of the flow, just as the swing of the pendulum is unrelated to the direction in which we know time to be flowing.

It has also been suggested that the observable finite speed of light must surely define the direction of time's flow. The arrival of a light signal must surely be later than its emission. But again there is no proof. The relativity discussion defines the speed of light as just that speed for which you cannot define which event occurred earlier and which later; in other words, you cannot uniquely distinguish emission from reception. The details of the two physical processes are indeed seen to be exact images of one another: the same momentum recoil, the same energy exchange. So, again, this gives no information on our subject. If we were observing many events, like a burst of many photons from one locality and a dispersed arrival of them, we might again make a decision of probability on statistical grounds. It would seem improbable that many diverse locations had emitted photons just so that they would all arrive closely packed and simultaneously, and so we would guess that the concentrated event was emission and the diffuse event, reception.

The largest scale of the energy flows is that of the universe, and it dominates all others. Heat is generated at very high temperatures by the nuclear processes in the interior of stars, and from there begins a downhill flow to lower and lower temperatures. In the course of this flow of degradation, it may chance to encounter a heat engine that can produce a limited amount of free energy or higher temperature heat, but only at the expense of an even faster degradation of the rest of that energy. Our earth happens to be a particularly favorable place for such a sidestep in the overall energy flow, and our own livelihood is dependent on this fortunate circumstance. A very small fraction of the heat output of the sun is temporarily held up by our planet, and some fraction of this in turn is there converted by heat engines into a more concentrated form, such as the chemical energy plants derive from sunlight. This gives us the chemical energy of the food we eat, and, through that, of all the things we can do. The final destination of all the heat is the dispatch into the depths of space of the expanding universe, from which it does not return, or returns degraded from the initial millions of degrees to a temperature very close to the absolute zero.

It is the expansion of the universe that is responsible for this overall flow of heat from the high temperature of the stars to the low temperature of the background. If we did not have the expanding universe around us, with its ability to swallow up whatever energy is sent out by the stars, only to return a minute fraction, then this process could not occur. If the same amount of energy came back as went out, we would be living in a uniform temperature universe, and no sources of free energy would be available to us. With only uniform heat all around us there would be no criterion that would distinguish the flow of time from past to future. Our concept of time and its unidirectional flow could not exist in such a world.

Peter L. Galison & D. Graham Burnett

Einstein, Poincaré & modernity: a conversation

Newton, forgive me . . .

– Albert Einstein, *Autobiographical Notes*

D. GRAHAM BURNETT: Peter, in 1997 you gave a plenary session lecture at the History of Science Society meeting in La Jolla entitled "Relentless Historicism: Machines and Metaphysics." I have a vivid memory of the presentation, which was, I think, the first time you shared with the wider community of historians and philosophers of science your research on Einstein, relativity, and the material culture of time in the fin de siècle. And you turned a lot of heads. Your argument went something like this: At the heart of Einstein's watershed 1905 paper on special relativity – the paper that shook the foundations of Newtonian physics – lies a 'thought experiment' about clock synchronization and the 'problem' of simultaneity; there, talking about trains arriving in stations and observers watching their watches, Einstein posed what turn out to be insurmountable challenges to Newton's notion of absolute time (and absolute space). This we knew. But then the talk got juicy: you went on to point out that this thought experiment might not be *merely* a thought experiment, since the business of synchronizing time frames through space was more than just abstruse theoretical physics in the late nineteenth and early twentieth centuries. It was a perfectly real, quotidian, and central preoccupation of railway companies, nation-states, and military planners. The increasing speed of railway travel in the second half of the nineteenth century had made it necessary to codify 'time zones' around the world – zones of conventionalized simultaneity, where people would ignore local time (say, the 'noon' of the sun), and go by the noon on their clocks: a subtle change, but an important one, since it

Peter L. Galison has just completed a new book, "Einstein's Clocks, Poincaré's Maps," that forms the basis of this dialogue. A Fellow of the American Academy since 1992, Galison is the Mallinckrodt Professor of the History of Science and of Physics at Harvard University. Galison's other books, including "Image and Logic" (1997) and "How Experiments End" (1987), explore the interaction between the principal subcultures of twentieth-century physics – experimentation, instrumentation, and theory – and also the cross-currents between physics and other fields.

D. Graham Burnett is an assistant professor of history in the Program in History of Science at Princeton University. He is the author of "Masters of All They Surveyed"(2000) and "A Trial By Jury" (2001), and a co-editor of "The History of Cartography" (1987 –).

put people across the globe in temporal step. There was no other way to run a railroad. Moreover, the design and manufacture of electromechanical systems that 'distributed' this new coordinated time – networks of clocks running in sync – was a major precision industry. Looked at in the right way, Einstein's thought experiment bore an uncanny resemblance to a set of wholly practical experiments going on all around him – even under his very nose, as he earned his living in the Berne Patent Office reviewing exactly these sorts of time-distribution devices. That day in La Jolla you left us with a question: Could we really understand Einstein's 1905 paper without understanding the rise of international time conventions and the technologies of industrial time-synchronization? Now you have written a book, *Einstein's Clocks, Poincaré's Maps: Empires of Time,* which delivers on this question and expands your original insight. For readers to whom all this is new, would you start by describing how trains and clocks figure in Einstein's landmark publication?

