Spacetime Warps and the Quantum World: Speculations about the Future*

Kip S. Thorne

I've just been through an overwhelming birthday celebration. There are two dangers in such celebrations, my friend Jim Hartle tells me. The first is that your friends will embarrass you by exaggerating your achievements. The second is that they *won't* exaggerate. Fortunately, my friends exaggerated.

To the extent that there are kernels of truth in their exaggerations, many of those kernels were planted by John Wheeler. John was my mentor in writing, mentoring, and research. He began as my Ph.D. thesis advisor at Princeton University nearly forty years ago and then became a close friend, a collaborator in writing two books, and a lifelong inspiration. My sixtieth birthday celebration reminds me so much of our celebration of Johnnie's sixtieth, thirty years ago.

As I look back on my four decades of life in physics, I'm struck by the enormous changes in our understanding of the Universe. What further discoveries will the next four decades bring? Today I will speculate on some of the big discoveries in those fields of physics in which I've been working. My predictions may look silly in hindsight, 40 years hence. But I've never minded looking silly, and predictions can stimulate research. Imagine hordes of youths setting out to prove me wrong!

I'll begin by reminding you about the foundations for the fields in which I have been working. I work, in part, on the theory of general relativity. Relativity was the first twentieth-century revolution in our understanding of the laws that govern the universe, the laws of physics. That first revolution was brought to us by Albert Einstein in two steps: special relativity in 1905 and general relativity in 1915, with a 10-year struggle in between, much like the intellectual struggle that Alan Lightman describes in this volume.

At the end of his struggle, Einstein concluded that space and time are warped by matter and energy, and this warpage is responsible for the gravity that holds us to the surface of the earth. He gave us a set of equations from which one can deduce the warpage of time and space around the cosmic objects that inhabit our universe. In the 85 years since then, thousand of physicists have struggled with Einstein's equations, trying to extract their predictions about spacetime warpage.

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Figure 1: Albert Einstein at age 26, when he was formulating special relativity — the first step in the first twentieth century revolution in our understanding the laws of nature. [Courtesy Albert Einstein Archives of the Hebrew University of Jerusalem.]

In my book *Black Holes and Time Warps, Einstein's Outrageous legacy*, I tell the story of that struggle, including the most interesting discovery it produced: the prediction of black holes. Robert Oppenheimer, shuttling back and forth between Berkeley and Caltech in the late 1930s, made the first, tentative form of the prediction, but it took the concerted efforts of hundreds of other physicists, in the 1950s, 60s, and 70s, to smoke out the full details of what a black hole is and how it should behave. My mentor John Wheeler was the modern pioneer of black holes and my friend Stephen Hawking, the latter-day prophet.

A black hole is the ultimate in spacetime warpage, according to Einstein's equations: It is made wholly and solely from that warpage. Its enormous warpage is produced by an enormous amount of highly compacted energy — energy that resides not in matter, but in the warpage itself. Warpage begets warpage without the aid of matter. That is the essence of a black hole.

If I had a black hole the size of the world's largest pumpkin, about 10 meters in circumference, then knowing Euclid's laws of geometry, you might expect its diameter to be 10 meters divided by $\pi = 3.14159...$, or about 3 meters. But the hole's diameter is far larger than 3 meters, perhaps more like 300 meters. How can this be? Quite simply: Euclid's laws fail in the hole's highly warped space.

Consider a simple analogy. Take a rubber sheet — a child's rubber trampoline. Stretch it out between the

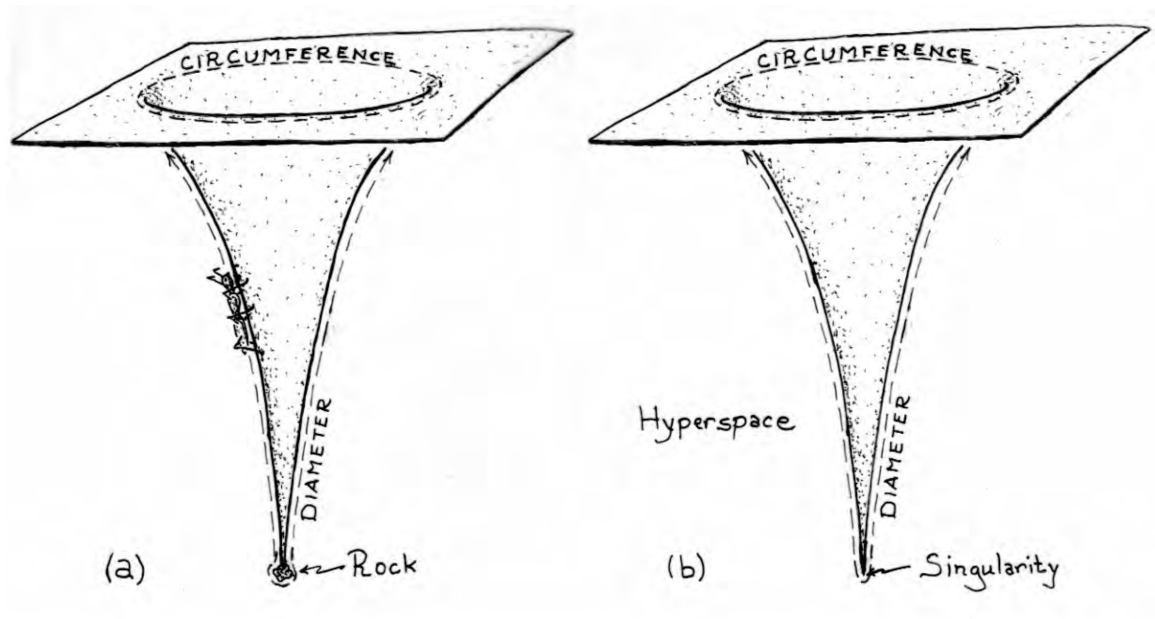


Figure 2: (a) A child's trampoline warped by a heavy rock and explored by an intelligent ant. (b) The warped space of a black hole as seen by a hyperbeing living in hyperspace.

tops of four high poles, then place a heavy rock at its center. The rock will bend the rubber downward as shown in Figure 2a. Now suppose that you are an ant living on the rubber sheet. The sheet is your whole universe. Not only are you an ant; you are a blind ant, so you can't see with your eyes the poles and rock that warp the sheet. But being a smart and inquisitive ant, you set out to explore your universe. You march around the circular edge of the sheet's indentation, pacing off its circumference: 30 meters, you conclude. Being schooled in the mathematics of Euclid, you predict a diameter of about 10 meters, but being also a skeptic of all prognostications, you set out to measure the diameter. You march inward toward the center; you march and march and march, and ultimately come out on the other side after 300 meters of travel, not the 10 meters predicted by Euclid. "The space of my universe is warped," you conclude; highly warped.

This story is a rather accurate depiction of a black hole. We can think of the 3-dimensional space inside and around a black hole as warped in a higher-dimensional flat space (often called "hyperspace"), just as the 2-dimensional rubber sheet is warped as depicted in Figure 2a. If I were a higher dimensional "hyperbeing" who lives in hyperspace, I would see the black hole's space to have a form very much like that of the rubber sheet; see Figure 2b.

