5
Warping spacetime

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5.1 Introduction

*It is a great honor and pleasure lecture here on Stephen's sixtieth birthday. And it's a special pleasure to be sandwiched, in the speaking schedule, between Roger Penrose and Stephen, because I shall talk about plans for testing the amazing theoretical predictions that Stephen, Roger and others made about black holes during the Golden Age of black-hole research, the era from the mid 1960s to the mid 1970s.

Fig. 5.1. Einstein a few years before formulating general relativity. [Courtesy Albert Einstein Archives of the Hebrew University of Jerusalem.]

But let me begin with an earlier era — with Albert Einstein, who in 1915 gave us general relativity. General relativity is Einstein's law of gravity, his explanation of that fundamental force which holds us to the surface of the Earth. Gravity, Einstein asserted, is caused by a warping of space and time—or, in a language we physicists prefer, by a warping of *spacetime*. The Earth's matter produces the warpage, and that warpage in turn is manifest by gravity's inward tug, toward the Earth's center.

The inward tug is not the only manifestation of spacetime warpage; the warpage is much richer than that. As we shall see, it curves space, it slows the flow of time, and it drags space into tornado-like motions — at least that is what Einstein's general relativity predicts.

Fig. 5.2.   Karl Schwarzschild, who discovered the solution to Einstein's equations which describes a nonspinning black hole. [Courtesy AIP Emilio Segrè Visual Archives.]

In early 1916, only a few months after Einstein formulated his mathematical laws of warped spacetime, Karl Schwarzschild discovered the

following mathematical solution to Einstein's general relativity equations:

$$ds^2 = -\left(1 - \frac{2M}{r}\right)dt^2 + \frac{dr^2}{1 - \frac{2M}{r}} + r^2(d\theta^2 + \sin^2\theta d\phi^2).\qquad(5.1)$$

At first sight, this appears to be a rather complicated formula, but as physics formulae go, it's actually quite simple.

Physicists realized rather quickly that this formula seems to describe an object that has "cut itself off" from the rest of the universe, an object to which John Wheeler, many decades later, would give the name *black hole*. But physicists could not believe such an outlandish interpretation of the math. For nearly 50 years the world's leading physicists, including Einstein himself, fought mightily against this concept of an object cut off from the universe. It was only in the early 1960s, as the culmination of a long intellectual struggle, that they gave in; that they finally accepted what the math seemed to be saying.

To help me explain what the math says, I have brought a black hole with me (see Figure 5.3). I normally carry my own black hole on the aeroplane when I travel, but with airline security so tight in the wake of 9/11, I've had to borrow one from Trinity College. If it really were a black hole, this Trinity black hole would be made not from matter, but entirely from a warpage of spacetime.

Fig. 5.3.   The author holding a black hole — actually, a Trinity College bowling ball.

One way to understand that warpage is to compare the hole's circumference with its diameter. Normally, of course, the ratio of a circumference to a diameter is equal to π, which is approximately 3. But for a black hole, in fact, this ratio is much smaller than 3. The hole's circumference is tiny compared to its diameter.

We can understand this by a simply analogy. We begin with a rubber sheet (a child's trampoline) with edges held high in the air by long poles. Onto the trampoline we place a heavy rock, which stretches the trampoline's center downward a great distance as shown in the left panel of Figure 5.4. Now, suppose that you are an ant living on this rubber

sheet; the sheet is your entire universe. Suppose, moreover, that you are a blind ant, so you can't see what is warping your universe. However, you can easily measure the warpage. By marching around the rim you can measure its circumference, and by marching down through the centre you can measure its diameter. You thereby discover that the circumference is tiny compared to the diameter, in violation of Euclid's laws of plane geometery.

How is this possible? Being people outside the trampoline, and not really blind ants, we know the cause: the rock has warped the trampoline's rubber, just as something has warped the space of a black hole.
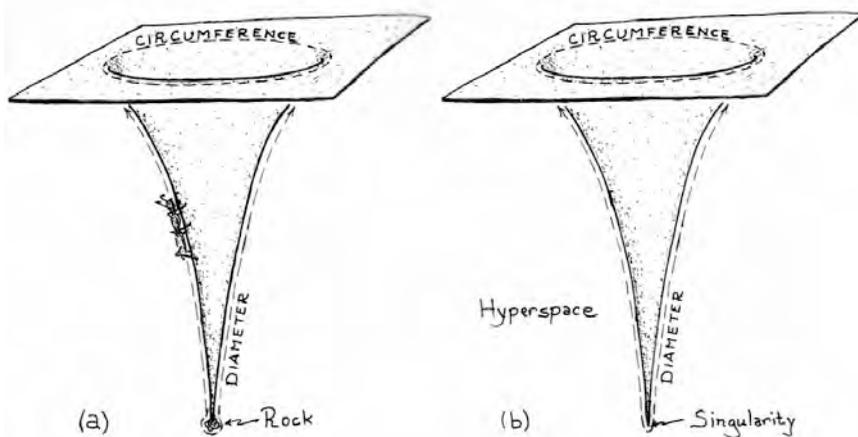

Fig. 5.4. A rubber sheet warped by a heavy stone (left) is an excellent analogy for a black hole's warped space (right).

This, in fact, is an excellent analogy. Consider an equatorial slice through the black hole. What is the geometry of that slice? If the hole's space were "flat" like the space that most people think we live in, the slice's geometry would be the same as that of a flat sheet of paper. But the hole's space is not flat; it is warped, so the slice must also be warped. We can visualize its warpage by pretending we are higher dimensional beings who live in a higher-dimensional flat space, in which the warpage occurs. Science fiction writers call this higher dimensional space *hyperspace.* Hypothetical hyperbeings in hyperspace could examine the hole's equatorial slice and discover it has the form shown in the right half of Figure 5.4.

Notice that the warped shape of the hole's space, as seen by a hyperbeing in hyerspace, is identical to the warped shape of the trampoline as

seen by people in ordinary space. In both cases, circumferences are much smaller than diameters, and smaller by the same amount.

At the trampoline's center there is a rock. At the hole's center there is a *singularity* like those discussed by Roger in his lecture. It is the rock's weight that warps the trampoline. Similarly, one might suspect, it is the singularity's mass that warps the black hole's space. Not so, it turns out. The hole's space is warped by the enormous energy of its warpage. Warpage begets warpage in a *nonlinear* self-bootstrapping manner that is a fundamental feature of Einstein's general relativity laws.

This does not happen in our solar system. The warpage of space throughout our solar system is so weak that the energy of warpage is miniscule, far too small to produce much self-bootstrapped warpage. Almost all the warpage in our solar system is produced directly by matter — the Earth's matter, the Sun's matter, the matter of the other planets.
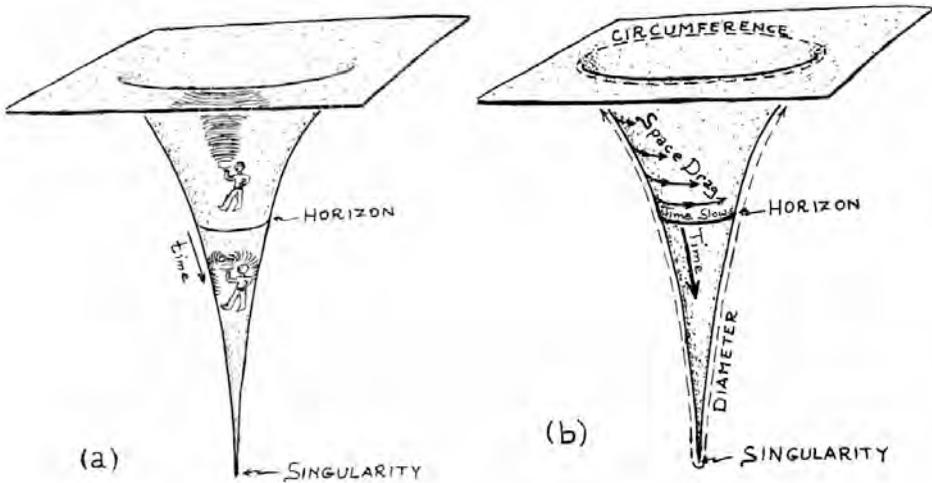

Fig. 5.5. (a) Kip falling into a black hole and trying to transmit microwave signals to you on the outside. (b) The curvature of space, the warping of time, and the dragging of space into a tornado-like motion around a spinning black hole.

Now, the most well known property of a black hole is not its warped space, but rather its trapping power, as depicted in the left panel of Figure 5.5. If I fall into a black hole carrying a microwave transmitter, say, then once I pass through a location called the hole's *horizon*, I am inexorably pulled on downward, into the singularity at its centre. Any signals that I try to transmit get pulled down with me, so nobody above the horizon can ever see the signals I send.

