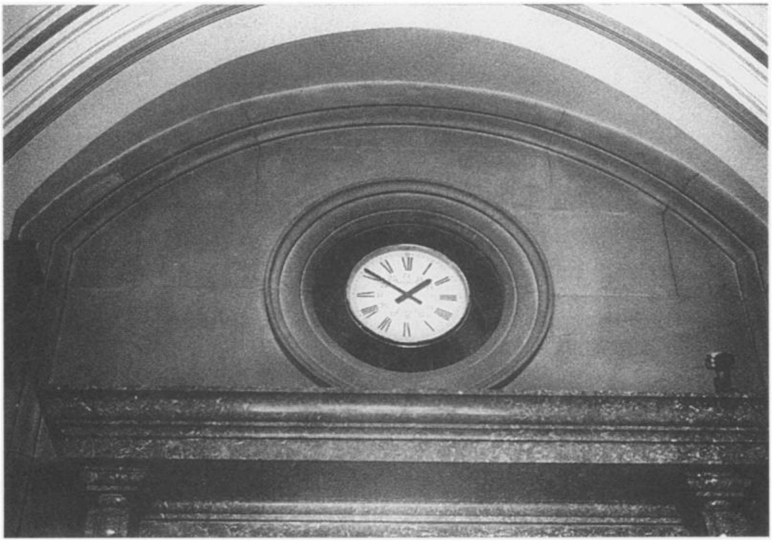

FIG. 7.—Coordinated clock, Federal Palace, Bern. Photo: author.

Germany, by most accounts the most advanced in its efforts to coordinate time, was still struggling with a hodgepodge of mechanical and electrical systems in 1891, when the aging Count Helmuth von Moltke came to speak, for the last time, to the Imperial German Parliament on 16 March; he died just over a month later.[9] As chief of the Prussian (and later German) general staff, von Moltke had dramatically reconceived the deployment of troops. Where earlier generations had sent armies over undependable roads, von Moltke exploited the railroads to supply, muster, and move troops over vast battlefronts. His successes with this strategy—in the Franco-Prussian War—no doubt brought the audience to attention when von Moltke pronounced on railroads, empire, and the military. In his scratchy voice he intoned:

> *Meine Herren,* . . . I will not long detain you, as I am very hoarse, on which account I have to ask your indulgence.
>
> That unity of time *[Einheitszeit]* is indispensable for the satisfactory operating of railways is universally recognized, and is not disputed. But, *meine Herren,* we have in Germany five different units of time. In north Germany, including Saxony, we reckon by Berlin time; in Bavaria, by that of Munich; in Württemberg, by that of Stuttgart;

9. The establishment of uniform time is discussed in Stephen Kern, *The Culture of Time and Space, 1880–1918* (Cambridge, Mass., 1983), pp. 11–14, and in Derek Howse, *Greenwich Time and the Discovery of Longitude* (Oxford, 1980), pp. 119–20. Simon Schaffer uses H. G. Wells's time machine as a guide through the turn-of-the-century intersection of the mechanized workplace and the literary and scientific engagement with time in "Time Machines" (unpublished manuscript, University of Cambridge).

FIG. 8.—Isle Tower, Geneva, 1880, three clocks. Centre d'iconographie genevoise. RVG N13x18 14934.

FIG. 9.—Isle Tower, Geneva, 1880, one clock. Centre d'iconographie genevoise. VG N13x18 1769.

> in Baden, by that of Carlsruhe; and on the Rhine Palatinate by that of Ludwigshafen. We have thus in Germany five zones, with all the drawbacks and disadvantages which result. These we have in our own fatherland, besides those we dread to meet at the French and Russian boundaries. This is, I may say, a ruin which has remained standing out of the once splintered condition of Germany, but which, since we have become an empire, it is proper should be done away with.

From the audience came the call "very true." Von Moltke went on to say that while this piecemeal ruin of time may only be an inconvenience for the traveler, it was an "actual difficulty of vital importance" for the railway business and, even worse, for the military. What, he asked, would happen in case of troop mobilization? There had to be a standard, one that would fall along the fifteenth meridian (about fifty miles east of the Brandenburg Gate) that would be the reference point. Local times within Germany would differ, but by a mere half hour or so on either extreme of the empire. "*Meine Herren,* unity of time merely for the railway does not set aside all the disadvantages which I have briefly mentioned; that will only be possible when we reach a unity of time reckoning for the whole of Germany, that is to say, when all local time is swept away."[10]

Von Moltke conceded that the public might dissent—wrongfully. But after some "careful consideration" the scientific men of the observatories would see things aright, and lend "their authority against this spirit of opposition." "*Meine Herren,* science desires much more than we do. She is not content with a German unity of time, or with that of middle Europe, but she is desirous of obtaining a world time, based upon the meridian of Greenwich, and certainly with full right from her standpoint, and with the end she has in view."[11] Farms and factory workers can offset their clock starting times as they wish. If a manufacturer wants his workers to start at the crack of dawn, then let him open the gates at 6:29 in March. Let the farmers follow the sun, let the schools and courts make do with their always loose schedules. Germany took action to extend its dominion of time, and much of Europe followed.

In Switzerland, the clock-world-famous Hipp (despite being arrested for consorting with anarchists) went on from his development of electrically maintained pendula to the practical deployment of a distribution system for time using low-tension circuits. Founded as a small telegraph

10. Helmuth von Moltke, "Dritte Berathung des Reichshaushaltsetats: Reichseisenbahnamt Einheitszeit," *Gesammelte Schriften und Denkwürdigkeiten des General-Feldmarschalls Grafen Helmuth von Moltke,* 8 vols. (Berlin, 1891–93), 7:38–39, 39, 40; trans. Sandford Fleming, under the title "General von Moltke on Time Reform," in *Documents Relating to the Fixing of a Standard of Time and the Legalization Thereof,* Canada Parliament Session 1891, no. 8, pp. 25, 25, 26; trans. mod.

11. Von Moltke, "Dritte Berathung des Reichshaushaltsetats: Reichseisenbahnamt Einheitszeit," p. 40; Fleming, "General von Moltke on Time Reform," p. 26; trans. mod.

and electrical apparatus factory in Neuchâtel, Hipp's company went from the establishment of the first network of public electric clocks in Geneva in 1861 to ever greater prominence; in 1889, it became A. de Peyer, A. Favarger & Cie. From 1889 to 1908 this concern extended the range of the mother clock beyond the dominion of railways to steeple clocks and even to the wake-up clocks inside hotels.[12] With the march of time into every street, methods were needed to extend indefinitely the number of units that could be branched together—a flood of patents followed perfecting relays and signal amplifiers. The Bern urban time network was inaugurated in 1890; improvements, expansions, and new networks sprouted throughout Switzerland. For not only was accurate, coordinated time important for European passenger railroads and the Prussian military, it was equally crucial for the dispersed Swiss clock-making industry that desperately needed means of consistent calibration.[13] But it was always practical and more than practical, at once material-economic necessity *and* cultural imaginary. Professor Wilhelm Förster of the Berlin Observatory, the observatory that set the Berlin master clock to the heavens, sniffed that any urban clock that did not guarantee time to the nearest minute was a machine "downright contemptuous of people."[14]

The burgeoning technology spun off patents in each sector of the network: patents on low-voltage generators, patents on electromagnetic receivers with all their escapements and armatures, patents on contact interrupters. Fairly typical of the kind of electrochronometric work blossoming in the years after 1900 was David Perret's novel receiver that would detect and use a direct-current chronometric signal to drive an oscillating armature, which was issued Swiss patent number 30351 at 5 P.M. on 12 March 1904. Or take Favarger's own receiver that did the opposite: it took an alternating current from the mother clock and turned it into the unidirectional motion of a toothed wheel. This patent—used widely—was submitted on 25 November 1902 and issued on 2 May 1905. There were patents on remote alarms, remote regulation of pendula, telephonic—even wireless—transmission of time; other patents arrived proposing clocks for railroad departures and arrivals, in addition to patents for clocks indicating time in other time zones (fig. 10).