The most intriguing thing about black holes is that, if I fall into one, there is no way for me ever to get back out, nor to send signals to you as you await me on the outside. This is illustrated in Figure 3a by a two-dimensional Kip falling into a black hole as seen by a hyperbeing in hyperspace. (I have suppressed

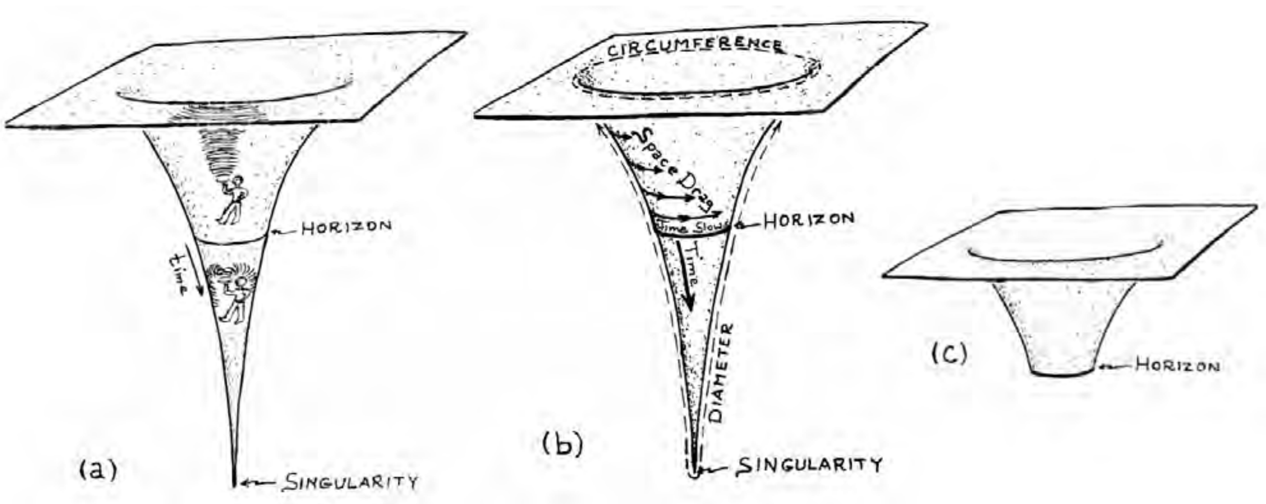


Figure 3: (a) Kip falling into a black hole and trying to transmit microwave signals to you on the outside. (b) The warpage of space and time, and the dragging of space into a tornado-like motion around a spinning black hole. (c) The warpage of space outside the horizon — the type of diagram to be used below.

one of our universe's three dimensions to make the picture understandable.) As I fall in, I carry with myself a microwave antenna that transmits signals to you on the outside, telling what I see.

Now, not only is the space through which I move warped, so is the time, according to Einstein's equations: The flow of time slows near the hole, and at a point of no return called the hole's *horizon* or edge, time becomes so highly warped that it starts to flow in a direction that normally would be spatial; the future flow of time is toward the hole's center. Nothing can move backward in time,[1] Einstein's equations insist; so once inside the hole, I and my microwave signals are drawn willy-nilly downward with the flow of time toward a *singularity* that lurks at the hole's core. You, waiting on the outside, can never receive my signals from beneath the horizon. They are caught by the flow of time and dragged away from you. I have paid the ultimate price, in exploring the hole's interior: I can't publish my discoveries.

Besides the bending of space and the slowing and downflow of time, there is a third aspect of a black hole's spacetime warpage: a tornado-like whirl of space and time around and around the hole's horizon (Figure 3b). Just as the whirl of air is very slow far from a tornado's core, so the whirl of spacetime is very slow far from the hole's horizon. Closer to the core or horizon, the whirl is faster. And near the horizon, the whirl of spacetime is so fast and strong that it drags *all* objects that venture there into a whirling orbital motion. No matter how hard a spaceship may blast its engines, once near the horizon it cannot resist the whirl. It is dragged, by the forward flow of time, around and around inexorably — and once inside the horizon, it is

[1]Or, more precisely, nothing can move backward through the *local* flow of time. If backward time travel is possible, then (as Novikov explains earlier in this volume) it can be achieved only by going on a round trip (e.g. through a wormhole), on which you are always moving forward with the local flow of the "river of time" but you return to where you started earlier than you set out. I shall prognosticate about this at the end of my lecture.

also dragged downward by the forward flow of time, toward the gaping singularity at the hole's core.

The whirl of spacetime around a black hole was discovered in 1963, buried in the mathematics of Einstein's equations, by Roy Kerr, a mathematical physicist from Christchurch New Zealand. Just as the bending of space and warping of time are produced by the hole's huge energy (the energy of the bending and warping themselves), so also the whirl of spacetime is produced by the hole's huge rotational angular momentum (an angular momentum that resides in the spacetime whirl itself). The warpage's energy and angular momentum create the warpage, according to Einstein's equations. Warpage begets warpage.

Because we can't see inside a black hole from the exterior, I will ignore its interior for awhile. I will cut off my pictures of holes at the horizon and just depict the holes' exteriors, as in Figure 3c.

Now, we relativity physicists have been terribly frustrated for the past quarter century. By 1975 we had fully smoked these black-hole predictions out of Einstein's equations and were turning to astronomers for observational confirmation or refutation. But since then, despite enormous effort, astronomers have failed to produce quantitative measurements of any black hole's spacetime warpage. Their great triumphs have been a number of near incontrovertible discoveries of black holes in the universe, but they have been unable to map, even crudely, the spacetime warpage around any of their discovered holes.

With this background in hand, I'm ready to start prognosticating. I'll begin with a prediction in which I have great confidence.

- **Prediction 1: In 2010–2015, a space based gravitational-wave detector named LISA will reveal the warpage of spacetime around many massive black holes in the distant universe, and will map that warpage in exquisite detail — all three aspects of the warpage: the bending of space, the warping of time, and the whirl of spacetime around the horizon.**

These black-hole maps, each a picture of what the hole would look like as seen by a hyperbeing in hyperspace, will complete the transformation of black holes from purely theoretical entities to objects for observational exploration.

Figures 4 and 5 depict the foundation for LISA's maps. A small black hole orbits around a far larger black hole in the distant universe. The small hole might weigh ten times as much as the sun and have a circumference about 180 kilometers (the size of San Francisco); the large hole might weigh a million suns and have a circumference about 18 million kilometers (4 times larger than the Sun); and the small hole would fly around the large hole at roughly half the speed of light, in an orbit only a few times bigger than the large hole's horizon.