By 1964, when the Golden Age began, we knew that the warpage of

spacetime around a black hole is actually rather complicated (right panel of Figure 5.5). There are three aspects to the warpage: First, there's the curvature of space, which I've been talking about. Second, there's a warping of time. The flow of time slows to a crawl near the horizon, and beneath the horizon time becomes so highly warped that it flows in a direction you would have thought was spatial: it flows downward towards the singularity. That downward flow, in fact, is why nothing can escape from a black hole. Everything is always drawn inexorably towards the future, and since the future inside the hole is downward, away from the horizon, nothing can escape back upward, through the horizon.

The third aspect of the warpage was discovered by Roy Kerr in 1963: black holes can spin, just as the Earth spins, and a hole's spin drags space around it into a vortex-type, whirling motion. Like the air in a tornado, space whirls fastest near the hole's center, and the whirl slows as one moves outward, away from the hole. Anything that falls toward the hole's horizon gets dragged, by the whirl of space, into a whirling motion around and around the hole, like an object caught and dragged by a tornado's wind. Near the horizon there is no way whatsoever to protect oneself against this whirling drag.

These three aspects of spacetime warpage — the curvature of space, the slowing and distortion of time, and the whirl of space —- are all described by mathematical formulas. Einstein's equations, in the hands of Schwarzschild and Kerr, have predicted the curvature, distortion and whirl unequivocally. They are the essence of a black hole; they are what a black hole is made of.

As I proceed with this lecture, until nearly the end when I return to Roger's topic of singularities, I will depict only the the warped spacetime *outside the hole's horizon* (right panel of Figure 5.5). The reason is that, once anything enters the horizon, it can't send signals back out; so there is no way for us to observe or probe the inside of a hole from the outside. Since I will talk about probing black holes with solar-system-based instruments, I will be limited to probing down to the horizon, but no further.

5.2 A first glimpse of the Golden Age: 1964-74

In 1964, as the Golden Age dawned, Stephen, Roger, I, and our compatriots were young, just finishing graduate school or recently finished. Roy Kerr had recently discovered that black holes can spin, John Wheeler had not yet named them, and the laws that govern them were still a mystery. The unfolding of that mystery in the Golden Age was wonderful, and Stephen and Roger were the leaders in revealing its wonders.

One of Stephen's most important contributions was to predict math-
ematically, using Einstein's equations, a fundamental property of every
quiescent black hole — every hole whose shape is constant, unchanging.
The horizon of a quiescent black hole, Stephen predicted, must have spher-
ical topology; it cannot have a ring-like topology like the surface of a donut
or bagel or tea cup (top half of Figure 5.6). All topologies are forbidden
except that of a sphere's surface. And if the black hole is spinning but
has constant, unchanging shape, Stephen predicted, then that shape must
be *circularly symmetric* around its spin axis, like the shape of a spinning
top. In other words, all the horizon's horizontal cross sections must be
circular, and not square or triangular or any other shape (bottom half of
Figure 5.6) . The reason, roughly speaking, is that, if the hole had any
other shape, then as it spins, the tornado-like whirl of space would create
outgoing ripples of spacetime warpage in its vicinity, just as a whirling
brick in a pond of water creates ripples on the pond's surface; and those
ripples would carry energy and angular momentum away from the hole,
thereby changing the shape of the hole's horizon. The hole, therefore,
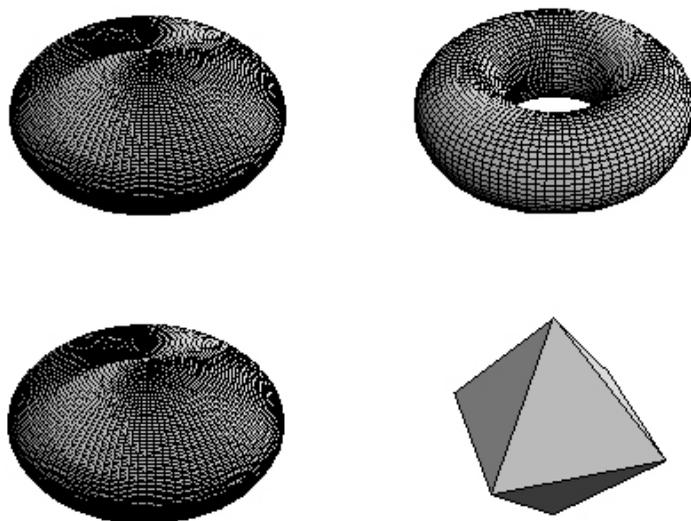would not be quiescent, as we insisted it be.

Fig. 5.6.   Two of Stephen's predictions from the Golden Age. Top: the horizon
of a quiescent black hole has spherical topology. Bottom: if the quiescent hole
is spinning, then its horizon is circularly symmetric.

Among the nicest features of the Golden Age was the way we all built on
each other's work. Hawking laid the foundations, and one after another

his compatriots built an edifice upon them — Werner Israel,[†] Brandon Carter, David Robinson, Pavel Mazur, Gary Bunting. The final edifice was a marvelous mathematical structure, which predicted that quiescent black holes in the macroscopic, astrophysical universe have just *two hairs*, in this sense: if you know just two properties of an astrophysical black hole, then you can deduce all its other properties, uniquely. The simplest two properties to discover are a hole's *mass* (how hard its gravity pulls), and its *spin* (how fast space on its horizon whirls around and around). Having measured a hole's mass and spin, you can deduce the full details of all other features of the hole's warped spacetime — all the details of its space curvature, all the details of its slowing and distortion of time's flow, and all the details of its space's whirling motion, both near the hole and far away.

One can draw maps of these three features of the warpage (space curvature, time distortion, space whirl), and the full details of those maps are predicted by Golden-Age mathematics, once the hole's mass and spin are known.

This marvelous Hawking-Israel-Carter-Robinson-Mazur-Bunting prediction is sometimes called *black-hole uniqueness.* John Wheeler has referred to it by saying *a black hole has no hair*, though it's more accurate to say that *a quiescent, astrophysical black hole has just two hairs: its mass and its spin.*

5.3 LISA: Mapping black holes with gravitational waves

Since the 1970s these remarkable predictions have remained untested. They seem to be an unequivocal consequence of Einstein's general relativity laws, but relativity might be wrong or (much less likely) we might be misinterpreting its mathematics.

It is a triumph of modern technology that we are now on the verge of being able to test these predictions. I am confident they will be tested within the next decade or so, by the following means:

In the distant universe there should be many "binary" systems made of a small black hole orbiting around a much larger black hole, as illustrated in the left panel of Figure 5.7. The small hole might be about the size of Cambridge and the large hole might be a little bigger than the Sun; quite a contrast. The small hole orbits around the big one, and as it moves, it creates ripples in the fabric of spacetime that propagate outwards like ripples on a pond. These ripples are called gravitational waves.

[†] Actually, Israel's contribution preceded Hawking's; Hawking shoved his foundations under it.
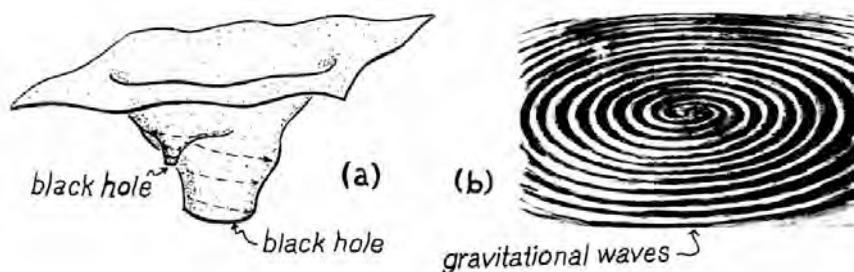
Fig. 5.7. Left: a small black hole orbiting a large black hole and gradually spiraling inward. Right: the gravitational waves produced by the small hole's inspiral.

A student of mine, Fintan Ryan, has used Einstein's equations to deduce that these ripples carry, encoded in themselves, full maps of all features of the big hole's spacetime warpage. As the small hole orbits the big hole, very gradually spiraling inward, it explores the big hole's warped spacetime, and it encodes on its outgoing waves a map of all it sees. This motivates a great challenge: detect the gravitational waves as they pass through our solar system, extract the maps that they carry, and use those maps to test the Golden Age predictions. My Caltech colleague Sterl Phinney has given the name *bothrodesy* to this enterprise, by analogy with *geodesy*, the science of measuring the shape of the Earth by probing its gravitational field. The "geo" of geodesy means Earth; the "bothro" of bothrodesy descends from the Greek word $\beta o \theta \rho o \varsigma$ (bothros) meaning "garbage pit", a description of a black hole introduced long ago by Stephen's classmate Brandon Carter.