12. For biographical details on Hipp, see Aymon de Mestral, *Mathias Hipp, 1813–1893; Jean-Jacques Kohler, 1860–1930; Eugène Faillettaz, 1873–1943; Jean Landry, 1875–1940* (Zurich, 1960), pp. 9–34. David S. Landes's work, *Revolution in Time: Clocks and the Making of the Modern World* (Cambridge, Mass., 1983), pp. 237–337, is excellent on the Swiss watch industry, though he is not focussed here on networks but rather on clock production.

13. See Favarger, *L'Électricité et ses applications à la chronométrie,* 3d ed. (Neuchâtel, 1924), pp. 408–9.

14. Gerhard Dohrn-van Rossum, *History of the Hour: Clocks and Modern Temporal Orders,* trans. Thomas Dunlap (Chicago, 1996), p. 350. See also Ulla Merle, "Tempo! Tempo! Die Industrialisierung der Zeit im 19. Jahrhundert," in *Uhrzeiten: Die Geschichte der Uhr und ihres Gebrauches,* ed. Igor A. Jenzen (Frankfurt am Main, 1989), pp. 166–78.

All these chronometric patents—along with a great many others related to them—had to pass through the Swiss patent office in Bern, and no doubt many of them crossed Einstein's desk.[15] Einstein began work in the Bern patent office on 16 June 1902 as technical expert, third class, where he was chiefly charged with the evaluation of electromagnetic patents.[16] Standing at his wooden podium he, like the other twelve or so technical experts in the patent office, methodically went through each submission, searching for the principles that lay at its core (fig. 11).[17] Einstein's expertise on electromechanical devices came in part from the family business. Indeed, Einstein's father, Hermann, and his uncle, Jakob Einstein, had built their enterprise out of his uncle's patents on sensitive, electrical clocklike devices for measuring electrical usage. One of J. Einstein & Cie.'s electrical meters, created by Jakob and Sebastian Kornprobst, was written up prominently in the report of the 1891 Frankfurt Electrotechnical Exhibit; just a few pages before is a mechanism (typical of the time) for mounting a backup mother clock to ensure the continued operation of a system of electrical clocks. So close were the electrical measuring systems and clockwork technologies that at least one of the Jakob Einstein-Sebastian Kornprobst patents explicitly registered its applicability to clockwork mechanisms more generally (fig. 12).[18]

Einstein's own later technical work (he held a great many patents) on what he called his *Machinchen* (a device for multiplying and measuring very small electrical charges) and his studies of the Einstein-de Haas effect (leading to his atomic theory of ferromagnetic atoms) were but two further examples of his particular interest in sensitive electromechanical

15. Hundreds of relevant patents are listed in the *Journal suisse d'horlogerie* during the relevant years (1902–5). Sadly, the Swiss patent office dutifully destroyed all papers processed by Einstein eighteen years after their creation; this was standard procedure on patent opinions, and even Einstein's fame led to no exception. See Fölsing, *Albert Einstein,* p. 104.

16. The most detailed linkage between Einstein's patent work and his scientific work is on gyromagnetic compasses and Einstein's production of the Einstein-de Haas effect. See Galison, *How Experiments End* (Chicago, 1987), chap. 2; in addition, see Thomas Hughes, "Einstein, Inventors, and Invention," *Science in Context* 6 (Spring 1993): 25–42, and Lewis Pyenson, *The Young Einstein: The Advent of Relativity* (Bristol, 1985). On Einstein's assignment to evaluate electrical patents, see Max Flückiger, *Albert Einstein in Bern: Das Ringen um ein neues Weltbild: Eine dokumentarische Darstellung über den Aufstieg eines Genies* (Bern, 1974), p. 62.

17. See Flückiger, *Albert Einstein in Bern,* p. 66.

18. See J. Einstein & Cie. and Sebastian Kornprobst, "Vorrichtung zur Umwandlung der ungleichmässigen Zeigerausschläge von Elektrizitäts-Messern in eine gleichmässige, gradlinige Bewegung," Kaiserliches Patentamt no. 53546, 26 Feb. 1890; "Neuerung an elektrischen Mess- und Anzeigervorrichtungen," Kaiserliches Patentamt no. 53846, 21 Nov. 1889; "Federndes Reibrad," Kaiserliches Patentamt no. 60361, 23 Feb. 1890; and "Elektrizitätszähler der Firma J. Einstein & Cie., München (System Kornprobst)," *Offizielle Zeitung der Internationalen Elektrotechnischen Ausstellung,* no. 28 (Oct. 1891): 949. See also Viktor Yakovlevitch Frenkel and Boris Efimovitch Yavelov, *Einshtein: Izobreteniia i eksperiment* (Einstein: invention and experiment) (Moscow, 1990), pp. 75–79, and Pyenson, *The Young Einstein,* pp. 39–53.

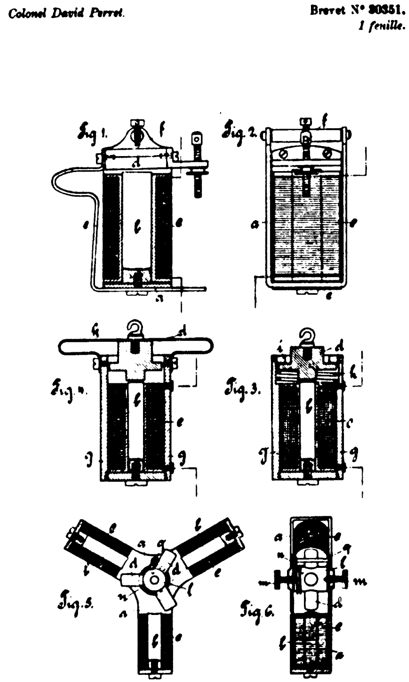

FIG. 10.—Swiss patent 30351 issued to David Perret, "Electro-aimant cuirassé," 12 March 1904.

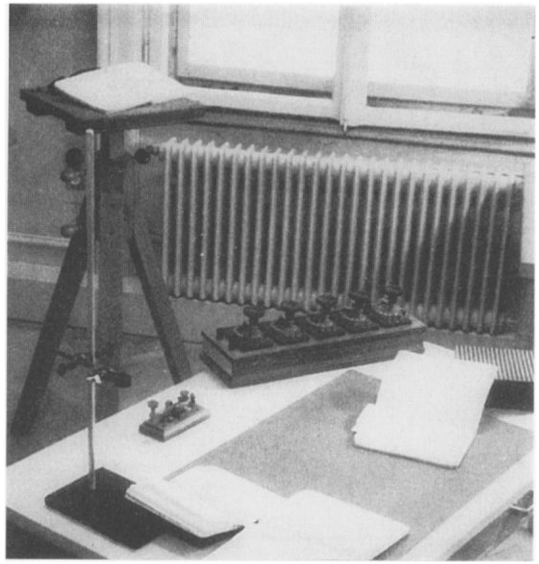

FIG. 11.—Einstein's podium, Bern patent office. From: Max Flückiger, *Albert Einstein in Bern: Das Ringen um ein neues Weltbild: Eine dokumentarische Darstellung über den Aufstieg eines Genies* (Bern, 1974), p. 57.

FIG. 12.—Jakob Einstein & Cie. Elektrotechnische Fabrik. Elektrizität. *Offizielle Zeitung der Internationalen Elektrotechnischen Ausstellung, Frankfurt am Main, 1891,* ed. H. Massenbach and Max Quarck, 20 Oct. 1891, p. 949.

devices. Electromagnetic clock coordination patents would have been right up his alley, as they centered around means of transforming small electrical currents into high-precision rotatory movements.[19]

Heading the patent office during Einstein's tenure was Friedrich Haller, a stern taskmaster to his underlings. Early on he reproached Einstein: "As a physicist you understand nothing about drawings. You have got to learn to grasp technical drawings and specifications before I can make you permanent."[20] In September 1903 Einstein received notice that his provisional appointment was permanent, though Haller was not ready to promote him, commenting that Einstein "should wait until he has fully mastered machine technology; he studied physics." That mastery came as Einstein plunged himself into the critical evaluation of the parade of patents that came before him. By April 1906 Einstein seems to have persuaded the authorities that, physics notwithstanding, he had indeed mastered the technology, and he was promoted to technical expert, second class. Haller now judged that Einstein "belongs among the most esteemed experts at the office."[21]