PETER L. GALISON: Certainly. Perhaps the greatest success of nineteenth-century physics was the prediction (and subsequent demonstration) of the existence of 'electric waves.' Light was nothing other than such a wave. Suddenly the ancient science of optics became no more than a subfield of electromagnetism. At the same time, this thrilling finding brought with it a puzzle: Physicists of the late nineteenth century, very reasonably, thought that a wave had to be a wave *in something.* After all, waves at the beach are waves in water, sound waves are waves in air, and so on. But light could travel in a vacuum – that is, apparently through empty space. This led most everyone to suppose that there had to be a special all-pervading (and as yet undiscovered) substance – the 'ether' – permeating everything, everywhere, present even in a vacuum. But experimentalists had no luck finding this elusive medium. Einstein's famous 1905 paper on relativity begins here. Generalizing from failed attempts to 'see' the ether (or, more correctly, to see any evidence that the earth was moving 'through' it), Einstein decided to scrap the ether altogether, and to go after the problem of the propagation of light in a different way. First, he stipulated that *all* the laws of physics – including electricity and magnetism – were the same in any constantly moving frame of reference. Then he added a seemingly simple (and modest) second assumption: Light travels at the same speed no matter how fast its source is moving. To anyone thinking of ether this was not so strange: Move your hands at any reasonable speed through a room of still air; once you clap your hands the sound waves propagate through the room at the same speed – independent of the original motion of your hands. Maybe light was like that: a lamp moving in the ether simply excited light waves that radiated out at a single speed independent of the motion of the lamp. Yet these two reasonable starting assumptions appeared to contradict one another. Suppose lamps were flying this way and that at various speeds, but that in some frame the light beams from those lamps were all traveling at 186,000 miles per second, just the speed predicted by the equations of electrodynamics. Wouldn't those same beams of light appear to be traveling at *different* speeds when seen from a different, moving frame of reference? If that was so, then the equations of electrodynamics would only be valid in one frame of reference, violating Einstein's first principle. It was to resolve this apparent contradiction that Einstein made his single most dramatic move: he criticized the very idea of time as it was usually understood. In particular, he relentlessly pursued the meaning of 'simultaneity.' Only by criticizing the foundational notions of time and space could one bring the pieces of the theory – that the laws of physics were the same in all constantly moving frames; that light traveled at the same speed regardless of its source – into harmony. And this is where the trains and clocks enter. Suppose, Einstein reasoned, that you wanted to know what time a train arrived in a train station. Easy enough: you see where the hand of your watch is at the time the engine pulls up alongside you. But what if you wanted to know when a train was pulling into a *distant* station? How do you know whether an event here is simultaneous with an event there? Einstein insisted that we need a simultaneity-fixing procedure, a definite system of exchanging signals between the stations that would take into account the time it took for the signal to get from one station to another. By pursuing this insight, Einstein discovered that two events that were simultaneous in one frame of reference would not be simultaneous in another. Moreover, since a length measurement involves determining the position of the front and back of an object *at the same time,* the relativity of simultaneity meant that *length* was relative as well. By removing the absolutes of space and time, Einstein restructured modern physics.

DGB: So what was at stake here was not only the universal ether, the substrate of the cosmos, but also *time* – that absolute, ever-unrolling, eternally immutable *flowing,* the Platonic time of which all worldly clocks were mere dilapidations. It was this time that Newton had understood was a necessary condition of his physics, and that he had placed beyond the realm of merely human investigation; it flowed in the "Sensorium of God."

PLG: Just by demanding a conventional clock-and-signal-based *procedure* to fix simultaneity, Einstein was breaking with the Newtonian idea of time. For Newton, there was absolute, true, mathematical time that ticked ever-constantly the same way for all observers. Clocks – all kinds – were only pale reflections, approximations to this metaphysical temporality. But Einstein's departure from Newtonian time went further, since once Einstein's starting points are accepted, dramatic consequences follow. For instance, if a train travels through our station and the engineer and caboose driver flash their lanterns towards the center of the train (at what we in the station judge to be simultaneous moments), we can ask what happens in the train. We on the station platform say: The mid-train conductor moves *towards* the site where the engine driver had flashed his lantern and *away* from the site where the caboose tender had flashed her lamp. So (say we station-based observers) the middle conductor receives the engine flash first. Since by assumption the middle conductor measures the two flashes as moving at equal velocities from equally separated points of origin, he concludes – as night follows day – that the two flashes were *not* sent simultaneously. So the two flashes that were simultaneous in the station frame are *not* simultaneous in the moving one. Simultaneity is relative to a frame of reference; it is *not* absolute. From an apparently prosaic starting point about clocks, trains, and light signals, Einstein had smashed one of the very centerpieces of classical physics.

DGB: This is perhaps the Einstein of myth and legend, the knight-errant in the borderlands of metaphysics who slays the last chimera of the crystalline spheres. A searcher in the realm of pure mind, he reconnoiters the Sensorium of God and finds it empty. But this image, you would remind us, is a distortion of Einstein's character, of what he thought he had done, and of his approach to problems as well, no?