The physical manifestation of the small hole's gravitational waves, as they pass through the solar system, is much like ripples on the surface of a pond. Suppose two corks are floating in the pond. As the water-wave ripples go by, the corks not only bob up and down; they also are pushed back and forth relative to each other. If you were a water skeeter living on the pond's surface, you might not be aware of the up and down bobbing, but you could see the corks move back and forth; you could watch their separation oscillate. If the waves were very weak but you were a smart water skeeter with laser technology, you might monitor the passing waves by using a laser beam — a laser-based surveying instrument — to measure the tiny oscillations of the corks' separation, as shown in Figure 5.8. This is precisely how we plan to detect and monitor gravitational waves:

A gravitational wave's ripply spacetime warpage, like the steady warpage of a black hole, is rich in its details, but the most useful feature of the wave's warpage is an oscillatory stretching and squeezing of space. The
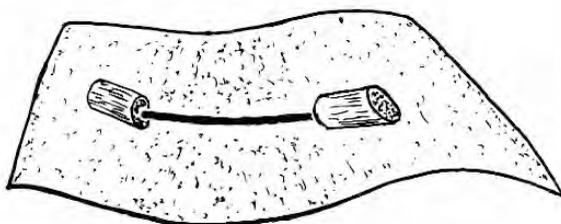
Fig. 5.8.   A laser beam monitors the separation of two corks on a pond, as water waves pass by.

stretch and squeeze are *transverse* to the wave's propagation. During the first half of the wave's oscillation cycle, it stretches space along one transverse direction while squeezing along the other, perpendicular direction; in the next half cycle it switches, squeezing along the first direction while stretching along the second. So if the wave is passing through me from front to back, I get stretched from head to foot and squeezed from the sides, then stretched from the sides and squeezed from head to foot, and so on.

The stretch and squeeze are far too weak for you or me to feel, but we expect to detect them by monitoring the separations between "corks" that float in interplanetary space. The "corks" will be spacecraft, the stretch and squeeze of space will push them back and forth relative to each other, and we will use a laser-based surveying instrument to monitor their oscillating separation, as shown in the left panel of Figure 5.9.

This gravitational-wave detection system is called *LISA*, the Laser Interferometer Space Antenna. A joint European/American mission with launch tentatively planned for 2011, LISA will consist of three spacecraft at the corners of an equilateral triangle with 5 million kilometer sides. The laser beams will shine along the triangle's edges, linking the spacecraft. The spacecraft will travel around the Sun in approximately the same orbit as the Earth, but following the Earth by about 20 degrees as shown in the right panel of Figure 5.9. The spacecraft will be *drag-free*: they will have very special, high-precision instrumentation to prevent them from being buffeted by the Sun's fluctuating radiation pressure and the fluctuating wind of gas that blows off the Sun — so they respond only to the steady gravitational pulls of the Sun and planets, and the waves' oscillatory stretch and squeeze of space.

The farther apart are the spacecraft, the larger will be their oscillatory dispacements relative to each other; that is why we'll place them so far apart. The ratio $\Delta L/L$ of the wave-induced displacement ΔL to the separation L is equal to the *gravitational-wave field*, which we denote h.
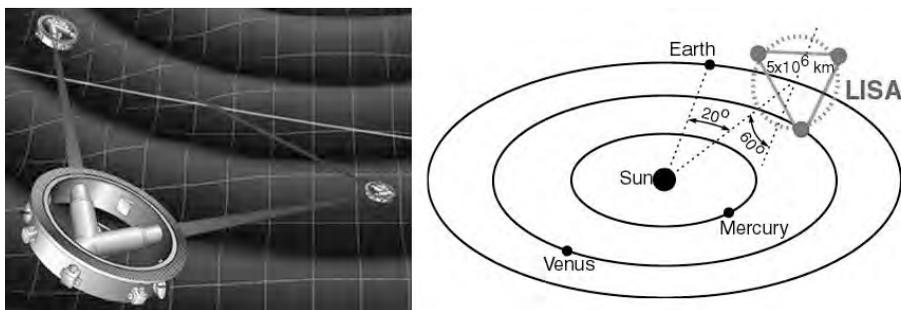
Fig. 5.9. LISA, the Laser Interferometer Space Antenna, which ESA and NASA will jointly build, launch, and use to monitor low-frequency gravitational waves. In the right panel LISA's size is exaggerated by about a factor 10 relative to the planetary orbits

This h is one aspect of the waves' spacetime warpage, and it oscillates with time t as the wave travels through LISA, so we sometimes write it "$h(t)$". In other words, the displacement ΔL is a fraction $h(t)$ of the separation: $\Delta L = h(t) \times L$.

Figure 5.10 gives some feeling for LISA's planned test of the Golden-Age predictions. The size of the black-hole pair, the big hole with the tiny one orbiting it, is about 5 million kilometers, so it takes about 20 seconds for light to travel across the small hole's orbit. Though the tiny hole's horizon has a circumference about the same as Cambridge's, its mass (or, more precisely, the strength of its gravitational pull on matter at some fixed distance) is enormous: about 10 times the mass (or pull) of the Sun; and the big hole's mass is humongous: about a million times that of the Sun. The big hole spins rapidly, about one revolution each 66 seconds, but out at the small hole's orbit the whirl of space is somewhat slower. As the small hole gradually spirals inward toward the big hole's horizon, it samples regions of faster space whirl and stronger pull, and so precesses faster and orbits faster. This gradually changing orbital motion and precession produce the gravitational waves that we seek, waves carrying an encoded map of the large hole's warped spacetime.

These gravitational waves travel out from the holes, through the great reaches of intergalactic space, to our solar system, a distance of about 3 billion light years, roughly 1/5'th the size of the observable universe. By the time they reach the solar system and pass through LISA, the waves have become very weak: they stretch and squeeze space by about one part in 10^{21}. In other words, the wave field h is $h \simeq 10^{-21}$.

LISA's size, $L = 5$ million kilometers, is about the same as the size of the small hole's orbit around the big hole and only a bit bigger than the big hole itself (Figure 5.10). The waves push LISA's spacecraft back
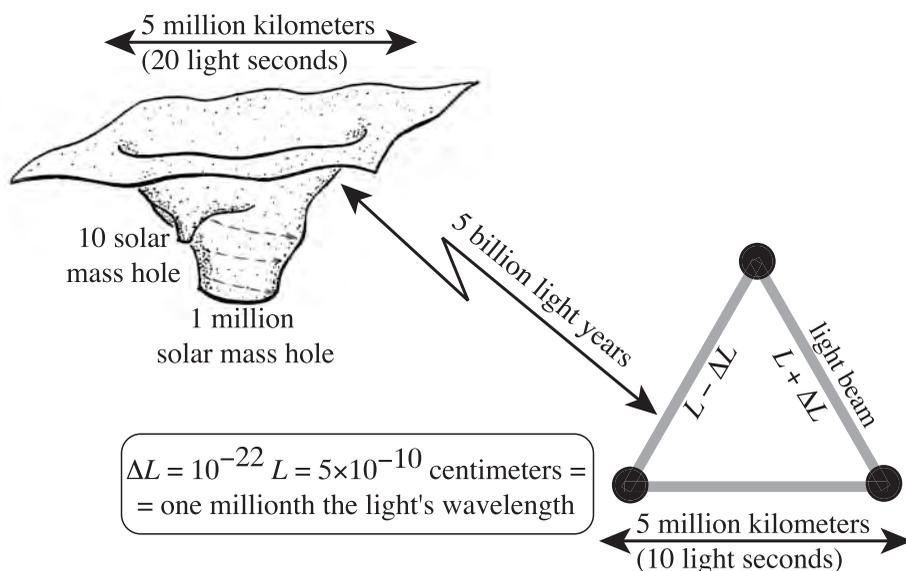
Fig. 5.10.   Some numbers for LISA's bothrodesy mapping of a massive black hole.

and forth by an amount $\Delta L = h \times L \simeq 5 \times 10^{-11}$ centimeters, which is roughly one millionth the wavelength of the light that is used to monitor the spacecraft motions. It is a remarkable fact that modern technology is capable of monitoring such tiny motions!

The waves imprint their oscillatory pattern $h(t)$ on the stretch and squeeze ΔL that LISA measures, $\Delta L = h(t) \times L$. This oscillating pattern, called the wave's *waveform*, is depicted in Figure 5.11. With each circuit around the big hole, the small hole produces two oscillations of the waveform. The precession of the orbit, induced by the whirl of space, causes the waveform's modulation pattern (nine humps and valleys in Figure 5.11). As the small hole gradually spirals inward toward its final, catastrophic plunge, the waveform gradually changes. The full map of the large hole's warped spacetime is encoded in this gradually changing waveform. This waveform is the key to bothrodesy.

During the entire last month of the small hole's life, it encircles the big hole 20,500 times, sending out 41,000 cycles of waves as it gradually spirals inward from a circumference three times larger than the big hole's horizon, to the horizon and its final, plunging death. The 41,000 wave cycles carry exquisitely accurate maps of all aspects of the big hole's warped spacetime, between three horizon circumferences and the horizon itself.

