Book Review for *Studies in History and Philosophy of Modern Physics*

# *Let's Do* Black Holes and Time Warps *Again:*
# *The Future of Spacetime*

The study of Einstein's theory of general relativity experienced a renaissance beginning in the early 60s. Prior to this resurgence of interest, general relativity was isolated from mainstream physics, and admired for its elegance, perhaps, but only from a distance. The generation of students who risked their careers by entering this neglected field has now reached the age of *festschrifts*. In June of 2000, Caltech hosted "Kipfest," a conference in honor of Kip Thorne's sixtieth birthday. Thorne started graduate school at Princeton in 1962 and began research in general relativity under John Wheeler's guidance in the heady early days of the renaissance. Since then he has played a prominent role in general relativity: as a co-author of the influential textbook *Gravitation*, as a leader in research regarding astrophysical applications of Einstein's theory, and as a co-founder and chief propagandist for the Laser Interferometer Gravitational Wave Observatory (LIGO), to mention a few aspects of his far-reaching work. Kipfest included fourteen speakers discussing fields to which Thorne has contributed. But the conference also reflected Thorne's long-standing commitment to communicating science to a general audience: Igor Novikov, Stephen Hawking, Timothy Ferris, and Alan Lightman gave popular talks at Kipfest, with Thorne himself tricked into delivering a fifth. *The Future of Spacetime* gathers together adaptations of these five lectures, along with a lengthy introductory essay by Richard Price.

The result is an uneven jumble. Most of the book offers variations on themes given a clearer, more comprehensive treatment in Thorne's masterful popular book, *Black Holes and Time Warps* (Thorne 1994, hereafter BHTW). Thorne's essay gives one take on the "future of spacetime," but anyone looking for a more wide-ranging discussion (as the title suggests) will be sorely disappointed. Almost a third of the book – including Price's introduction and the glossary – has been added to make it more palatable for a popular audience. Novikov and Hawking's essays have been only lightly adapted from their original form as lectures, and include a number of unenlightening and poorly reproduced illustrations. For example, p. 98 features a picture of Hawking's grandson, and Hawking's contribution includes several other illustrations that may have worked as comic relief for a lecture audience, but fall flat here. As a result, this is a much slimmer volume than its length (220 pages) would suggest. Despite their limitations, these essays touch on a number of issues of interest to historians and philosophers of physics.

The volume opens with Price's concise introduction to several aspects of relativity, ranging from the Lorentz transformation to event horizons and wormholes. Price uses spacetime diagrams to effectively convey some of the conceptual intricacies of relativity, and this approach can be quite useful pedagogically (although it is hardly unique to Price). I will discuss the next three essays, the contributions from Hawking, Novikov, and Thorne, below. The final two essays take up broader themes not directly related to spacetime theories. Lightman offers a vivid comparison of his dual vocations as a novelist and physicist. Ferris bemoans the shortage of quality science writing, and discusses the challenges of writing about science for a public that is “estranged” from it. By Ferris’s lights, effective science writing (illustrated here with scenes he wrote for a movie about Einstein) conveys an understanding of “science as a process” (p. 156) rather than a collection of dry facts.

Unfortunately, Hawking and Novikov’s contributions both illustrate one common failing of science writing. They exploit the pop-culture appeal of a topic that sounds more like science fiction than real physics, without adequately explaining why the topic has inspired such interest. Readers of BHTW will recall that the study of time travel does in fact owe its origin to science fiction. Carl Sagan called Thorne and asked how to send the heroine of his novel *Contact* to Vega in a matter of minutes rather than years. Thorne realized that the heroine could use a wormhole propped open by matter fields with negative energy density. Appropriate wormhole solutions could even be used as a time machine; more precisely, these solutions include closed timelike curves (CTCs). (Timelike curves represent the trajectories of possible observers in general relativity; the end of all exploring, for an observer traveling on a *closed* timelike curve, is to literally arrive back where she started.) CTCs had been discovered long before 1985, but several papers by Thorne and his collaborators spurred the interest of other physicists.