Einstein's window on the electrochronometric world came at a crucial time. For despite von Moltke's resounding support and the undamped enthusiasm of the advocates of one world time, Albert Favarger, one of Hipp's chief engineers and the man who effectively succeeded him at the helm of his company, was not at all content. At the 1900 Exposition Universelle, the International Congress on Chronometry met to discuss the status, inter alia, of clock coordination efforts (fig. 13).[22] At the outset of his speech to the congress Favarger rose to ask how it could be that the distribution of electrical time was running so distressingly far behind the related technologies of telegraphy or telephony. First, he suggested, there were technical difficulties; remotely coordinated clocks could rely on no obliging friend ("ami complaisant") to oversee and correct the least difficulty, whereas the steam engine, dynamo, or telegraph all seemed to run with constant human companionship ("SD," p. 198). Second, there was a technician gap: the best technical people were staffing power and communication devices, not time machines. And finally, he lamented, the public was not funding time distribution as it should. Such lagging boosterism baffled Favarger: "Could it be possible that we have not experi-

19. On the "little machine" *(Machinchen)*, see John Stachel et al., "Einstein's 'Machinchen' for the Measurement of Small Quantities of Electricity," editorial note in *The Swiss Years: Correspondence, 1902–1914*, vol. 5 of *The Collected Papers of Albert Einstein*, trans. Anna Beck, ed. Stachel et al. (Princeton, N.J., 1995), pp. 51–55; on the Einstein-de Haas effect, see Galison, *How Experiments End*, chap. 2, and Frenkel and Yavelov, *Einshtein*, chap. 4.

20. Quoted in Flückiger, *Albert Einstein in Bern*, p. 58.

21. Quoted in Pais, *Subtle Is the Lord*, pp. 47–48.

22. See Favarger, "Sur la distribution de l'heure civile," in Congrès International de Chronométrie, *Comptes rendues des travaux, procès-verbaux, rapports, et mémoires*, ed. E. Fichot and P. de Vanssay (Paris, 1902), pp. 198–203; hereafter abbreviated "SD."

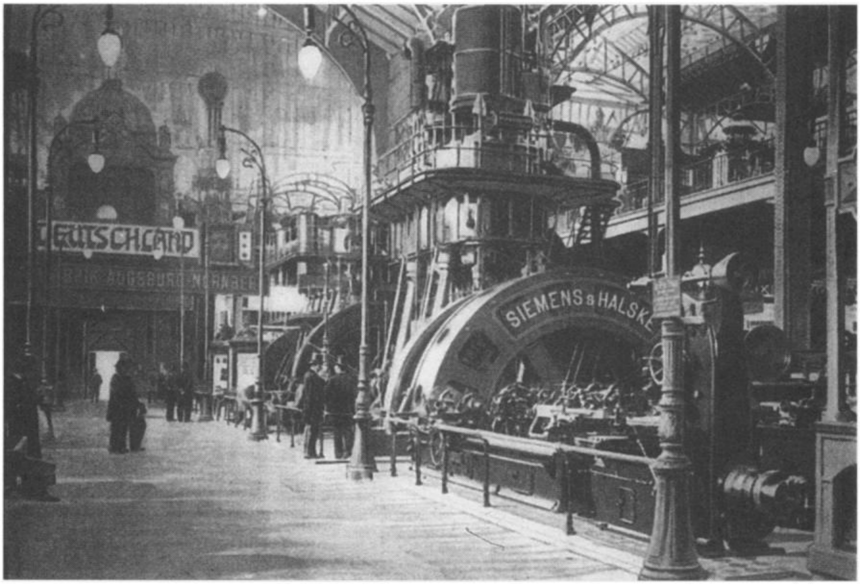

FIG. 13.—Exposition Universelle. From *Encyclopédie du siècle: L'Exposition de Paris de 1900* (Paris, 1900).

enced the imperious, absolute, I would say collective need of time exactly, uniformly, and regularly distributed? . . . Here's a question that borders on impertinence when addressed to a late nineteenth-century public, laden with business and always rushed, a public that has made its own the famous adage: Time is money" ("SD," p. 199).

As far as Favarger was concerned, the sorry state of time distribution was all out of proportion with the exigencies of modern life. He insisted that humans needed a system of exactitude and universality correct to the nearest second. No old-fashioned mechanical, hydraulic, or pneumatic system would do—electricity was the key to the future, a future that would only come about properly if humankind broke with its mechanical clock past riven by anarchy, incoherence, and routinization. In its place, a world of electrocoordinated clocks must be based on a rational and methodical approach. As he put it,

> You don't have to run long errands through Paris to notice numerous clocks, both public and private, that disagree—which one is the biggest liar? In fact if even just one is lying one suspects the sincerity of them all. The public will only gain security when every single clock indicates unanimity at the same time at the same instant. ["SD," p. 200]

How could it be otherwise? Trains often barreled through the countryside in opposite directions on single tracks, and a shunting error of timekeeping could and did lead to calamity. Remote time regulation merging observatories, railroads, and telegraphy was all that stood between a smooth ride and smoking debris. Time went up for sale, and astronomers, telegraphers, and clockmakers all profited as they sent coordinated time down the railway lines. The first time zones were these long, thin territories carved by steel tracks.[23]

Favarger reminded the assembled exposition attendees that the speed of trains roaring through Europe was mounting—100, 150, even 200 kilometers per hour. Those running the trains and directing their movements—not to speak of the passengers trusting their lives to speeding carriages—had to have correct times. At fifty-five meters per second every tick counted, and the prevalent but obsolete mechanical systems of coordination were bound to be inferior. Only the electric, automatic system was truly appropriate: "The nonautomatic system, the most primitive yet the most widespread, is the direct cause of the time anarchy that we must escape" ("SD," p. 201).

Time anarchy. No doubt Favarger's reference was in part to the anarchism that had taken a powerful hold among the Jura watchmakers, as Pyotr Kropotkin testified in his *Memoirs of a Revolutionist.* To be sure, Kropotkin recorded, the theoretical issues raised by Bakunin and others against economic despotism were important,

> but the equalitarian relations which I found in the Jura Mountains, the independence of thought and expression which I saw developing in the workers, and their unlimited devotion to the cause appealed even more strongly to my feelings; and when I came away from the mountains, after a week's stay with the watchmakers, my views upon socialism were settled. I was an anarchist.[24]

Hipp himself had been arrested, but Favarger was clearly worried about more, about the broader disintegration of personal and societal regularity. Only electrical distribution of simultaneity could provide the "indefinite expansion of the time unification zone" ("SD," p. 202). Favarger's support for distant simultaneity was, all at once, political, profitable, and pragmatic.

Should we be able to escape from this dreaded "anarcho-clockism," we would have a chance to fill a great lacuna in our knowledge of the world. For, Favarger insisted, even as the International Bureau of Weights and Measures had begun to conquer the first two fundamental quanti-

23. See Carlene Stephens, "'The Most Reliable Time': William Bond, the New England Railroads, and Time Awareness in Nineteenth-Century America," *Technology and Culture* 30 (Jan. 1989): 1–24 and "Before Standard Time: Distributing Time in Nineteenth-Century America," *Vistas in Astronomy* 28, pts. 1–2 (1985): 114–15.

24. Peter Kropotkin, *Memoirs of a Revolutionist,* trans. pub. (Montreal, 1989), p. 267.

ties—space and mass—time, the final frontier, remained unexplored (see "SD," p. 203). And the way to conquer time was to create an ever widening electrical network, enslaved to an observatory-linked mother clock that would drive relays multiplying its signals and send automatic clock resets into hotels, street corners, and steeples across continents. Tied in part to Favarger was a company that aimed to synchronize Bern's network. When, on 1 August 1890, Bern set the hands of its coordinated clocks in motion, the press hailed it as a "revolution in clocks."[25] It must not be forgotten that from many places in Bern you could clearly see several grand public clocks; when, that August, they all began running in step, time order became visible.

Swiss newspapers were not alone in seeing clock coordination as a matter of wide cultural import. To North American time booster Sandford Fleming and his allies in the 1890s the establishment of "universal" or "cosmic" time was both practical and more than practical—a boon to communication and transportation but also a "noiseless revolution" that would bring progress in all spheres of cultural and personal life.[26]

During the 1890s Einstein was not yet concerned about clocks at all; but as a young man of sixteen in 1895 he was already very much concerned with the nature of electromagnetic radiation. Even to his untutored imagination something was wrong with the customary conception of radiation as a wave in static, substantial ether. Suppose, he thought to himself, that one could catch up to a light wave—as classical physics might infer. Then, like a surfer riding an ocean wave train, he would see the electromagnetic field unfold before him oscillating in space but utterly unchanging in time. However, this corresponded to nothing ever observed.[27] Four years later Einstein was still agonizing over the nature of moving bodies and electrodynamics. To his beloved Mileva Marić he reiterated his sense that naive ether theories would simply have to go.

