radium in the early 1900s was a kind of chemical research already belonging to the 19th-century past. Rutherford's explanation of the atomic nucleus, they argue, was creating a new image of physics in which chemistry was at the service of the physicists. Chemistry by the 1920s and '30s had been "effectively reduced to physics" (p. 309).

Knight, in devoting two concluding chapters in his history to the theme of chemistry as a "reduced" modern science with its basic principles coming from the more "fundamental" science of physics, takes a similar view. Chemistry is now a "service" science, he suggests. Indeed, Knight begins his history with the rather extraordinary statement that chemistry is a science with its glorious future behind it.

Brock is by no means so glum. He seems not to think that chemistry is physics. "Theoretical chemistry," he writes, "is still a quirky empirical science based upon a Schrödinger equation that can hardly ever be solved" (p. 505). Also not quite so generally glum as their judgment about radioactivity might seem, Bensaude-Vincent and Stengers note that the argument for chemistry as a "reduced" science ignores the history by which natural laws and theories have been negotiated *between* the provinces of chemistry and physics, not simply deduced from physics. They conclude their history with a challenge for new styles of engagement in a chemical history that is far from over.

Yet they, like the other authors, surprisingly fail to explore the ways in which some fundamental chemical concepts have been and remain distinct from physical concepts. All but Knight reflect on the power of modern chemical methods to create natural products like Vitamin B_{12} or unnatural products like C_{60}, the buckminsterfullerene soccer-ball–shaped molecule. Do these achievements represent only "service" science? The authors do not reflect on the artistic, conceptual, and practical preoccupations of those chemists who relish the individuality and uniqueness of molecules. Multiple representations of a molecule's structure and function, as well as explanations of molecular behavior that are time- and environment-dependent, distinguish a good deal of modern chemistry from modern physics.

Ironically, despite his reductionist conclusion, Knight comes closest to exploring the differences between chemistry and physics. Citing Primo Levi's literary masterpiece *The Periodic Table*, Knight writes briefly (p. 176) about some of the chemist's ways of thinking, concluding with a point of view that can be found in chemists' writings throughout the 19th and 20th centuries: that chemistry comes down to a chemical "feeling," the intuition based in experience that allows the chemist to know which reactions will and will not go.

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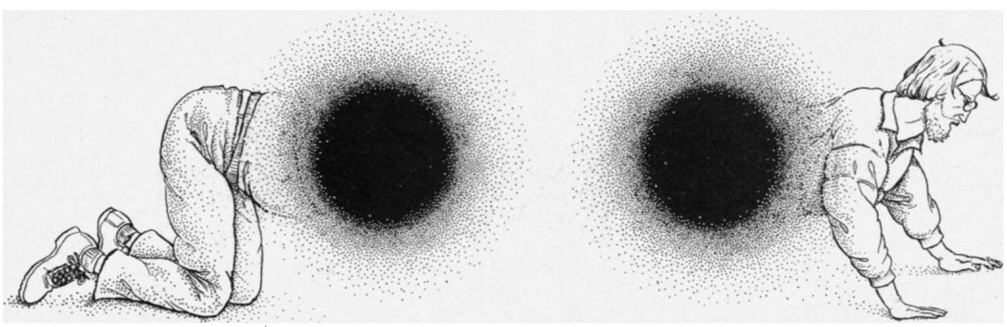
Adventures in Space-Time

Black Holes and Time Warps. Einstein's Outrageous Legacy. KIP S. THORNE. Norton, New York, 1994. 619 pp., illus. $30. Commonwealth Fund Book Program.

The theory of gravity as developed by Einstein has become a beautiful fossil. Its fate is to be worshiped by the lesser mortals who will hammer away at the more tedious details as the rare loopholes are slowly plugged. *Black Holes and Time Warps* is a hymn to the glories of general relativity. It is one of the few popular science books that I have actually read cover to cover. It has a unique style, with personal anecdotes and facts gleaned from taped interviews with the leading players intermingled with scientific explanations that are sometimes—but more often not—tough to follow.