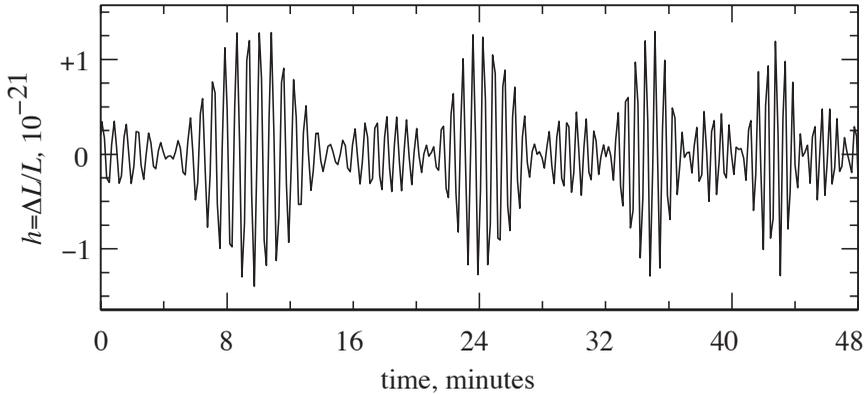From these encoded maps, we can deduce with high precision the mass

Fig. 5.11.   The gravitational waveform passing LISA shortly before the small hole reaches the end of its inspiral and begins a catastrophic plunge into the big hole's horizon. This waveform was computed by Scott Hughes, a former student of mine, by solving Einstein's general relativity equations. LISA is assumed to be in the equatorial plane of the big hole, and the small hole's orbit is inclined 40 degrees to that plane.

of the big hole and its spin, and from the mass and spin and the Hawking-et-al. Golden-Age uniqueness theorem, we can predict all the other details of the maps. If the measured maps agree with the predictions we will have a marvelous confirmation of the Golden-Age theory of black holes. If they disagree, we will struggle to understand why.

Bothrodesy will not be our only harvest from the small hole's waveforms. We will also probe other predictions from the Golden Age. For example, Stephen, working with Jim Hartle (who is also lecturing here today), predicted in 1971 that, as the small hole moves around the big one, it must raise a tide on the big hole's horizon (Figure 5.12 – a tide that very similar to the one that the Moon and Sun raise on the Earth's oceans. This tide then pulls on the small hole, thereby changing its orbit and thence its emitted waveforms; and the small hole pulls on the tide, thereby changing the big hole's spin and mass. From the observed waveforms we can test, with exquisite accuracy, Stephen and Jim's predictions for how the orbit and the horizon evolve when the small hole and tide pull on each other.

5.4 The Golden age again: Colliding black holes

Let us return to the Golden Age, and turn from quiescent black holes to highly dynamical black holes — holes of similar masses and sizes that
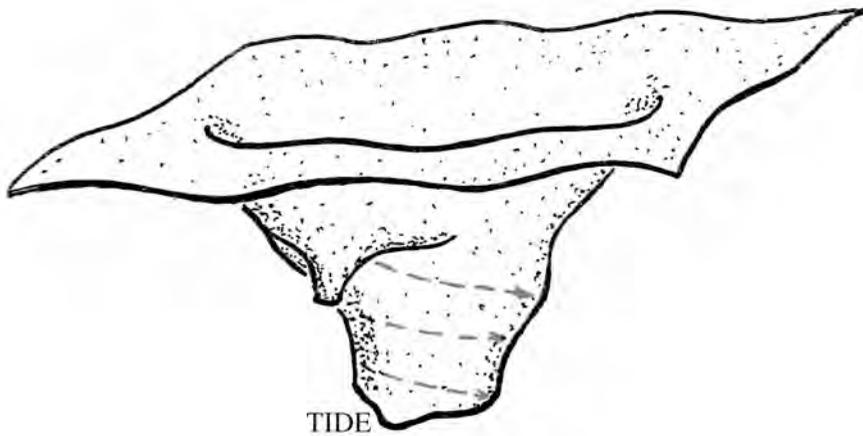
Fig. 5.12.   A small black hole orbiting a larger neighbour, raises a tide like the Moon on the Earth

collide, vibrate wildly, and merge.

The key to understanding dynamical holes was Stephen's concept of a hole's *absolute event horizon*. Building on Roger's prior black-hole studies, Stephen realized that he would gain great predictive power by defining the horizon to be the boundary between regions of spacetime that cannot send signals to the outside universe and that can. Regions that can't communicate with the outside universe would be in the hole's *interior*; those that can communicate would be in the *exterior*.

This definition seems obvious, but it was not. Until then, Roger, Stephen and others had used a different definition for the horizon, one with less predictive power. The immediate payoff of Stephen's new definition was his famous *second law of black-hole mechanics*: the surface area of black hole's horizon can never decrease, and in fact will generally increase, at least a little bit, when it interacts with other objects — e.g., when another hole raises a tide on it, or when something falls into it. Moreover, Stephen deduced, whenever two black holes collide and merge, as in Figure 5.13, the sum of their horizon areas will continually increase throughout the collision, througout the wild vibrations, and throughout the merger, leaving the final, quiescent hole's surface area larger than the sum of the initial holes' areas.

Stephen's proof of the second law actually has a "hole" in it. His proof relied on something that he was almost sure was true, but that nobody had proved as of 1970, and nobody has proved even today; it relied on Roger's *Cosmic Censorship Conjecture*: the conjecture that the laws of physics prohibit naked singularities. A singularity, as Roger has described
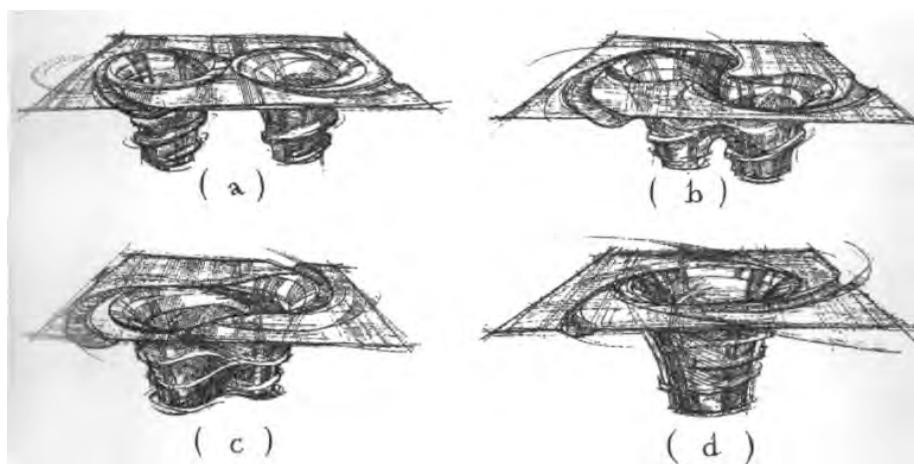
Fig. 5.13.   The collision and merger of two black holes: an artist's conception. [Courtesy the LIGO Project, California Institute of Technology.]

in his lecture today, is a region of spacetime where the warpage is infinitely strong. In the Golden Age, Roger proved that the core of every black hole must harbor a singularity; such a singularity is said to be *clothed*, since it is hidden inside the hole's horizon. A singularity outside all holes, by contrast, would be "naked"; it could be seen by anyone, humans included, in the external universe.

If naked singularities are permitted, then one they could be used to make a black hole's horizon shrink, invalidating Stephen's second law. Thus, Roger's cosmic censorship and Stephen's second law are entwined.

A dynamical hole has lots of "hair". One cannot predict its properties from a knowledge of its mass and its spin. Its horizon may bulge out in this manner, dimple inward in that manner, and swirl in different directions at different locations like the surface of the ocean in a storm. In the early 1970s my students Bill Press, Saul Teukolsky and Richard Price discovered the details of how a dynamical hole loses its hair. The dynamical hole can pulsate, Press discovered using computer simulations. Teukolsky, building on earlier work of others, formulated the theory of those pulsations; and Price deduced the details of how the pulsations die out, carrying away the "hair" and leaving the hole in its final, quiescent state.

5.5 LIGO/VIRGO/GEO:
Probing colliding black holes with gravitational waves

All these Golden-Age predictions — Roger's cosmic censorship, Stephen's second law, and my students' vibrational hair loss — will be tested by monitoring the gravitational waves from black-hole collisions. These waves, moreoever, will show us how warped spacetime behaves when it is highly distorted and highly dynamical, vibrating in hugely nonlinear ways. We've never been clever enough to deduce this behavior from Einstein equations. Gravitational waves are the key to learning it.

The venue for these tests and discoveries will be an international network of *earth-based* gravitational-wave detectors that is just now going into operation, and that almost certainly will watch black holes collide before the end of this decade — before LISA flies and maps quiescent holes.