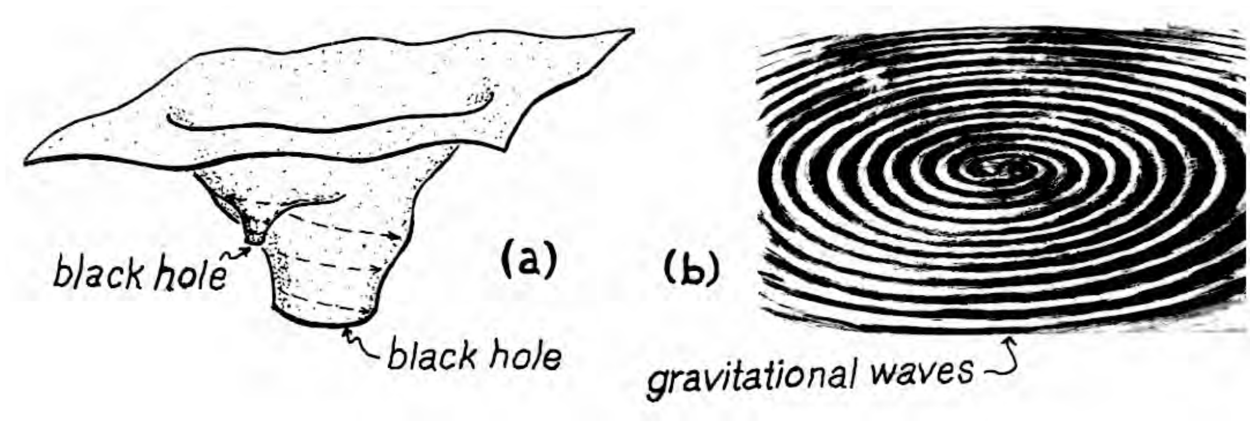


Figure 4: (a) A small black hole orbiting a large black hole and gradually spiraling inward. (b) The gravitational waves produced by the small hole's inspiral.

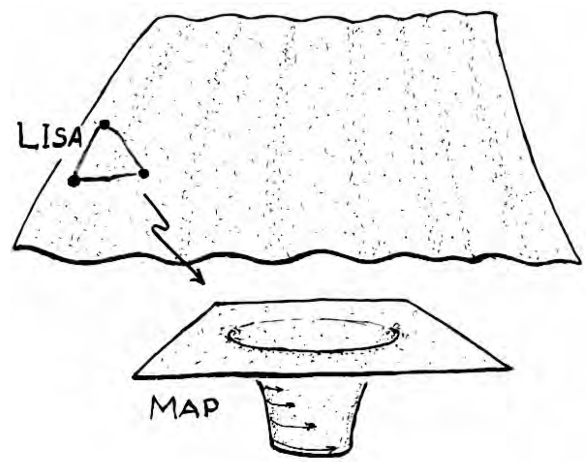


Figure 5: After traveling across the great reaches of intergalactic space, the gravitational waves buffet LISA. LISA monitors and records the waves' waveforms, and from the recorded waveforms we extract a map of the large black hole's spacetime warpage.

As the small hole orbits around and around the large hole, it is sort of like you stirring your finger around and around in a pond of water. Just as your finger creates ripples on the water's surface that go flowing outward across the pond carrying information about your finger's motion, so the spacetime warpage of the small, fast-flying hole creates ripples of warpage in the fabric of spacetime around the large hole. With each complete circuit around the large hole, the small hole produces two complete oscillations of the outgoing ripples: two crests and two troughs. The ripples are called *gravitational waves*, and they propagate out into the universe at the same speed as light. A few years ago Fintan Ryan, a graduate student I was mentoring, showed that these waves carry encoded in their *waveforms* a detailed map of the large hole's spacetime warpage, which is being explored by the small hole as it orbits

These gravitational waves travel across the far reaches of intergalactic space, billions of light years. Ulti-

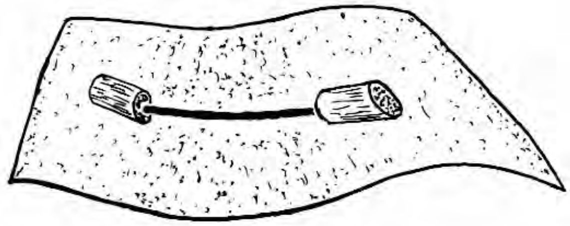


Figure 6: Just as water waves on a pond can be monitored by using a laser beam to measure the distance between two bobbing corks, so LISA will monitor gravitational waves by using a laser beam to measure the distances between spacecraft.

mately they reach and enter our Milky Way galaxy, and then our solar system, where they buffet LISA, the Laser Interferometer Space Antenna (Figure 5). LISA is designed to monitor the waves' ripples as they go by, and record their full details. From those details we expect to decode the map that the waves carry — the map of all three aspects of the large hole's warpage,

The principle on which LISA is based is depicted in Figure 6. Two spacecraft, floating in interplanetary space, are analogous to two corks floating on the surface of a water pond. As water waves go by, their crests and troughs stretch and squeeze the distance between the corks. The corks' relative motion can be monitored with high precision using the same technique as surveyors use: the round-trip travel of a laser beam.

Similarly, the gravitational waves stretch and squeeze space as they pass, making LISA's spacecraft move back and forth relative to each other, and that relative motion is monitored by laser beams. The greater the separation L between the spacecraft, the greater will be the tiny oscillations ΔL in their separation. The oscillating ratio $\Delta L/L$ is equal to the oscillating gravitational-wave field. The pattern of the oscillations as a function of time t, $\Delta L(t)/L$, is the field's gravitational waveform. This waveform is analogous to the patterns that sound waves produce when displayed on an oscilloscope, and it carries the map of the big black hole.

Figure 7 shows how one aspect of that map— the tornado-like whirl of space around the large hole — is encoded in the waveform. The space whirl drags the small hole's orbit with it, causing the orbit to precess. As seen from earth (if we could see that far with our eyes), the orbit alternates between edge on and approximately face-on. Correspondingly, the amplitude of the waves' oscillations (two oscillations per orbital circuit) is driven alternately smaller then larger, so the waves are modulated as shown in the figure. With two edge-on events in each full precession, the waveform is modulated twice as fast as space whirls.

Assume, for simplicity, that the orbit is circular and only slightly inclined to the large hole's equator, the

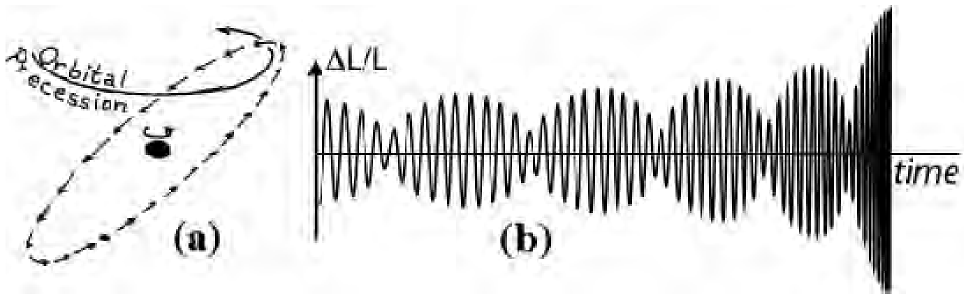


Figure 7: (a) The spin of the large black hole drags space into motion around itself, thereby causing the orbit of the small hole to precess. (b) The gravitational waves from the orbiting, precessing small hole produce tiny oscillations in the difference ΔL between the lengths of two of LISA's arms. This graph shows $\Delta L/L$ as a function of time. Each traversal of the small hole around the large hole produces two oscillations in ΔL; the precession of the orbit causes a modulation of the oscillations' amplitude and phase.

small hole weighs 10 suns, and the large hole spins very rapidly[2] and weighs a million suns. Then one year before the small hole plunges through the large hole's horizon, its orbital circumference is just 3.4 times bigger than the horizon and there are 92,000 orbits (184,000 wave cycles) left until plunge. The waves' oscillation period is 4.8 minutes from which we infer an orbital period (as measured by earth-based clocks) of $2 \times 4.8 = 9.6$ minutes, and the waveform modulation period is 42 minutes *from which we infer that at 3.4 horizon circumferences, the space-whirl period is* $2 \times 42 = 84$ *minutes*.