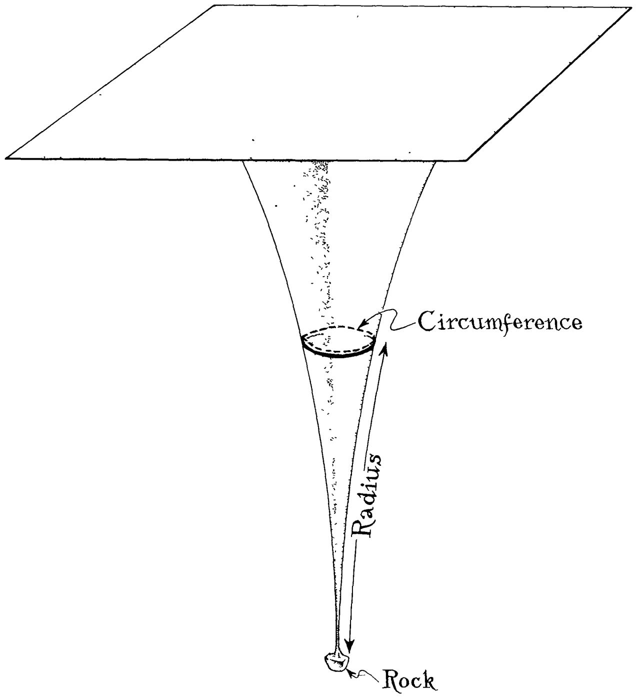
The few post-Einstein advances, such as the search for black holes, have resulted from a collaborative effort. The relativists provided only one ingredient for the necessarily complex broth that eventually yielded a solution. Other contributors were the astrophysicists, who made realistic models, and the astronomers, who knew where and how to look. Kip Thorne is very much a gambling man, and his various wagers are frequently cited in this book. He places 95 percent odds that a black hole has already been identified. To the outsider, these odds would not warrant a game of Russian roulette, unless he or she were a fool, a gambler, or perhaps an idealistic believer that "beauty is truth, truth beauty—that is all ye know on earth, and all ye need to know." The search for beauty drove Einstein to distraction in his lifelong attempts to unify the theories of electromagnetism and gravitation. Unification of the fundamental forces—electromagnetic, nuclear, and gravitational—has indeed proved elusive. However, this has not perceptibly slowed the flood of particle theorists who work at the frontiers of gravitation theory.

Wormholes were a fad that some brave souls thought might contain the key to unlocking the ultimate secrets of nature. A wormhole is a potential tunnel from the inside of one black hole to another. Along with black holes, they are a topic beloved by science-fiction writers: A space-time traveler can emerge in the past. Thorne is one of the world's scientific authorities on time machines. In the title of his first paper on these bizarre objects he referred to them as "closed time-like loops" in order to hinder journalistic recognition—an endeavor that was successful, at least in the short term. Unfortunately, to reach a wormhole, one has to penetrate the event horizon of a black hole. This is a difficult task, as any conventional material is ripped to shreds by the overwhelming tidal forces as one approaches the horizon. Thorne instead advocates the use of naked singularities. These are horizon-free but hard to find, even in the red-light district of downtown Pasadena. Indeed, there is a conjecture due to Roger Penrose that such objects are forbidden to exist.



Kip Thorne crawling through a hypothetical, very short wormhole. [From *Black Holes and Time Warps*]

This cosmic censorship does not frustrate Thorne even for a moment. Appealing to Heisenberg's uncertainty principle, he notes that wormholes, and naked singularities in the bargain, may come and go out of thin air—actually a perfect vacuum—for brief instants. Over the Planck time, a mere 10^{-43} second later, the wormhole closes. No laws of nature are violated if one borrows energy or mass from the vacuum for a sufficiently (unmeasurably) short time, provided the loan is promptly repaid. Thorne's next goal is to keep an emerging wormhole propped open. This can be done with exotic material whose energy density (rest mass plus pressure contribution) is negative. Never mind that mere mortals, and astronomers, have never encountered such stuff. It is not forbidden by the laws of physics, and that is enough for Thorne to leap forward down the wormhole. He emerges at some point in space and time, far in the future, or perhaps in the past.



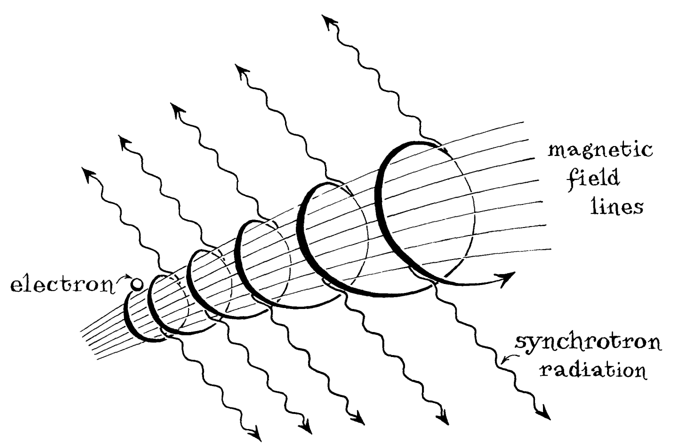
"Cosmic radio waves are produced by near-light-speed electrons that spiral around and around in magnetic fields. The magnetic field forces an electron to spiral instead of moving on a straight line, and the electron's spiraling motion produces the radio waves." [From *Black Holes and Time Warps*]