PLG: Einstein, without any doubt, is the best-known scientist ever, and he occupies an astonishingly robust cultural place. He doesn't seem to come into and fall out of fashion as much as he is simply appropriated for new purposes with each generation. But one of the perennial features of Einstein-the-icon is the figure of the great mind living in a world apart, the ultimate loner. No doubt Einstein himself is in some measure responsible for this image, since, in later life, he reflected nostalgically on solitude, isolation, and creativity. For instance, he wrote wistfully of the lighthouse attendant, whose world could be that of undistracted thought. So we think of him as the person who could not quite navigate the physical world, and associate that incapacity with a romantic picture of scientific genius. This in turn leads to an odd rewriting of the way he lived his life and did his work.

DGB: Was the patent office Einstein's 'lighthouse'?

PLG: This has generally been the story – Einstein at the patent office is the genius at his day job: at best a source of bread and butter, at worst a distraction, but in some deep way irrelevant to understanding his science.

DGB: When did you begin to get a different idea of how the story might be told?

PLG: I was standing at a train station in northern Europe admiring a line of clocks that went along the platform. And I noticed that the minute hands were all at the same point – I could just see them all lined up. I thought, "These are wonderful clocks; isn't that impressive that they can make them to hold such regularity?" Then I noticed that the second hands were clicking in synchrony too, which was startling, and I thought, "These can't be that accurate – you can't have clocks running like this that are not synchronized in some way, or else they'd get out of phase." Suddenly I wondered if Einstein had paid attention to synchronized clocks in train stations. If he had, it would give a very tangible sense to that most famous of all scientific thought experiments in his 1905 paper. It would make his move towards a criticism of absolute time both figurative *and* literal. So I went back and I started poking around – and found myself in the midst of an absolutely immense literature on fin-de-siècle timekeeping and clocks. As you know, there was at the time an urgent technological problem of coordinating time along train tracks. More than that: in Europe the center of precision-coordinated timekeeping was Switzerland, and if all this industry was based in Switzerland they must have been processing patents right and left. I went to the patent office, and found myself surrounded by a huge number of patents with diagrams of clocks linked by signals. There were even proposals for patents and articles in the technical journals about clocks linked by radio waves. All this seemed extremely close to the kind of materialization of time that preoccupied Einstein. Of course, the clock factories and inventors had no interest in 'frames of reference' or in all the 'physics of the ether.' But the importance of distributing simultaneity by electromagnetic means was clear to everyone. Here was a technical problem located in Switzerland, centered in Berne, and with ideas coming to a point in Einstein's patent office. It all seemed remarkable; and it is there that I began this work.

DGB: And yet Einstein certainly wasn't the only physicist at the turn of the century preoccupied with time...

PLG: Not at all. In fact, even as I worked on "Einstein in the Patent Office" (and prepared the paper you mentioned), I kept wondering, "Who else would have, should have, been in this mix? And who else from the physics community would have been concerned with ideas of simultaneity?" There is one other person who cared about simultaneity at least as much as Einstein – and earlier – and that was Henri Poincaré. He certainly saw that clock coordination was essential for defining what we mean by simultaneity.

DGB: Einstein may be a household name, but the same cannot be said for Poincaré.

PLG: I suppose household name, like time and simultaneity, is a relative concept. In France, Poincaré has long been a hero. Known for his innovations in the qualitative studies of chaotic systems, for his invention of the mathematical theory of topology, for his contributions to mathematical physics, and for his philosophy of conventionalism, Poincaré was without any question the most renowned French scientist of the late nineteenth and early twentieth century. And that, in France, meant he was an extraordinarily visible figure whose books about science, philosophy, and morality were best-sellers. He also wrote dramatically and often about the new theory of relativity to which he contributed importantly. Crucially for our understanding of his ideas of simultaneity, Poincaré was, beginning in the early 1890s, deeply involved in time-distribution networks.

DGB: At the Bureau des Longitudes?

PLG: Yes, where he would serve several terms as president. And this was crucial, because the astronomers and geographers of the Bureau were working intensively with the telegraphic transmission of time. This was not for domestic railroad use – or at least not in the first instance. Rather, these engineers and scientists were working at a much higher level of precision. They needed to determine simultaneity so distant observers could determine their relative longitude.

DGB: For cartographic purposes, since longitude measurements are measurements of time?[1]

PLG: Precisely. Their goal was to map the nation, the empire, and then much of the world. Specifically, they aimed to find points of reference – for instance, in North Africa, Senegal, Ecuador, and Vietnam – from which the further mapping of the interiors could proceed. Maps were important for extraction of

1 The earth rotates once on its axis each day, or 360 degrees every 24 hours, or 15 degrees every hour. Longitude is measured with respect to some arbitrary zero line – say, the meridian of Paris. So if we know that the sun is directly over our heads (it is noon where we are) and we get a telegraph message from Paris saying it was noon there an hour before, we know we are 15 degrees west of Paris.