One month before plunge, the orbital circumference is just 1.65 times larger than the horizon, the waves' oscillation period is 1.6 minutes, and there are 40,000 wave cycles left until plunge. The waveform modulation period is 8.6 minutes, *from which we infer a space-whirl period of 17.2 minutes at 1.65 horizon circumferences.*

One day before plunge, the orbital circumference is 1.028 times larger than the horizon, the wave period is 38 seconds and there are 2,000 wave cycles left. The observed modulation period is 43 seconds, so *the period of the space whirl at 1.028 horizon circumferences is 2 minutes*.

In this manner, from the waveform's changing modulation pattern, we can map the whirl rate of space as a function of location outside the horizon. With 184,000 cycles of waves to work with in the last year of the small hole's life, all coming from within 5.8 times the size of the large hole's horizon, we expect to achieve an exquisitely accurate map.

LISA will consist of three laser-linked spacecraft residing at the corners of an equilateral triangle (Figure 8). By a variant of "laser interferometry" the differences in the lengths of the triangle's three arms will be monitored, and from the two independent arm-length differences we will deduce the waves' two independent

[2]For experts in the mathematics of black holes: I am assuming "a/M = 0.999".

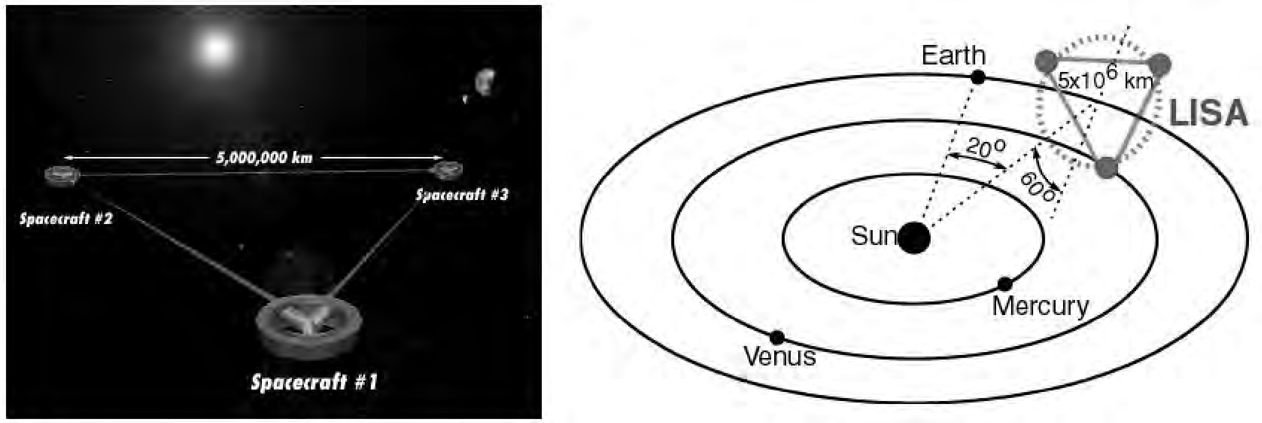


Figure 8: LISA will consist of three laser-linked spacecraft at the corners of an equilateral triangle, 5 million kilometers on a side. In the right diagram its size is exaggerated by about a factor 10 relative to the planetary orbits.

waveforms. To extract the full map and simultaneously learn the small hole's mass and spin, the orbit's details, the large hole's orientation in space, and the distance from the holes to earth, we must monitor both waveforms, not just one.

The distances L between LISA's three spacecraft will be 5 million kilometers (13 times larger than the Earth-Moon separation), and they will travel around the sun in the same orbit as the Earth, but following the earth by about 20 degrees (50 million kilometers). After traveling across the great reaches of intergalactic space, the gravitational waves have become very weak: $\Delta L/L$ a little less than 10^{-21} — one part in a billion trillion. Correspondingly, the tiny oscillations ΔL in the spacecraft separations are about 10^{-10} centimeters, which is one millionth the wavelength of the laser light used to monitor the oscillations, and one hundredth the diameter of an atom. Our ability to measure such tiny motions is a tribute to modern technology!

LISA will be built and operated jointly by NASA and the European Space Agency (ESA) and is tentatively planned for launch in 2010. It was conceived (though not with this name) in the mid 1970s by several of my physicist friends — Peter Bender of the University of Colorado, Ronald Drever of Glasgow University, and Rainer Weiss of the Massachusetts Institute of Technology. Many physicists have worked hard over these past 25 years to perfect LISA's design, to figure out what kinds of wave-emitting objects it should see and what science can be extracted from their waves, and to convince NASA and ESA that LISA should be flown. At last, in the past year, LISA has won the endorsement of politically powerful committees of scientists and now seems on a fast track toward fulfilling my first prediction: exquisitely accurate maps of huge black holes in the 2010 – 2015 time frame.

I will turn, now, to my second prediction:

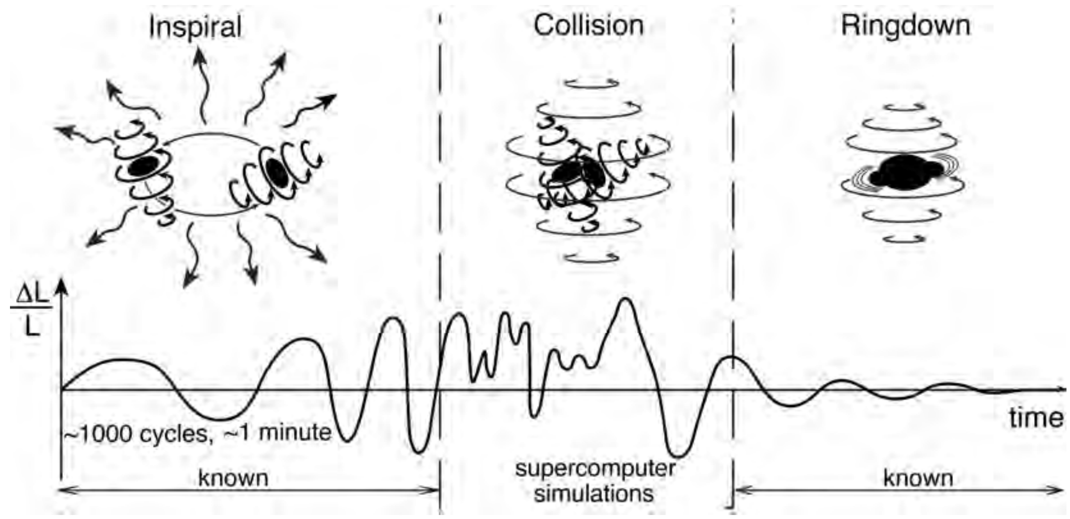


Figure 9: Upper part: The inspiral and collision of two black holes orbiting each other. Lower part: Schematic graph of the gravitational waveform emitted by the holes.

