



PROJECT MUSE®

## The Media of Relativity: Einstein and Telecommunications Technologies

Jimena Canales

Technology and Culture, Volume 56, Number 3, July 2015, pp. 610-645  
(Article)

Published by Johns Hopkins University Press  
DOI: [10.1353/tech.2015.0097](https://doi.org/10.1353/tech.2015.0097)



➔ For additional information about this article

<http://muse.jhu.edu/journals/tech/summary/v056/56.3.canales.html>

# The Media of Relativity

## Einstein and Telecommunications Technologies

JIMENA CANALES

---

**ABSTRACT:** How are fundamental constants, such as “c” for the speed of light, related to the technological environments that produce them? Relativistic cosmology, developed first by Albert Einstein, depended on military and commercial innovations in telecommunications. Prominent physicists (Hans Reichenbach, Max Born, Paul Langevin, Louis de Broglie, and Léon Brillouin, among others) worked in radio units during WWI and incorporated battlefield lessons into their research. Relativity physicists, working at the intersection of physics and optics by investigating light and electricity, responded to new challenges by developing a novel scientific framework. Ideas about lengths and solid bodies were overhauled because the old Newtonian mechanics assumed the possibility of “instantaneous signaling at a distance.” Einstein’s universe, where time and space dilated, when the shortest path between two points was often curved and non-Euclidean, followed the rules of electromagnetic “signal” transmission. For these scientists, light’s constant speed in the absence of a gravitational field—a fundamental tenet of Einstein’s theory—was a lesson derived from communication technologies.

“. . . we are dealing here with the propagation of an influence that could, for example, be used for sending an arbitrary signal.”

—Albert Einstein to Wien, 26 August 1907, in *The Collected Papers of Albert Einstein*, vol. 5, 40

How are fundamental constants, such as “c” for the speed of light, related to particular technological environments? Our understanding of the con-

Jimena Canales is the Thomas M. Siebel Chair in the History of Science at the University of Illinois, Urbana-Champaign. She would like to thank Bernhard Siegert, Lorenz Engell, and Sigrid Weigel for inspiration. Suzanne Moon and the anonymous referees of *Technology and Culture* deserve special thanks for criticism and guidance. The author presented a lecture on this topic at the Internationales Kolleg für Kulturtechnikforschung und Medienphilosophie (IKKM) in Germany on 4 July 2012. Unless otherwise noted, citations from Einstein’s works and correspondence refer to *The Collected Papers of Albert Einstein*, and translations from French and German are the author’s.

©2015 by the Society for the History of Technology. All rights reserved.  
0040-165X/15/5603-0002/610-45

stant  $c$  and Einstein's relativistic cosmology depended on key experiences and lessons learned in connection to new forms of telecommunications, first used by the military and later adapted for commercial purposes. Many of Einstein's contemporaries understood his theory of relativity by reference to telecommunications, some referring to it as "signal-theory" and "message theory." Prominent physicists who contributed to it (Hans Reichenbach, Max Born, Paul Langevin, Louis de Broglie, and Léon Brillouin, among others) worked in radio units during World War I. Physicists began to retrospectively interpret the old Newtonian mechanics as based on a belief in a means of "instantaneous signaling at a distance." Even common thinking about lengths and solid bodies, argued Einstein and his interlocutors, needed to be overhauled in light of a new understanding of signaling possibilities. Pulling a rod from one side will not make the other end move at once, since relativity had shown that "this would be a signal that moves with infinite speed." Einstein's universe, where time and space dilated, where the shortest path between two points was often curved and which broke the laws of Euclidean geometry, functioned according to the rules of electromagnetic signal transmission. For some critics, the new understanding of the speed of light as an unsurpassable velocity—a fundamental tenet of Einstein's theory—was a mere technological effect related to current limitations in communication technologies.

Fundamental constants are considered such essential fixtures of the universe that they are strongly associated with the extraordinary set of coincidences that led to the existence of a universe that produced, sustained, and housed human life on Earth. "If the fundamental constants of nature" were any different, argues statistician David J. Hand, "life as we know it would not exist, and we would not be here to see the stars."<sup>1</sup> But the situation is actually quite the reverse: if we had not been here to see the stars, the fundamental constants as we know them would not exist. How did we get our account of universal constants backward? The history of how  $c$  for the speed of light became a fundamental constant can help us answer that question.

Einstein was intimately familiar with mass-media technologies, particularly radio. When two of the pioneers of radio technologies in Germany (Adolf Slaby and Georg Graf von Arco, director of the Society for Wireless Telegraphy, later known as Telefunken) needed help with patent litigation against Marconi, they turned to Einstein for help. They "believed him to be one of the few persons who understood wireless science and technology."<sup>2</sup> Einstein was also chosen to discuss the topic of mass communication directly during a radio-transmitted address at the German Radio and Audio Show in Berlin on 22 August 1930. He extolled the potential benefits of radio and emerging mass-media technologies, pleading with listen-

1. David J. Hand, *The Improbability Principle*, 218.

2. Thomas P. Hughes, "Einstein, Inventors, and Invention," 34.

ers to be thankful for the wonders of science as much as of engineering and to remember “the fact that it is the engineers who make true democracy possible.”<sup>3</sup> Einstein used these innovations to publicize his views about science, technology, and politics.

Yet Einstein, much like Isaac Newton before him and Stephen Hawking afterward, described the work of scientists as marked by solitude. An “isolated life,” he explained, was most conducive for “creative” scientific work, which he compared to “such occupations as the service of lighthouses and lightships.” The supposed solitary nature of scientific labor contrasted sharply with Einstein’s life as a scientist and public intellectual. His so-called “lighthouse” speech was a highly public event. Delivered in front of some 10,000 people, it was recorded so that it could be used as a soundtrack for a newsreel.<sup>4</sup>

How did Einstein’s involvement with technology affect his theoretical work? Historians have focused mostly on the role of clocks. Even though the word “clock” appeared more than fifty times in his relativity theory paper (1905), his life’s work is still considered as the paradigmatic example of pure, theoretical science, which, only if applied, can lead to technological results, from atomic energy to GPS. For the most part, Einstein’s contributions continue to be safely confined within the realm of theoretical science.<sup>5</sup>

Einstein’s involvement with technology was complex and varied. It is now clear that even “those who prefer their scientists unsullied by commercialism” can no longer overlook his sustained interest in many different technologies, such as gyroscopes, refrigerators, and clocks.<sup>6</sup> These efforts, furthermore, were not limited to his years at the Bern Patent Office but continued afterward, even when he was widely recognized for his theoretical work and had moved to America. In some of his public comments about the effects of technology on the modern world, Einstein was at first mostly optimistic. Yet his enthusiasm did not last long: “What comes to

3. Albert Einstein, Anlässlich der Eröffnung der 7. Deutschen Funkausstellung und Phonoschau. Recording at Deutsches Rundfunkarchiv, Frankfurt am Main.

4. For Isaac Newton’s rhetoric of isolation, see Simon Schaffer, “Newton on the Beach.” For Stephen Hawking, see Hélène Mialet, *Hawking Incorporated*. For Einstein’s so-called “lighthouse speech,” see Albert Einstein, “Speech in Royal Albert Hall.”

5. “Uhr” and “Uhren” in the original German are translated variously as clock/s and watch/es in different English versions. Yet scholars still claim that “neither Einstein nor his colleagues wrote about any connection between his formulation of his theory and any timing technologies.” See, for example, Alberto A. Martínez, “Material History and Imaginary Clocks. In this view, “technocultural” factors do not enter into Einstein’s work because Einstein *himself* did not *explicitly* draw a connection between his science and clock technology as distinct topics. For a reevaluation of relativity theory in light of timekeeping technologies, see Peter Galison, *Einstein’s Clocks, Poincaré’s Maps: Empires of Time*; Peter Galison, “Einstein’s Clocks: The Place of Time.”

6. Hughes, “Einstein, Inventors, and Invention,” 38. József Illy, *The Practical Einstein*. For Einstein on gyroscopes, see Peter Galison, *How Experiments End*.

the mind of a sensible person when hearing the word technology?” “Avarice, exploitation, social divisions amongst people, class hatred,” he responded. Technology, he concluded, was the “wayward son of our era.”<sup>7</sup> Even his positive assessment of radio had vanished a few years after he spoke of it, when the industry became centralized. “False information is spread by a muzzled press, a centralized radio service, and school education,” he warned.<sup>8</sup> But what Einstein said about technology needs to be separated from his experience with it.

## Technology, Rationality, and War

Discussions about the purity of science in the face of technology are as old as science itself, yet one conception stands out from the rest. The most common view takes technology to be “applied science,” as reflected in the motto for the 1933 Chicago World’s Fair: “Science Finds, Industry Applies, Man Conforms.”<sup>9</sup> While historians and philosophers have denounced the “deceptive illusion” that “modern technology is applied physical science,” this view persists in our public discourse and in much recent scholarship.<sup>10</sup> “Hertzian devices,” explained a historian of early radio, “emerged from experimental physics” and “inspired engineers.”<sup>11</sup>

Since the early decades of the twentieth century, debates about the relation of science to technology have become theologically charged. When science is understood as “pure theory,” those who look at technology and its effects tend to “curse it as the work of the devil.”<sup>12</sup> Recently, philosopher of science Philip Kitcher has found that “much of the rhetoric about the importance of seeking the truth seems to develop its own form of theology, viewing the high priests of the sciences as dedicated to a sacred task,” referring in particular to the work of E. O. Wilson and Carl Sagan.<sup>13</sup> Tainting science, especially theoretical science, with technology can therefore be perceived as a transgression akin to profanation, since even among today’s theoretical physicists there is still “the feeling of being some kind of secular priest.”<sup>14</sup> Theological valances come with moral ones, as theoretical

7. Albert Einstein, “Die Freie Vereinigung für technische Volksbildung.”

8. Albert Einstein, “A Re-examination of Pacifism.”

9. Cited in Ronald Kline, “Construing ‘Technology’ as ‘Applied Science.’”

10. Martin Heidegger, “The Question Concerning Technology,” 23.

11. Sungook Hong, *Wireless*, 22.

12. Heidegger, “The Question Concerning Technology”; “pure theory” on 21, “devil” on 26.

13. Philip Kitcher, *Science, Truth, and Democracy*, 147.

14. Silvan Sam Schweber to Arne Hessenbruch, interview. Paul Forman considers attempts to relate science to technology as misguided “ideological initiatives”: “The Primacy of Science in Modernity, of Technology in Postmodernity, and of Ideology in the History of Technology.”

physicists are widely sanctioned to dole out advice for how “every parent and grandparent” should “behave.”<sup>15</sup>

To this day, questions about the relation of theoretical physics to technology strike at the center of how we think of moral responsibility more generally. While Einstein was a self-proclaimed pacifist, “half of his salary came from a Prussian industry that held military contracts.”<sup>16</sup> How can we start to think about these contradictions?