ores, for military domination, for the cutting of roads, and the laying of railroad lines. Railroad lines brought in more cable, and therefore more mapping, and so on. All of this constituted a major technical program, a great national moment. And the timing is fascinating. Poincaré really became a public figure starting in 1887 or so. And by 1892 he was involved with the Bureau of Longitude, where he tackled problems of time conventions – from the decimalization of the hour to reconciling the longitude of the Paris and Greenwich observatories. I remember staring at these reports from the 1890s, trying to figure out what the Bureau's telegraphic time-finders were doing, and expecting that I'd find that – as in the case of Einstein's patent office – the fixing of simultaneity was a fairly crude affair. But this work was anything but crude! Instead, I saw that by the 1890s it was altogether routine for the astronomer-engineers to *take into account the time the electrical signal took to go from one place to another*. That, I thought – I had assumed – was exclusively a preoccupation of physicists and their 'relativity.' But it turned out that Poincaré's colleagues at the Bureau were precisely worried about this, and their concern is plain as day once you look at their data. Columns in the official reports are labeled: "time of transmission." The engineers even sent their time signals on round-trips to compensate for errors. The more I looked at it, the more specific the connections seemed. So in January 1898, when Poincaré wrote his famous philosophical article "The Measure of Time," introducing the simultaneity convention via the metaphor of telegraphic longitude finders, he had in mind an abstraction but also a concrete procedure. A procedure from next door.

DGB: So here, in a real material network of telegraphic transmissions (assembled for geodetic purposes), lies the whole schematic of 'relativistic' physics: As you put it in the book, "*simultaneity is a convention, nothing more than the coordination of clocks by a crossed exchange of electromagnetic signals, taking into account the transit time of the signal.*" This is physics, but it is also technology at the turn of the century. And yet, in a way, Poincaré isn't the guy who 'gets' the physics of relativity. Or at least this is how he is usually remembered: He was so close, but he turned away from the more radical interpretation of his thinking, and the real discovery was left to Einstein, no?

PLG: What Poincaré first publishes, in January 1898, is the idea that in principle simultaneity is nothing other than the exchange of signals between clocks, taking into account the time of transfer between the clocks of the electric signal or of light. It is a philosophical point (published in the *Review of Metaphysics and Morals*) that is, on my reading, also deeply technological. Between 1898 and 1900 he doesn't apply the scheme to the physics – he thinks of the correction to Newtonian physics as being too small, just another longitude-finder's fix. And the reason that he says it's just another error is because that was how it was being treated by his colleagues in the Bureau of Longitude. Then, in late 1900, Poincaré was invited to speak at a gathering to honor H. A. Lorentz, perhaps the leading theoretical physicist of the day, and an innovator in the electrodynamics of moving bodies. He was also an admired friend of Poincaré's and a father figure to Einstein – so Lorentz was a looming figure in late-nineteenth-century physics. Poincaré, preparing for this event during a period when he was involved with the details of the Bureau (and still actively presenting the time coordination idea to philosophers), suddenly sees that he can reinterpret a purely mathematical idea of time in Lorentz's physics as a *physical coordination procedure*. In other words, Poincaré looks at the formal way that Lorentz has dealt with the problem, and he says to himself: "No! Really, this is just the telegraph problem that I had written about philosophically two years before!" From December of 1900, Poincaré put the time-coordination procedure into his *physics*. He writes about it, and he lectures about the philosophical significance of the physics of time coordination. So it works out that both Poincaré and Einstein were interested in the problem of the philosophical nature of time, the technical ways in which clocks could be set to distribute time, and the physics of how time should enter the theory of electrodynamics of moving bodies.

DGB: Still, physicists and historians of physics have spilled much ink on why Poincaré 'missed' being the first to develop Einstein's version of relativity – Poincaré was too conservative, he was too much the mathematician. In your book you try to put this question aside, and having situated both physicists in a broader story – a story about how simultaneity was *actually produced* at the turn of the century, as well as its technical and cultural resonance – you then return to their different perspectives in the conclusion. For there is still a question, isn't there? Given that they're both in this mix that you describe – both preoccupied with the "empires of time" in the realms of technology, physics, and even metaphysics – how is it that they come out of it with such different 'takes'? As I understand it, your answer would have us put aside the idea that Einstein was the 'modern' and Poincaré fell 'behind the times.' In fact, you even suggest at one point that we can hold them next to each other as representatives of "two modernities." Would you say a little more about this tempting idea?

PLG: In the years following 1905, Einstein and Poincaré were working on many of the same problems, both at the absolute top of the profession, both maintaining massive correspondence with many of the same colleagues and friends (including Lorentz). Both were deeply interested in the philosophy of science, both were writing on the side for popular audiences. These were scientists who in many ways were very similar, and yet they did not exchange a single postcard through the entirety of their lives – and neither ever even footnoted the other's work on space and time. It puts one in mind of the way that Freud treated Nietzsche: in some ways they were too close and too alien at the same time. It became unbearable for Freud to approach the work of his predecessor. On special relativity neither Poincaré nor Einstein ever argued with the other; they simply acted as if they lived in parallel but nonintersecting universes. Now Poincaré is often depicted as the reactionary who was too backward to absorb fully the radical thoughts of Einstein. That, I believe, is absolutely the wrong way of thinking about it. Both Einstein and Poincaré were concerned with a new and modern physics and a new and modern world. Poincaré wrote essays and gave many lectures about the new mechanics, always emphasizing the enormous novelty of these changes in physics. It simply is not possible to describe him as simply trying to conserve, to reinstate an older physics. But his idea of what needed to be changed was different. It was not Einstein's.