- **Prediction 2: Sometime between 2002 and 2008 (i.e., before LISA's 2010 launch), earth-based gravitational-wave detectors will watch black holes collide and watch their collisions trigger wild vibrations of spacetime warpage. By comparing the observed waves with supercomputer simulations, we will discover how the warpage behaves when it interacts with itself dynamically and nonlinearly.**

When water waves become so high that they "interact with themselves dynamically and nonlinearly," the result can be the breaking, crashing froth that topples and engulfs surfers — or it can be an enormous tidal wave that travels across oceans at high speed, hits shores, and wreaks havoc. The analogous nonlinear, dynamical behavior of spacetime warpage is largely a mystery today. By combined gravity-wave observations and supercomputer simulations we hope to discover it.

The vehicle for our discovery, a collision between two black holes in the distant universe, is depicted in Figure 9. Each hole is like a tornado. Spacetime whirls around its horizon like air whirling around a tornado's core. And as the holes orbit each other, their huge orbital angular momentum also drags spacetime into a whirling motion, so we have two tornados embedded in a third larger tornado and crashing together, and we want to know what happens when the tornados are made not from whirling air, but from a whirling spacetime warpage. To learn the answer will require a three-pronged attack: supercomputer simulations, gravitational-wave observations, and detailed comparison of the simulations and observations.

The simulations are being pursued by about fifty scientists in Europe, the United States, and Japan. These scientists are called *numerical relativists* because they are attempting to solve Einstein's general relativity

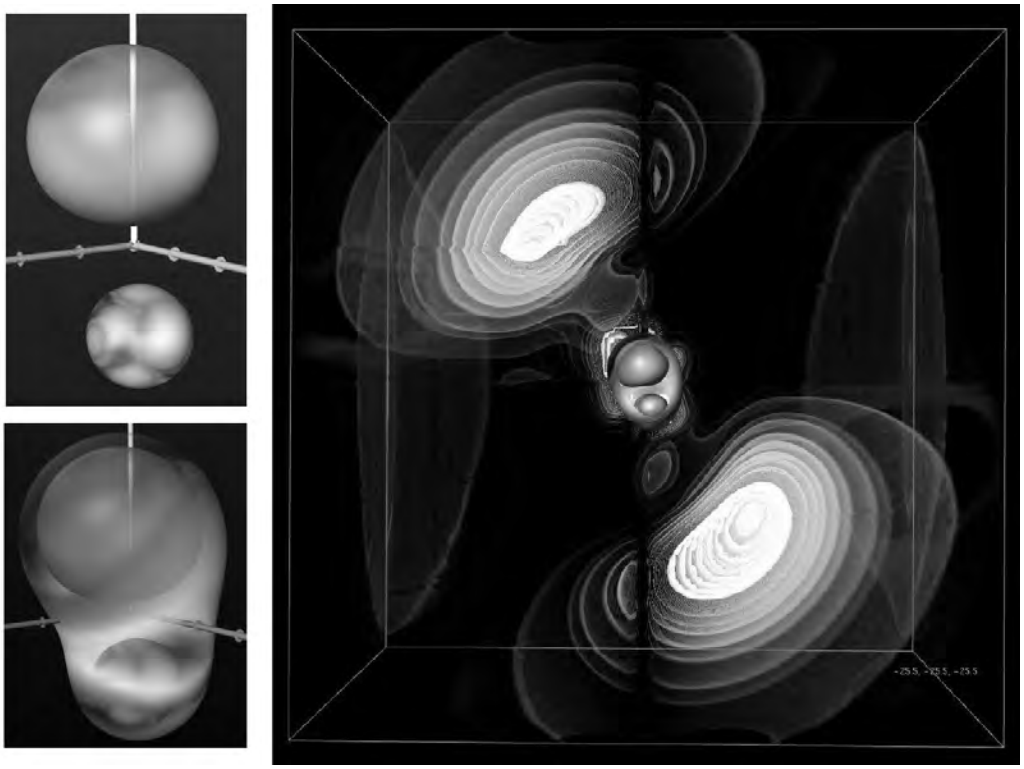


Figure 10: Simulation of the glancing, but nearly head-on collision of two black holes with different sizes, as computed numerically on a supercomputer by a group at the Albert Einstein Institute in Golm, Germany, led by Edward Seidel and Berndt Brügman. Upper left: apparent horizons (close approximations 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. [Courtesy Albert Einstein Institute, Max Planck Society.]

equations numerically, on computers. I have bet these numerical relativists that gravitational waves will be detected from black-hole collisions before their computations are sophisticated enough to simulate them. I expect to win, but hope to lose, because the simulation results are crucial to interpreting the observed waves.

Figure 10 is an example of the current state of the simulation effort. It shows some features of a nearly head-on collision of two non-spinning black holes with different sizes. Nothing startling happens in *this* collision as a result of the warpage's dynamical nonlinearities. By contrast, when the holes are rapidly spinning with random spin directions and collide from a shrinking, circular orbit (Figure 9), I expect complicated and wild vibrations of the warpage.

Figure 11 shows three of the earth-based gravitational-wave detectors that will discover the waves from black-hole collisions sometime between 2002 and 2008, if my prediction is correct. These three detectors, two in a common facility at Hanford Washington (left picture) and one at Livingston Louisiana (right

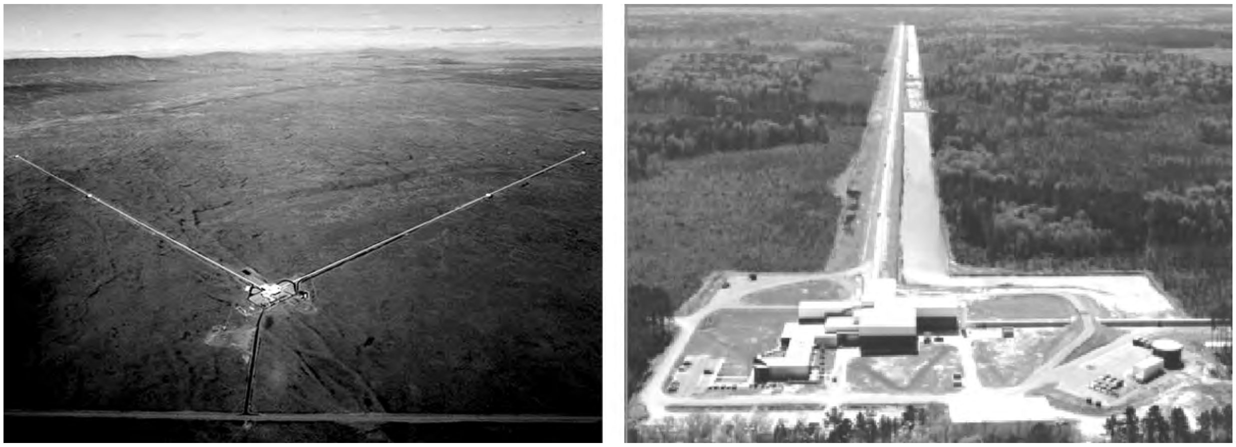


Figure 11: Aerial views of the LIGO gravitational-wave detectors at Hanford, Washington (left) and Livingston, Louisiana (right). [Courtesy LIGO Project, California Institute of Technology]