JULY

2015

VOL. 56

Nineteenth- and twentieth-century physics were tightly, although not unproblematically, linked to electrical engineering. Scientists during this period engaged in “boundary-work” with other technical professions to bolster their expertise, to explain the usefulness of their profession, and, at other times, to distance their work from military and industrial connections.<sup>17</sup> Norbert Wiener, for example, was heavily invested in giving his work “an intellectual, scientific trajectory, divorced from the traditions of technical practice from which it sprang” that were so clearly connected to World War II.<sup>18</sup>

In what follows, I explore a different way of understanding the impact of technology on theoretical science, and of understanding its importance in general culture. It is neither about scientists’ portrayal of their own work, their professional affiliations, their direct involvement with technology, or their remuneration from engineering, military, or industrial sources. I am interested, instead, in investigating the role played by technologies in shaping rationality more broadly. Changes in our everyday technical landscape affect individual subjectivities and theoretical science in subtle, covert, and profound ways. They affect how rational subjects think, reason, and act. These changes affect theoretical science not only in the period of its development but throughout its adoption and subsequent uptake. The realization that no message can travel at speeds faster than light, often associated with Einstein’s theory of relativity, was one such realization, tightly coupled with the development of light-based communication technologies.

In order to trace Einstein’s relationship to technology, scholars have rightly focused on cutting-edge marvels that must “have gone through

15. Adam Frank, “Welcome to the Age of Denial.” Frank calls on readers to consider science as “a way of behaving in the world,” rather than to consider it as occupations connected to “the giant particle accelerators and space observatories.”

16. Alberto A. Martínez, “The Questionable Inventions of the Clever Dr. Einstein,” 52.

17. Thomas F. Gieryn, “Boundary-Work and the Demarcation of Science from Non-Science”; Ronald Kline, “Foundational Stories,” 120; Kline, “Construing ‘Technology’ as ‘Applied Science.’” For the relation of physics to electrical engineering, see Graeme Gooday, “The Questionable Matter of Electricity”; Graeme Gooday, “La jonction entre science et industrie”; Graeme Gooday, “Teaching Telegraphy and Electro-technics in the Physics Laboratory.”

18. David A. Mindell, *Between Human and Machine*, 286.

Einstein's hands."<sup>19</sup> We can now complement that research and move from a narrow sphere of action and limited sense of responsibility to an inquiry into the role of technological transformations that affect broader swaths of society and change what rational subjects consider realistic and possible, in ethical and technical terms. Technologies reconfigure experience in ways that affect what Aristotle referred to as the "unity of action" across fields. As our experience of causality and effective agency changes with new technological transformations, our understanding of the past as much as of the future shifts as well.

How do changes in communication technologies affect rational subjects and shape theoretical science? The role played by communications media in theoretical science is more complex than that of electrical engineering in the era of Maxwell and Hertz, nautical commerce in the time of Newton, or ballistics in Galileo's era. In contrast to many of the classic cases that historians have studied to tease apart science and technology, in the case of communications media we need to ask, additionally, how both impact the very core of what we consider to be an autonomous thinking-and-speaking subject and moral actor.

In what follows, I trace how new terms and concepts related to contemporary communication technologies appeared in Einstein's work, as he struggled to create a new scientific paradigm for the era of global communications. At the crux of my narrative is the "light signaling protocol," a procedure known to have played a "central role" in his famous 1905 relativity paper and later work.<sup>20</sup> The success of "arguably the most famous scientific paper in history" hinged on specific transformations that affected our understanding of causality and effective agency during this period.<sup>21</sup> These changes affected science and technology in ways that cannot be ranked hierarchically, where either science has primacy over technology or the other way around, but which occurs prior to their classification as either of these two categories. The term "light signal"—central to Einstein's theory of relativity—did not belong exclusively to either category. In areas that ranged from the military to the arts, it obtained a new meaning in connection to new means of communication (fig. 1).

Although the finite speed of light had been noted since the seventeenth century, most scientists before Einstein believed that certain "signals" could also convey information instantaneously. In classical physics, forces can propagate instantaneously and no transmission velocity needs to be considered. But instantaneous signals could invalidate all of Einstein's momen-

19. Martínez, "The Questionable Inventions of the Clever Dr. Einstein," 50.

20. Galina Granek, "Poincaré's Light Signaling and Clock Synchronization Thought Experiment and Its Possible Inspiration to Einstein." The "pervasiveness of this analysis in later writings" is noted in John D. Norton, "Einstein's Investigations of Galilean Covariant Electrodynamics prior to 1905," 92.

21. Dennis Overbye, *Einstein in Love*, 135.



JULY  
2015  
VOL. 56



FIG. 1 *L'Optique*, allegory of light-based signaling, with torch, mirror, and telescope; engraved by Charles-Nicolas Cochin, 1737, Paris, after Jacques de la Joue. 12 x 14.5 inches on laid paper. (Source: In author's collection.)

tous predictions about the relativity of simultaneity and of time. Even solid bodies, under Einstein's interpretation, should be considered in terms of signals that took time to be transmitted. "Let us imagine a rod of a certain length," he explained. "If we pull on one side, the other end will move at once." Yet this old way of thinking about solids needed to be overhauled: "This would be a signal that moves with infinite speed." His theory showed that no such signal could ever exist.<sup>22</sup> Einstein's revolutionary interpretation of time, space, and the universe was, at its core, a media revolution.

### Military Light Signals during World War I

"The comparison of light with other 'stuff' is not permissible," explained Einstein to an attentive audience.<sup>23</sup> In 1911, they remained largely unconvinced. But soon his argument would make a lot more sense to many more people. On the battlefields of World War I, soldiers and commanders alike saw how the transmission of light behaved in ways that differed

22. "Diskussion," iv.

23. Ibid., viii.



markedly from the transmission of sound and other things. The military practice of “sound and flash ranging” used to determine the exact location of enemy artillery relied precisely on those differences.

What was the best way for men with a scientific background to contribute to the war? Physicist Joseph S. Ames, professor of physics at Johns Hopkins University, had a clear answer. In “The Trained Man of Science in the War” he explained how they could contribute by sharing their work on light signaling. Physicists, he argued, were the “obvious” experts in certain kinds of communication technologies and therefore useful to the military: “But consider a problem like this: to devise a light signal, which can be used by day or by night, and which will be absolutely invisible to the enemy. Who can solve that? The answer is obvious: only a physicist.” Ames celebrated the work of General George O. Squier, chief signal officer of the U.S. Army Signal Corps, whose Ph.D. from Johns Hopkins permitted him “to know his subject from the scientific standpoint as few military officers can know it.”<sup>24</sup> Light signals were so closely associated with war that when artist Otto Dix conceived one of his most famous paintings depicting the horrors of World War I, he decided to produce a work widely known as *Lichtsignale* (fig. 2).

### World War I Communications: “Sound and Flash Ranging”

How should we think about theoretical science in light of the media transformations of the early twentieth century? From the time Einstein wrote his famous paper, light signaling technologies concerned the military as much as they did physicists. Starting in the nineteenth century, these systems were used for maritime and meteorological communications, but their main function resided in how they could be used for the “defense of the nation,” which included (in America) “efficiently protecting the populations from the depredations of the Indians.”<sup>25</sup>

The practice of comparing light, sound, and actual explosions became standard artillery practice in World War I. These comparisons proved invaluable during the British victory at Cambrai in 1917 and during the “black day” for the German Army at Amiens in 1918.<sup>26</sup> In order to determine the exact position from where weapons were being fired, field commanders compared the time of an actual explosion, the time it was set in

24. J. S. Ames, “The Trained Man of Science in the War,” 403, 407.

25. Th. Moureaux, “Le Service des signaux de l’armée,” 45. In the United States, signalmen were charged with photographing and documenting World War I. In July 1917 a Photographic Section was established within the army Signal Corps. By the end of the war, the Signal Corps had taken approximately 30,000 photographs and had accumulated 750,000 feet of film. Rebecca Robbins Raines, *Getting the Message Through*, 188–89.

26. William Van der Kloot, “Lawrence Bragg’s Role in the Development of Sound-Ranging in World War I,” 273.

JULY  
2015  
VOL. 56



FIG. 2 Otto Dix, *Leuchtkugel* (The Flare), commonly known as *Lichtsignale*, 1917, in Städtische Galerie Albstadt. 16 x 15.5 inches, gouache on paper. (Source: ©2015 Artists Rights Society (ARS), New York/VG Bild-Kunst, Bonn.)

motion, and when the explosion was heard or seen: “When a gun ejects its shell in the direction of the enemy, the latter hears in succession three sounds; first due to the passing of the shell through the air, in general a hissing sound; then the proper sound from the gun mouth, a boom; and finally the sound of the explosion of the shell.” By knowing the speed of sound, officers could triangulate the location of the gun, allowing them to strike back accurately.<sup>27</sup> Sound ranging was complicated, affected as it was by myriad environmental factors including weather-related wind patterns. For this reason, it had to be compared against information gleaned through flash ranging.

Comparing the difference between the sound of ejection, flight, and explosion with available visual light signals provided information that affected the outcome of key World War I battles. Physicists, many of whom would become involved with relativity theory, played key roles in flash and

27. Ames, “The Trained Man of Science in the War,” 408.

sound ranging. In France, General Gustave-Auguste Ferrié was in charge of wireless communications, where he worked closely with Louis de Broglie to improve transmission from the Eiffel Tower. Louis's brother Maurice de Broglie, a retired navy officer, worked on submarine signaling technologies. Henri Abraham and Charles Fabry collaborated with the Americans on sound and flash ranging.<sup>28</sup> Astronomer Charles Nordmann from the Paris Observatory, an expert in wireless time-distribution technologies who would become one of the most important popularizers of relativity theory in France, paired with Lucien Bull of the Marey Institute to build sound-ranging instruments.<sup>29</sup> Paul Langevin, who worked closely with Einstein on relativity, even attempted to commercialize the sound-wave detection equipment he developed during the war.<sup>30</sup>

In Germany, Hans Reichenbach was enlisted in the country's radio unit and physicist Max Born enlisted in the signal corps to work on sound ranging.<sup>31</sup> When Born arrived in Berlin, he would become a close friend of Einstein and dedicate himself after the war to teaching and writing about relativity theory. In England, William Lawrence Bragg was responsible for the British sound-ranging effort, along with his father William Henry Bragg, who worked on submarine detection. Princeton physicist Augustus Trowbridge led the American Flash and Sound Ranging Service. After the war, he proudly announced to scientists and philosophers alike how "on the signing of the armistice the entire front of the second American army was covered with both flash and sound ranging."<sup>32</sup> Karl T. Compton, physicist and president of MIT, recounted Trowbridge's wartime collaboration with physicists Robert A. Millikan and Charles E. Mendenhall, and their efforts at building equipment at Princeton's Palmer Laboratory and at Bell Labs, which they tested at the Sandy Hook Proving Ground.<sup>33</sup>

In the context of physicists' World War I work, we can understand why so many of the technical as well as popular accounts of relativity that proliferated after the war used the "flash and bang" trope to explain its central lessons. A typical example of this pedagogical tactic appears in an article on relativity by American astronomer William H. Pickering, published in *Popular Astronomy* in 1920. The author noted that "if instead of the sound of a gun being used as a signal on the train, we had fired a bullet" it would reach the observer at a different time. An entirely different calculation (one

28. Karl T. Compton, "Biographical Memoir of Augustus Trowbridge, 1870–1934," 228.

29. Van der Kloot, "Lawrence Bragg's Role in the Development of Sound-Ranging in World War I," 275.

30. Bernadette Bensaude-Vincent, *Langevin, science et vigilance*.

31. Van der Kloot, "Lawrence Bragg's Role in the Development of Sound-Ranging in World War I," 280.

32. Augustus Trowbridge, "Sound and Flash Ranging," 522. He recounted his wartime experience with sound and flash ranging at the American Philosophical Society on 26 April 1919.