LISA is the gravitational analog of a radio telescope: it will detect and study waves whose wavelengths are long, the size of the Earth-Moon separation or the Earth-Sun separation or larger. The Earth-based detectors are analogs of optical telescopes: they will detect and study waves with short wavelengths, the size of the Earth or smaller.
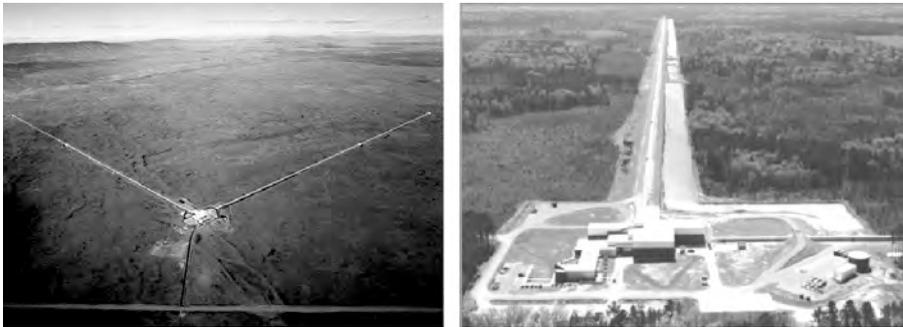
Fig. 5.14.   Aerial views of the LIGO gravitational-wave detectors at Hanford, Washington (left) and Livingston, Louisiana (right). [Courtesy LIGO Project, California Institute of Technology]

Figure 5.14 shows the biggest of the earth-based detectors: those of the Laser Interferometer Gravitational-Wave Observatory (LIGO). Though constructed by scientists from Caltech and MIT with American funds, LIGO has become a partnership of scientists from many nations: the United States, United Kingdom, Germany, Russia, Australia, Japan, India, and others. LIGO is partnered in the network with VIRGO, a French/Italian detector in PISA Italy, and with GEO600, a much shorter UK/German detector in Hanover Germany. The GEO600 scientists are developing and testing advanced technology for future detectors — tech-

nology that will be incorporated into LIGO when it is upgraded in 2008. If, as I expect, the advanced technology is successful in GEO600, it will permit this short detector to be a successful partner with the larger ones during the next few years, before the LIGO upgrade.

By combining the outputs of all these gravitational-wave detectors, we can watch black holes collide and test the Golden-Age predictions.

Figure 5.15 sketches how these detectors work. In place of three spacecraft moving through interplanetary space, an earth-based detector has four heavy cylinders, made initially of quartz and later of sapphire, that hang from overhead supports and swing back and forth in response to a gravitational wave. As in LISA, we use laser beams to monitor the cylinders' relative motions, motions produced by the waves' oscillatory stretch and squeeze of space. Because these motions are detected by interfering the light from the detector's two arms (with one arm squeezed and the other stretched), the detector is called an *interferometer*; hence, LIGO's name, "Laser Interferometer Gravitational-Wave Observatory".
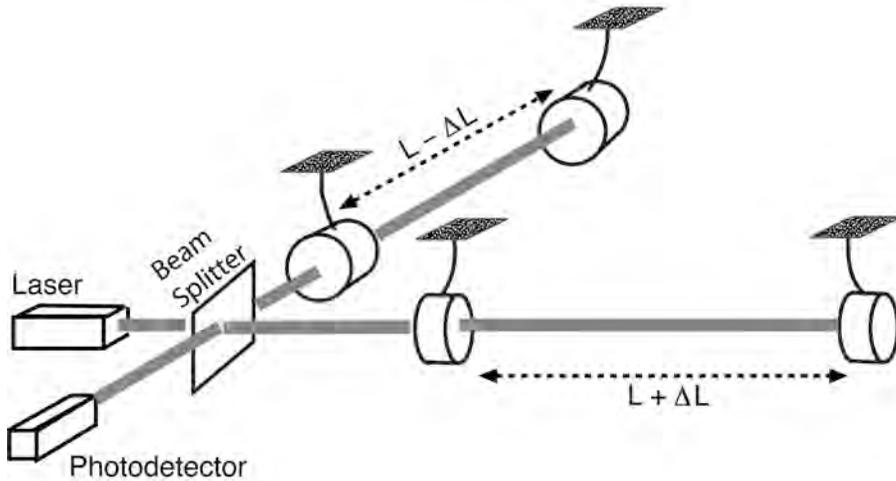
Fig. 5.15.   Sketch of an earth-based gravitational-wave interferometer

In Figure 5.16, I depict the collision of two black holes, with sketches that emphasize the whirl of space but ignore the holes' curvature of space and warping of time. Each hole drags space into a tornado-like whirl as shown, and the holes' orbital motion also creates a space whirl; so the holes are much like two tornados embedded in a third larger tornado that all come crashing together, violently. This cataclysmic collision is much more energetic than any other kind of event in the universe, but it involves no matter, so it cannot emit electromagnetic waves. The only waves it emits are waves made of the same stuff as the holes, waves of spacetime

warpage, gravitational waves. Gravitational waves are the only means by which we can ever see such cataclysms, our only window onto them.

Fig. 5.16.   Inspiral and merger of two black holes

From the waves emitted during the holes' gradual inspiral, we can infer the two holes' masses and spins and surface areas. From the collision waves we can learn how spacetime beh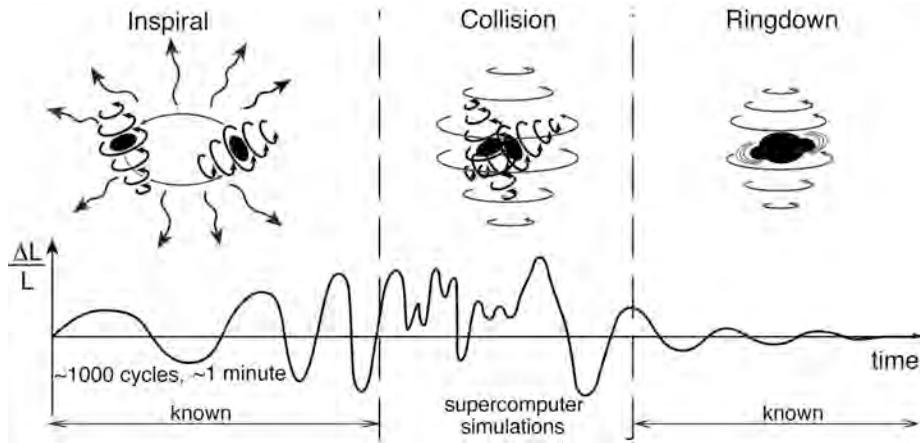aves when violently, nonlinearly warped. The collision, Stephen predicted in the 1970s, will produce a single final hole; and my students showed that this final hole must be born ringing like a bell, though its ringing will quickly die out; the hole will "ring down". From the ringdown waves we can infer the mass and spin and surface area of the final black hole.

By adding the measured areas of the initial hole and comparing with the measured area of the final hole, we can test Stephen's second law of black hole mechanics. If the total area does not increase, then Stephen is wrong, Einstein's general relativity laws are wrong, and we will have a great crisis in physics. By scrutinizing the ringdown waves, we will see details of how the final hole loses all its excess hairs. And we will test Roger's cosmic censorship conjecture by asking the simple question, "Is the final object a black hole? or is it a naked singularity." If a black hole, then the waves will have one form; if a singuarity, they will be very different.

Especially interesting, I think, will be the collision waves. To decipher the dynamical behavior of violently, nonlinearly warped spacetime from the collision waveforms will not be easy. The key to deciphering will be comparison with supercomputer simulations of black-hole collisions. We must go back and forth between the observed waveforms and waveforms predicted by simulations, iterating the simulations over and over again
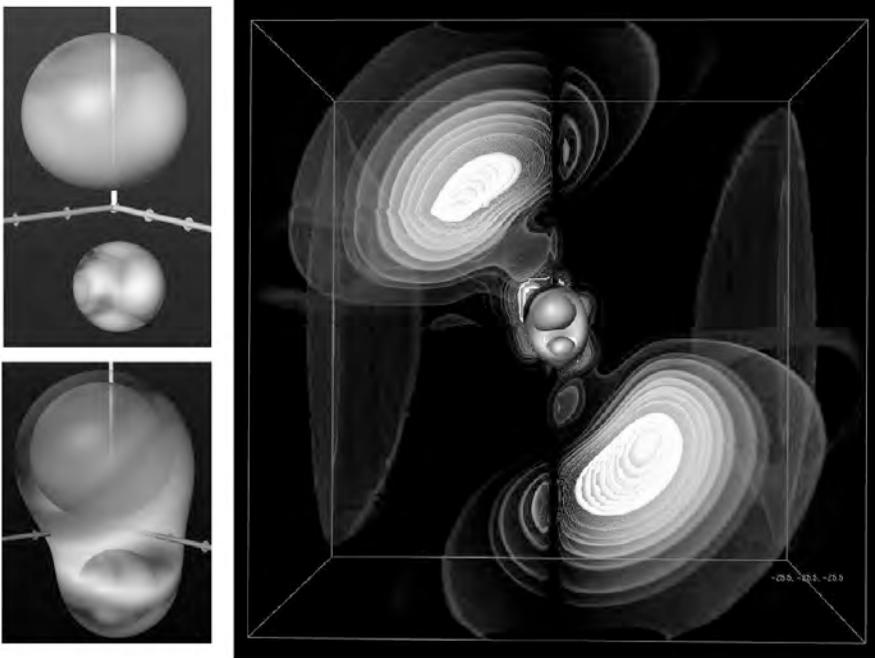
Fig. 5.17. Simulation of the glancing, but nearly head-on collision of two black holes with different sizes, as computed on a supercomputer by a group at the Albert Einstein Institute in Golm, Germany, led by Edward Seidel and Berndt Brügman. Upper left: apparent horizons (close approximations to the true horizons) of the two holes shortly before the collision. Lower left: apparent horizon of the merged hole shortly after the collision, with the individual apparent horizons inside. Right: double-lobed gravitational-wave pattern produced by the collision, with the three apparent horizons at the center. [This visualization by Werner Begner is courtesy the Albert Einstein Institute, Max Planck Society.]