picture), make up LIGO, the *Laser Interferometer Gravitational Wave Observatory*. LIGO is part of an international network that includes, also, a French-Italian detector called VIRGO, in Pisa, Italy, a British-German detector called GEO600, in Hanover, Germany, and a Japanese detector called TAMA in a suburb of Tokyo.

LIGO and its partners are the culmination of four decades of research by hundreds of dedicated scientists and engineers. LIGO itself began in 1983 as dream of Rai Weiss at MIT, and Ron Drever and me at Caltech, and has grown into a reality thanks to the leadership of MIT's Weiss, and Caltech's Robbie Vogt, Stan Whitcomb, and Barry Barish, the Director of LIGO since the start of construction in 1994. Barish has built LIGO into a collaboration of about 350 scientists and engineers at about 25 institutions in the US, Britain, Germany, Russia, Australia, India and Japan. The enthusiasm, dedication, and effectiveness of this talented team is a marvel to behold. I'm counting on them to make my second prediction come true.

How will they do it? What kind of detectors have they built to see black holes collide? Each LIGO detector is similar to LISA. LISA's three spacecraft, which ride on the passing waves like corks on water, are replaced by four cylindrical mirrors that hang by wires from overhead supports (Figure 12), two in the corner building and one each in end buildings of the L-shaped structure shown in Figure 11. The lengths of the L's two arms are $L = 4$ kilometers. When gravitational waves fly past, oscillating much faster than the mirrors' pendular swinging frequency (much faster than one cycle per second), the mirrors ride the waves like a cork along horizontal directions, though the wires prevent them from riding the waves vertically. The waves' stretch and squeeze of space causes the mirrors to wiggle back and forth horizontally relative to each other, just as LISA's spacecraft wiggle back and forth. The wiggle is opposite on the detector's two arms (Fig. 12), so one arm is lengthened by an amount ΔL and the other shortened by ΔL. As for LISA, the time varying ratio $\Delta L/L$ is the gravitational waveform, and laser light is used to monitor this waveform:

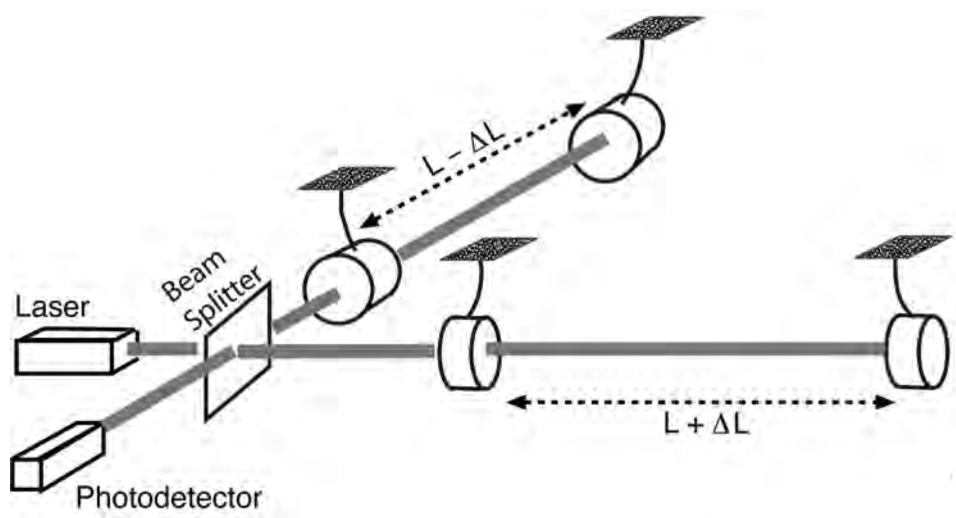


Figure 12: Schematic diagram of an earth-based laser-interferometer gravitational-wave detector.

Light from the laser is sent through a beam splitter (Figure 12), so half the light goes into each arm. The light bounces back and forth in the arms about 100 times, then emerges, and the two beams interfere with each other at the beam splitter. When one arm lengthens and the other shortens, the intensity of the light going toward the photodetector increases; when the other lengthens and the first shortens, the photodetector sees a decreased intensity. This *laser interferometry* produces a photodetector signal that is proportional to the waveform $\Delta L/L$.

LIGO's three interferometers will be fully operational by summer 2002, and LIGO and its international partners will then begin their first gravitational-wave search. Depending on Nature's kindness, LIGO's initial sensitivity, $\Delta L/L$ about 10^{-21}, *might* or might not be good enough to observe black-hole collisions. After three years of searching (and observing, we hope!), LIGO's initial detectors will be replaced by *advanced detectors* with sensitivity 15 times better so they can look out into the universe 15 times farther, encompassing a volume about 1000 times greater. These advanced detectors should be able to see black-hole collisions out to "cosmological distances" (a large fraction of the universe). At these distances, astrophysicists expect many collisions each year, and perhaps many each day. This estimate gives me confidence in my predictions: LIGO and its partners will begin observing black-hole collisions sometime between 2002 and 2008.

I now turn from confident predictions for the present decade, to an informed speculation about the decade 2020 – 2030.

- **Informed Speculation 3: In the decade 2020 – 2030, LIGO and its partners and a space-based successor to LISA will watch every black-hole collision in the universe with hole masses below 3 million suns, and every neutron-star / black-hole collision, and every neutron-star/ neutron-**

> **star collision. They will see many collisions each day. The result, after comparing the observed waves with numerical-relativity simulations, will be a huge catalog of collisions and their detailed properties, much like the catalogs of stars and galaxies produced by optical, radio, and X-ray astronomers in the 20th century.**

The *neutron stars* in this speculation are objects governed by a combination of the general relativistic laws of spacetime warpage, and the laws of *quantum mechanics*.

Quantum mechanics was the second great 20th century revolution in our understanding of physical law. Whereas the laws of spacetime warpage (the first revolution) normally act on macroscopic scales, on objects the size of a human or much larger, the laws of quantum mechanics act on microscopic scales, on objects the size of atoms or smaller. The quantum laws are as different from everyday experience as the laws of spacetime warpage, but in an even more weird way: they insist that such simple ideas as the location and speed of a particle are intrinsically imprecise, and can be defined only probabilistically: a certain probability to find the particle here, another probability to find it there, and so forth. I shall discuss this weirdness shortly.

