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Introduction

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The first direct observational detection of gravitational waves by the Laser Interferometer Gravitational-Wave Observatory (LIGO) consortium on September 14, 2015, was a momentous event in the history of science. It shares a number of features with another decisive event of the previous century, the first direct observational detection of gravitational light bending during the solar eclipse of May 25, 1919. This, too, was a tiny effect predicted by a bold theory but was barely detectable given the day's technology. Its observational confirmation, like that of LIGO, took many years of preparation and involved failed attempts, its case made more difficult by the adversities of war and international hostility. Yet both investigations provided strong support for Einstein's theory of general relativity, a theory grounded on a willingness to question and seriously modify deeply entrenched notions of space and time.

Soon after the historic event took place, a meeting of leading scientists, historians, and philosophers was held at the California Institute of Technology to reflect on Einstein's legacy and to discuss its enduring validity. The meeting, which had been planned before the LIGO observation took place, reflected a centenary of Einstein's general theory. As it turned out, the detection occurred almost exactly a hundred years after Einstein published his foundational field equations. The meeting at Caltech, and the present volume, bring together leaders of the LIGO project with historians and sociologists of science to reflect on the event and its implications. The accounts in this volume offer a virtual participation in the process of science in the making, accompanied by informed historical, sociological, and philosophical reflection.

Barry Barish was principal investigator and director of the LIGO laboratory in its crucial period between the mid-1990s and 2005, when the project transitioned from a local endeavor at the two founding institutions Caltech and MIT to a multinational, multi-institutional large-scale science project involving eighteen nations, more than one hundred institutions, and in excess of a thousand individuals. His contribution opens the volume to remind us of the rapid pace of science, so rapid indeed that the detection overtook the initial planning of the anniversary conference at Caltech. Barish, one of the recipients of the 2017 Nobel Prize awarded for the discovery of gravitational waves, provides a concise account of the LIGO collaboration. His contribution conveys the sense of a rapidly expanding field that exploded into a spectrum of activities after a long period of preparation and gestation. Further observations of wave events followed the initial one on September 14, 2015. His words evoke a field in which one sensational, new event is hardly processed and prepared for public announcement when the next renders the first old news. Barish's contribution itself reflects the rapidly increasing success: he added a note in proof to announce that a second gravitational event (GW151226) had been detected during the first run (O1) of advanced LIGO, which took data between September 12, 2015, and January 19, 2016. That was followed by several more detections during the second observation run (O2) from November 30, 2016, to August 25, 2017. During that period, LIGO not only produced further evidence for binary black hole mergers but also yielded evidence for the merger of a binary neutron star as a first observation of a gravitational-wave event in conjunction with its electromagnetic counterpart. More new data can be expected from the third observation run (O3), which is projected to begin taking data in February 2019. This run will include, in addition to the two LIGO interferometers, data taken from the European observatory VIRGO, which should allow more accurate localization as well as give, for the first time, information about the polarization of gravitational radiation.

Kip Thorne, who with Barish and Rainer ("Rai") Weiss was awarded the 2017 Nobel Prize, was for many years a principal mover of the project directly to detect gravitational radiation, having begun theoretical investigations into the subject in the late 1960s. His contribution to this volume provides a broad perspective on the significance of the endeavor, emphasizing its importance for our understanding of the observable universe's curved space-time. Thorne's reflections beautifully convey his long-standing fascination with general relativity's counter-intuitive implications as he describes the development of the LIGO project from its first ideas to the large-scale international discovery machine. No one can tell this story better and with more authority than Kip Thorne, the institutional father of LIGO. Indeed, he has gone further in conveying the wonder of gravitational physics, serving as scientific adviser to the film *Interstellar*, which trades on the possibilities suggested by some of the field's implications.

Alessandra Buonanno, director at the Albert Einstein Institute for Gravitational Physics in Berlin and Professor of Physics at the University of Maryland, provides insight concerning what may begin to be detected with new gravitational-wave "telescopes." A principal aim of the extraordinary technology developed for the LIGO interferometer was and remains to provide qualitatively new information in the fields of astrophysics and cosmology. Buonanno sketches the possibilities now opened by gravitational-wave astronomy. She explains the intricate and fascinating astrophysical processes that take place when black holes or neutron stars collide, inspiral, merge, and settle down, and explains what gravitational and electromagnetic signals we can expect from those violent processes.