DGB: You characterize Poincaré as an 'ameliorist' at one point.

PLG: Yes, I think he is. In another context his nephew once said of Poincaré that he wanted to "fill in the white spaces on the maps." That really gets at something important. In much of his work, whether it was in mathematics (for instance in his discovery of chaos, where he literally made a new kind of map for mathematics, 'Poincaré maps'), or administration (for instance in his work trying to map and track the details of a mining accident), or geodetics (for instance in his directing the surveyors who were representing the surface of the earth), he was always trying to fix things, to fill things in, with a great faith in science. He was the ultimate Third Republic French savant – a believer in progress, a believer in using reason to make technical things work, a believer in improving the world and solving its crises. Poincaré saw himself as 'reforming' time to save Lorentz's extraordinary new theory.

DGB: And this comes out of his training as an engineer, no? Which is so important to the way you depict him...

PLG: Yes, Poincaré's modernism is exactly the modernism of the progressive, late-nineteenth-century engineer – somebody who faced all problems as solvable, from the social and political to the scientific and technical. He even played an important *technical* role in absolving Dreyfus when he reanalyzed the 'proof' that Dreyfus had authored an incriminating sheet of paper known as the 'bordereau.' Poincaré's modernism favored scientific-intuitive understanding (in mathematics as in the physics of the ether) and utterly avoided all reference to the spiritual or mystical. It was a modernism that expected the French to lead a rational and ultimately internationalist reformation of all manner of things from the standard meter on up. As far as Poincaré was concerned, physics had often faced crises – and in each instance had or could solve the difficulty by an application of a reparative reason. So it was with space and time. These concepts had to be fixed for physics to survive. Poincaré's own ideas about changing the time concept would, he hoped, repair the theory, just as space had been repaired by Lorentz's assumption that moving objects contracted in their direction of motion. But Poincaré kept the fundamental distinctions between 'true time' (in the frame of the ether) and 'apparent time' as measured in any other frame of reference. And of course he kept the ether – which he thought he needed for a productive, intuitive physics. So, for Poincaré, the reinterpretation of time was a necessary patch to keep Lorentz's theory working, one more idea in the kit of ideas that would fix the broken engine of physics.

DGB: And Einstein?

PLG: Well, Einstein had a different picture of what modern physics should be. Einstein had as his ideal neither a machine on which we would do repairs, nor a set of assumptions that would maximize our human convenience in assembling a theory. Instead, Einstein aimed for a reformulation of physics in which the order of theory itself would mirror the order of the world. If the world of phenomena showed no observable distinction between frames of reference then (so Einstein believed) neither should the theory: a symmetry in the phenomena should show up as a symmetry in the theory. 'Apparent time' and 'true time' were terms he would never utter. Einstein's ideal of a physical theory was thermodynamics, which began with two simple assumptions: first, that energy was the same; and second, that the disorder of a system, the 'entropy,' always increased. From these starting points you went to town, deriving everything else from them. There was (as far as Einstein was concerned) a classical simplicity to thermodynamics: its two pillars supporting all the other elements of the edifice. And Einstein wanted, here and in many of his other works, to build his theories out of principles in this way. He too chose two starting assumptions for relativity theory: first, any observer moving at a constant speed would have the same laws of physics; second, the speed of light is always constant no matter how fast or in what direction the light source was moving. In order to reconcile these two ideas, he argued, it was necessary to put basic ideas of space and time on a defensible and nonarbitrary footing. So Einstein's idea of time really begins at the beginning of the theory, and is necessary to get off the ground at all – in the service of simplifying, unifying, and streamlining the theory. Poincaré's theory was differently epistemological, less concerned with "What can we know of an external Nature, and how can we secure that knowledge?" than with his aim of fixing the theory such that it correctly predicted phenomena while maximizing convenience. Poincaré's modernism aimed at an aggressive program of technical repair; Einstein's at a purifying reformulation. Poincaré fastened on simplicity-for-us, assiduously avoiding reference beyond the human. Einstein's modernism aimed for a kind of depth, a matching between representation and the world not just in predictions but deeper in the theory itself. Einstein, after all, in his later years loved to talk about how much choice God had at the beginning of the universe (not a personal God but an underlying order). Poincaré never even grazed that kind of metaphysics. All that said, it would be gross distortion to treat Poincaré as a reactionary or a failed Einstein. The modernism of Picasso is not the modernism of Pollock; and to force the very different breaks with the past into a single line of progression is to lose sight of history.

DGB: The irony here is that, far from being the wild-haired radical, Einstein is revealed to be, if anything, deeply 'classical' in his conception of physics.

PLG: Well, in some ways, Einstein is the *most* classical of classical physicists. He is somebody who saw himself in a way as purifying, simplifying, symmetrizing – bringing out elements of a less baroque physics. There are many moments, famous moments, in his career, when he objects to the way physics has turned – notably in quantum mechanics. By exploring the relationships of classical physics, by deepening them, and by connecting different domains of thought previously held to be disjunct, Einstein, I believe, saw himself as a kind of radical classicist.