to get agreement, and then scrutinize the simulations to see how space-time was behaving during the collision. A community of scientists called "numerical relativists" has been developing the computer-software tools for these simulations since the mid 1970s, nearly as long as experimenters have been developing gravitational-wave technology. The simulation tools are extemely complex and entail numerous pitfalls, so they are not yet finished. Much work is yet to be done, but it should be complete by the time of LIGO's 2008 upgrade, and hopefully sooner. Figure 5.17 shows shows the results of a recent simulation with partially working software tools.

5.6 Quantum behavior of human-sized objects

The upgrade of LIGO was planned from its outset. To move in one step from the prototype interferometers of the 1980s and 90s to LIGO's mature, big interferometers would have been too big and dangerous a leap. An intermediate step, the "initial interferometers" that are now beginning to operate, was essential. With the initial interferometers we can solidify our techniques and technology in preparation for the upgrade to the mature or "advanced" interferometers. If we are lucky, the initial interferometers will see black-hole collisions; and with the advanced interferometers we are confident of seeing many collisions and doing rich observations.
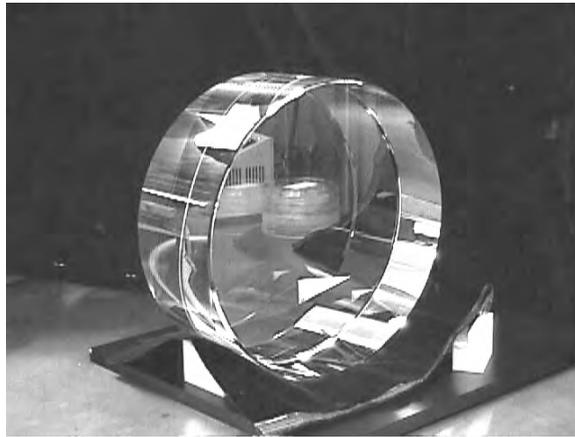
Fig. 5.18.   A LIGO mirror, which will be seen to behave quantum mechanically in LIGO's upgraded interferometers, in 2008

Much of the advanced-interferometer technology is being developed here in the UK, at the University of Glasgow, though other researchers are making major contributions, for example in Russia and Australia and at Caltech and MIT. This advanced technology is bringing us into the domain where, for the first time in human history, we will watch human-sized objects behave quantum mechanically.

We have heard about quantum mechanics in earlier talks today. For example, Jim Hartle described his research with Stephen on applying quantum mechanics to the entire universe, but we do not yet have the technology to test those ideas. The only solid tests of quantum mechanics that we humans have ever performed are in the microscopic realm of atoms and molecules and photons and subatomic particles. But this will change soon: LIGO's advanced interferometers, in 2008 and onward, will be able to monitor the motions of 40 kilogram sapphire mirrors (Figure 5.18) —

monocrystals of sapphire — to a precision about 1/10,000th the diameter of an atomic nucleus. This precision is half the width of the quantum mechanical wave function of what we call the "centre of mass degree of freedom" of the mirror. This complicated phrase means that in LIGO, in 2008 and onward, we will be watching our 40 kilogram mirrors behave quantum mechanically. We are developing a whole new branch of high technology, called *quantum nondemolition technology*, to deal with the mirrors' macroscopic, probabilistic, quantum mechanical behavior. This effort, in fact, is my own research passion today. I have largely turned my back on relativity research, temporarily, so as to help bring quantum nondemolition technology to fruition. I'm doing this in collaboration with my students and the Russian research group of Vladimir Braginsky, who pioneered quantum nondemolition.

5.7 Probing the big bang with gravitational waves

Let's turn now from colliding black holes and LIGO technology, to singularities in the fabric of spacetime. In 1964, Roger Penrose proved that every black hole is inhabited by a singularity. If you fall into the black hole, then its singularity will tear you apart and destroy you in a complicated way. As Roger described in his lecture today, singularities are governed by the laws of quantum gravity. This means they should be a wonderful arena in which to probe those laws.

Is there any hope ever to do experimental or observational studies of singularities? Yes, there is one singularity we can hope to study: the big-bang singularity in which the universe was born; the singularity that created all of the material of which were are made — our bodies, the Earth, the universe. The universe got tremendously transmuted after emerging from the big bang; it is radically different today than at the beginning. But there is hope of penetrating those transmutations, any hope of probing all the way back through the history of the universe to the big bang itself and observe the big bang's details.

Figure 5.19 explains that hope. As we look out into the sky from the Earth (right end of Figure 5.19) we see cosmic microwave radiation, microwave photons coming from all directions. Martin Rees described these microwave photons this morning. They bring us a marvelous picture of what the universe looked like when it was 100,000 years old. We cannot use these photons study the universe when it was any younger than 100,000 years, because in the first 100,000 years of its life, the universe was filled with gas so hot and dense that photons could not propagate through it. The photons just got scattered or absorbed, and all the information about the big bang, that they might once have had, was destroyed.
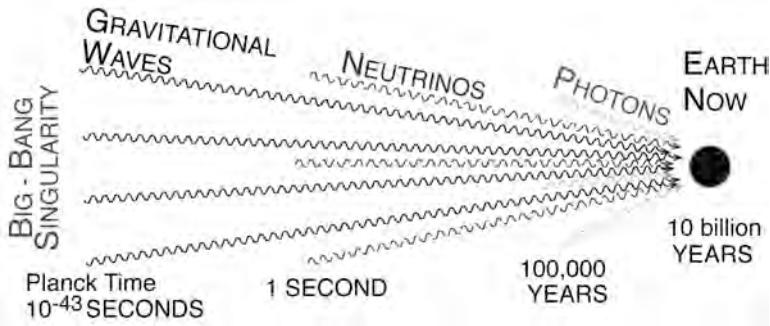
Fig. 5.19.   Unlike photons and neutrinos, only gravitational waves can look back to the earliest moments of the universe

There is a fundamental particle called a neutrino that is far more penetrating than a photon, and that should also have been created in the big bang. If and when we someday see neutrinos from the very early universe, we can use them to make pictures of the universe when it was one second old. But before then, the universe's gas was so hot and dense that neutrinos could not penetrate it. Like photons, they were scattered and absorbed, losing all the information about the big bang that they ever possessed.

The laws of physics tell us that the only form of radiation with enough penetrating power to emerge from the big bang unscathed is gravitational radiation (Figure 5.19). Any gravitational waves created in the universe's big-bang birth should have emerged and propagated, unscathed by any absorption or scattering by matter, from then all the way to now. However, these primordial waves were probably distorted and amplified by interacting with the universe's large-scale, dynamically changing spacetime warpage, during the first tiny fraction of a second of the universe's life. Fortunately, the amplification may have made the waves strong enough to detect, and the distortions may be decipherable; they are far less troublesome than the complete loss of information that photons and neutrinos suffer at the hands of the hot, primordial gas.

Thus, gravitational waves are our ideal tool – in fact our only tool – for directly probing the big bang and the first one second of our universe's life. A holy grail of gravitational wave detection over the coming decades, then, will be to study in detail this first second and the big-bang singularity. These studies' initial success may come from a very different kind of gravitational-wave detector than LIGO or LISA: from imprints that gravitational waves place on the polarization of the cosmic microwave photons. But time is too short for me to tell you about that.

5.8 Cosmic censorship: Betting with Stephen

So the prospects are good to study one singularity — the birth of the universe. But is there any hope ever to find and study, or make and study, singularities in the present-day universe — *naked singularities*?

Whereas Stephen W. Hawking firmly believes that naked singularities are an anathema and should be prohibited by the laws of classical physics,

And whereas John Preskill and Kip Thorne regard naked singularities as quantum gravitational objects that might exist unclothed by horizons, for all the Universe to see,

Therefore Hawking offers, and Preskill/Thorne accept, a wager with odds of 100 pounds stirling to 50 pounds stirling, that when any form of classical matter or field that is incapable of becoming singular in flat spacetime is coupled to general relativity via the classical Einstein equations, the result can never be a naked singularity.