Why should physicists or philosophers devote any attention to such bizarre spacetimes? There are (at least) two interesting lines of thought to pursue. First, bizarre spacetimes may shed light on our understanding of the laws of nature. Philosophers have focused on alleged paradoxes of time travel: if I travel back in time and kill my grandfather, then I would not have been born, and could not have entered a time machine with murderous intentions. This threat of blatant inconsistency can be avoided, however, as Novikov illustrates with a less violent scenario (cf. pp. 508-516 of BHTW). Imagine shooting a billiard ball through a wormhole, such that the ball exits from the other end of the wormhole, *before* it enters, on a collision course with the initial shot. As with the grandfather paradox, a collision apparently leads to inconsistency: if the ball knocks itself off course, how can it enter the wormhole? However, there are a number of *consistent* solutions, in which the impact is a glancing blow and the ball still travels through the wormhole. Novikov comments that the study of these solutions can help “to sharpen our understanding of causality” (pp. 57, 82-85), and leaves it at that. But the more interesting issue is the apparent narrowing of physical possibility in time travel spacetimes. The billiard-ball solutions illustrate that there may be *consistency constraints* due to the global structure of spacetime. But what is the nature of these consistency constraints (assuming that they exist)? They seem to have the modal force associated with laws of nature: a locally allowed initial state leading to a globally inconsistent trajectory is simply *impossible*. And yet these constraints differ dramatically from the laws familiar from other areas of physics: they are not local, and they depend on a complicated specification relating the initial state to the global structure of the spacetime. Consideration of time travel spacetimes undermines the usual distinction between laws of nature and initial conditions, since consistency constraints may qualify as law-like constraints on an initial state. This strikes me as a much more fruitful area for further research than arm-chair philosophizing about the grandfather paradox.[1]

The second interesting avenue of research attempts to squeeze a prohibition on creating CTCs from the laws of classical general relativity and fledgling versions of quantum gravity. These no-go results aim to demonstrate that it is impossible to build a time machine by manipulating matter and energy in a finite region, even with advanced technology and unlimited funding. A successful time machine operator would need to twist and warp spacetime to such a degree that CTCs inevitably arise. But clarifying the sense in which the CTCs are "due to" the operator's manipulations is tricky. In general relativity, specifying the metric and matter fields in some finite region K only fixes the state within the domain of dependence of K. The state at points outside this region may be affected by influences that are not "registered" by the state on K. But the CTCs must lie outside of the domain of dependence. Earman and Smeenk (1999) propose a "potency condition": a time machine is defined to be a finite region of spacetime such that every "suitable" maximal extension of it contains CTCs. (The strength of this condition depends upon how "suitable" is cashed out.)

Hawking's essay describes his various attempts to prove a no-go result. Hawking (1992) introduced a definition of time machines that has become the industry standard: the Cauchy horizon, the surface marking the boundary of the domain of dependence, must be "compactly generated," i.e., it must be generated by light rays emerging from a finite region of spacetime. (See Earman and Smeenk 1999 for a criticism of this definition and comparison to the potency condition.) He proved a no-go result for fields with positive energy density based on this definition. But Thorne and others objected that quantum fields could be used to avoid the theorem, since they can have negative energy density. A second round of results focused on whether the stress-energy tensor for quantum fields "blows up" as the Cauchy horizon is approached. Here Hawking admits that even these results are not fool-proof: for some quantum states, the stress-energy tensor does not diverge on the Cauchy horizon (p. 101). But he offers a new no-go theorem intended to show that the probability associated with a spacetime with CTCs must be incredibly low. It is far from clear how this result, derived in the context of Euclidean quantum gravity (a "queasily infirm" theory, as Thorne puts it), relates to the earlier no-go theorems. In particular, the meaning of probabilities in this approach to quantum gravity is one of the deep conceptual problems facing the program. As in some of his other popular writing, Hawking glosses over these difficulties and does not mark the transition from well-understood results to more speculative ideas. In any case, Hawking's efforts illustrate that the attempt to prove no go theorems is enmeshed with deep foundational questions regarding the laws of classical general relativity and quantum gravity.

Thorne's essay alone is nearly worth the price of the volume.[2] He enthusiastically outlines the results he expects LIGO and its successor LISA to produce within the next

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[1] There have been a few clear discussions of the nature of consistency constraints; see, in particular, Earman 1995 and Arntzenius and Maudlin 2000.

[2] But for those unwilling to pay the price, an earlier version of this talk (complete with transparencies and an audio track) is available on Thorne's webpage.

thirty years, ranging from observations of black hole collisions to measurements of primordial gravitational waves. The scientific community has not always shared this enthusiasm: LIGO has been the target of frequent criticism, and skeptics still doubt whether the first generation detectors of this $300 million dollar device will see *anything*. Despite already losing two bets regarding the detection of gravitational waves (to Bruno Bertotti in 1988 and Jeremiah Ostriker in 2000), Thorne does not shy away from bold predictions. Regardless of whether LIGO and LISA provide deep insights into quantum gravity, as Thorne projects, the large-scale research effort devoted to building, operating, and interpreting data from these observatories will undoubtedly shape research in general relativity for decades to come. Thorne also highlights an intriguing feature of LIGO: in 2008, LIGO's 40 kg sapphire mirrors are expected to shatter the existing record for the largest object displaying quantum behavior. This would undermine modifications of quantum mechanics, such as the GRW collapse theory, that entail classical behavior for macroscopic systems. In practice, this feature of LIGO has led Thorne and others to design "non-demolition measurements" in order to maximize detector sensitivity.

In summary, these essays report on contemporary research that philosophers may gain a great deal by studying. It is unfortunate that the contributions do not always reach the high standards for popular science writing set by Thorne's own work.

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