> D[ear] D[ollie],
> I returned the Helmholtz volume and am now rereading Hertz's propagation of electric force with great care because I didn't understand Helmholtz's treatise on the principle of least action in electrodynamics. I'm convinced more and more that the electrodynamics of moving bodies as it is presented today doesn't correspond to reality, and that it will be possible to present it in a simpler way. The introduction of the term "ether" into theories of electricity has led to the

25. Quoted in Jakob Messerli, *Gleichmässig pünktlich schnell: Zeiteinteilung und Zeitgebrauch in der Schweiz im 19. Jahrhundert* (Zurich, 1995), p. 126.

26. Fleming, *Time-Reckoning for the Twentieth Century* (Washington, D.C., 1889), p. 357. See Ian R. Bartky, "The Adoption of Standard Time," *Technology and Culture* 30 (Jan. 1989): 41 for links of Fleming to Cleveland Abbe and other meteorologists.

27. See Einstein, "Autobiographical Notes," in *Albert Einstein: Philosopher-Scientist*, ed. Paul Arthur Schilpp, 3d ed. (La Salle, Ill., 1970), p. 53.

> conception of a medium whose motion can be described, without, I believe, being able to ascribe physical meaning to it.[28]

Electricity and magnetism, Einstein concluded, would be definable as the motion of "true" electrical masses with physical reality through empty space. Ether, the centerpiece of nineteenth-century physical theories, was gone. So before Einstein set foot into the patent office crucial pieces of the relativity puzzle were in place: he knew Maxwell's equations, he was committed to a realistic picture of moving electrical charges, and he had dismissed the ether. But none of these considerations directly bore on the problem of how to treat time.

Meanwhile, some of the greatest physicists of the nineteenth century were beginning, out of desperation, to experiment with mathematical variations in the way the time variable t transformed in different reference frames. But all of them—Poincaré, Lorentz, Abraham—kept firmly to the notion of a true ether rest frame, and none of them accorded equal weight to these local times and the true (absolute) physical time of the ether rest system. Poincaré, Lorentz, and Abraham wanted to *begin* with special assumptions about the basic forces of nature, the forces that held together the atomic building blocks of interferometer arms, the forces that kept electrons from exploding because of their electrostatic self-repulsion. Out of such constructive, built-up theories of matter they sought to *deduce* kinematics—the behavior of matter in the absence of force. Einstein wanted none of that; he aimed for a theory that would start with simple physical principles, the way thermodynamics began with the conservation of energy and the increase of entropy. Poincaré, Lorentz, and Abraham were willing to make special assumptions about how an artificial, calculation-useful notion of time varied from frame to frame. None of them launched their detailed physics with a physical, principled set of assumptions about measured space and coordinated time.

So things stood in the years after Einstein arrived at the patent office in 1902.[29] In his patent work he had, in the instructions given by Haller,

28. Einstein to Mileva Marić, 10? Aug. 1899, in Einstein and Marić, *The Love Letters*, trans. Shawn Smith, ed. Jürgen Renn and Robert Schulmann (Princeton, N.J., 1992), p. 10. On Einstein's specific knowledge of aspects of electrodynamics, see Holton, "Influences on Einstein's Early Work," *Thematic Origins of Scientific Thought*, and Miller, *Albert Einstein's Special Theory of Relativity*.

29. Here is not the place to offer a reconstruction of all aspects of Einstein's path to special relativity. The reader is referred to an excellent short synthesis in Stachel et al., "Einstein on the Special Theory of Relativity," editorial note in *The Swiss Years: Writings, 1900–1909*, vol. 2 of *The Collected Papers of Albert Einstein*, ed. Stachel et al. (Princeton, N.J., 1989), pp. 253–74, esp. pp. 264–65, which argues that the rough sequence of Einstein's work was (1) conviction that only relative motion of ponderable bodies was significant; (2) abandonment of Lorentz's assignment of physical significance to absolute motion; (3) exploration of alternative electrodynamics justifying emission hypothesis of light relative to source; (4) abandonment of this alternative electrodynamics as Einstein assumes velocity of

the directive to be critical at every stage: "When you pick up an application, think that anything the inventor says is wrong." To follow blindly would be to court disaster by following "the inventor's way of thinking, and that will prejudice you. You have to remain critically vigilant."[30] It was advice for patent work, but it applied as well to the ethereal realms of physics. For in the electrodynamics of moving bodies Einstein had a problem that had troubled him on and off for some seven years, a problem that was with increasing force agonizing the leading physicists of the day. Meanwhile, all around him, literally, was the burgeoning fascination with electrocoordinated time. Every day Einstein took the short stroll from his house, left down the Kramgasse, to the patent office; every day he must have seen the great clock towers that presided over Bern with their coordinated clocks, and the myriad of street clocks branched proudly to the central telegraph office. After all, he had to walk under one of the most famous of them, the Zeitglockenturm, and by many others (figs. 14, 15, and 16). Sometime in the middle of May 1905—and we note that Einstein moved to the edge of Bern's unified time zone on 15 May—he and his closest friend, Michel Besso, cornered the electromagnetism problem from every side. "Then," Einstein recalled, "suddenly I understood where the key to this problem lay." He skipped his greetings the next day when he met Besso: "'Thank you; I've completely solved the problem.' An analysis of the concept of time was my solution. Time cannot be absolutely defined, and there is an inseparable relation between time and signal velocity."[31] Pointing up at a Bern clock tower—one of the famous synchronized clocks in Bern—and then to a clock tower in nearby Muri (not yet linked to the Bern mother clock), Einstein laid out his synchronization of clocks (figs. 17 and 18).[32]

Within a few days Einstein sent off a letter to his friend Conrad Habicht imploring him to send a copy of his dissertation and promising four new papers in return. "The fourth paper is only a rough draft at this point, and is an electrodynamics of moving bodies which employs a modification of the theory of space and time; the purely kinematic part of this paper [beginning with the new definitions of time synchronization] will surely interest you."[33] Ten years of thought had gone into this problem,

light independent of the velocity of the source; (5) critique of the usual conception of temporal and spatial intervals, and especially of distant simutaneity; and (6) physical definition of simultaneity and the construction of a new kinematic theory. Here my focus is on (5), the introduction of a conventional notion of distant simultaneity.

30. Quoted in Flückiger, *Albert Einstein in Bern,* p. 58.

31. Einstein, "How I Created the Theory of Relativity," lecture, Kyoto, 14 Dec. 1922, trans. Yoshimasa A. Ono, *Physics Today* 35 (Aug. 1982): 46.

32. See Josef Sauter, "Comment j'ai appris à connaître Einstein," in Flückiger, *Albert Einstein in Bern,* p. 156, and Fölsing, *Albert Einstein,* p. 155.

33. Einstein to Conrad Habicht, Bern, [18 or 25 May 1905], *The Swiss Years: Correspondence, 1902–1914,* p. 20.

FIG. 14.—Kramgasse Zeitglockenturm, Bern, 1890. Burgerbibliothek Bern, negative 10379.

FIG. 15.—Electrical street clock, northeast corner of Kesslergasse (today Münstergasse), Bern, circa 1893–1900. Large format postcard. Burgerbibliothek Bern, negative 10382.

but time synchronization was the final, crowning step in the development of special relativity.

In this light, Einstein's paper, completed by the end of June 1905, can now be read in a very different fashion. Instead of a pure "Einstein philosopher-scientist" merely earning his keep in the patent office, we can see him also as "Einstein patent-officer-scientist" refracting the underlying metaphysics of his relativity theory through some of the most symbolized mechanisms of modernity. The train arrives in the station at seven o'clock, as before, but now it is not just Einstein who is worried about what this means in terms of distant simultaneity. No, determining train arrival times using electromagnetically coordinated clocks was *precisely* the technological issue that had been racking Europe. Patents now raced through the system, improving the electrical pendula, altering the receivers, introducing new relays, and expanding system capacity. Time coordination in the central Europe of 1902–5 was no arcane subject; it was front and center for the clock industry, the military, and the railroad *as well as* a symbol of the interconnected, sped-up world of modernity.