The loser will reward the winner with clothing to cover the winner's nakedness. The clothing is to be embroidered with a suitable concessionary message.

Stephen W. Hawking   John P. Preskill & Kip S. Thorne
Pasadena, California, 24 September 1991

Fig. 5.20.   The Hawking-Preskill-Thorne bet

The physics "establishment" is epitomised by Roger Penrose (who denies being part of the establishment) and Stephen Hawking. The establishment's viewpoint on naked singularities is firm and unequivocal: Naked singularities are forbidden. You will never find them and can never make them; there is no hope ever to study them in the laboratory. This assertion is embodied in Roger's *cosmic censorship conjecture*, which says that all singularities except the big bang are hidden inside black holes — that is, they are clothed by horizons.

Eleven years ago Stephen and I and John Preskill, a colleague of ours at Caltech, made a bet on this (Figure 5.20).

Our bet says:

> Whereas Stephen Hawking firmly believes that naked singularities
> are an anathema that should be prohibited by the laws of classical

physics. And whereas Preskill and Thorne regard naked singulari-
ties as quantum gravitational objects that might exist unclothed by
horizons for all the universe to see. Therefore Hawking offers, and
Preskill and Thorne accept, a wager ...

And then there is a bunch of verbiage that was designed to protect
Stephen's side of the bet, followed by our final conclusion:

[Hawking bets that] the result can never be a naked singularity. The
loser will reward the winner with clothing to cover the winner's naked-
ness. The clothing is to be embroidered with a suitable concessionary
message.

Fig. 5.21.   Left: Stephen concedes he has lost our cosmic-censorship bet. Right:
The politically incorrect T-shirt that Stephen gave us. [Left photo, taken at
Caltech, is courtesy Irene Fertik, University of Southern California.]

Stephen has conceded! The left panel of Figure 5.21 shows a photograph
of Stephen's concession, at a public lecture in California. You see me
there, bowing with pleasure as John looks on with glee. It's not every day
that Stephen gets proved wrong! With his concession, Stephen gave each
of us the promised article of clothing: a T-shirt with his concessionary
message. Sadly, I must tell you that Stephen's message (right panel of
Figure 5.21) was not entirely gracious! He placed on the T-shirt a scantily-
clad woman. (My wife and Stephen's were aghast at this, but Stephen
has never been politically correct.) As you notice, the woman's towel says
"*Nature abhors a naked singularity*". Stephen conceded, but he asserted
that Nature abhors that which he concedes Nature can do. So why did he
concede, and why was he so ungracious, so apparently self contradictory
in his concession?

Stephen's concession was forced upon him by supercomputer simulations of imploding waves. The original, pioneering simulations were by Matthew Choptuik at the University of Texas, using the type of wave that is easiest to simulate, a so-called "scalar wave"; but subsequent, similar simulations have been done with gravitational waves by Andrew Abrahams and Chuck Evans at the University of North Carolina. I will describe the gravitational-wave simulations.
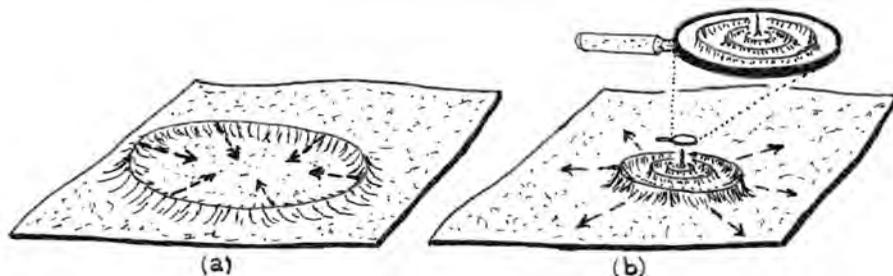

Fig. 5.22. The supercomputer simulations of imploding waves, which triggered Hawking to concede that the laws of physics permit naked singularities, at least in principle.

Think of somehow creating gravitational waves, ripples in the fabric of spacetime, and sending them all inward toward a common centre (left panel of Figure 5.22). Give the imploding waves almost but not quite enough energy to make a black hole at the centre, through their nonlinear self-interactions. Choptuik (and Abrahams and Evans) simulated this, and their simulations revealed spacetime behaving in an amazing manner. As the waves' spacetime ripples neared the centre, they interacted with each other in a wild, nonlinear way, making spacetime "boil" like water in a pot. The boiling created violent spacetime distortions with ever shortening wavelengths, and gravitational waves of ever shortening wavelength flowed out from the boiling centre, carrying information about the boiling. If the ingoing waves had had a bit more energy, the boiling would have made a tiny black hole. If the waves had had a bit less energy, the boiling would have been weaker and transitory, producing no object at the center at all. But with a carefully tuned wave energy, the boiling produced, right at the centre, a naked region of infinitely strong spacetime warpage — a naked singularity. Almost all the ingoing wave energy got converted by boiling into outgoing waves, so this singularity was left with only an infinitesimal energy inside it; and we are pretty sure it could survive for only an infinitesimally short time (though the simulations were not able to tell us for certain). However, a singularity is a singularity, whether infinitesimal or note, so Stephen had to concede.

Stephen, however, was persuaded by Choptuik's simulations that Nature actually abhors naked singularities. To force Nature to make a naked singularity, Choptuik had to fine-tune the ingoing waves' energy. If the ingoing energy was slightly too small, no singularity would form at all. If slightly too large, the singularity would form clothed, surrounded by a black-hole horizon. And if tuned perfectly, the waves would produce only an infinitesimal naked singularity. What better evidence could one ask for that Nature really abhors naked singularities and does everything it can to avoid them, Stephen asked?

And so we renewed our bet with altered wording. The new bet begins:

> Whereas Stephen Hawking, having lost a previous bet by not demanding genericity [genericity means that the naked singularity should be formed without fine tuning], still firmly believes that naked singularities are an anathema and should be prohibited by the classical laws of physics, therefore ... Hawking offers, and Preskill/Thorne accept a wager that ... A dynamical evolution from generic initial conditions ... can never produce a naked singularity... . [Here I'm omitting a lot of verbiage designed, again, to protect Stephen's side of the bet.] The loser will reward the winner with clothing to cover the winner's nakedness. The clothing is to be embroidered with a suitable, **truly** concessionary message.

I'm afraid that John and I will lose this renewed bet; but we made the bet, nevertheless, as a challenge to the next generation of physicists. It is a challenge that can be probed theoretically by mathematical manipulations of Einstein's equations, and computationally by supercomputer simulations, and also observationally: We shall search for big, generic, naked singularities using gravitational-wave detectors. For example, LISA may make many maps of the warped spacetimes surrounding massive compact bodies, bodies into which smaller objects spiral, emitting gravitational waves. Each map will reveal the structure of the massive body, whether it is a black hole or something else. It is likely that all the maps will be of black holes, but among them we might find a naked singularity, or some other, unexpected type of body. What an amazing discovery that would be!

5.9 Time travel

I shall conclude with a brief history of Stephen and Kip on backward time travel, since this is something to which Stephen devotes a chapter of his new book, *The Universe in a Nutshell*. My brief history begins with wormholes.

Figure 5.23 shows a wormhole embedded in hyperspace. It is rather like two black holes (recall the right half of Figure 5.4) but without the

singularities. You can go in one mouth, pass through the wormhole's throat, and and come out the other mouth. We have all seen wormholes in the film *Contact*, in *Star Trek*, and elsewhere, so I don't need to explain them any more than that.

In 1988, together with my student Michael Morris, I realised that, although general relativity permits the existence of wormholes, to hold a wormhole open, one must thread its throat with material that has negative energy. We still don't know whether the laws of physics permit the accumulation of enough negative energy in a wormhole's throat to hold the wormhole open, but I shall ignore this issue and forge onward.

In 1988, with Morris and another student Ulvi Yurstever, I realised that, if you have a wormhole, then it is very easy (in principle at least) to make a time machine. The top panel of Figure 5.24 shows me and my wife, Carolee, each holding a wormhole's mouth. To convert This wormhole into a time machine, Carolee, carrying her wormhole mouth, hops in her spaceship and zooms out through the universe at very high speed (easy in principle but not in practice!) and then zooms back to Earth. Her motion changes how time hooks up through the wormhole: If I I climb into my wormhole mouth, I emerge through hers immediately, it seems to me; but I emerge long after I climbed in, as seen by anyone who stays outside the wormhole (bottom panel of Figure 5.24); I have traveled to the future without aging. If Carolee climbs through the wormhole, she emerges much before she entered; she has traveled to the past. This is discussed in more detail in the last chapter of my book *Black Holes and Time Warps*.

