In its usual presentation, the new or "modern" physics of the early twentieth century is depicted as a study in galloping generalization. On one end of a vast linear spectrum: a mid-century factory floor covered by an assembly of electromagnets, electronics, meters. On the other: an ethereal realm of the most abstract theories of physics. What links the two? What relation is there between the concrete things of the laboratory-factory and the mathematical physical signs scrawled on a blackboard or journal article? Here, a few telegraphic notes against the idea of a single linear scale from most concrete to most abstract—a brief that such a linear scheme of progressive abstraction gets the history, philosophy, and physics wrong.

Viewed as a historical parable, the process of a sequential shedding of the material, particular, and concrete might be called one of *ascending* abstraction. From the grubby details of an experiment, the first stage up might be merely phenomenological, non-explanatory curve-fitting. Such purely descriptive curves are then (so goes the usual story) ramped up in generality and eventually captured by laws. Those laws are progressively embedded in other, more general ones, until the process stops with the overarching unifying theories of physics. From the familiar seventeenth-century story, here is a textbook model (problematic in many ways, but useful as an illustration of how the story gets told) for the great movements of the twentieth. Start with Tycho Brahe's naked-eye measurement of planetary positions from his castle redoubt at Oraniburg: planetary positions measured against the fixed stars. Johannes Kepler captured that data by ellipses in the sense that all the measured points are on or near the elliptical orbit and the elliptical orbit interpolates between the actual data. Up another step: Kepler's laws (e.g., if one imagined a line from the sun to a planet, that line would sweep out in equal areas in equal times) characterized *all* the planetary orbits. Finally, Newton used his theory of gravitation to appropriate Kepler's laws—Newton could *deduce* Kepler's laws and ellipses from the universal law of gravity.

A mathematical curve (ellipse) is more abstract than the actual angular positions of the planets that Brahe marked down in his logs. Kepler's law of equal areas is more abstract still, and, just in virtue of being further removed from the observations, Newton's $F=m1m2/r^2$ is yet more abstract. Each level seems to embrace the others, and abstraction appears as a species of generalization coupled with an ontological shift of register away from materiality. Each step up the Great Chain of Abstraction appears to be a step toward generalization as well.

But generalization alone does not seem to be exactly equivalent to abstraction: in biological classification, the classification hierarchy runs like this: Individual -> species -> genus -> family -> order -> class -> phylum -> kingdom -> domain -> life.

A genus is defined by the set of features common to the species, and a family picked out by characteristics common to genuses. Species of the tree-frog family Rhacophoridae, for example, can, at first glance, look astonishingly different—one species is typically 1.5 cm long and another 12 cm—yet they have enough in common to be grouped together. Similarly, many families with some shared traits wind up under the suborder Neobratrachia, which in turn is part of an order, all the way up to the kingdom of Animalia. This hierarchy feels like generalization—but while Animalia seems more general than Neobratrachia, it is not clear that Animalia is more abstract (ontologically). The set of all Animalia may be more general than that of all red foxes, but being more inclusive doesn't seem to make it more abstract—at least not in the physicists' sense (general relativity or string theory).

Metaphysically inclined philosophers have frequently wanted to make causal inefficacy the identifying feature of abstract entities. The square root of two doesn't cause anything to happen; my hammer might. So how would this characterization of abstraction hold up in the context of physics? The highest-flyers of generalization in early-twentieth-century "modern" physics would, without doubt, be relativity and quantum mechanics—alongside their post–World War II fusion in relativistic quantum-field theory. An example: from the 1930s through the '50s, the standard way of narrating the history of relativity was to rehearse the many unsuccessful attempts to detect the ether. Those attempts became more and more precise, driving the ether, so to speak, into an ever-tighter corner until, finally, Einstein applied the coup de grâce. Einstein: "The luminiferous ether will prove to be a superfluous concept." With the ether gone, absolute space seemed eviscerated. In its place, Einstein offered a new physics in which every constantly moving frame of reference was equivalent to every other. One could no longer pick out a privileged frame of reference that would count as absolute space or define the frame in which absolute time would tick off its intervals. Theory, in the view of ascending abstraction, stood as a summary, the peak of a mountain trail blazed with a long, inexorable series of laboratory experiments.

But should Einstein's work on relativity in 1905 be seen as the harbinger of this kind of high-peak abstraction?[1] Born into a family that made precision electromechanical devices, Einstein was always at ease with electrical engineering. Far from the popular portrait of him as a mechanical incompetent, as a student he skipped advanced classes in mathematics to tinker in the basement laboratory. For years after graduation, he worked as a patent officer, evaluating proposals, writing opinions, assessing technological validity—he testified as an expert witness in patent-violation suits and secured his own patents on gyrocompasses and even a refrigerator. It was while working in the patent office that, in 1905, Einstein had his "miracle year" in science—publishing on relativity, the light quantum, Brownian motion, and the equivalence of mass and energy, $E=mc^2$.