This brings us to the key issue facing would-be time travelers. Suppose Thorne were to meet his mother as a young girl and kill her. The logical inconsistency seems a devastating argument against the possibility of such a journey. Thorne does not dare tackle the matricide problem, but he argues that there is a possible solution. Consider a billiard ball on a trajectory that allows it to fall down a wormhole. It reemerges in its past to collide with its earlier self, knocking itself onto a different trajectory. But this cannot happen: nature, or rather physics, abhors, and some say forbids, causality violation. The wormhole's gravity defocuses the billiard ball's path. When it emerges, the ball has a high likelihood of missing itself. In fact the situation is not so different from the everyday problem faced by quantum physicists of whether Schrödinger's cat survives the release of poison gas triggered by radioactive decay. Quantum uncertainty may even have resolved the matricide puzzle. Again, Thorne places his bets, but this time he is unwilling to assign high odds to the existence of time machines.

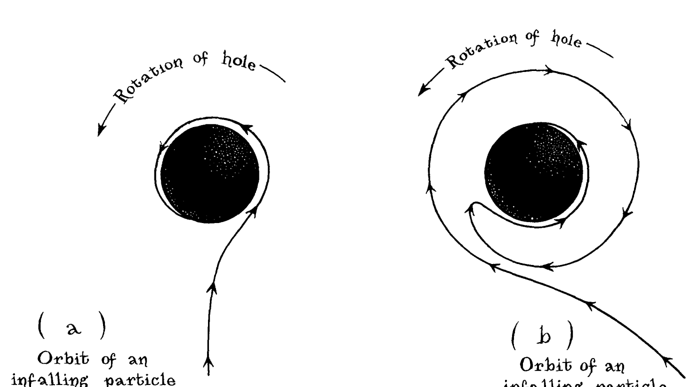
Einstein's ghost pervades this book. Thorne seems genuinely to believe that there is no higher goal in physics than the measurement of gravitational waves, a phenomenon predicted by Einstein but not yet detected in a terrestrial laboratory. In fact, astronomers Joseph Taylor and Russell Hulse were awarded a Nobel Prize last year for their discovery of an orbiting pair of neutron stars that are slowly approaching one another as they lose orbital energy by emitting gravitational radiation. The theory of general relativity has been verified in this system to a precision exceeding 99.7 percent.

Yet this success has not deterred Congress from pushing the Laser Interferometer Gravitational-Wave Observatory (LIGO) project into the reluctant arms of the National Science Foundation. A pair of interferometers is under construction, at a cost of \$230 million, by Caltech and MIT at sites in the states of Washington and Louisiana. Thorne is the most vocal cheerleader for this endeavor to detect gravitational radiation, which has misleadingly cloaked itself as an "observatory." Despite its name, any astronomy on the symphony of waves from merging black holes in remote galactic nuclei will have to await a greatly refined second-generation detector, and undoubtedly a vastly more expensive undertaking.

Even NASA has been sold on Einstein:



"The trajectories in space of two particles that are thrown toward a black hole. (The trajectories are those that would be measured in a static, external reference frame.) Despite their very different initial motions, both particles are dragged, by the swirl of space, into precisely the same lockstep rotation with the hole as they near the horizon." [From *Black Holes and Time Warps*]



"A heavy rock placed on a rubber sheet (for example, a trampoline) distorts the sheet as shown. The sheet's distorted geometry is very similar to the distortions of the geometry of space around and inside a black hole. For example, the circumference of the thick black circle is far less than 2π times its radius, just as the circumference of the hole's horizon is far less than 2π times its radius." [From *Black Holes and Time Warps*]

Stanford University and Lockheed are developing Gravity Probe B, a satellite gyroscope experiment scheduled for launch in 1998 at an estimated total cost of at least $500 million. Its goal is to measure one parameter that characterizes the spin of a gravitational field predicted by general relativity. Some scientists consider that the result is already known; others doubt that the degree of accuracy required for the gyroscope to remain stable—a thousandfold better than has been achieved on the ground—can be attained in space; and still others note that even if Gravity Probe B were to find a discrepant result, the only sensible reaction would be to lobby for funds to refly an independent experiment. So complex is Gravity Probe B that only if the anomaly were confirmed would it be believed.