33. Compton, "Biographical Memoir of Augustus Trowbridge, 1870–1934," 227–30.

JULY  
2015  
VOL. 56

independent of the velocity of the train), he explained, was required for light. Pickering carefully elaborated on “the analogy of the bullet” to light by imagining a train equipped with “guns” on either end. “Suppose that on a calm day when the train is stationary we fire a gun from the engine,” how would this scenario be different from the case where the train was in motion? What “if the gun was at the rear of the train” he asked?<sup>34</sup> Even pacifist astronomer Arthur Eddington, who avoided the draft by organizing the eclipse expedition that proved Einstein’s theory, used the example of a rifle bullet to explain relativity, and discussed it by reference to the “simultaneity of a flash and a bang.”<sup>35</sup>

Parisian astronomer Charles Nordmann drew from his experiences developing flash- and sound-ranging technologies during the war to explain relativity in his commercially successful *Einstein et l’univers* (1921). Nordmann compared the speed of light directly against that of the shell fired by the Krupp-manufactured “Big Bertha” howitzer during Germany’s advance toward Belgium to highlight the special characteristics of light: “The initial speed of the Bertha shell is only approximately 1,300 meters per second. For movements so slow, any relativistic contraction is negligible,” he explained. Electrically charged “projectiles,” he continued, were “much smaller than the shells of European artilleries, but, in turn, they are launched at infinitely greater initial velocities against which even those of the Bertha compare poorly.”<sup>36</sup>

Mary F. Cleugh, author of *Time and Its Importance in Modern Thought* (1937), identified the common “flash and bang” trope present in the scientific literature on the topic: “The time-lag between ‘flash’ and ‘bang’ shows that sound has a finite velocity, and from that an analogy may be made to the case of light.” A reader who might at first resist theory would have to come around to it with these “carefully graduated series” of battlefield examples:

But if he is given a carefully graduated series of examples, beginning with the familiar “flash and bang” of a distant gun, going on to two guns between which he stands, and ending with a full-blown Einstein and trains and light signals, he will admit that it follows from these that simultaneity is, after all, relative.

How did practical wartime lessons end up having such a central place in Einstein’s theory of the universe, affecting even something as philosophical as our everyday notion of time? Cleugh was baffled by “the importance of light-signals” in our scientific understanding of time in physics and in the cosmos. She was at first skeptical: “It is one thing to say that we cannot make judgments of simultaneity with regard to events at some distance from each other without the help of a light signal,” but “it is quite another

34. William H. Pickering, “The Theory of Relativity,” 336–38.

35. Arthur Stanley Eddington, *Space, Time, and Gravitation*, 103.

36. Charles Nordmann, *Einstein et l’univers*, 64, 97.

to define simultaneity as depending on light-signals.” So why was time defined by reference to light signals? After surveying alternative ways of conceiving time, most of which were not based on light signals and would therefore escape from the paradoxes of relativity, she eventually gave up. There was no choice but to “admit in the end that time is merely a function of light.”<sup>37</sup> In a century marked by telecommunications technologies based on electrodynamic “light signals,” it certainly was.

### Difficulties Defining “Signal Velocity” circa 1905

The World War I context was quite different from the one in which Einstein first conceived of his theory. In his famous “annus mirabilis” theory of relativity paper (1905), Einstein initially used no fewer than three terms to describe the transmission of light: *Lichtstrahl* (light ray), *Lichtzeichen* (light signs) and *Lichtsignale* (light signals). Two years later, he was much clearer. He abandoned “ray” and “sign” in favor of “signal.” What prompted this change in his terminology and what was its significance for science and for our understanding of the universe?

In a set of key publications that followed his 1905 paper, Einstein replied to the objections of some prominent critics in a clear and novel way. In the process he also distinguished his own contribution from that of his colleague Hendrik Lorentz. His distinction hinged on a particular understanding of *light signals as communication signals*. The “light signals” of relativity theory, he explained, were actually “electromagnetic influences” that could be “one-time” and “voluntary” and that could, “for example, be used for sending an arbitrary signal.”<sup>38</sup> This new definition of the term “light signal” was key, as it helped Einstein respond to the objections that the existence of speeds faster than those of light would invalidate his conclusions. In years to come, this particular reconfiguration of his work would take on a decisive importance in the establishment of relativity. In 1905 Einstein asked readers to consider what happens if “a ray of light starts out from A at time  $T_A$ , is reflected from B at time  $T_B$ , and arrives back at A at time  $T'_A$ .” He then asked readers to consider the velocity of this light ray as constant. Einstein was nearly done with his argument. With a few additional simple calculations, he arrived at one of the most astounding claims of his theory, that a clock traveling close to the speed of light would mark time differently than a stationary one. Had Einstein revolutionized our understanding of time and space? In 1905 he had claimed that “the velocity of light physically *plays the part* of infinitely great velocities,” but he had not yet shown that it was the fastest velocity possible for the transmission of signals.

37. Mary Frances Cleugh, *Time and Its Importance in Modern Thought*, 58, 62.

38. Einstein to Wien, Bern, 26 August 1907. In *The Collected Papers of Albert Einstein* (hereafter CPAE), vol. 5, 40–41.

JULY

2015

VOL. 56

A close reading of his work shows him initially struggling with his terminology, sometimes using the term “ray,” other times “sign,” and even creating new terms by hyphenating or concatenating words, such as “sign-effect” and “arbitrary-voluntary signaling.” After he settled on the term “*Lichtsignale*” and narrowed its definition, he increasingly reframed the theory of relativity in a new way. He started to refer to “relativity theory” as his own work, distinguishing it from others, and he drew much wider conclusions from it.

In two articles authored in 1907 Einstein started defining the term light signal by reference to electromagnetic communication signals. One was published in the *Annalen der Physik*, the same prestigious venue that printed his famous 1905 paper, and the other appeared in *Jahrbuch der Radioaktivität und Elektronik*, a premier technology journal. In the second publication, Einstein boldly distinguished his work from Lorentz’s. In both papers, Einstein repeated almost verbatim one key paragraph which gave his earlier paper new life and meaning.

In this new 1907 work, light no longer “played the part” of infinitely great velocities—it was an unsurpassable velocity because Einstein now used it in narrower terms, exclusively in those of its role in the actual “spreading of an effect”:

We will now show that not only the assumption of an instantaneous spread of some effect, but also more generally, any assumption of the spreading of an effect with a velocity greater than the velocity of light is incompatible with the theory of relativity.<sup>39</sup>

Einstein was now much clearer about why the speed of light could not be surpassed. In the *Annalen* paper, he explained how it could not be beaten in the case of the “spreading of an effect.” There was nothing “illogical” in thinking about instantaneous transmission, but Einstein was confident enough to state that it did not occur in practice in terms of the “spreading of an effect” with “causal” consequences through a “transfer mechanism.” After discussing the supposed instantaneity of light, he explained why it could not fit with our experience of the world:

Even though, in my opinion, this result does not contain a contradiction from a logical point of view, it conflicts so absolutely with the character of all our experience that the impossibility of the assumption  $W > V$  [propagation velocity of an effect greater than the speed of light] is sufficiently proved by this result.<sup>40</sup>

This sentence from the science journal *Annalen der Physik* was repeated almost verbatim in the more technological journal *Jahrbuch der Radio-*

39. Albert Einstein, “Über die vom Relativitätsprinzip geforderte Trägheit der Energie,” §3 p. 381.

40. *Ibid.*, §3 p. 382.



*aktivität und Elektronik*. In the *Jahrbuch* paper his terminology was more technical. Velocities greater than light could not be found for “arbitrary-voluntary signaling” (*willkürlichen Signalgebung*). No effect of *this kind*—willful and arbitrary—could be “propagated faster than light in a vacuum.”<sup>41</sup>

What happens when “the observer in A sends a sign-effect to the observer in B” Einstein asked repeatedly.<sup>42</sup> In both articles Einstein used the term “sign-effect” (*Wirkung Zeichen*), but he started to clarify the meaning of this term depending on how it related to the speed of light. The *Jahrbuch* engineering publication (1907) explained that the speed of light could only be considered as infinitely great in the case of an “arbitrary-voluntary signal” which could never surpass the value of “a universal constant *c*” (where *c* designates the speed of light). In other words: “a universal constant *c*” was the maximum speed of an “arbitrary-voluntary signal.”<sup>43</sup> In the *Annalen* publication he associated this type of effect with “an act of will.” He carefully explained the difficulties of superluminal signal transmission (“sign-effects”) by citing the rules of causality: “This result signifies that we would have to consider as possible a transfer mechanism whose use would produce an effect which precedes the cause (accompanies by an act of will [*Willensakt*], for example).”<sup>44</sup> Einstein drew broad conclusions by thinking of physics in terms of the causal transmission of willful emissions. “The time *T* that elapses between the sign emission [*Zeichengebung*] in A and the sign reception [*Zeichenempfang*] in B” in *the case of willful causal* transmission was the time that interested him. These particular characteristics of transmitting effects allowed him to define time in a radically new way. These were precisely the signals transmitted through the growing telecommunications network of his era.

### Abandoning “Local Time”

Einstein’s new understanding of his theory in terms of the “willful” emission and reception of “sign-effects” was directly connected to his new understanding of time. In the *Jahrbuch* paper, he distinguished his position from that of Lorentz, who had first developed the relativity equations Einstein used.<sup>45</sup> Historians have observed that Einstein’s theory, in contrast to Lorentz’s, no longer referred to one of the *t* variables in the relativ-

41. Albert Einstein, “Über das Relativitätsprinzip und die aus demselben gezogenen Folgerungen,” §5 p. 423.

42. Einstein, “Über die vom Relativitätsprinzip geforderte Trägheit der Energie,” §3 p. 381.

43. Einstein, “Über das Relativitätsprinzip und die aus demselben gezogenen Folgerungen,” §5 p. 415.

44. Einstein, “Über die vom Relativitätsprinzip geforderte Trägheit der Energie,” §3 pp. 381–82.

45. For a historical study of Einstein’s authorship of relativity, see Richard Staley, *Einstein’s Generation*, and Richard Staley, “On the Histories of Relativity.”