By addressing the problem of distant simultaneity, Einstein was engaging a powerful and highly visible new technology that conventionalized simultaneity, first to synchronize train lines and to set longitude, and then to fix time zones. It was in this world that Einstein brought a conventional basis into his vision of a principled physics. A trace of the existing

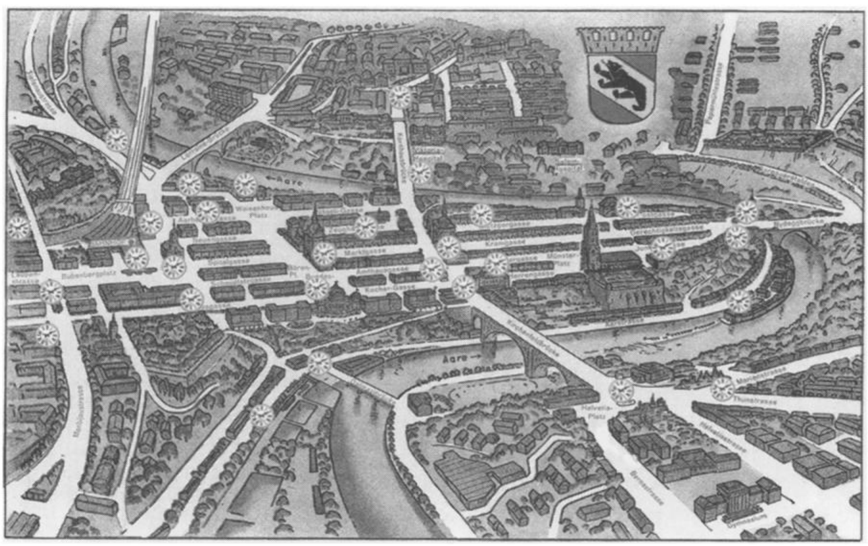

FIG. 16.—Map of electrical clock network in Bern. Harvard Map Collection, using data from Jakob Messerli, *Gleichmässig pünktlich schnell.*

FIG. 17.—Bern-Muri map. Skorpion-Verlag.

time coordination system is there to see in the 1905 paper itself. Reconsider the scheme of coordination that Einstein *explicitly refused* to accept: an observer equipped with a clock at the center of the coordinate system. That master clock bolted to space position (0,0,0) determines simultaneity when electromagnetic signals from distant points arrive there at the same local time. But now this standard centered system no longer appears as an abstract straw man. This branching, radial clock coordination structure, visible in wires, generators, and clocks, displayed in book after book on timekeeping, *was precisely that of the European system of the mother clock along with its secondary and tertiary dependents* (see figs. 19, 20, and 21). When center-issued signals arrived at distant points, be they in the next room or a hundred kilometers away, they were *defined* as simultaneous; on that basis trains were run, troops were rousted, and telegraph messages were sent. It is even in this period that preparations were being made to send the time coordination signal out by radio waves. There was an intense burst of activity on such radio coordination systems in 1904 both in Switzerland and in France as workers tested, developed, and began deploying the new radio time system. The director of *La Nature* himself took up his pen to record new developments in the distribution of time by wireless methods. Reporting on experiments conducted at the Paris Observatory, he noted that with the aid of a chronograph distant synchronization now appeared to be possible to within two or three hundredths of a second—and the wireless technologies promised to distrib-

FIG. 18.—Muri Clocktower, circa 1900. Gemeindeschreiberei Muri bei Bern.

ute time everywhere throughout Paris and its surrounding suburbs. Not only would scientific goals be advanced, such as the determination of longitude, but freed from the constraints of physical wire, time could be broadcast out to boats at sea and even into the ordinary household.[34] By 1905 the American navy was using radio-controlled clocks, and by 1910 the Eiffel Tower station was fixing the hands of clocks across Europe (fig. 22). According to one leading radio time worker in 1911, planning for radio simultaneity had begun with radio itself, presumably sometime around 1901.[35] But whether by telegraph line or by wireless, centralized time distribution was the temporal-physical glory of the unified German empire that von Moltke wanted, made corporeal through the grand *Primäre Normaluhr* at the Silesischer Bahnhof in Berlin or the baroque and elegant *horloge-mère* of Neuchâtel.

For the telegraphers, geodesists, and astronomers, Einstein's novel time coordination scheme could clearly be understood in terms of the

34. See Henri de Parville, "Distribution de l'heure par télégraphie sans fil," *La Nature*, 30 July 1904, pp. 129–30. Experiments were conducted by G. Bigourdan, astronomer at the Paris Observatory, and presented to the Académie des Sciences on 27 June 1904; these results were printed in the *Comptes rendues de l'Académie* and quoted *in extenso* (along with the work of others including the director of the observatory at Neuchâtel) in "La Télégraphie sans fil et la distribution de l'heure," *Journal suisse d'horlogerie* 29 (Sept. 1904): 81–83.

35. On wireless time setting, see, for example, Joseph Roussel, *Le Premier Livre de l'amateur de T.S.F.* (Paris, 1922), esp. pp. 150–52. Julien Auguste Boulanger and Gustave Auguste Ferrié, *La Télégraphie sans fil et les ondes électriques*, 7th ed. (Paris, 1909) dates the Eiffel Tower radio station to 1903. Ferrié, "Sur quelques nouvelles applications de la télégraphie sans fil," *Journal de Physique*, 5th ser., 1 (1911): 178–89, esp. p. 178, indicates that planning for wireless time coordination began at the start of work on wireless; Edmond Rothé, *Les Applications de la télégraphie sans fil: Traité pratique pour la réception des signaux horaires* (Paris, 1913) discusses the details of radio-communicated time coordination procedure.

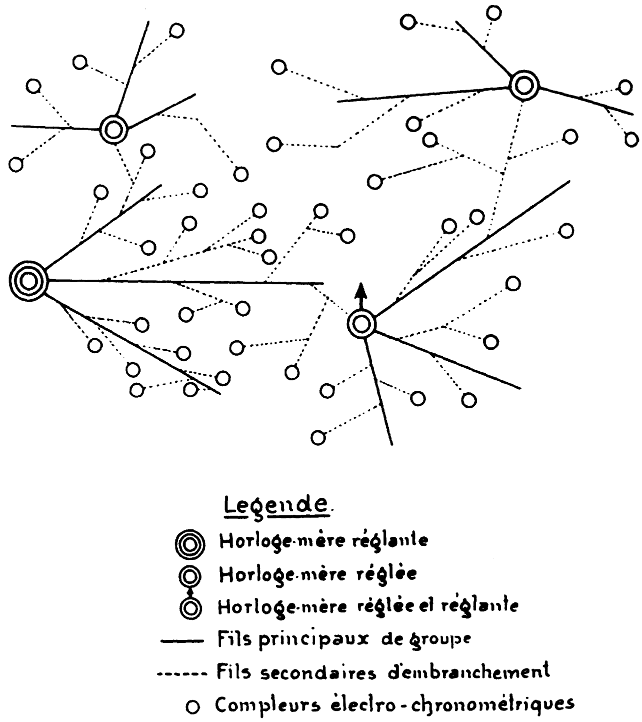

Fig. 282

FIG. 19.—Time synchronization network I. From A. Favarger, "L'Électricité et ses applications à la chronométrie," *Journal suisse d'horlogerie* (1884–85): 320; rpt. in Favarger, *L'Électricité et ses applications à la chronométrie*, p. 394.

already extant clock coordination methods. At the École Professionelle Supérieure des Postes et Télégraphes, on 19 November 1921, when Léon Bloch sought to explain the meaning of time, he turned his audience's attention to the actual and widespread technology that they would have known like the backs of their hands:

> What do we call time on the surface of the earth? Take a clock that gives astronomical time—the mother pendulum of the Observatory of Paris,—and transmit that time by wireless to distant sites. In what does this transmission consist? It consists of noting at the two stations that need synchronization, the passage of a common luminous or hertzian signal.[36]