Now, quantum mechanics, among other things, governs the nuclear force — the force that binds neutrons and protons together in atomic nuclei. We normally probe the nuclear force in particle accelerators, by slamming protons or neutrons or atomic nuclei into each other. These collision experiments have taught us many details of the nuclear force, but not all: They have taught us surprisingly little about how the nuclear force behaves when you have huge numbers of neutrons jammed together into a small volume to form *bulk nuclear matter*. The reason is that atomic nuclei don't get very big. They get up to a few hundred neutrons and protons in a single nucleus, but not more.

What happens when you have millions or gajillions of neutrons and protons all crammed into a tiny volume? The only place such bulk nuclear matter occurs in the universe today, so far as we know, is inside a neutron star, where the densities can be 30 times higher than in an atomic nucleus. So neutron stars are the key to unravelling the mysteries of bulk nuclear matter.

The quantum mechanical nuclear force determines the enormous pressure in the core of a neutron star — a pressure that tries to make the star explode. Spacetime warpage produces the enormous gravitational pull that tries to crush the neutron star, converting it into a black hole. (The enormity of the warpage is typified by the bending of space inside and around the star, as depicted in Figure 13.) Inside the star, the crushing force of gravity is precisely counterbalanced by the explosive force of the nuclear pressure. The star's circumference is determined by this balance: The stronger the nuclear pressure, the larger the circumference; so by measuring the circumference, and also the mass so we know the force of the star's

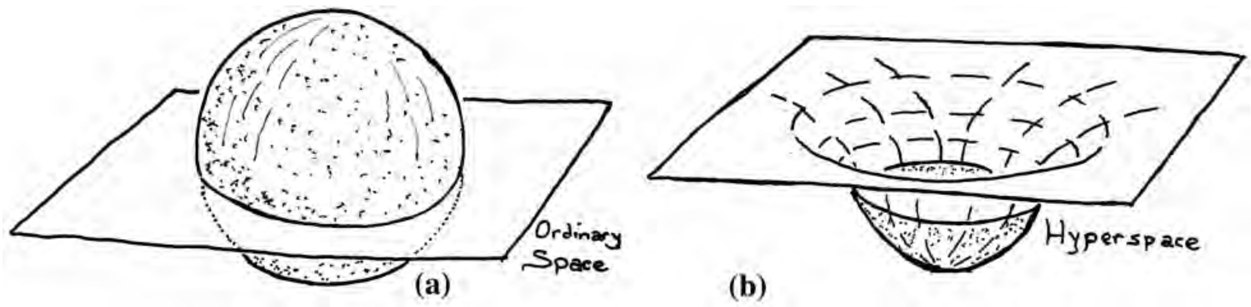


Figure 13: The warpage of space inside and around a neutron star: An equatorial slice through a star [diagram (a)], when osberved from a higher dimensional, flat hyperspace in which our universe is embedded, has the shape shown in diagram (b). The star's circumference may be about twice its diameter rather than π times its diameter.

gravity, we can infer the strength of the nuclear pressure — or, more precisely, we can learn about the nuclear *equation of state*: the nuclear pressure as a function of density.

Although hundreds of neutron stars have been discovered with radio, optical, and X-ray telescopes, and many of their features have been probed that way, these electromagnetic observations have given us only a crude knowledge of the star's circumferences and thence of the nuclear equation of state. The masses of about a dozen neutron stars have been measured, all coming out very near 1.4 suns so they contain about 10^{57} neutrons; but their circumferences have been measured so crudely that we only know they lie somewhere between about 25 and about 50 kilometers.

This leads to my next prediction:

- **Prediction 4: Sometime in the years 2008–2010 LIGO's advanced detectors, and those of its partners, will begin probing the properties of bulk nuclear matter by monitoring the gravitational waves produced when a black hole tears a neutron star apart. The observed waves, when combined with numerical-relativity simulations of the star's destruction, will tell us the star's circumference to about 10 per cent accuracy. This and other features of the waves will teach us much about the nuclear equation of state.**

Figure 14 depicts an example of the destruction of a neutron star by a black hole, with an accompanying emission of gravitational waves. The star and hole initially encircle each other in an orbit that gradually shrinks due as it loses energy to gravitational waves. From the inspiral waves we can infer the masses and spins of the hole and star. As the star nears the hole's horizon, it encounters ever increasing spacetime warpage, which ultimately tears the star apart. The larger the star's circumference, the more easily it gets torn, so the earlier the tearing starts. Thus (as my graduate student Michele Vallisneri has shown), from the

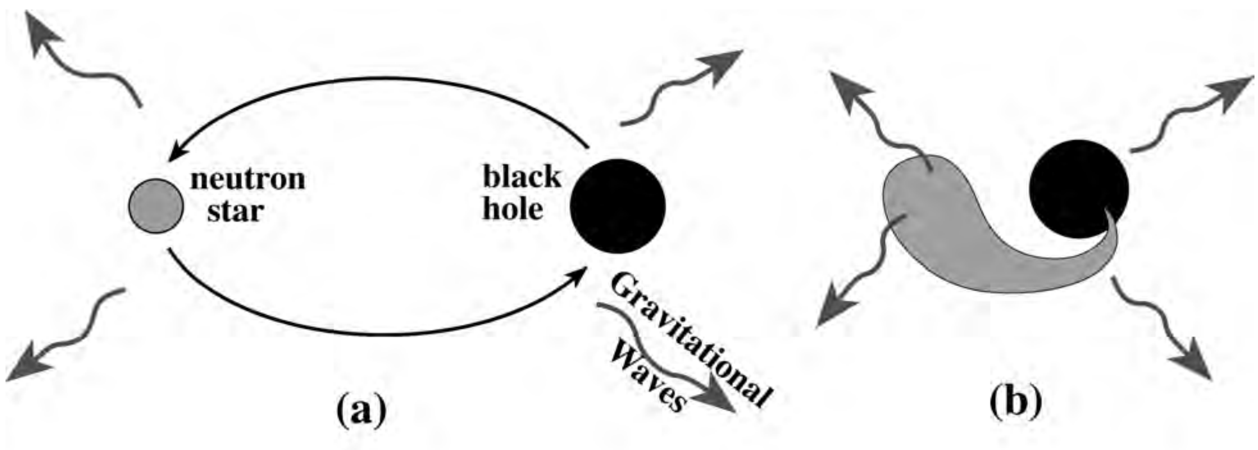


Figure 14: A neutron star and black hole orbiting each other [diagram (a)] will gradually spiral inward as they lose energy to gravitational waves. As the star nears the hole, the hole's spacetime warpage may tear the neutron star apart as shown in diagram (b).

onset of tearing we can infer the star's circumference and thence some details of its equation of state; and by comparing the waves produced during the tearing with numerical relativity simulations, we should be able to infer other equation-of-state details.