JULY  
2015  
VOL. 56

ity equations as “local time.” For Einstein, both referred equally to time. He described Lorentz’s conception as an “artificial means of saving the theory.” He also started using a different label for his work, which up to then was usually referred to as the Einstein-Lorentz theory, referring separately to “the H. A. Lorentz theory and the principle of relativity.”<sup>46</sup>

Was Einstein’s explanation of relativity in terms of “arbitrary-voluntary signal” transmission connected to the abandonment of Lorentz’s “local time”? As Einstein realized that instantaneousness could not exist in the case of light signal transmission, he also became increasingly confident in his claim that no other universal definition of time could compete against his. In 1907 Einstein had listed the “character of all of our experience” as proving why signals could never travel faster than light. That aspect of his contemporary experience was the main reason why he argued that scientists had to adopt his theory.

Wilhelm Wien, one of the most important scientists of the time and a man who held top research, teaching, and administrative positions in Germany, was not convinced by Einstein. The senior scientist wrote to Einstein asking him to clarify certain claims in his 1905 paper. He asked him about the possibility of superluminal propagation velocities, knowing fully well that—if these existed—they would completely invalidate all of Einstein’s conclusions.<sup>47</sup> Wien reminded the junior patent examiner that his relativistic definition of time did not work for these kinds of cases. In 1905 Einstein had merely stated that “for superluminal velocities our considerations become meaningless.” Now a colleague was asking him directly how meaningless, or meaningful, his contributions really were. Einstein was forced to clarify. What could Einstein do to save his theory?

“You have raised here a most interesting question!” wrote Einstein, then a largely unknown patent examiner, to Wien in the summer of 1907. Einstein had good reasons to be excited. He “threw” himself into a “writing frenzy” trying to answer the question as best he could. It took him weeks to craft a response, periodically checking in with his interlocutor to make sure he was on the right track.

With a tone of irritation, the senior scientist complained to Einstein that when reading his work “one can understand whatever one wants” from his equations of propagation velocities, and that they did not necessarily lead to his conclusions. His colleague did not stay quiet about what he considered clear faults in Einstein’s reasoning. After writing first to Einstein for clarification, he immediately contacted Lorentz.<sup>48</sup> By the end of the month, Einstein had penned an answer. The definition of time and

46. Einstein, “Über das Relativitätsprinzip und die aus demselben gezogenen Folgerungen,” 413.

47. Galina Weinstein, “Einstein on the Impossibility of Superluminal Velocities.”

48. See letter from Wien to Lorentz, 17 August 1907, and Lorentz’s response, 22 September 1907, 218–21.

simultaneity which he used in his paper, he explained to his colleague, was right if the time signals he described in it were understood in a specific way, not as any kind of signals but as *communication* signals.

“There seems to be a misunderstanding between us, which I shall now try to clarify.” Einstein explained that the exchange of “light signals” that he referred to should be understood as information-transfer signals. Relativity theory was concerned with communication signaling—not with just any type of signals. The difference between his argument and Wien’s, Einstein explained, was that Einstein did not refer to “a periodical process” but instead focused on “the propagation of an influence that could, for example, be used for sending an arbitrary signal.” Superluminal velocities, he clarified, did not exist for *these* kinds of signals.<sup>49</sup>

The signals that concerned Einstein could be changed “at will” and unpredictably. His notion of signal was one which could be “arbitrary” and which could be “one-time (not regularly recurring)” and which was “not yet determined by past” processes. He thus defined “signaling” in *physics* in the same terms that it was used for the purpose of communication, distinguishing the concept from the transmission of “*Zeichen*” (signs) which could be periodic or predetermined.

Einstein urged Wien to change his understanding of “propagation velocity” in terms of “signal” transmission. For this, he turned to the results of his colleague Emil Wiechert who had studied the velocity of an “optical signal,” concluding that it should always be less than the speed of light “in any medium.”<sup>50</sup> Superluminal velocities could not play a role in technologies that depended on the transmission of these “optical signals” because they were always either equal to or less than the speed of light. Einstein had stumbled on an answer to his critic:

I now designate the kind of velocity that, according to the theory of relativity, cannot be greater than the velocity of light in a vacuum as “signal velocity.” This is a velocity by which a one-time (not regularly recurring) influence, which is not yet determined by past electrodynamic processes, is propagated; thus, we are dealing here with the propagation of an influence that could, for example, be used for sending an arbitrary signal.

Wien’s objections, he argued, were invalid because they did not apply to these cases: “The propagation velocity . . . in your analysis is not a ‘signal velocity’ because . . . this velocity refers to a periodical process.”<sup>51</sup>

In correspondence with Wien, and referencing Wiechert’s research, Einstein started to consider the speed of light as the fastest *signaling* veloc-

49. Einstein explained at that time that the light signals he described did not “rule out” superluminal velocities in other cases.

50. Einstein to Wien, Lenk, 7 August 1907, in *CPAE*, vol. 5, 35–36.

51. Einstein to Wien, Bern, 26 August 1907, In *CPAE*, vol. 5, 40.

ity possible. He described key problems in physics in terms of the scenario of sending (“emanation”) and receiving (“perception”) an “electromagnetic influence.”<sup>52</sup> In this way, he differentiated the concept of “signal velocity” from that of “group velocity.” Two years earlier, in 1905, he had explained how, in his theory of relativity, “the velocity of light physically *plays the part* of infinitely great velocities,” but he had not yet claimed that it was the fastest velocity possible for the transmission of “arbitrary” and “one-time” electromagnetic signals. After his discussions with Wien, light was no longer playing a part or a role. Light *was* an “infinitely great velocity”—if considered in terms of electromagnetic signaling practices.

### The Media of Time: Telegraphing into the Past

Once Einstein clarified the meaning of signal in physics, other scientists were quick to understand relativity in terms of communication technologies. In 1911, during the famous presentation of relativistic effects that would later be known as the twin paradox, physicist Paul Langevin, one of the most important popularizers of relativity theory and a close friend of Einstein, presented it in a way that stressed its connection to signaling techniques. Before Einstein, he explained, scientists thought that pulling “a string to ring a bell . . . permitted instantaneous signaling.” But Einstein had shown that “[t]here should not exist a messenger or a signal that can travel at speeds greater than three hundred thousand kilometers per second.”<sup>53</sup> He urged listeners to abandon their intuitive understanding of solid bodies by considering them instead in terms of their signaling potential. When Langevin explained the concept of causality, of how one event “could effectively act on another,” he described it simply in terms of signal transmission technologies. “It is the principle of telegraphy,” he concluded, to an audience of flummoxed philosophers.<sup>54</sup> While Einstein was still struggling to explain and promote his theory with Langevin’s help, he grew excited to learn about technological innovations that would make their arguments more convincing. “Moving light sources of several 1000 miles” are now “available,” he wrote with excitement to his friend Paul Ehrenfest, hoping that these would help them ascertain relativistic effects more easily<sup>55</sup> (fig. 3).

Led by Einstein, relativity scientists started to consider the difference between the past and the future in terms of signaling possibilities. They defined the past as the time of signal *emission* when compared against the time of *reception*. And the future was the time of *reception* if compared against the time of *emission*. There were no cases where a “signal would

52. Einstein to Wien, Bern, 23 August [July] 1907, in *CPAE*, vol. 5, 32–33.

53. Paul Langevin, “L’évolution de l’espace et du temps,” 39, 43.

54. Paul Langevin, “Le temps, l’espace et la causalité dans la physique moderne,” 26.

55. Einstein to Paul Ehrenfest [Prague, before June 1912], in *CPAE*, vol. 5 (*English translation supplement*), 310.

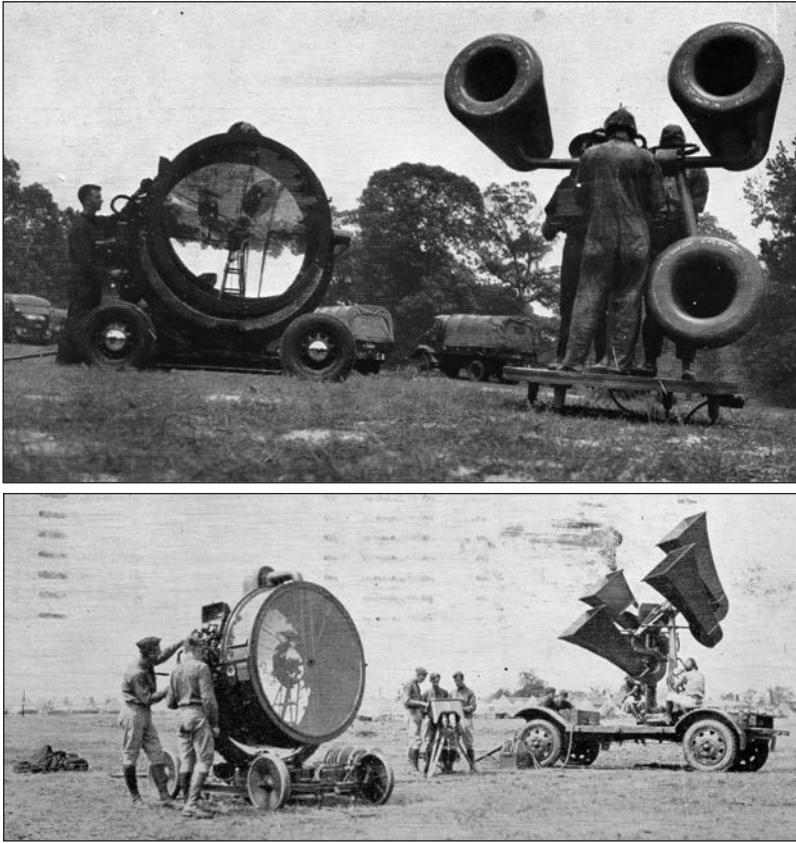


FIG. 3 Postcards depicting military searchlights and sound-detection equipment. Top: “50-Inch Searchlight and Sound Detector,” published by W. R. Thompson & Co. Bottom: “Plane Detector and Searchlight, First Army War Maneuvers, 1939, Plattsburg Area,” published by Santway Photo-Craft Company, Watertown, N.Y. (Source: Postcards in author’s collection.)

have arrived at its goal before being emitted: The effect would precede the cause.<sup>56</sup> Langevin explained that if the rules of relativity theory were violated, “we could telegraph into the past, as Einstein has said, and we would consider that absurd.”<sup>57</sup> Scientists quickly drew models of space and time according to relativity theory. The famous image of the light cone, a common fixture in popular and specialized accounts of the special theory of relativity, represented the past and the future in terms of signaling possibilities. The “here and now” was a point from which signals could be sent into the future and where past signals had already arrived (fig. 4).