36. Léon Bloch, *Le Principe de la relativité et la théorie d'Einstein* (Paris, 1922), pp. 15–16. Dominique Pestre characterizes Bloch (and his brother) as physicists who were unusual for their time in France by virtue of writing textbooks that looked positively on the new physics of the early twentieth century, and who characteristically wrote using a series of progressive

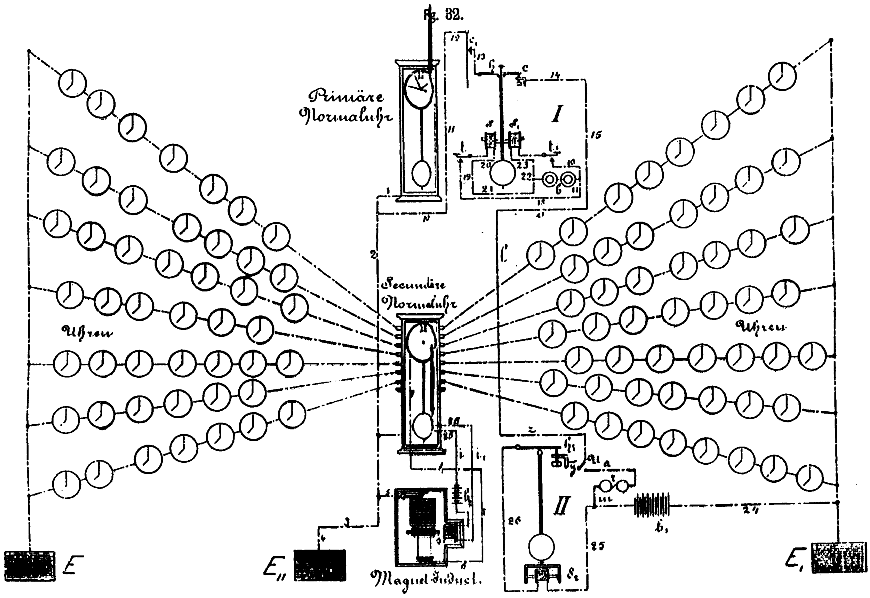

FIG. 20.—Time synchronization network II. From Ladislaus Fiedler, *Die Zeittelegraphen und die elektrischen Uhren vom praktischen Standpunkte* (Vienna, 1890), pp. 88–89.

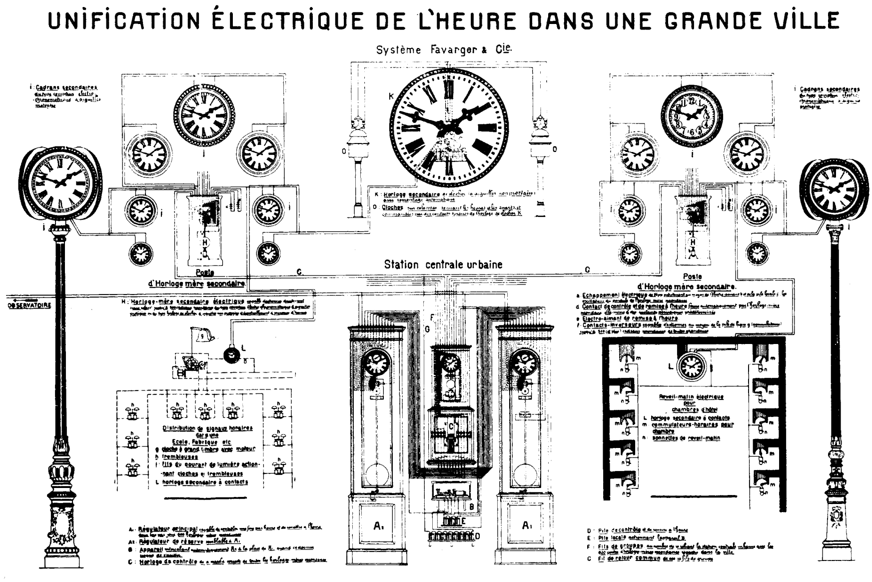

FIG. 21.—Unification électrique de l'heure dans une grande ville. From A. Favarger, *L'Électricité et ses applications à la chronométrie,* pp. 427–28, pl. 4.

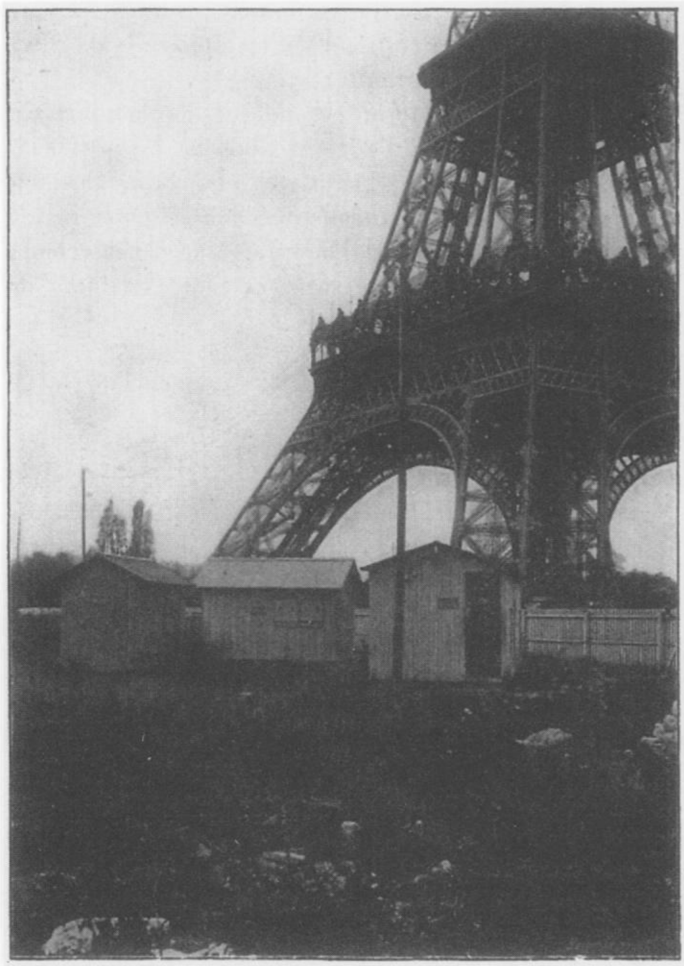

FIG. 22.—Eiffel Tower radio station. From Julien Auguste Boulanger and Gustave Auguste Ferrié, *La Télégraphie sans fil et les ondes électriques,* 7th ed. (Paris, 1909), p. 429.

At least at the Postes et Télégraphes, relativity was understood through their real infrastructure of coordinated clocks. Yet more than the mere invocation of clock synchronization is involved. By 1924, and very probably some time before then, clock coordinators had begun (following Einstein) to take account of the finite velocity of radio waves. Einstein's universal time machine had rapidly drawn from the technological world,

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generalizations from the concrete to the abstract (no doubt to appeal to their more experimentally oriented colleagues). See Dominique Pestre, *Physique et physiciens en France, 1918–1940* (Paris, 1984), pp. 18, 56, 117.

reshaped the physical-metaphysical one, and now begun to reconfigure machinery.[37]

Indeed, given the physical—and cultural—impact of clock coordination, and its place in such a variety of settings, one might well ask if before 1905 anyone else besides Einstein was worried about defining time through a rigorous synchronization that took on board the finite velocity of light. Astonishingly enough there was one other person, someone who perhaps quite reasonably had been a member of the French Bureau of Longitudes since 4 January 1893, ascending to its presidency in 1899 (and in 1909), longitude determination having been for centuries the domain where clock coordination had been critical. To boot he was professor at the École Professionelle Supérieure des Postes et Télégraphes from 4 July 1902; when electrocoordinated clocks came on the scene it was Postes et Télégraphes that took charge. That other was, of course, Poincaré.[38] He—like Einstein—introduced clocks coordinated by the exchange of a luminous signal.