Rather quickly after Morris, Yurtsever and I discovered how to convert a time wormhole into a time machine, I realized — in work with my postdoc Sung-Won Kim — that the moment one tries to activate this time machine, it might destroy itself in a massive explosion (Figure 5.25);
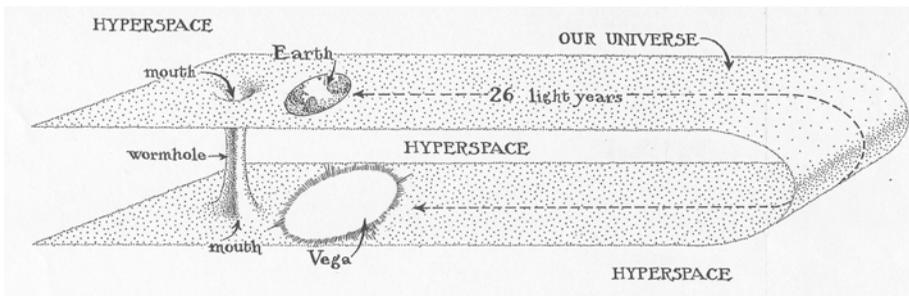
Fig. 5.23. A hypothetical wormhole connecting our solar system to the vicinity of the star Vega. [From my book *Black Holes and Time Warps: Einstein's Outrageous Legacy* (W.W. Norton, New York, 1994).]
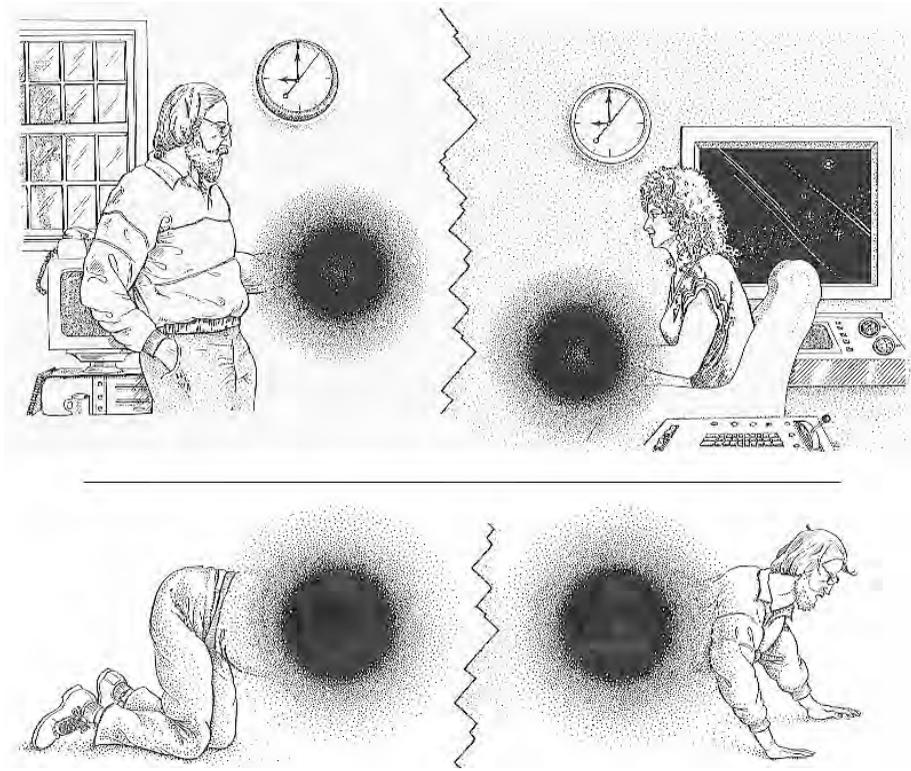
Fig. 5.24.   Time travel. [Adapted from my book *Black Holes and Time Warps: Einstein's Outrageous Legacy* (W.W. Norton, New York, 1994).]

and several other physicists independently discovered the same thing. The explosion is caused by quantum mechanical fluctuations of radiation, so-called "vacuum fluctuations", that fly through the wormhole just when it is becoming a time machine, pile up on themselves in space at the same moment of time, and thereby become infinitely energetic. For a slower explanation, see my book.

In 1990, when Kim and I examined this explosion mathematically using the laws of physics, we found that *every* time machine, whether made from a wormhole or by some other method, must suffer a similar explosion. However, it appeared to us that, at least in some cases, the explosion might be weak enough for the wormhole to escape destruction. Perhaps a very advanced civilization could make a time machine after all.

We circulated a manuscript to our colleagues, describing our calculations and conclusions, and Stephen responded almost immediately. There is little politeness in our community when one of us believes the other is wrong. "You're wrong!" Stephen said. He wrote a manuscript explaining

Fig. 5.25. A wormhole explodes at the moment we tray to convert it into a time machine. [From my book *Black Holes and Time Warps: Einstein's Outrageous Legacy* (W.W. Norton, New York, 1994).]

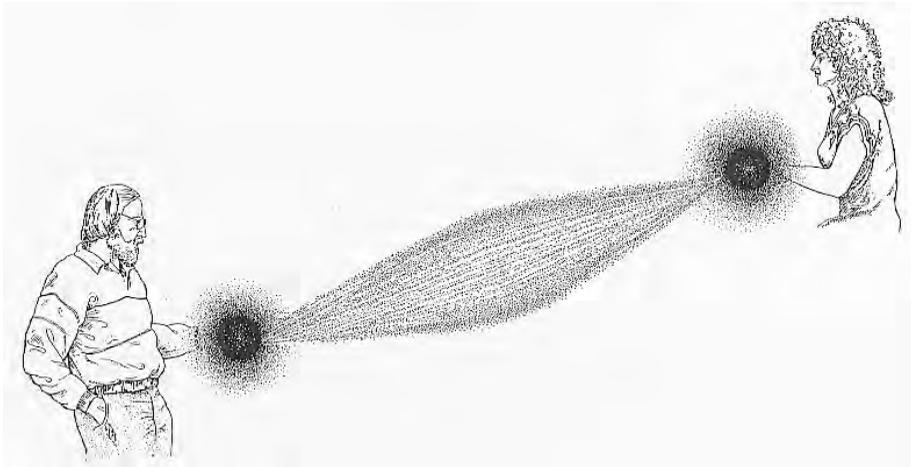why, and submitted it to the most prestigious of physics journals, *The Physical Review.*

The editors sent me his manuscript to referee. The refereeing took me many days because Stephen's paper, entitled "The Chronology Protection Conjecture", was very sophisticated. In his manuscript, in a real *tour de force*, Stephen worked out the details of the theory of the creation of time machines in confined regions of space, and then argued rather convincingly that our explosion would always be so strong that it would destroy the time machine at just the moment you tried to activate it. As Stephen said, the explosion would "keep the world safe for historians"; nobody can go back in time and try to change history. This was Stephen's *Chronology Projection Conjecture* — a conjecture, not a theorem, because both he and I were working with the laws of physics in a domain where we are uneasy about whether they really are correct, a domain where classical general relativity begins to fail and must be replaced by the ill-understood laws of quantum gravity.

Over the years since 1990, there has been much debate back and forth over whether these explosions are *always* strong enough to destroy a time machine at the moment a very advanced civilization tries to activate it. The bottom line that almost all the experts would agree on at present is that we are not absolutely sure. Probably yes, the explosion always destroys its time machine, but only the laws of quantum gravity know for sure. To be certain, we must master those laws.

On my 60th birthday, a year and a half ago, Stephen gave me a gift. His

gift was a first attempt to estimate, using the laws of quantum gravity, the quantum mechanical probability that a time machine will survive the destruction, the probability that one can succesfully make a time machine and go backward in time. Stephen's calculation gave an extremely small probability for time-machine survival: about 1 part in 10^{60}, i.e. 0.000000000000000000000000000000000000000000000000000000000001

And so Stephen, on this, the occasion of your 60th birthday, I will give you an equally interesting gift. I'm afraid it is more in the form of a promissory note than a concrete physics result. Your birthday gift is that our gravitational-wave detectors – LIGO, GEO, VIRGO and LISA – will test your Golden-Age black-hole predictions, and they will begin to do so well before your 70th birthday. Happy Birthday, Stephen!

Acknowledgments

Useful References for Further Reading

[1.] For a more leisurely discussion of the Golden-Age predictions, and of the basic ideas of gravitational-wave detection, see my book *Black Holes and Time Warps: Einstein's Outrageous Legacy* (W.W. Norton, New York, 1994).

[2.] For a leisurely and fairly up to date discussion of gravitational-wave detection, see Marcia Bartusiak, *Einstein's Unfinished Symphony*, (National Academy Press, Washington D.C. 2000).

[3.] For a somewhat technical summary of research on gravitational-wave sources and detection as of early 2002, see Curt Cutler and Kip S. Thorne, "An overview of gravitational wave sources," in Proceedings of the GR16 Conference on General Relativity and Gravitation, ed. N. Bishop (World Scientific, 2002), in press. Available on the Web at http://xxx.lanl.gov/abs/gr-qc/0204090.

[4.] For Stephen's description of his ideas and research on time travel, see Chapter 5 of his book *The Universe in a Nutshell* (Bantam Books, New York, 2001).