56. Einstein, “Le principe de relativité et ses conséquences dans la physique moderne,” sec. 7., 135.

57. Langevin, “L’évolution de l’espace et du temps,” 44.

JULY  
2015  
VOL. 56

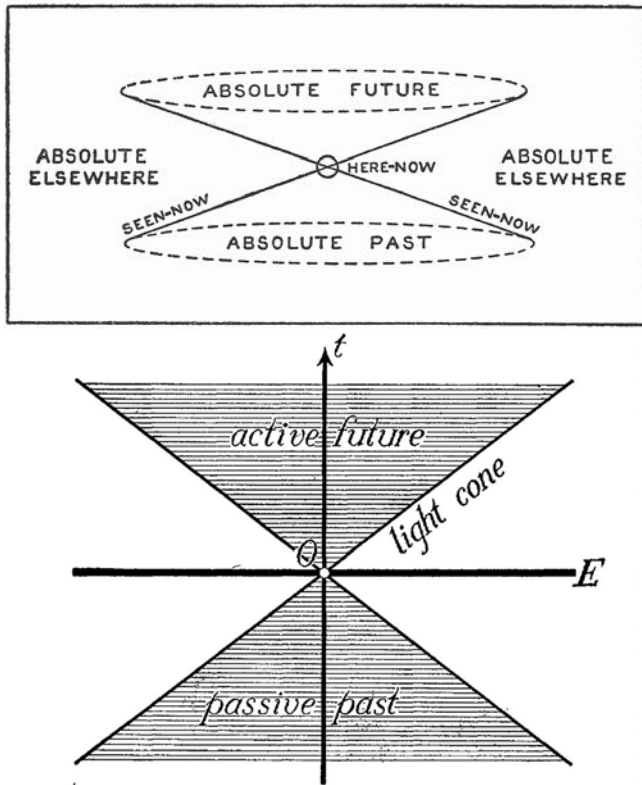


FIG. 4 Light cones depicting the path of a light ray through spacetime. Top: By Arthur Eddington. (Source: Arthur Eddington, *The Nature of the Physical World*, 48.) Bottom: By Hermann Weyl. (Source: Hermann Weyl, "The Mathematical Way of Thinking," 440.)

Emerging telecommunications (first telegraphy and later radio) sent messages across vast distances that had been previously covered only by transportation technologies, such as ships, trains, and automobiles. Before World War I, triode vacuum tubes were only manufactured in bulk in the United States. But after the war, Europeans ramped up production so that they could be used for military wireless communications.<sup>58</sup> The development of multiplexing allowed telegraph and telephone to share the same infrastructure. Once telegraph signals could be sent through telephone wires using frequencies that did not play a role in speech transmission (from 0 to 150 Hz), the carrying capacity of telecommunications networks was significantly expanded.<sup>59</sup> After the war, commercial and civilian radio communications, starting with finance and journalism, flourished.

58. Lewis S. Feuer, *Einstein and the Generations of Science*, 214.

59. Bernhard Siegert, *Relays: Literature as an Epoch of the Postal System*, 189.

When Einstein developed his general theory of relativity, which in contrast to the special one encompassed acceleration and gravitation, one of its most revolutionary assertions was that the universe was essentially curved. The shortest path between two points was not, as in Euclidean geometry, a straight line. The shortest path between two points was defined as that traveled by *an electromagnetic signal* and which could be considered (in the presence of a gravitational field) as a curve.

Cosmological and astronomical implications of Einstein's theory were often described by reference to the possibility of communicating with someone in outer space.<sup>60</sup> In Britain, Eddington described it by reference to the difficulties in maintaining a conversation, and even a love affair, with a lady on Neptune, while Wildon Carr similarly explained the "time of transmission" in the theory of relativity by reference to a telephone conversation with someone on another planet.<sup>61</sup>

American physicist Percy Bridgman used the example of sending "wireless signals" to a "confederate in the nebula."<sup>62</sup> In Germany, mathematician Hermann Weyl described in an article titled simply "The Mathematical Way of Thinking" that the question of "whether two men, say Bill on Earth and Bob on Sirius, are contemporaries" depended on "whether it means that Bill can send a message to Bob, or Bob a message to Bill, or even that Bill can communicate with Bob by sending a message and receiving an answer, etc."<sup>63</sup> In France, physicist Jean Becquerel described the reality of time dilation in terms of a traveler and an observer on Earth by imagining them exchanging time signals via electromagnetic waves or "T.S.F. signals."<sup>64</sup>

Louis de Broglie, who worked in the radio service unit during World War I and was one who used the Eiffel Tower for military wireless transmission, assessed relativity theory almost exclusively in terms of telecommunications. "[T]he Einstein rules" were clear "just giving and receiving signals," explained American philosopher William Montague.<sup>65</sup> Alfred North Whitehead, among the first to write about the theory after it was successfully confirmed by the results of Eddington's famous eclipse expeditions, understood Einstein's work entirely as a treatise about signaling

60. For the literary context of these thought experiments, with a particular focus on Eddington, see Katy Price, *Loving Faster than Light*.

61. Wildon Carr, "Symposium: The Problem of Simultaneity."

62. "Even in thought the only way for me to find what is happening 'now' in the distant nebula is to send a wireless message to my confederate in the nebula, who will receive it after one hundred million years, and then must consult what may be his equivalent for the library of the British Museum, where he will almost certainly find only the sketchiest sort of record of what was happening one hundred million years ago." Percy W. Bridgman, "The Concept of Time," 98.

63. Hermann Weyl, "The Mathematical Way of Thinking," 440.

64. Jean Becquerel, "Débats sur la relativité," 26.

65. William Pepperell Montague, "The Einstein Theory and a Possible Alternative," 151.



and messaging.<sup>66</sup> Eddington himself described to popular audiences how the theory of relativity perfectly explained “the consequences of being able to transmit messages concerning events” from one place to another.<sup>67</sup> The world described by Einstein was the way it was, explained the astronomer, because “signaling is only possible” in certain conditions and not in others.<sup>68</sup> It showed how nothing “capable of being used as a *signal* can travel faster than 299,796 kilometers a second.” The past existed when it “would be possible for us to have already received a wireless message announcing its occurrence.”<sup>69</sup> Direct references to telecommunications technologies appear again and again in theoretical, philosophical, and even popular accounts about the value and validity of Einstein’s work. Light was “the swiftest messenger in the world,” explained one writer who presented the theory to a popular audience.<sup>70</sup> Even those skeptical of Einstein’s theory engaged with it in technological terms, arguing that the constancy of the speed of light was a mere technological effect related to current limitations in contemporary communication technologies.

Consider the technical media challenges during this period of actually building an “audible tick-tock” that could be heard “everywhere in the world.” Einstein asked himself this question, which was tightly related to the technical challenges of establishing global communications. He came to the conclusion that scientists and the public at large should rid themselves of their longstanding belief that time in one part of the globe was simultaneous to time in another part of it—forgetting delays in transmission speeds. “There is no audible tick-tock everywhere in the world that could be considered as time,” Einstein explained in unpublished notes where he kept track of the “most important ideas of relativity theory.”<sup>71</sup>

The challenges facing the concept of universal time, which Einstein considered in terms of actual clocks, were the same as those facing contemporary telecommunications, struggling to send news across the world in *the shortest possible time*. If wireless time distribution services functioned with the delays of electromagnetic signal transmission, and if clocks measured time, there was no reason to believe these same effects would not affect time in the universe as well. For a decade and a half after its publication, Einstein’s work was considered equally as relevant for technology as for science. Eddington underlined the paradoxical technoscientific role of light in Einstein’s work, where it was clearly connected to actual communication

66. Alfred North Whitehead, *An Enquiry Concerning the Principles of Natural Knowledge*, 53.

67. Arthur Stanley Eddington, *The Nature of the Physical World*, 65.

68. *Ibid.*, 66.

69. Arthur Stanley Eddington, *The Theory of Relativity and Its Influence on Scientific Thought*, 17 n.11.

70. Benjamin Ives Gilman, “Relativity and the Lay Mind. II,” 508.

71. Albert Einstein, “Die hauptsächlichen Gedanken der Relativitätstheorie,” 1. Published as “The Principal Ideas of the Theory of Relativity” in *CPAE*, vol. 7, 5.



technologies while it was also surprisingly “fundamental.” The actual velocity of light, something that could seem too tied to current signaling technology limitations and “a rather arbitrary decree of nature,” explained Eddington, was a “fundamental velocity.” By “a lucky coincidence,” both of them were the same, he explained: “there is a physical entity—light—that moves habitually at the same speed of the fundamental velocity.”<sup>72</sup> Was Einstein simply lucky? He would soon have to explain to a growing number of critics why this “coincidence” was more than sheer luck.

## A Radio Engineer Comes to Einstein’s Defense

Given the overwhelming assessment of Einstein’s work in terms of signaling technologies, why should his research be considered in cosmological rather than merely practical terms? Starting in 1910, Einstein would frame his research in a manner that distanced it sharply from telecommunications. He described its implications for signaling as a “consequence” of a much broader physical theory, and a profoundly counterintuitive one at that. They were what “follows immediately” from his theory, not its starting point. The inability “to send signals that would travel faster than light in a vacuum” was a “consequence, as strange as it is interesting,” of his theory.<sup>73</sup>

More important, how were its connections to military concerns effaced? Both tasks were undertaken by Hans Reichenbach, founder of logical positivism, who promoted a simplistic view of science as the result of combining clear empirical observations with mathematical principles. After being released from the army’s radio unit, Reichenbach attended Einstein’s lectures in Berlin. Captivated by his teacher, he was hooked on physics for the rest of his life. He dedicated his first book to Einstein, and in the years that followed, Reichenbach and Einstein would become close.

It took decades before Einstein and Reichenbach were able to convince listeners that the universe and time—cosmological time—should be understood and defined by reference to light signals. In May 1921, during his lectures at Princeton University, Einstein claimed that “it is *immaterial* what kind of processes one chooses for such a definition of time.” But if immaterial, why that particular choice, light, asked his listeners? Einstein responded: “It is advantageous, however, for the theory, to choose only those processes concerning which we know something certain. This holds for the propagation of light *in vacuo* in a higher degree than for any other process which could be considered.”<sup>74</sup> Next year he was much bolder. In a

72. Arthur Stanley Eddington, *Espace, temps et gravitation*, 10. Quoted in Gaston Bachelard, *La Valeur inductive de la relativité*, 149.

73. Einstein, “Le principe de relativité et ses conséquences dans la physique moderne,” sec. 7, 134–35.

74. Albert Einstein, *The Meaning of Relativity: Four Lectures Delivered at Princeton University*, 31.

controversial discussion with philosopher Henri Bergson, he would imply that his definition of time was “objective” whereas other more philosophical notions were not.<sup>75</sup> By then, he had developed a more convincing response to his critics, in collaboration with Reichenbach.

In early January 1921, in a famous lecture titled “Geometry and Experience,” Einstein marshaled forceful arguments explaining why light signals were a fundamental key to the universe and not simply connected to technological novelties, no matter how wonderful.<sup>76</sup> His solution was frequently remarked upon: Why should scientists consider them essential for understanding time and space in the universe?<sup>77</sup> Was Einstein’s focus on light signals justified in scientific terms? For most of his professional life, critics argued that this one particular aspect of his work had not been properly explained. A particular concern centered on the reasons for adopting a definition of time based on light signals, understood in terms of the principle of the constancy of light, over other ways of understanding time. Why this way to define time and not another? If light signals were fundamental to the workings of the universe, then he should say why in terms of elementary atomic concepts, something that was (and still is) far from possible. Late in life Einstein admitted that he still could not argue for the adoption of a conception of time based on light signals from a foundational theory of “moving atomic configurations,” but he reminded his critics of other pressing reasons which he had thought out in collaboration with Reichenbach.<sup>78</sup>

Reichenbach’s early publications included highly philosophical texts as well as lowbrow popular engineering manuals. Unable to earn a living as a philosopher, he supported himself instead by teaching at the Technische Hochschule at Stuttgart, supplementing his income by becoming the editor of *Die Radio-Reihe*, a series of radio manuals financed with paid advertisements<sup>79</sup> (fig. 5).