1. Peter Galison, *Einstein's Clocks, Poincaré's Maps* (New York: W. W. Norton, 2003).

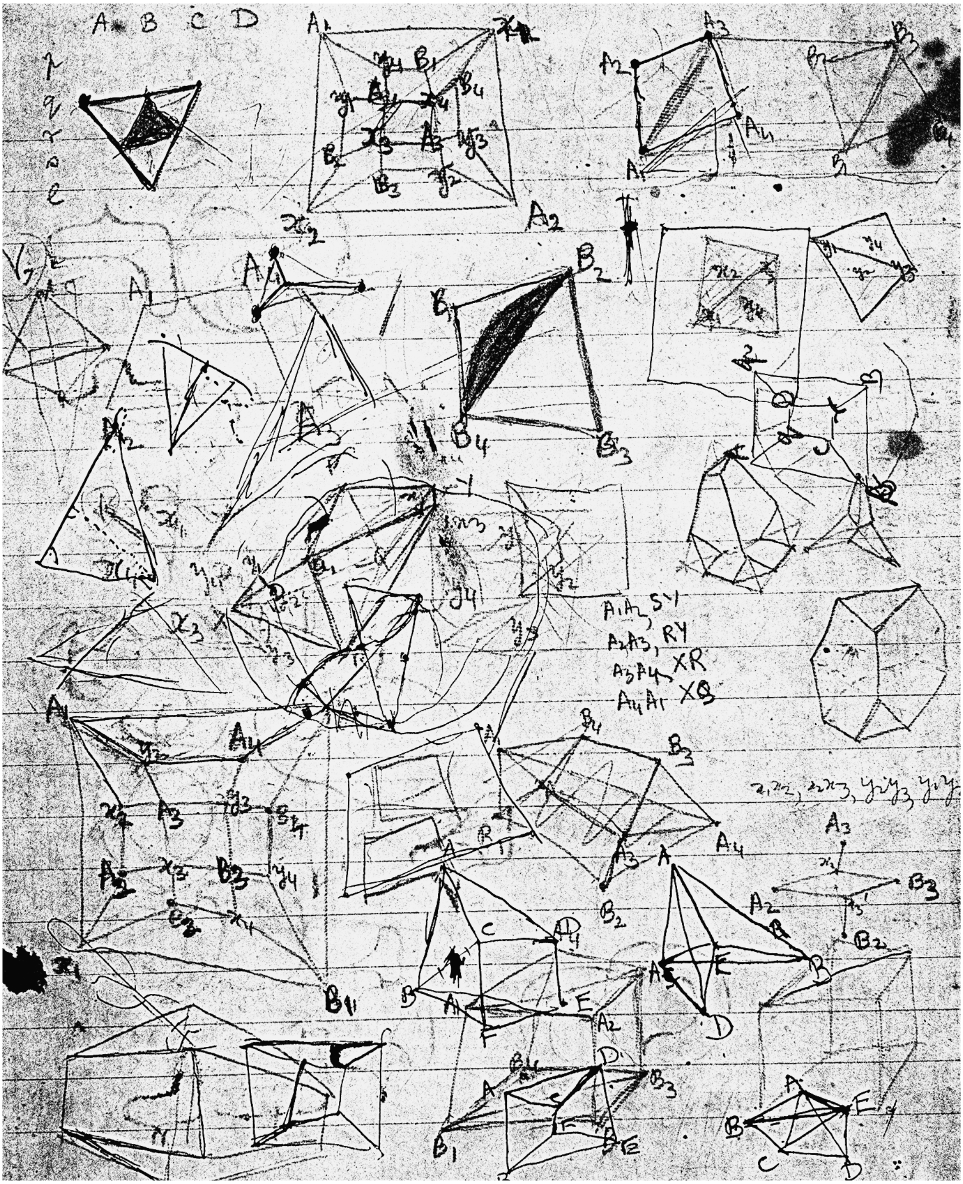
Indeed, the most salient piece of Einstein's contribution to relativity was his exchange of time for *times*—and that piece was tightly wound around the triple intersection of the technology, the physics, and the philosophy of his day. Henri Poincaré, the French mathematician, philosopher, and physicist, was both the object of young Einstein's intense study and, to a certain degree, his competitor. Both scientists used metaphors that were more than metaphors to reformulate their notion of time. In a foundational article on the meaning of time, Poincaré wrote in 1898 that simultaneity was to be defined by a procedure illustrated by two longitude-determining telegraphers who set their clocks by the exchange of an electric pulse in order to map the world. Was this merely a thought experiment, a brain-in-the-vat counterfactual? Not at all. Poincaré was at that time about to direct the prestigious Paris Bureau of Longitude—the time-defining procedure that he introduced in his article for the *Revue de métaphysique et de morale* was precisely the one that his myriad military surveyors employed from Le Havre to Haiphong.