These tests of Einstein's theory are beautiful in concept. The reality is that in times of budget compromise and cuts, more tangible science is being sacrificed to test fundamental ideas that no one really disputes. Of course, finding a nearby wormhole would circumvent all of these concerns. One could bypass the budgetary pains of development and deployment and, with a single bound through time, go straight to the ultimate goal. *Black Holes and Time Warps* combines no-holds-barred propaganda for Einstein's dream with science writing at its lucid best. One does not have to concur with its precepts to enjoy a book that is definitely worth reading.

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Gravimetrists in Action

The Rise and Fall of the Fifth Force. Discovery, Pursuit, and Justification in Modern Physics. ALLAN FRANKLIN. American Institute of Physics, New York, 1993. viii, 141 pp., illus. $29.95 or £25.

"In the case of news, we should always wait for the sacrament of confirmation," declared Voltaire in 1760. Scientists cling to Voltaire's recommendation very tightly, especially when news arrives that heralds the possible breakdown of an established scientific paradigm. A well-known case in point was the widely publicized announcement in January 1986 of the possible discovery of a new force in nature that was slightly weaker than gravity, of an intermediate range, and dependent on the composition of the interacting masses. It was economically dubbed the "fifth force."

To the physics community, and to gravitational physicists in particular, this was a rather jolting event—so much so that in the years since then literally scores of individuals have felt compelled to investigate for themselves the theoretical and experimental foundations of the conjectured force. Enthusiasm both for and against its existence ran high during the first few years of study, but around 1990 the preponderance of evidence began to favor conventional physics. The fifth force, as originally conceived, was no longer a viable candidate as a new physical interaction, and most of the excitement originally associated with it gradually began to fade from the scene.

From at least two perspectives, however, this was not the end of the story. First, most of the data from the experimental side of the effort were generated by techniques originally introduced one or more centuries ago to study Newtonian gravitation. These techniques included gravimetry up and down mine shafts and towers, torsion pendulum observations of the attraction between test masses, and Galileo-type falling body experiments, among others. The sudden and intense interest in the fifth force caused a resurgence of interest in gravitational phenomenology, and especially in the development of advanced versions of each of these different types of measurement scheme. General relativity and gravitation as a whole have benefited greatly from this impetus. Apparatus and techniques capable of performing more precise tests of the weak equivalence principle have been introduced, and their use has placed very stringent limits on the parameters in the Yukawa form of violation of the inverse-square law of gravitation.

A second and more subtle point (but one that has not gone unnoticed) is that the case of the fifth force presents a well-documented vignette of physics as it is practiced today that is of great value to those who study the philosophy and history of science. Allan Franklin is one of those who saw things this way. With *The Rise and Fall of the Fifth Force* he has provided a most interesting look at this episode in modern science.

The book actually serves two distinct purposes. First, it is a thorough, well-referenced scientific review of the fifth-force saga. It delves deeply into the physical arguments that led Ephraim Fischbach and his colleagues to hypothesize the existence of the force and goes on to describe the evolution of their thinking as events unfolded. The story of the fifth force is very much that of the interplay of results from various experimental searches for it, and the author has taken great care to sort through the original conflicts that fueled much of the subsequent debate. The book is richly illustrated with graphical data and photographs of the experimental arrangements. All of this helps the reader follow the path taken by the research community in pursuit of the hypothesized force.

What makes this book unique, though, is the way it opens windows on the methods by which scientific inquiry proceeds by introducing the reader to historical analysis techniques. We are shown that there are many levels at which scientific evidence is evaluated and significantly different contexts within which decisions are made about whether confirmation of particular observations has occurred.

Another interesting feature of the book is its incorporation of selected records from several months' worth of electronic mail exchanged between the principal figures in the story. Not only does this provide insight into the day-to-day thinking that went into the research, it plays up the way in which "private communications" are now quite often exchanged by colleagues. In addition, the inclusion in the discussion section of a Bayesian analysis of the plausibility of the fifth force as proposed in its original form helps the reader see how one could arrive at probabilistic predictions of the force's chances of existing, given some quantitative information about the experimental evi-

"The entrance to the tunnel in the cliff near Index, Washington, the site of [Paul] Boynton's experiment." With this experiment, which used a torsion pendulum made of aluminum and beryllium, Boynton found a positive result for the presence of the fifth force. The experiment was conducted in the tunnel to maximize the effect of a composition-dependent force. [From *The Rise and Fall of the Fifth Force*; courtesy of Paul Boynton]