In his accounts of radio technology for enthusiasts, Reichenbach explained that, if one considered light to travel at the approximate speed of 300,000 km/s, then “the time it takes the wave to travel from Nauen to New York is only about 1/50 second.” For practical purposes, he pointed out, this delay could be neglected and thus: “we can say with good sense that the waves arrive at the same time in New York that they are sent in Nauen.” The idea that the transmission speed of light was an unsurpassable velocity was

75. Jimena Canales, *The Physicist and the Philosopher*.

76. The classic work on Einstein’s “Geometry and Experience” is Michael Friedman, “Geometry as a Branch of Physics: Background and Context for Einstein’s ‘Geometry and Experience.’” For a clarification of the issues at stake, see Marco Giovanelli, “Talking at Cross-Purposes.”

77. See Einstein’s late-in-life reformulation of the questions in “Geometry and Experience,” in Albert Einstein, “Reply to Criticisms,” 676–81.

78. *Ibid.*, 673.

79. Hans Reichenbach, *Was ist Radio?*



FIG. 5 Front cover and advertising (p. 2) for Reichenbach's radio manual. (Source: Hans Reichenbach, *Was ist Radio?* In author's collection.)

an essential claim in Einstein's work, but Reichenbach did not reference it in his engineering manual. His "good sense" was enough to convince him that light was special: "Only the speed of light is so great"<sup>80</sup> (fig. 6).

"Telegraphy is as old as Mankind," explained Reichenbach, confidently claiming that "the prehistoric man who raised his arm up to wave to his contemporaries telegraphed." The only significant difference between the gestures of prehistoric man and cutting-edge wireless telegraphy was "the thousands of years of scientific work that lay in between."<sup>81</sup> Reichenbach highlighted the triumphant role of science in the thousands of years from prehistoric days to the present; he elided the piecemeal practical transformations of technology from the beginning of history to modern civilization.

Always attentive to what his professor said and wrote, Reichenbach jumped to Einstein's defense and developed the central ideas of "Geometry and Experience" more fully. He came up with a convincing, though slightly roundabout, way of justifying the special status of light signals in the work of his teacher, friend, and mentor. The reason they were particularly descriptive of the universe, he argued, was based on a concept given

80. *Ibid.*, 23–24.

81. *Ibid.*, 5.

JULY  
2015  
VOL. 56

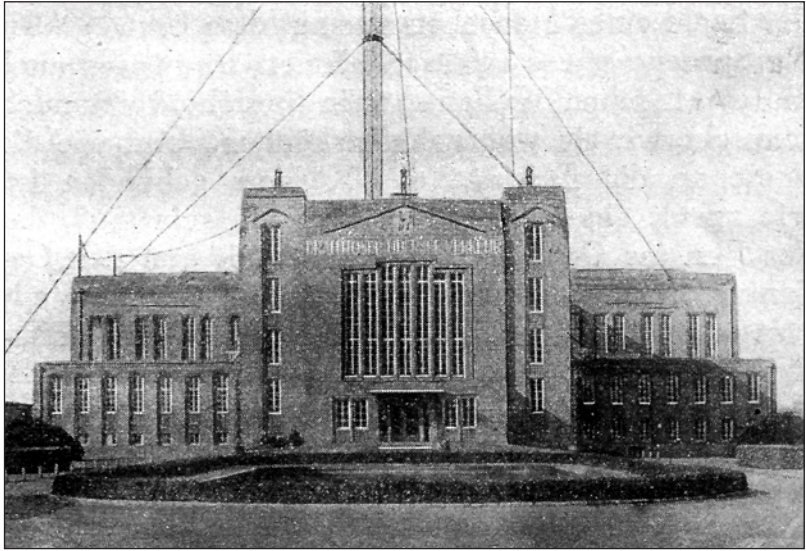


FIG. 6 Reichenbach's example of a radio station in Nauen, Germany.  
(Source: Hans Reichenbach, *Was ist Radio?* p. 29. In author's collection.)

“by definition,” namely the constancy of the speed of light in the absence of a gravitational field.<sup>82</sup> But this “definition” was neither arbitrary nor merely convenient. It should not be understood by reference to particular technical devices—it was a “fact” and a universal one at that.

To the end of his life, Reichenbach explained Einstein's theory by reference to signaling: “Einstein's relativity of simultaneity is closely associated with the assumption that light is the fastest signal.” He used the words signal and message repeatedly. He went as far as describing the Michelson-Morley experiment as an experiment about “signals,” arguing that “the assumption that light is the fastest signal” was “an idea which could not be conceived before the negative outcome of such experiments as that of Michelson.”<sup>83</sup>

Reichenbach used the example of the “telephone” and “radio telephone” to illustrate how we could grow “accustomed” to the reality described by Einstein.<sup>84</sup> He turned to the common example of communicating with someone in outer space. “[I]f a telephone connection with the planet Mars were established,” he explained, “we would have to wait a quarter of an hour for the answer to our questions.” If our communication technologies functioned with a similar delay in that way, then “the relativ-

82. Hans Reichenbach, “Der gegenwärtige Stand der Relativitätsdiskussion. Eine kritische Untersuchung,” 365–66.

83. Hans Reichenbach, “The Philosophical Significance of the Theory of Relativity,” 301.

84. “Radio telephone”: Hans Reichenbach, *The Rise of Scientific Philosophy*, 155.

ity of simultaneity would become as trivial a matter as the time difference between the standard times of different time zones today.”<sup>85</sup> Although Reichenbach constantly mentioned new telecommunications technologies and practices in his text, in the philosophical view of scientific development he was promoting, they appeared as nothing more than illustrative and pedagogical examples.

While constantly employing terminology and examples from the world of telecommunications to explain Einstein’s theory, Reichenbach stressed its theoretical and cosmic aspects over its mundane connections. He ignored the immediate war conditions that led him to work with radio in the first place and the financial incentives that led to the publication of the radio series with him as editor. Instead, Reichenbach distanced the theory of relativity from current technologies and their limitations. What was recounted as engineering knowledge in his radio manuals appeared as a universal truth in his scientific and philosophical texts.

### From Technological to Fundamental

How can something be technological and historically situated as well as fundamental and universally valid? In order for Einstein’s interpretation of relativity to prevail, the criticisms of influential French polymath Henri Poincaré, and his vision of the relation of science to technology and of both to mathematics, needed to be countered.<sup>86</sup> Poincaré’s philosophy valued scientific theories in terms of their practical validity rather than in terms of their universal status. Einstein had to combat Poincaré’s arguments in order to show why his light-signal-based theory was not simply one alternative explanation of physical effects, but rather a fundamental law of nature. Einstein first forcefully fought against Poincaré’s conventionalist philosophy in “Geometry and Experience” (1921). Reichenbach would immediately enter the ring as well.

The specific topic of Einstein’s attack against Poincaré was Riemannian geometry, which Einstein used in developing his general theory, but also at stake was the status of Euclidean geometry over non-Euclidean geometry, the latter closely associated with Einstein’s theory of relativity. Experiments clearly showed that the movement of light did not follow the laws of Euclid. But Einstein argued that his non-Euclidean geometry was not merely another useful mathematical formulation used to study a certain physical object (light); rather, he considered it a model of the actual geo-

85. Reichenbach, “The Philosophical Significance of the Theory of Relativity,” 308.

86. For Poincaré on telegraphy and wireless, see Henri Poincaré, “Étude de la propagation du courant en période variable sur une ligne munie de récepteur.” For a summary of his work and research in this area, see Henri Poincaré, “Mes principaux ouvrages relatifs à la physique,” 415. Gaston Darboux et al. to the Nobel Prize Committee, ca. 1 January 1910, 433.

metrical structure of the universe itself. The non-Euclidean shape of the universe, revealed through the behavior of light signals, was “a question of physics proper which must be answered by experience, and not a question of a convention to be chosen on grounds of mere expediency.”<sup>87</sup>

Poincaré considered claims about the mathematical shape of the universe as essentially misguided principles. The question of which geometrical system should be used to represent the universe, he argued, was completely the same as asking which measurement standard should be chosen. Inquiring into the validity of Euclidean over non-Euclidean geometry was simply the same as asking if one should use the yard or the meter.<sup>88</sup> Einstein admitted that if geometry was understood in this way, Poincaré was *sub specie aeterni* right.<sup>89</sup> But he disagreed with the view that measurements based on light signals were simply based on a conventional measuring standard.

Reichenbach sharpened the criticisms against Poincaré that Einstein first introduced. He attacked the idea that mathematics was more of a practical tool than a reflection of how the world actually was. He chastised Poincaré for espousing the view that scientists could chose between different geometries, claiming instead that only one of them described the “geometry of the physical world.”<sup>90</sup> Einstein’s theory was not simply a particular way of understanding the universe, he insisted, it revealed the shape of the universe itself. Reichenbach thus established the dual role of light signals as technological, but more important, fundamental. Einstein could have it both ways. Light-signal-based descriptions of the universe could be more than a convenient tool for science; they were much more *by definition* and *empirically* so as well. To answer those who wanted to know if light was actually constant and not merely defined as such, he stressed that it was “an empirical fact” that measurements could be and were undertaken in the manner described by Einstein.<sup>91</sup> For this reason, it was “experimentally well-confirmed.”<sup>92</sup> In 1928 Reichenbach once again explained why he thought that Einstein was entirely justified in his light-signal-based conception of the universe, arguing that it was “a matter of fact that our world” was a place where scientific measurements were undertaken in this manner. Were they? The choice of measuring system could potentially be seen as conventional, as Poincaré argued. But the actual reality of how people measured was not.<sup>93</sup>

87. Albert Einstein, “Geometry and Experience,” 238.

88. Henri Poincaré, *Science and Hypothesis*, 50.

89. Einstein, “Geometry and Experience,” 236.

90. Reichenbach, *The Rise of Scientific Philosophy*, 133.

91. Reichenbach, “Der gegenwärtige Stand der Relativitätsdiskussion,” 365–66.

92. Hans Reichenbach, “La signification philosophique de la théorie de la relativité,”

35. In technical terms, he argued that “the world” admitted a “univocal” definition of measurement.

93. Hans Reichenbach, *Philosophie der Raum-Zeit-Lehre*, 25.



## Measurement and Light Signals

Communications media affected the notion of scientific measurement during this period. In “Geometry and Experience,” Einstein proceeded to explain the traditional way of measuring, one based on using marked rulers. “[T]wo tracts are said to be ‘equal to one another’ if the marks of the one tract can be brought to coincide permanently with the marks of the other.” His explanation was hardly original. Poincaré had described it a number of times.<sup>94</sup> Poincaré had pointed out that relativity (which he associated with the equations of Lorentz and not with Einstein’s interpretation) was based on a different form of measurement, one that considered light paths as equal depending on the time taken to traverse them. The old way of defining measurement in terms of the comparison of lengths “is no longer true in the current theory.” Measurements, in the new system, were taken by comparing the arrival time of light signals. While Poincaré merely described the differences between these two ways of conceiving measurement, Einstein urged scientists to adopt the second one. A measurement “tract,” that was previously defined in terms of a rigid solid, should be re-defined in terms of the “path of light.”