DGB: And yet he was, perhaps despite himself, a kind of time bomb in that classical tradition.

PLG: I think here that Einstein's extraordinary apology to Newton – where Einstein writes, in this odd and intimate way, "Newton, verzeih' mir'" – is, in a sense, his coming to terms with the fact that in his pursuit of this purifying classical vision he disrupted it. In a way it is a note to himself – a note about his own life trajectory, a note on the transformation that resulted from an attempt to deepen and streamline a classical vision.

DGB: One reading of your book would be that you think you have discovered the 'smoking gun' for this very transformation, the smoking gun for nothing less than the theory of relativity itself: Einstein is at his patent desk, looking at diagrams of electromechanical networks for time distribution along railway lines. "Eureka!" he shouts, and he sits down to demolish the idea of absolute time and space. I know that you don't care for this reading, and you don't think this is your story, but it will be tempting for many readers...

PLG: It is absolutely *not* how I think of the problem – not for Poincaré, not for Einstein. Almost all of my work stems from a concern with the strange juxtaposition of the very abstract and the very concrete. This is not a question that is by any means restricted to physics, but physics makes it abruptly clear how suddenly we pass from symbols to materiality. In *Einstein's Clocks, Poincaré's Maps* I want to get away from two widespread ideas: first, a notion that science proceeds by a kind of Platonic ascension, an evaporative or sublimating process that takes the material into the abstract. Material relations do not eject ideas or produce ideas like ripples on the surface of deep-flowing currents. And here coordinated clocks did not *cause* Einstein to introduce the synchronizing procedure. Telegraphic longitude mapping did not force Poincaré to the simultaneity procedure. Conversely, physics does not advance by pure condensation – it would be a terrible distortion to see physics beginning in a realm of pure ideas, and then gradually acquiring the weight of materiality until they stand in corporeal form as the objects of everyday life. So the reason that I find this moment of late-nineteenth- and early-twentieth-century contemplation of time so interesting is that it represents *neither* of these unilateral directions (concrete-to-abstract or abstract-to-concrete). Instead there is an extraordinary oscillation back and forth between abstraction and concreteness. I like this mix – this high-pressure interaction of material technologies, philosophy, and physics. Each was in play, in different ways, and 'simultaneity' was at stake in each domain: in Lorentz's mathematical 'local time,' in the technological exchange of time signals, in the philosophical critique of absolute time. In their own ways, Poincaré and Einstein were reading philosophy, working at technological projects, grappling with electrodynamics. Einstein certainly knew pieces of what Poincaré had done (how much and exactly when is a longer story). Then came Poincaré's moment in December 1900 (and Einstein's in May 1905) when a statement about what simultaneity *is* suddenly participated in all three arcs – the crossing point.

DGB: Technology, metaphysics, physics.

PLG: What interests me about this story is precisely that you can't start to tell it if you think that it's all on one scale, or all is really grounded in only one of these domains. Or rather you see very limited pieces of it while vast blocks of the story become unmotivated, even incomprehensible. So if you tell the story of time coordination as a pure history of ideas then Poincaré's references to telegraphy and telegraphic longitude remain...

DGB: incoherent...

PLG: Incoherent, or, more precisely, they appear as fully abstract thought experiments, with the subject (the ground of the metaphor) chosen arbitrarily. But what is interesting to me about it is that as you start to tell the story, no matter where you start – and in some ways you have a choice about where to begin – you need the other levels. Otherwise the story contains arbitrary elements: Why, for example, is Poincaré publishing about the same procedure for coordinating time in a journal of philosophy of metaphysics and morals, in the Annals of the Bureau of Longitude, and in the physics publications? I think that the very quick back and forth between scales actually points to a dimensionality of history that simply is wiped out if you try to narrate it from a single line. This is a theme of my work, that the metaphorical and the literal are inextricable: that the literal is always referring outwards metaphorically and the metaphorical flickers back into the literal. Asking about the history of physics leads at some key moments both to very material circumstances and to the ethereal layers of metaphysics as well. In the book, I am constantly trying to avoid the historiography of both sublimation and condensation. Instead, I find a peculiar state of vapor and water known as 'critical opalescence' to be a better metaphor for the relationship between the abstract and the concrete. For under particular pressure and temperature, vapor flashes back into liquid and liquid into vapor at every scale, from a few molecules to the whole system. The light that we shine on the opalescent mixture reflects back in every color, at every scale. In the late nineteenth century, synchronized time was more like that: debates over synchronizing time – debates over the conventionality of time itself – took place at the scale of buildings, blocks, cities, countries, and the planet, while at the same time arguments came fast and furious about the philosophical and physical basis of time. What I wanted to know – very specifically – was how a simple proposition, "time – simultaneity – is nothing other than the coordination of clocks, taking into account the electrical signal-time between them," could function jointly in this multiplicity of trajectories: physics, metaphysics, technology.

DGB: Where somebody was actually *making that notion real* by creating synchronized zones, by creating coordinated clocks, even as the same proposition was transforming our understanding of the physical world, and, perhaps, our place in it.