For his part, Einstein began the most startling part of his relativity paper with a story about train clocks. How do we know the train arrives at the station at 7 p.m.? I look at my watch: if the train engine pulls in front of the watch when the watch hand is opposite the 7, I say it is so. But how do I know if the train arrives at another station at 7 p.m.? Then I have to synchronize clocks, and Einstein, like Poincaré, invoked the necessity of sending electromagnetic signals from point A to point B, taking into account the time of flight. Abstract? Very—a fundamental challenge to the nature of time. Concrete? Entirely—Einstein was looking at coordinated-train electric-clock patents by the dozens.

Here, in many ways, was the most abstract physics idea ever promulgated, one that excited a culture, infuriated right-wing demagogues, and precipitated an upheaval in physics. Was it a metaphor about telegraphers and train engineers? Yes. Was it more than a metaphor? Yes.

Alternatively, the abstraction story of modern physics can be run backwards—physicists reach high for abstractions and there follows a cascade down, a *descending* abstraction. Particle physics begets nuclear physics; nuclear physics leads to atomic physics; atomic physics drives us to molecular physics and chemistry . . . and eventually we arrive, many departments down, at the factory floor. Now, physicists knew and know perfectly well that they can't actually deduce, say, nuclear physics from particle physics—much less where elephants go to die from quantum electrodynamics. What they mean is that certain principles of chemistry could, in principle if not in fact, be explained by the underlying physical principles.

No one exemplifies the *descending abstraction* strategy as well as the British theoretical physicist Paul Dirac, known as the "purest soul" of otherworldliness. Looking backwards from 1931—after his astonishing discovery of the now eponymous equation that described the relativistic electron—he wrote that the physi-



File labeled "Calculations" in the Paul Dirac Papers. Date unknown.

cists of the nineteenth century expected their mathematics to get more and more complicated, but to remain grounded in traditional axioms. That did not happen:

> Non-Euclidean geometry and noncommutative algebra, which were at one time considered to be purely fictions of the mind and pastimes of logical thinkers, have now been found to be very necessary for the description of general facts of the physical world. It seems likely that this process of increasing abstraction will continue in the future and the advance in physics is to be associated with continual modification and generalization of the axioms at the base of mathematics rather than with a logical development of any one mathematical scheme . . . [2]

But whether we build up from concrete things to abstract ones or leap to the heights of abstraction and step down, one idea remains in common: the long linear spectrum. It seems to me that we often face a very different relation of concrete and abstract. Dirac's papers are the paradigm of formal, imageless, algebraic exposition. Often disdaining even words, he took equations and their intrinsic beauty to be the alpha and omega of scientific reason. But there is more here. On a never-published scrap of paper written forty years after his fundamental equation, Dirac contrasted the algebraic abstraction with the almost tactile form of geometrical thought: "I prefer the geometric method. Not mentioned in published work because it is not easy to print diagrams. With the algebraic method one deals with equ[ations] between algebraic quantities. Even tho I see the consistency and logical connections . . . they do not mean very much to me. I prefer the relationships which I can visualize in geometric terms."[3]

There was more: in his papers lies a thick stack of geometrical musings. As a young man growing up in a working-class section of Bristol, he came of age being taught to think in projective geometry, the long-abandoned project, begun during the French Revolution, to bring reasoning to the citizens. When Dirac moved up and out of Bristol, to Cambridge, he joined a world that valued abstraction—but out of sight, he "suppressed" his training in the mechanical arts, electrical engineering, and projective geometry, translating, as it were, out to the "modernity" of algebra alone.

So here is my view: the concrete does not sit at the antipode of abstraction. There is no line chart from concrete to abstract, and the metaphors of physics often take us simultaneously up to ideas and down to grubby machines. The most abstract concepts of modern science do not abandon the most concrete: they enfold them.

2. P.A.M. Dirac, "Quantised Singularities in the Electromagnetic Field," *Proceedings of the Royal Society*, A 133, 60 (1931), p. 60.
3. Peter Galison, "The Suppressed Drawing: Paul Dirac's Hidden Geometry," *Representations* (Fall 2000), p. 146.

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