When using rulers, scientists had to physically align two different objects against each other. In the early nineteenth century, the exigencies of measurement often required an observer to travel to the object to be measured in order to compare it against a standard brought along. To measure hard-to-reach places, scientists could use optical instruments that required aiming or leveling of an instrument against the image of an object, as with a theodolite. These precision measurements were done with instruments furnished with fine reticules or micrometers to bring two marks in line with each other or find the exact center of circles and dots. Such practices were very different from those described by Einstein—comparing the time of the arrival of two light signals against each other.

Einstein’s work on signals was connected to key changes in how scientists thought of observation and measurement more generally.<sup>95</sup> Measurement practices continued to be diverse, but underneath this practical diversity lay a new consensus about what *ideal* measurements were, from which scientists drew implications about the shape of the universe and the relation of experience to geometry.

## Conclusion: Light Signals Dominate the Airwaves

References to signals and messages abounded in the work of Einstein and his commentators during this period. The physicist and his interlocutors not only used these preexisting concepts, they defined their meaning.

94. Henri Poincaré, “Sur la dynamique de l’électron,” 1–32.

95. Lorraine Daston and Elizabeth Lunbeck, *Histories of Observation*.



JULY  
2015  
VOL. 56



FIG. 7 Einstein's telephone on his desk in his Berlin apartment (Haberlandstrasse 5), n.d. (Source: Bildarchiv Preussischer Kulturbesitz, Berlin. Photo credit: BPK, Berlin/Bildarchiv Preussischer Kulturbesitz/Art Resource, New York. Reprinted with permission.)

Before Einstein, the term “signal” in *physics* did not necessarily entail an element of transmission with a delay or the transportation of a message.

Commercial applications for long-distance signaling technologies flourished after World War I. The relevance of Einstein's light-signal-based theory increased in the wider culture as electrodynamic technologies transmitted more and more messages across wider distances. Einstein, and a rapidly growing number of civilian users, increasingly used the telegraph and telephone for personal purposes. By the winter of 1920 Einstein had a telephone in his Berlin apartment, which he placed prominently on top of his desk<sup>96</sup> (fig. 7). Commentors on Einstein's theory writing in the decades after the war years did not need to have been working directly with communication technologies to see it in those terms. They did not need to have direct experience working in war with radio, like Reichenbach, Born, Langevin, Nordmann, or de Broglie.

96. Carl Beck to Einstein, Chicago, 28 December 1920, in *CPAE*, vol. 10, 344.

A complete history of how technological media were written out of our understanding of twentieth-century physics remains to be investigated. In the case of relativity, few men were as responsible as Reichenbach for erasing the connection between theory and contemporary technologies. Ironically, few had as much firsthand experience working with light signals as he did. For Einstein's seventieth birthday, Reichenbach hailed him as a man whose work took "sensorial perception and analytical principles as sources of knowledge," nothing more and nothing less, leaving no place for telegraph, telephone, or radio.<sup>97</sup> Reichenbach's philosophical understanding of "experiment," one which dominated Anglo-American philosophy for the rest of the century, did not include a role for technology at all, let alone contemporary technologies. In his logical positivist view of experiment, technology was inferior to science and unrelated to its progress. There was no place in science for things like the "telephone" or "radio-telephone," which he repeatedly used to explain the theory.

In 1951 Reichenbach, who had risen in the ranks from radio engineer to professor of philosophy at UCLA, published his most popular book, *The Rise of Scientific Philosophy*. Once again, he countered some of the objections to Einstein's work that considered its conclusions as emerging from arbitrary definitions or practical conventions. He again claimed that in Einstein's theory the constancy of light was given by definition. He also consistently argued in favor of simply *defining* the speed of light as a constant quality, and then deriving all other important constants from it. Speaking as a philosopher, he explained that when Einstein said "there can be no faster signal than light" he did not merely mean "that no faster signal is known to us." Rather, Einstein meant that light was the fastest signal—regardless of how that fact became known.<sup>98</sup> That "light was the fastest signal"—originally an elementary lesson in the world of telecommunications—was now a firmly established law of nature.

## Bibliography

### *Archival and Unpublished Sources*

Bildarchiv Preussischer Kulturbesitz, Berlin

Weinstein, Galina. "Einstein on the Impossibility of Superluminal Velocities," unpub. ms., 2012

### *Published Sources*

Ames, J. S. "The Trained Man of Science in the War." *Science* 48, no. 1243 (1918): 401–10.

Bachelard, Gaston. *La Valeur inductive de la relativité*. Paris: J. Vrin, 1929.

Becquerel, Jean. "Débats sur la relativité: I. Critique par M. J. Becquerel de

97. Reichenbach, "The Philosophical Significance of the Theory of Relativity," 309–10.

98. Reichenbach, *The Rise of Scientific Philosophy*, 153.

- l'ouvrage 'Durée et simultanéité' de M. Bergson." *Bulletin scientifique des étudiants de Paris* (March 1923): 18–29.
- Bensaude-Vincent, Bernadette. *Langevin, science et vigilance*. Paris: Belin, 1987.
- Bridgman, Percy W. "The Concept of Time." *Scientific Monthly* 35, no. 2 (1932): 97–100.
- Campbell, W. W., and Joel Stebbins. "Report on the Organization of the International Astronomical Union." *Proceedings of the National Academy of Sciences of the United States of America* 6, no. 6 (1920): 349–96.
- Canales, Jimena. *The Physicist and the Philosopher: Einstein, Bergson, and the Debate that Changed Our Understanding of Time*. Princeton, NJ: Princeton University Press, 2015.
- Carr, Wildon. "Symposium: The Problem of Simultaneity: Is There a Paradox in the Principle of Relativity in Regard to the Relation of Time Measured to Time Lived?" In *Proceedings of the Aristotelian Society, Supplementary Volumes*. Vol. 3: *Relativity, Logic, and Mysticism*, 15–41. London: Williams & Norgate, 1923.
- Cleugh, Mary Frances. *Time and Its Importance in Modern Thought*. London: Methuen & Co., 1937.
- The Collected Papers of Albert Einstein*. Vol. 3: *The Swiss Years: Writings, 1909–1911*. Edited by Don Howard et al.; translated by Anna Beck. Princeton, NJ: Princeton University Press, 1993.
- \_\_\_\_\_. Vol. 5: *The Swiss Years: Correspondence, 1902–1914*. Edited by Martin J. Klein et al. Translated by Anna Beck. Princeton, NJ: Princeton University Press, 1993.
- \_\_\_\_\_. Vol. 6: *The Berlin Years: Writings, 1914–1917*. Edited by A. J. Cox et al. Translated by Alfred Engel. Princeton, NJ: Princeton University Press, 1996.
- \_\_\_\_\_. Vol. 7: *The Berlin Years: Writings, 1918–1921*. Edited by Michel Janssen et al.; translated by Alfred Engel. Princeton, NJ: Princeton University Press, 2002.
- \_\_\_\_\_. Vol. 10: *The Berlin Years: Correspondence, May–December 1920; and Supplementary Correspondence, 1909–1920*. Edited by Diana Kormos Buchwald et al.; translated by Ann Hentschel. Princeton, NJ: Princeton University Press, 2006.
- Compton, Karl T. "Biographical Memoir of Augustus Trowbridge, 1870–1934." *National Academy of Science Biographical Memoirs* 18 (1937): 217–44.
- Daston, Lorraine, and Elizabeth Lunbeck. *Histories of Observation*. Chicago: University of Chicago Press, 2010.
- "Diskussion." *Vierteljahrsschrift Naturforschenden Gesellschaft Zürich* 56, no. 2 (1911): II–IX.
- Eddington, Arthur Stanley. *Espace, temps et gravitation*. Translated by J. Rossignol. Paris: J. Hermann, 1921.

- \_\_\_\_\_. *The Theory of Relativity and Its Influence on Scientific Thought*. Oxford: Clarendon Press, 1922.
- \_\_\_\_\_. *The Nature of the Physical World*. Everyman's Library: Science. Edited by Ernest Rhys. London: J. M. Dent & Sons, 1935 (1928).
- \_\_\_\_\_. *Space, Time, and Gravitation: An Outline of the General Relativity Theory*. Cambridge Science Classics. Cambridge: Cambridge University Press, 1987 (1920).
- Einstein, Albert. "Über die vom Relativitätsprinzip geforderte Trägheit der Energie." *Annalen der Physik* 23 (1907): 371–84.
- \_\_\_\_\_. "Über das Relativitätsprinzip und die aus demselben gezogenen Folgerungen." *Jahrbuch der Radioaktivität und Elektronik* 4 (1907): 411–62.
- \_\_\_\_\_. "Le principe de relativité et ses conséquences dans la physique moderne." *Archives des sciences physiques et naturelles (Genève)* 29, nos. 1, 2 (1910): 5–28, 125–44.
- \_\_\_\_\_. "Die Freie Vereinigung für technische Volksbildung." *Neue Freie Presse*, 24 July 1920, 8.
- \_\_\_\_\_. *The Meaning of Relativity: Four Lectures Delivered at Princeton University, May, 1921*. London: Methuen & Co., 1922.
- \_\_\_\_\_. "A Re-examination of Pacifism." *Polity* 3, no. 1 (January 1935): 4–5.
- \_\_\_\_\_. "Autobiographical Notes." In *Albert Einstein: Philosopher-Scientist*, edited by Paul Arthur Schilpp, 3–94. LaSalle, IL: Open Court, 1949.
- \_\_\_\_\_. "Geometry and Experience." Translated by Sonja Bargmann. In *Ideas and Opinions*, edited by Carl Seelig, 232–46. New York: Three Rivers, 1954.
- \_\_\_\_\_. "Reply to Criticisms." In *Albert Einstein: Philosopher-Scientist*, edited by Paul Arthur Schilpp, 665–88. LaSalle, IL: Open Court, 1970 (1949).
- \_\_\_\_\_. "Manifesto to the Europeans" (1914). In *The Collected Papers of Albert Einstein (English Translation Supplement)* vol. 6, 28–29.
- \_\_\_\_\_. "Die hauptsächlichen Gedanken der Relativitätstheorie." In *The Collected Papers of Albert Einstein*, vol. 7, Doc 44a, after December 1916, 3–7.
- \_\_\_\_\_. "Speech in Royal Albert Hall, 3 October 1933." In *Einstein on Politics: His Private Thoughts and Public Stands on Nationalism, Zionism, War, Peace, and the Bomb*, edited by David E. Rowe and Robert Schulmann, 278–81. Princeton, NJ: Princeton University Press, 2007.
- \_\_\_\_\_. Anlässlich der Eröffnung der 7. Deutschen Funkausstellung und Phonoschau in Berlin, 22 August 1930. Recording at Deutsches Rundfunkarchiv, Frankfurt am Main. Available at [http://www.einstein-website.de/z\\_biography/redefunkausstellung.html](http://www.einstein-website.de/z_biography/redefunkausstellung.html).
- Feuer, Lewis S. *Einstein and the Generations of Science*. New York: Basic Books, 1974.
- Forman, Paul. "The Primacy of Science in Modernity, of Technology in