PLG: Exactly. In 1899, Poincaré was arguing with Greenwich astronomers about how to get their astronomical clocks synchronized, giving a lecture in which he reinterpreted Lorentz's time concept, and presenting to the philosophers his arguments against absolute space and time. All of this occurred essentially at once – no one domain *drove* the others. Precisely the simultaneity of all this presents the historian with two great challenges. One is to show how the domains come together. But the other is to exhibit the quasi-stability of each of these discourses, games, or traditions.

DGB: And to do this we must, as you say, "look up to see down, and down to see up."

PLG: The juxtapositions, the links – all this is *historical*. It is now a commonplace for string theorists to think of physics and algebraic geometry 'going together'; twenty-five years ago that wasn't obvious at all. For those turn-of-the-century decades it made perfect sense to mingle machines and metaphysics. For us, perhaps, the nearness of things and thoughts seems to have vanished, at least where time is concerned. When Poincaré and Einstein looked into the details of electrical engineering, when they stared at generators, radios, and cables, they saw in them critical problems of physics and philosophy. Conversely, they could hardly consider philosophical questions of time and space without asking about central features of physics – or technology.

DGB: With hindsight, we will surely discover that we now have our own "philosophical machines." It is tempting to say that the computer is for us what the clock was for much of the history of science: a machine to think with.

PLG: Moments of critical opalescence in the history of science – moments when a huge variety of scales are implicated – are not frequent. But the development of the modern computer is such a moment – as was the late-nineteenth-century deployment of synchronized clocks. It simply isn't possible to tell the story of information theory, for example, without invoking the history of computation. Conversely, there can be no coherent history of electronic computation without showing in detail how the hardware story crossed with the development of theories of information – or theories of brain function.

DGB: But let's pull back for a moment. How does the story you tell in this book fit with larger narratives in the history of clocks and timekeeping? Is Einstein's relativistic time 'just' time? Is it the apotheosis of the classic history of technology story about time, that wonderful story of progressive human efforts to push time up out of the dirt and the grass, the pulse of the blood and the organic cycles of days and seasons, and to create instead an abstract, disembodied, 'pure' time – a flowing that would be monitored with fantastically precise devices, devices so precise that they would become critical tools of investigation of nature, and reveal and measure, through time, the myriad quirks and wobbles of the cosmos? With Einstein's time, perhaps, that abstraction outreaches itself, in a way, and collapses back onto us, onto the earth, onto the contingencies of here and there. Does that make sense?

PLG: You can tell that story of the earlier physics of time, as you suggest: Time passed from a world in which the sublunary sphere was thought of as corrupt and material to another realm, beyond the superlunary, to the inaccessible reaches of Newton's pure, mathematical time. The story of the late nineteenth century, though, is one in which the abstraction and concreteness of time are both present. Conventionalizing time through the exchange of signals forced the made-ness of time into the domain of the visible: time zones imprinted the technical fabrication of simultaneity in everyday life. Physicists, philosophers, psychologists, astronomers – all were debating how to *make* time, how to measure it precisely and ship it from place to place. As Poincaré and Einstein inserted technical, engineered time into the physics of electrodynamics, they very deliberately set aside reference to Newtonian absolutes. They brought the abstract into the concrete – not by jettisoning the realm of the ideas for the sun and seasons, but by joining the material to the abstract. We could say that the modernity of time is made visible by the absence of time-in-itself, by the absence of time-as-absolute.

DGB: In a way, that traditional history of time and timekeeping, particularly as cultivated by historians of science and technology, has been a story of the 'demythologizing' of time. Sure, people went on using time imagery for didactic or symbolic functions – from *vanitas* paintings of skulls to devotional hourglasses. But the history of time in science and technology has been the story of *abstracting* that pure and precisely metered flow from such accretions of 'meaning.' And yet, the products of such progressive purifications are always themselves reintegrated into the realm of human meaning-making. For instance, the emerging concept of 'geological time' in the eighteenth and nineteenth centuries rapidly came to be entangled with systematic theology and deist notions of natural law – were rocks a particular lesson in eternity? This sort of endless 'folding' between science and signification makes me wonder: Was there – is there – a didactic or symbolic significance in Einstein's time?

PLG: You might approach this in two ways. One would be to look at the specificity of the way Einstein and his physicist interlocutors treated time, and the other would be to explore how time was taken up in the wider cultural sphere. For example, Einstein was very amused by the 'twin paradox' in which one twin travels out and back at relativistic speeds and ends up much younger than his stay-at-home sibling (he called this "the thing at its funniest"). But Einstein's heart was always elsewhere – his real investment was in the *in*variants he found (for example, the absolute speed of light, or the identity of the laws of physics for all inertial reference frame observers). He was consistently more interested in these aspects of the theory than he was in the differing perspectives of each observer on space and time. But clearly the wider public was, and has remained, fascinated precisely with the relativity of time. From jokes to art and ethics, Einstein has been invoked to justify the tenet that the most basic of concepts were 'just relative.'

DGB: And yet – and this is so easy for the lay reader to overlook – 'relativity' is predicated on a cosmic and universal *absolute*.