Dan Kennefick, professor of physics at the University of Arkansas and a longtime collaborator of the Einstein Papers Project at Caltech, provides an intimate, historical account of the LIGO project. In addition to training as a historian, while a graduate student Kennefick was early involved in the efforts led by Kip Thorne to prepare the theoretical grounds underlying the empirical search for gravitational waves that eventuated in LIGO's success. Drawing on his own experience and direct involvement, Kennefick points to the role of theorists and theoretical controversies in shaping the successful outcome of the quest, emphasizing in particular the importance of detailed numerical modeling. The large-scale simulations of such astrophysical catastrophes as black hole collisions through the explicit numerical solution of Einstein's equations provided the filters by which the raw interferometric data was interpreted. In 2005, a breakthrough became possible when it was realized that special coordinate conditions allowed the uninterrupted simulation of the full cycle of the inspiral, merger, and ring down of a binary black hole. That breakthrough allowed LIGO researchers to interpret the interferometric signals in terms of specific astrophysical causes, including estimates of distance as well as of initial and final masses.

Jürgen Renn, director at the Max Planck Institute for the History of Science, lays out a long-term history of research into the theory of relativity and gravitation that culminated in LIGO's successful detection of waves. He reaches back to the preconditions that underpinned the theory of general relativity and the details of the heuristics deployed by Einstein in his search for the field equations. That almost exactly a century passed between Einstein's publication of the equations and the first direct observation of ripples in space-time is, of course, a numerical contingency. But it is a contingency that appeals to the historical mind. Renn takes it as a challenge for the historian to account for the longue durée of a historical process that began with a theoretical conjecture, that underwent ups and downs in the structure's appeal and deployment by the physics community, settling at long last into a multimillion-dollar, large-scale endeavor that lasts for decades until delivering what had until then been a long-sought and discussed possibility. Renn focuses on the interplay between theoretical premises and experimental design, describing the transformation of the field from its origin in the imagination of a single mind to a collaborative enterprise involving thousands of scientists.

Harry Collins, professor of sociology at the University of Cardiff, has been interested in, and indeed associated with, the LIGO project for decades as a sociologist. Large-scale scientific projects, involving hundreds or thousands of researchers, technicians, and other personnel and enjoying levels of funding that surpass the means of individual groups or institutions, represent, Collins points out, a social reality of their own. This is particularly the case with LIGO, which was funded by the National Science Foundation at an unusually high level for more than two decades before achieving success. LIGO's efforts put ever more stringent constraints on the observability of gravitational-wave events as its instruments became steadily and impressively more accurate. Collins has observed the ongoing research with the eye of a critical and skeptical sociologist since the early seventies. He tells an intriguing story concerning an attempt by a LIGO predecessor, Joe Weber, to detect the effect. Given the technology available in the 1970s, Weber employed resonant bars. These large aluminum cylinders, Weber argued, would be set into vibration by passing gravitational waves. Despite the near unanimous rejection by the community of his early claims of detection, Weber, Collins argues, should be seen as a pioneer of the field because his experimental work created the community interest that made further work possible—most immediately the indirect observation of waves in 1975 by Hulse and Taylor due to energy loss by a neutron star binary.

Diana Buchwald, professor of history at Caltech and director of the Einstein Papers Project, focuses on Einstein's relationship with the California Institute of Technology. Not only is Caltech a founding institute and core partner of the LIGO endeavor, since 2000 it has been host to the long-term, multi-volume editorial project of the *Collected Papers of Albert Einstein*. Under Buchwald's aegis, to date eight volumes of writings and correspondence from the years 1918 to 1927 have been published. This is particularly apposite since Caltech's relationship with the founder of general relativity and the originator of the idea of gravitational waves goes back to the very beginnings of the theory, when Einstein corresponded in 1913 with the Caltech astronomer George Hale about the possibility of observing gravitational light deflection. Had historical circumstances been slightly different, Caltech might have become Einstein's home after he was forced to leave Germany and emigrate to the United States following the acquisition of power by the Nazis. He spent three winters in the early 1930s at Caltech, before finally accepting an offer at the Institute for Advanced Study in Princeton, which became his home for more than twenty years until his death in 1955.

Don Howard, professor of philosophy at the University of Notre Dame, focuses on the impact that Einstein's theory had for our modern understanding and philosophy of science. Philosophical reflection of science in the twentieth century underwent profound transformations with the advent of general relativity. Indeed, philosophy of science in a modern sense was created, Howard suggests, in its present form not the least by Einstein himself in a debate with philosophical interlocutors such as Moritz Schlick, Hans Reichenbach, Rudolf Carnap, Ernst Cassirer, and others. Howard goes back to the early years of the radically new understanding of space and time when it was first explored by philosophers. Howard describes how, in response, they reconsidered long-standing problems in the relationship between empirical and conceptual content, discussing in so doing the principal aspects of theory verification, the distinction between the a priori and convention, and the ontological structure of physical theory. Philosophy of science in the 1920s, Howard argues, reacted primarily and importantly to Einstein's theory of general relativity. In light of LIGO's first direct observation of gravitational waves, predicted by Einstein one hundred years before, this debate has lost nothing of its relevance.

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