JULY  
2015  
VOL. 56

- Postmodernity, and of Ideology in the History of Technology.” *History of Technology* 23, nos. 1, 2 (2007): 1–152.
- Frank, Adam. “Welcome to the Age of Denial.” *New York Times*, 22 August 2013, A27.
- Friedman, Michael. “Geometry as a Branch of Physics: Background and Context for Einstein’s ‘Geometry and Experience.’” In *Reading Natural Philosophy*, edited by David Malament, 193–230. Chicago: Open Court, 2002.
- Galison, Peter. “Einstein’s Clocks: The Place of Time.” *Critical Inquiry* 26, no. 2 (winter 2000): 355–89.
- \_\_\_\_\_. *Einstein’s Clocks, Poincaré’s Maps: Empires of Time*. New York: W. W. Norton, 2003.
- \_\_\_\_\_. *How Experiments End*. Chicago: University of Chicago Press, 1987.
- Gaston Darboux et al. to the Nobel Prize Committee, ca. 1 January 1910. In *La Correspondance entre Henri Poincaré et les physiciens, chimistes et ingénieurs*, edited by Scott Walter, 433. Basel: Birkhäuser, 2007.
- Gieryn, Thomas F. “Boundary-Work and the Demarcation of Science from Non-Science: Strains and Interests in Professional Ideologies of Scientists.” *American Sociological Review* 48, no. 6 (1983): 781–95.
- Gilman, Benjamin Ives. “Relativity and the Lay Mind. II.” *The Journal of Philosophy* 24, no. 19 (1927): 505–21.
- Giovanelli, Marco. “Talking at Cross-Purposes: How Einstein and the Logical Empiricists Never Agreed on What They Were Disagreeing About.” *Synthese* 190, no. 17 (2013): 3819–63.
- Gooday, Graeme. “Teaching Telegraphy and Electrotechnics in the Physics Laboratory: William Ayrton and the Creation of an Academic Space for Electrical Engineering 1873–84.” *History of Technology* 13 (1991): 73–114.
- \_\_\_\_\_. “La jonction entre science et industrie.” *Les Cahiers de science et vie* 51 (1999): 36–40.
- \_\_\_\_\_. “The Questionable Matter of Electricity: The Reception of J. J. Thomson’s ‘Corpuscle’ among Electrical Theorists and Technologists.” In *Histories of the Electron: The Birth of Microphysics*, edited by Jed Z. Buchwald and Andrew Warwick. 101–34. Cambridge, MA: MIT Press, 2001.
- Granek, Galina. “Poincaré’s Light Signaling and Clock Synchronization Thought Experiment and Its Possible Inspiration to Einstein.” In *Albert Einstein Century International Conference*, edited by J.-M. Alimi and A. Füzfa, 1095–1102. College Park, MD: American Institute of Physics, 2006.
- Hand, David J. *The Improbability Principle: Why Coincidences, Miracles, and Rare Events Happen Every Day*. New York: Scientific American, 2014.

- Heidegger, Martin. "The Question Concerning Technology." In *The Question Concerning Technology and other Essays*, 3–35. New York: Harper and Row, 1977 (1954).
- Hong, Sungook. *Wireless: From Marconi's Black-Box to the Audion*. Cambridge, MA: MIT Press, 2001.
- Hughes, Thomas P. "Einstein, Inventors, and Invention." *Science in Context* 6 (1993): 25–42.
- Illy, József. *The Practical Einstein: Experiments, Patents, Inventions*. Baltimore: Johns Hopkins University Press, 2012.
- Kitcher, Philip. *Science, Truth, and Democracy*. Oxford Studies in Philosophy of Science. Oxford: Oxford University Press, 2001.
- Kline, Ronald. "Construing 'Technology' as 'Applied Science': Public Rhetoric of Scientists and Engineers in the United States, 1880–1945." *Isis* 86, no. 2 (1995): 194–221.
- \_\_\_\_\_. "Foundational Stories." *Technology and Culture* 54, no. 1 (2013): 117–29.
- Kox, A. J., ed. *The Scientific Correspondence of H. A. Lorentz*. New York: Springer, 2009.
- "La Théorie de la relativité: Séance du 6 avril 1922." *Bulletin de la Société française de philosophie* 22, no. 3 (1922): 349–70.
- Langevin, Paul. "L'évolution de l'espace et du temps." *Scientia* 10 (1911): 31–54.
- \_\_\_\_\_. "Le temps, l'espace et la causalité dans la physique moderne." *Bulletin de la Société française de philosophie* 12, no. 1 (1912): 1–46.
- Letter from Wien to Lorentz, 17 August 1907, and Lorentz's response, 22 September 1907. In *The Scientific Correspondence of H. A. Lorentz*, edited by A. J. Kox, 218–21. New York: Springer, 2009.
- Martínez, Alberto A. "Material History and Imaginary Clocks: Poincaré, Einstein, and Galison on Simultaneity." *Physics in Perspective* 6, no. 2 (2004): 31–48.
- \_\_\_\_\_. "The Questionable Inventions of the Clever Dr. Einstein." *Metascience* 23, no. 1 (2014): 49–55.
- Mialet, Hélène. *Hawking Incorporated: Stephen Hawking and the Anthropology of the Knowing Subject*. Chicago: Chicago University Press, 2012.
- Mindell, David A. *Between Human and Machine: Feedback, Control, and Computing before Cybernetics*. Baltimore: Johns Hopkins University Press, 2002.
- Montague, William Pepperell. "The Einstein Theory and a Possible Alternative." *The Philosophical Review* 33, no. 2 (1924): 143–70.
- Moureaux, Th. "Le Service des signaux de l'armée aux Etats-Unis." *La Nature: Revue des sciences et de leurs applications aux arts et à l'industrie* no. 446 (17 December 1881): 44–45.
- Nordmann, Charles. *Einstein et l'univers*. Paris: Hachette, 1921.

JULY  
2015  
VOL. 56

- Norton, John D. "Einstein's Investigations of Galilean Covariant Electrodynamics prior to 1905." *Archive for History of Exact Sciences* 59, no. 1 (2004): 45–105.
- Overbye, Dennis. *Einstein in Love*. New York: Penguin, 2000.
- Pickering, William H. "The Theory of Relativity." *Popular Astronomy* 28 (1920): 334–44.
- Poincaré, Henri. *Science and Hypothesis*. New York: Dover, 1952 (1902).
- \_\_\_\_\_. "Étude de la propagation du courant en période variable sur une ligne munie de récepteur." *Éclairage électrique* 40 (1904): 121–28, 161–67, 201–12, 241–50.
- \_\_\_\_\_. "Sur la dynamique de l'électron." *Rendiconti del circolo matematico di Palermo* 21 (1906): 1–55.
- \_\_\_\_\_. *La Correspondance entre Henri Poincaré et les physiciens, chimistes et ingénieurs*, edited by Scott Walter. Basel: Birkhäuser, 2007.
- \_\_\_\_\_. "Mes principaux ouvrages relatifs à la physique" (ca. June 1908). In *La Correspondance entre Henri Poincaré et les physiciens, chimistes et ingénieurs*, edited by Scott Walter, 415. Basel: Birkhäuser, 2007.
- Price, Katy. *Loving Faster than Light: Romance and Readers in Einstein's Universe*. Chicago: University of Chicago Press, 2012.
- Raines, Rebecca Robbins. *Getting the Message Through: A Branch History of the U.S. Army Signal Corps*. Army Historical Series. Washington, DC: Center of Military History, U.S. Army, 1996.
- Reichenbach, Hans. "Der gegenwärtige Stand der Relativitätsdiskussion. Eine kritische Untersuchung." *Logos* 10, no. 3 (1921): 316–78.
- \_\_\_\_\_. "La signification philosophique de la théorie de la relativité." *Revue philosophique de la France et de l'étranger* 93 (1922): 5–61.
- \_\_\_\_\_. *Was ist Radio? Mit 27 Abbildungen und einer Tafel der Sendestationen*. *Das Radio-Reihe*, vol. 1. Edited by Hans Reichenbach. Berlin: Richard Carl Schmidt & Co., 1924.
- \_\_\_\_\_. *Philosophie der Raum-Zeit-Lehre*. Berlin: W. de Gruyter & Co., 1928.
- \_\_\_\_\_. "The Philosophical Significance of the Theory of Relativity." In *Albert Einstein: Philosopher-Scientist*, edited by Paul Arthur Schilpp, 289–311. LaSalle, IL: Open Court, 1949.
- \_\_\_\_\_. *The Rise of Scientific Philosophy*. Berkeley: University of California Press, 1951.
- Rowe, David E., and Robert Schulmann, eds. *Einstein on Politics: His Private Thoughts and Public Stands on Nationalism, Zionism, War, Peace, and the Bomb*. Princeton, NJ: Princeton University Press, 2007.
- Schaffer, Simon. "Newton on the Beach: The Information Order of *Principia Mathematica*." *History of Science* 47, no. 3 (2009): 243–76.
- Siebert, Bernhard. *Relays: Literature as an Epoch of the Postal System*. Writing Science. Edited by Timothy Lenoir and Hans Ulrich Gumbrecht. Stanford, CA: Stanford University Press, 1999.



- Silvan Sam Schweber to Arne Hessenbruch, interview, 27 August 2001. Available at [http://authors.library.caltech.edu/5456/1/hrst.mit.edu/hrs/materials/public/Schweber\\_interview.htm](http://authors.library.caltech.edu/5456/1/hrst.mit.edu/hrs/materials/public/Schweber_interview.htm).
- Smith, Merritt Roe, and Leo Marx. *Does Technology Drive History? The Dilemma of Technological Determinism*. Cambridge, MA: MIT Press, 1994.
- Staley, Richard. "On the Histories of Relativity: The Propagation and Elaboration of Relativity in Participant Histories in Germany, 1905–1911." *Isis* 89, no. 2 (1998): 263–99.
- \_\_\_\_\_. *Einstein's Generation: The Origins of the Relativity Revolution*. Chicago: University of Chicago Press, 2008.
- Trowbridge, Augustus. "Sound and Flash Ranging." *Science* 49, no. 1274 (1919): 521–23.
- Van der Kloot, William. "Lawrence Bragg's Role in the Development of Sound-Ranging in World War I." *Notes and Records of the Royal Society of London* 59, no. 3 (2005): 273–84.
- Weyl, Hermann. "The Mathematical Way of Thinking." *Science* 92, no. 2394 (1940): 437–46.
- Whitehead, Alfred North. *An Enquiry Concerning the Principles of Natural Knowledge*. Cambridge: Cambridge University Press, 1919.