PLG: Indeed – there is a great irony here, since Einstein preferred to see his work as 'Invariant Theory' but knew he could not buck the worldwide trend to label it 'Relativity Theory.'

DGB: So while the public seized on the relativity of time, what did physicists take from Einstein's intervention?

PLG: The critical gaze that Einstein cast on the notion of time promptly put other concepts under the microscope. Einstein had made time and simultaneity stand with, not behind, experience and procedure. Now physicists wanted to know how this rebuilding of a concept could be extended into quantum theory: What was causality? What did it mean for a particle to have a momentum and a position? Over the decades that followed, physical concepts fell one after another from a priori metaphysical heights to the ground where they (coupled to other concepts) met experimental inquiry. Time invariance – that a movie of the physical world should be playable backwards and forwards – was not, it seemed, the rule of a priori law. Nor was parity invariance (that the mirror reflection of phenomena should always be physically possible). Now from a distant philosophical perspective one might say that the criticism of causality, for example, was even more dramatic than Einstein's and Poincaré's critique of Newtonian absolute time. But the critique of time came first, and in a deep and abiding sense it guided the rebuilding of physical knowledge for generations after 1905. This, I believe, is because the reformation of time was not just a change in a particular doctrine ("time is better measured this way than that way"). At stake was what it meant to have a physical concept *at all*.

DGB: And at stake too was how one gains access to such a concept, no? Since 'abstraction' – or, as you call it, 'sublimation' – is not merely a way to tell historical stories; it is also a way to think about nature, it is a way to think about what science itself is and how it should be done. And yet Einstein's pursuit of time leads to a simultaneous apotheosis and inversion in the larger history of time in science and technology. His is an exercise in abstraction that is also, improbably, a kind of reification.

PLG: Understanding the history of time always involves examining exactly that relationship between the abstract and the concrete, and, for Einstein, understanding time itself demanded this as well. What I find so remarkable about the fin de siècle is that not just in relativity theory, but in the whole cultural surround, the categories of time and space exhibit a kind of abstract concreteness (or concrete abstraction). When the French finally persuaded the international community to 'sanction' the meter in 1889, they held an elaborate ceremony, and a ritualized 'burial' of the standard. At the moment the assembled dignitaries and scientists sealed the iridium-platinum rod in its triple-locked chamber (and shared out the keys), this precisely engineered rod rose to become 'M' – the object that could measure but not be measured. Practical? Of course; industrialists desperately needed a reference meter. But symbolic? How could one say no?

DGB: When people start playing with absolutes, when they start to conjure them – they do, we do, the strangest things. It takes strange activity to bring absolutes into the contingencies and localities of human life. You can be sure that people are going to start making some very unusual gestures, and bring out keys and locks and boxes and bury things in the ground and make funny noises...

PLG: And particularly in the Third Republic, where religious iconology morphed into scientific-technical procedure. Time, too, was similarly concrete-abstract. In the 1890s, for example, Poincaré joined a commission on the decimalization of time. On one reading, this was entirely a practical affair – railroad administrators argued passionately for the simplicity that 9.56 or 22.34 o'clock would afford by allowing travelers to calculate time differences by simple subtraction. On another, though, it was entirely symbolic: a reanimation of the dream of rationality so passionately advocated during the French Revolution and brought to international prominence through the Convention of the Meter in the 1880s. Reflections on time are so often like this – practical and more than practical, utterly utilitarian and highly symbolic.

DGB: Hence, the practical utility, for Newton, of a 'physics time' that lived in, of all places, the *Sensorium of God*. Talk about practical and more than practical! But I still wonder: Did Einstein and Poincaré bring time back to earth? Remove it from the realm of first and final things?

PLG: Yes and no. True, they grasp time from the domain of the pure absolute. True, they rope it into procedure of electro-chronological coordination. But they surely do *not* sever time from its wide and deep bonds with modernity. Both scientists' writings on the 'new mechanics' (with its non-absolute time) were widely read by artists, philosophers, and writers. Both – though in different ways – saw the relativity of time as a fundamental piece of the new physics.

DGB: The meaning of the clock would never be the same.

PLG: And yet, of course, clocks have never been just gears and pointers. Some were mounted in late-medieval towers, establishing dominion of property and faith. In paintings they stood as harbingers of death. By the late nineteenth century, mounted in factories, observatories, and trading rooms, they stood for the modern ambitions of regulated life, precision-mapped territory, and the instantaneity of contemporary life. It is against this seven-hundred-year clock history that relativity entered, and when it did, there were certain to be no small effects.

DGB: 'Grand narrative' historians have long talked about the conflict between 'church time' and 'merchant time' in the late-medieval period: the steeple clock versus the factory clock. On the one hand the time of God, on the other the time of labor and money. Your story of Einstein and Poincaré, of clocks and maps in the fin de siècle, could be read – playfully, I admit – as the final confrontation of these two chronometries of European civilization: in 1905 the Sensorium of God gets tied to the tracks of railway time...

PLG: But modernity is not – or perhaps should I say 'not just' – a train wreck! Instead, what we see in this story is that the great metaphors of time – trains and maps – chosen by Einstein and Poincaré are both the most imaginative of all thought experiments, and, at the same time, the most everyday technologies of the modern world.