Poincaré's first exploration of simultaneity came in 1898, when he argued that simultaneity was not an absolute concept, insisting that we have no direct intuition to any such notion. What we do have are certain rules, rules that we must invoke in order to do the quite concrete technical work of, for example, longitude determination. "When sailors or geographers determine a longitude they have precisely the problem to solve that we have been treating here; they must, without being at Paris, determine the time at Paris. How do they do it?" They could move a clock (with all the problems that attend such an effort), they could both refer to an astronomical event, or, finally, "they could make use of the telegraph. It is clear first of all that the reception of a signal in Berlin, for example, is posterior to the sending of that same signal from Paris."[39] This is not a purely hypothetical example. Commentators have often treated Poincaré's telegraphy reference as if it were an imaginary problem, an instance of abstract philosophical rumination. It was not. By 1898 an actual system of clock coordination existed in the service of longitude determination. Indeed, the geodetic and meteorological demand for coordinated time (to determine longitude) had joined with the exigencies of railroad economy and safety to launch the project of time zones.[40]

37. See Bureau des Longitudes, *Réception des signaux horaires: Renseignements météorologiques, sismologiques, etc., transmis par les postes de télégraphie sans fil de la tour Eiffel, Lyon, Bordeaux, etc.* (Paris, 1924), pp. 83–84.

38. See Ernest Lebon, *Henri Poincaré: Biographie, bibliographie analytique des écrits* (Paris, 1909), pp. 16–17.

39. Henri Poincaré, "La Mesure du temps," *Revue de métaphysique et de morale* 6 (1898): 11–12, 12, hereafter abbreviated "M"; rpt. in Poincaré, *La Valeur de la science* (1905; Paris, 1970), p. 53; trans. George Bruce Halsted, under the title "The Measure of Time," *The Value of Science* (New York, 1907), p. 35, hereafter abbreviated "MT"; trans. mod.

40. See Bartky, "The Adoption of Standard Time," pp. 25–56.

Poincaré, as noted, was a senior member of the Bureau of Longitudes in 1898, and his reference was not to telegraphy as an abstract instance of finite signal propagation but rather, explicitly, as a means of clock-coordinated longitude work:

> In general, the duration of the transmission [from Paris to Berlin] 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 such a correction is not made because it would be smaller than observational errors, but its theoretical necessity is not diminished from our point of view, which is that of providing a rigorous definition [of simultaneity]. ["M," p. 12; "MT," p. 35; trans. mod.]

"Theoretically necessary" was the recognition that simultaneity was *always* conventional. And in this instance, at least, Poincaré's conventionalism was tied more than homonymically to the grubby world of real conventions that were, at precisely this conjuncture, setting time zone simultaneity, railway simultaneity, and national time unification.

Sometime after the spring of 1902 Einstein might have read Poincaré's "The Measure of Time." We know from Einstein's friend Maurice Solovine that their little discussion group (grandly titled the Olympia Academy) definitely read a later Poincaré work, *Science and Hypothesis,* that cited the 1898 work.[41] Critical as Poincaré was of any attempt to pretend that time-coordinating conventions were intuitive absolutes, on *practical* grounds, as he suggested in the remarks above, he did not militate for the abandonment of Newtonian kinematics. Ordinary rules of simultaneity, "the fruit of an unconscious opportunism," were "not imposed upon us and we might amuse ourselves in inventing others; but they could not be cast aside without greatly complicating the enunciation of the laws of physics, mechanics and astronomy" ("M," p. 13; "MT," p. 36). Corrections to the Newtonian world, Poincaré believed, would be small and complicated, so "theoretical necessity" would be trumped by the demands of simplicity. Einstein looked at distant simultaneity almost exactly as had Poincaré. But where Poincaré saw the new light-signal synchronization as leading to inevitable complexity, Einstein saw it as the harbinger of a vastly *simpler* physics.[42]

41. "Poincaré's *Science and Hypothesis* . . . engrossed us and held us spellbound for weeks" (Maurice Solovine, introduction to Einstein, *Letters to Solovine,* trans. Wade Baskin [New York, 1987], p. 9). See, for example, "La Mécanique classique," chap. 6 of Poincaré, *La Science et l'hypothèse* (Paris, 1902), esp. p. 111: "Not only don't we have a direct intuition of the equality of two durations, but we don't even have one of the simultaneity of two different events that occur in two different sites; this is what I explained in an article titled 'The Measure of Time.'"

42. Between 1900 and 1904 Poincare kept his programmatic statements about simultaneity largely separate from his explorations into the details of electrodynamics. But even

The turn-of-the-century Euro-American world was crisscrossed with overlapping networks of coordination: webs of train tracks, telegraph lines, meteorological networks, longitude surveys under the watchful, increasingly universal, clock system. In this context, the clock coordination system introduced by Einstein was, in a nontrivial sense, a world-machine, a vast, at first only imagined network of clocks. At the risk of seeming self-contradictory, there is a sense in which Einstein's special theory of relativity was a machine, an imaginative one, to be sure, but one built nonetheless on a real skein of wires that synchronized time machines by the exchange of electromagnetic signals.

Such a *technological* reading of this most *theoretical* paper suggests one final observation. It has long struck scholars that the style of "On the Electrodynamics of Moving Bodies" does not even look like that of an ordinary physics paper. There are essentially no footnotes, very few equations, no mention of new experimental results, and a lot of banter about simple physical processes that seem far removed from the frontiers of science.[43] Pick up a typical paper from the *Annalen der Physik* and a very different form appears in nearly every article: they typically begin with an experimental problem, a calculational correction; they are filled with references to other papers. But read Einstein's paper through the eyes of the patent world and suddenly it looks not so strange—at least in style. As one recent author has commented, patents are *precisely* characterized by their refusal to lodge themselves among other patents through footnotes—that would compromise the entrepreneurial advantage the author seeks. The simplistic banter is not unusual; patents are in fact written for a "person skilled in the art" (as patent language had it), not specialist readers.[44] And

when Poincaré did introduce his notion of local time into his electrodynamics to insist on the conventionality of judgments of simultaneity, he did not, as Einstein did, use light-signal coordination to reorganize mechanics and electrodynamics in such a way that force-free analysis of space and time clearly begin before any considerations of electron deformations and molecular forces come into play. For Einstein, it was precisely the point that kinematics, the play of temporal and spatial measures, would enter before dynamics. But here is not the place to sort out the relative contributions of these two physicists. Compare Henri Poincaré, "Relations entre la physique expérimentale et la physique mathématique," in *Rapports présentés au Congrès International de Physique,* ed. Ch.-Éd. Guillaume and L. Poincaré, 4 vols. (Paris, 1900), 1:1–29, and Henri Poincaré, "L'État actuel et l'avenir de la physique mathématique," *Bulletin des sciences mathématiques* 28 (1904): 302–24. For a comparison of Einstein and Poincaré's understanding of the electrodynamics of moving bodies, see Miller, *Albert Einstein's Special Theory of Relativity,* and Pais, *Subtle Is the Lord.*

43. This has been pointed out many times, for instance by Leopold Infeld in *Albert Einstein: His Work and Its Influence on Our Times* (New York, 1950), p. 23; Holton, "Influences on Einstein's Early Work," in *Thematic Origins of Scientific Thought;* and Miller, *Albert Einstein's Special Theory of Relativity* and "The Special Relativity Theory: Einstein's Response to the Physics of 1905," in *Albert Einstein: Historical and Cultural Perspectives,* ed. Holton and Yehuda Elkana (Princeton, N.J., 1982), pp. 3–26.

44. Greg Myers, "From Discovery to Invention: The Writing and Rewriting of Two Patents," *Social Studies of Science* 25 (Feb. 1995): 77.

the story told by the author aims to describe a procedure rather than point the way in a long train of work.

Given the embedding of this scientific-technological intervention in the wider world of time coordination another puzzle arises. In a sense Einstein—the same Einstein who at sixteen had abandoned his German citizenship and who over a lifetime lambasted the "herd life" of "the military system"—had, ironically, at age twenty-six, completed von Moltke's project.[45] Time was identified with timekeeping, and *Einheitszeit* became the technopolitical endpoint of establishing, procedurally, distant simultaneity in an ever expanding domain. Einstein's clock synchronization system, like its predecessors, reduced time to procedural synchronicity, tying clocks together by electromagnetic signals. And in Einstein's scheme clock unity extended beyond city, country, and empire, beyond continent, indeed, beyond the world, to the infinite, now pseudo-Cartesian, universe as a whole.

But the irony inverts. For while Einstein's clock coordination procedure built on at least fifteen years of intense efforts towards electromagnetic time unification, he had, devastatingly, removed one crucial element of von Moltke's vision. There was, in Einstein's infinite clock machine, no *Primäre Normaluhr,* no *horloge-mère,* no master clock. His was a coordinated system of infinite spatiotemporal extent, but its infinity was without center—no Silesischer Bahnhof linked upwards through the Berlin observatory to the heavens and downwards to the edges of empire. By infinitely extending a time unity that had originally been grounded in the imperatives of German national unity, Einstein had both completed and subverted the project. He had opened the zone of unification, but in the process he not only removed Berlin as the *Zeitzentrum* but also designed a machine that upended the very category of metaphysical centrality. With time coordination now defined by the exchange of electromagnetic signals, Einstein could finish his description of the electromagnetic theory of moving bodies with no spatial or temporal reference to any specially picked out ether rest frame. He had a theory of relativity in which the asymmetry between reference frames was gone.

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Times change. Einstein left the Bern patent office in 1909 for the University of Zurich, then went to Prague, and eventually in 1914 took up his post at the University of Berlin. After World War I Favarger, that avatar of Swiss chronometric unity, published his technical 550-page third edition of his treatise on electrical timekeeping, framing it, once again, in broadly cultural terms. The Great War, he argued, had contributed powerful technical developments, but it also destroyed a great part

45. Einstein, "The World as I See It," *Ideas and Opinions,* trans. Sonja Bargmann, ed. Seelig (New York, 1954), p. 10.

of the human wealth that sustained peace had created. The world remaining was by contrast "a heap of ruins, of miseries, and of suffering."[46] To exit this disaster, at least materially, work would save humanity, and work, mechanics teaches us, is a product of time and force. Time, he goes on to say, "cannot be defined in substance; it is, metaphysically speaking, as mysterious as matter and space." (Even stolid Swiss clockmakers were driven to metaphysics by time.) All the activities of man, whether conscious or unconscious—sleeping, eating, meditating, or playing—take place in time; without order, without specified plans, we risk falling into anarchy—into "physical, intellectual and moral misery." The remedy: the precise measurement and determination of time with the rigor of an astronomical observatory. But measured time cannot remain in the astronomers' redoubt; time rigor must be distributed electrically to anyone who wants or needs it: "we must, in a word, popularize it, we must *democratize* time" for people to live and prosper. We must make every man "*maître du temps,* master not only of the hour but also of the minute, the second, and even in special cases the tenth, the hundredth, the thousandth, the millionth of a second."[47] Distributed, coordinated time was more than money for Favarger; it was each person's access to orderliness, interior and exterior. Throughout the late nineteenth and early twentieth centuries, coordinated clocks were never just gears and magnets.

My hope in exploring the material culture of clock coordination is to set Einstein's place in a universe of meaning that crossed mechanisms and metaphysics. More generally, my hope here—and elsewhere[48]—for studies in the material culture of science is to avoid two equally problematic positions on the relation of things to thoughts. On one side we have a long tradition of unregenerate materialism or empiricism, a view that ideas emerge causally and univalently from the disposition of objects and the impressions they make upon us. In the history of physics, empiricism of a specifically logical positivist sort directly and unambiguously shaped an inductive, observation-centered account of scientific development, codified in the *Harvard Case Histories in Experimental Science* but present throughout the 1950s and into the 1960s. In that frame, theory, and the philosophy with which it was associated, was an always provisional addition, not the bulwark of science. Einstein here appears as having taken the inexorable next step in an inductive process that gradually drove out the ether: the ether couldn't be measured to first order in the ratio of velocity to the speed of light *(v/c),* it wasn't there to second order in *v/c,* and therefore (so the argument went), Einstein concluded that the ether was superfluous.[49] No doubt there is much to be said for this experiment-

46. Favarger, *L'Électricité et ses applications à la chronométrie,* p. 10.

47. Ibid., p. 11.

48. See Galison, *Image and Logic: A Material Culture of Microphysics* (Chicago, 1997).

49. Representations of Einstein's relativity as a culmination of increasingly accurate "no ether" measurements are rife; perhaps the most scholarly attempt to locate Einstein's

grounded Einstein—his fascination with the detailed conduct of the fast electron experiments and his gyrocompass work at the Physikalisch-Technische Reichsanstalt reveal a theorist with a clear sense of laboratory procedure and the operation of machines. Things structured thoughts.

On the other side, and characteristic of the inverse project, was the antipositivist movement of the 1960s and 1970s that largely aimed at reversing the previous generation's epistemic order: programmes, paradigms, and conceptual schemes came first, and these reshaped experiments and instruments all the way down. Now thoughts fully structured things. Einstein on the antipostivist screen appears as the philosophical innovator who dispensed with the material world altogether in a sustained drive for symmetry, principles, and operational definitions. Much truth here, too; from the antipositivist reaction we learned to be sensitive to those moments when Einstein was chary of experimental results, dubious, for example, about supposed laboratory refutations of special relativity and about nominal astronomical contradictions with the general theory.

Granting both historiographical traditions their due, I am not proposing to split the difference, and I am certainly not advocating a technological reductivism. Instead, it seems to me that we have, in the form of a philosophically informed and historicized material culture, a way out of this binary oscillation between a historiography of implicit idealism or implicit materialism. Work on telegraphs, steam engines, scientific instruments, and astronomical observation over the last years has set questions that refuse the untenable either/or of things and thoughts.[50] In each instance we can explore the philosophical issues engaged with historically specific values and symbols.

When Einstein came to the Bern patent office in 1902 he entered into a world in which the triumph of the electrical over the mechanical was already symbolically wired to dreams of modernity. He found a world in which clock coordination was a practical problem (trains, troops, and telegraphs) demanding workable, patentable solutions in exactly his area of greatest concern and professional occupation: precision electromechanical instrumentation. The patent office was anything but a deep-sea

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formulation as a mere variant of the early ether-electron theories is to be found in Edmund Whittaker, *A History of the Theories of Aether and Electricity* (London, 1953), where the chapter "The Relativity Theory of Poincaré and Lorentz" includes the remark: "Einstein published a paper [in 1905] which set forth the relativity theory of Poincaré and Lorentz with some amplifications, and which attracted much attention. He asserted as a fundamental principle the *constancy of the velocity of light* . . . which at the time was widely accepted, but has been severely criticised by later writers" (p. 40). See Holton, *Thematic Origins of Scientific Thought*, esp. chap. 5, and Miller, *Albert Einstein's Special Theory of Relativity*.

50. See Schaffer, "Late Victorian Metrology and Its Instrumentation: A Manufactory of Ohms," in *Invisible Connections: Instruments, Institutions, and Science*, ed. Robert Bud and Susan E. Cozzens (Bellingham, Wash., 1992), pp. 23–59; M. Norton Wise, "Mediating Machines," *Science in Context* 2 (Spring 1988): 77–114; and Galison, *Image and Logic*.

lightship. No, the office was a grandstand seat for the great parade of modern technologies. And as coordinated clocks went by, they weren't traveling alone; the network of electrical chronocoordination signified political, cultural, and technical unity all at once. Einstein seized on this new, conventional simultaneity machine and installed it at the principled beginning of his new physics. In a certain sense he had completed the grand time coordination project of the nineteenth century, but by eliminating the master clock and raising the conventionally set time to a *physical principle,* he had launched a distinctively modern twentieth-century physics of relativity.

Hypersymbolized—by which I mean many competing interpretations were in play—the regulated coordination of *Einheitszeit* meant, alternately, imperial empire, democracy, world citizenship, and antianarchism. What they held in common was a sense that each clock signified the individual and that clock coordination came to stand in for a logic of linkage among people and peoples. As such, the project for country or worldwide regulation elicited specific conditions of possible technocultural moves—that is, moves that would at once bear both scientific-technological and cultural significance.

It has become a commonplace over the last thirty years to pit bottom-up against top-down explanations. Neither will do. Borrowing a medieval saying aimed at capturing the links between alchemy and astronomy, we might put it this way: In looking down—to the electromagnetically regulated clock networks—we see up—to images of empire, metaphysics, and civil society. In looking up—to the metaphysics of Einstein's operationalized distant simultaneity, to the shifting culture of space, time, and motion—we see down—to the wires, gears, and pulses passing through the Bern patent office. We find metaphysics in machines, and machines in metaphysics.