Black-hole collisions and the destruction of neutron stars are just two of many kinds of gravitational-wave sources that LISA, LIGO and their partners will see and will use to probe the fundamental laws of nature and their roles in the Universe. But rather than discuss others, I shall now turn to a remarkable prediction about human technology and quantum mechanics:

- **Prediction 5: In LIGO in 2008, we will begin to watch 40 kilogram sapphire cylinders behave quantum mechanically. A "quantum nondemolition technology" will be created to deal with this quantum behavior, and already in 2008 it will be incorporated into LIGO's advanced gravity-wave detectors. This new technology will be a branch of a new field of human endeavor, called " quantum information science, which also includes quantum cryptography and quantum computing.**

This prediction is remarkable. Textbooks say that the domain of quantum mechanics is the microscopic world, the world of atoms and molecules and fundamental particles. We have long known that *in principle* quantum behavior could also show up in the macro world, the world of human beings, but the possibilities were so remote that we left it out of our textbooks; we hid it from our students. We must hide it no more. We must be ready, in 2008, to see the quantum mechanical *uncertainty principle* rear its head into the macro

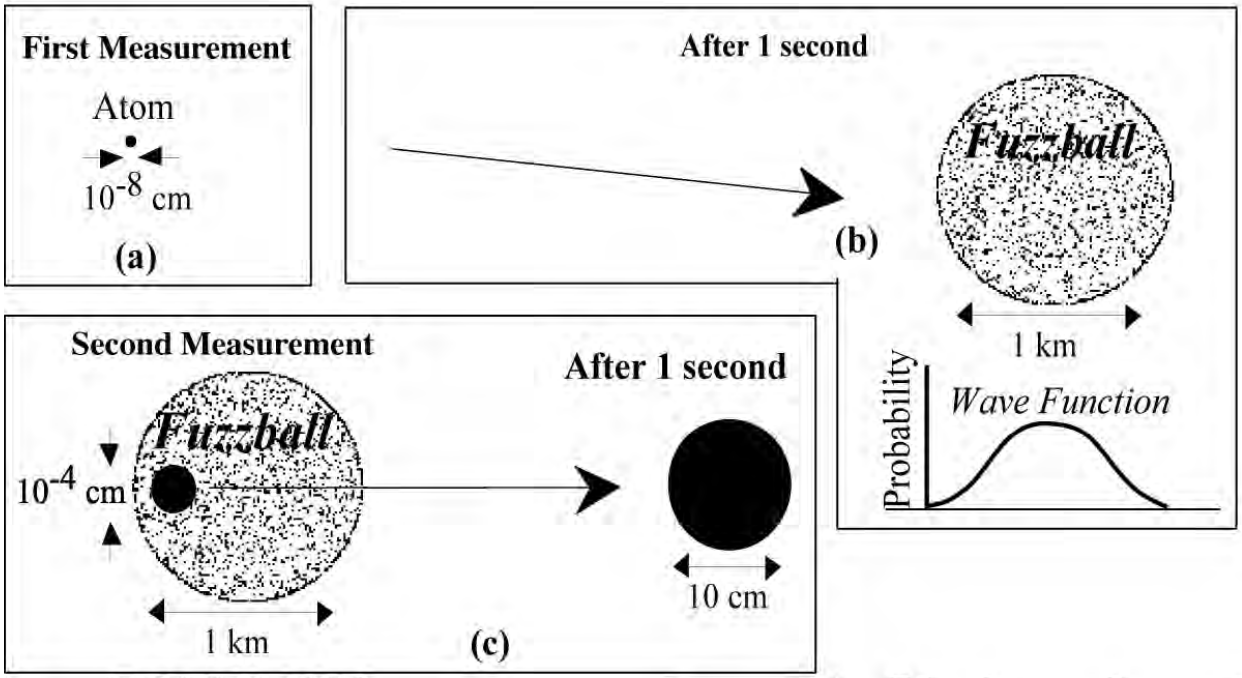


Figure 15: The Uncertainty Principle illustrated by successive measurements of an atom's location.

world, in LIGO's 40 kilogram mirrors, and we must learn how to evade the uncertainty principle.

Figure 15 illustrates the uncertainty principle in the domain of atoms where it has long held sway. Suppose we make two successive measurements an atom's location, and in our first measurement we achieve a precision equal to the size of the atom itself, 10^{-8} centimeters [diagram (a)]. The uncertainty principle says that by our very act of measuring where the atom is, we create an uncertainty in the atom's velocity. That uncertainty will cause the atom to move in an unknown and *unknowable* direction, at an unknown and *unknowable* speed. As a result, it is impossible to predict where the atom will be at the time of the second measurement. We can only say that it has a high probability to be located in some specific region, sometimes called the atom's *quantum fuzzball* [diagram (b)]. The longer we wait between measurements, the larger will be the fuzzball. If we wait just one second, the uncertainty principle predicts a fuzzball size of *one kilometer*! The probability for finding the atom at various points inside this one-kilometer fuzzball is described by the atom's *wave function* [diagram (b)]. The laws of quantum mechanics give us precise ways to predict this wave function, i.e. the probability for where the atom is, but the exact location is unpredictable.

Suppose that, when the fuzzball has expanded to one-kilometer size, we make a second measurement of the atom's location, this time with an accuracy 10,000 times worse than the first — an accuracy of 10^{-4} centimeter. This second act of measurement suddenly shrinks the 1 kilometer fuzzball to 10^{-4} centimeter size [diagram (c)], and also produces a new velocity uncertainty. According to the uncertainty principle, the

Figure 16: Left: A mirror for the initial LIGO interferometers, resting on a velvet cushion. Right: The mirror being hung by wires in its cradle in LIGO. [Courtesy LIGO Project, California Institute of Technology.]

velocity uncertainty is inversely proportional to the accuracy of the location measurement, so during one second of time after our second measurement, the fuzzball grows to a size of 1 kilometer divided by 10,000, or just 10 centimeters [diagram (c)].

As weird as the uncertainty principle may seem, it is reality. It has been verified in many laboratory experiments.

A key feature of the uncertainty principle is that the velocity uncertainty created by a location measurement is not only inversely proportional to the location accuracy; it is also inversely proportional to the mass of the measured object. That is why we have never yet seen a human-sized object behave quantum mechanically: Our huge human masses — 10^{28} times larger than the mass of an atom — cause our velocity uncertainties and quantum fuzzballs to be exquisitely small.

It is a remarkable tribute to the LIGO scientists that their technology will reveal the tiny fuzzball behavior of 40 kilogram mirrors in 2008 (if my prediction is correct). Figure 16 shows the kind of mirrors I am talking about. The mirrors in the pictures are the ones for LIGO's first detectors, the detectors that will begin their gravity-wave search in 2002. These initial mirrors weigh 11 kilograms not 40, and are made of quartz not sapphire, but the advanced 40-kilogram sapphire mirrors in 2008 will look very much like these.

The influence of the uncertainty principle on one of LIGO's advanced 40 kilogram sapphire mirrors is depicted in Figure 17. The light beam that measures the mirror's location does so by averaging over a 10-centimeter-diameter light spot on the mirror's face, and averaging over about one millisecond of time — far longer than the periods of thermal vibration of the mirror's individual atoms. This averaging guarantees that the beam measures the average location of all the atoms — i.e. it measures the location of the mirror's *center-*

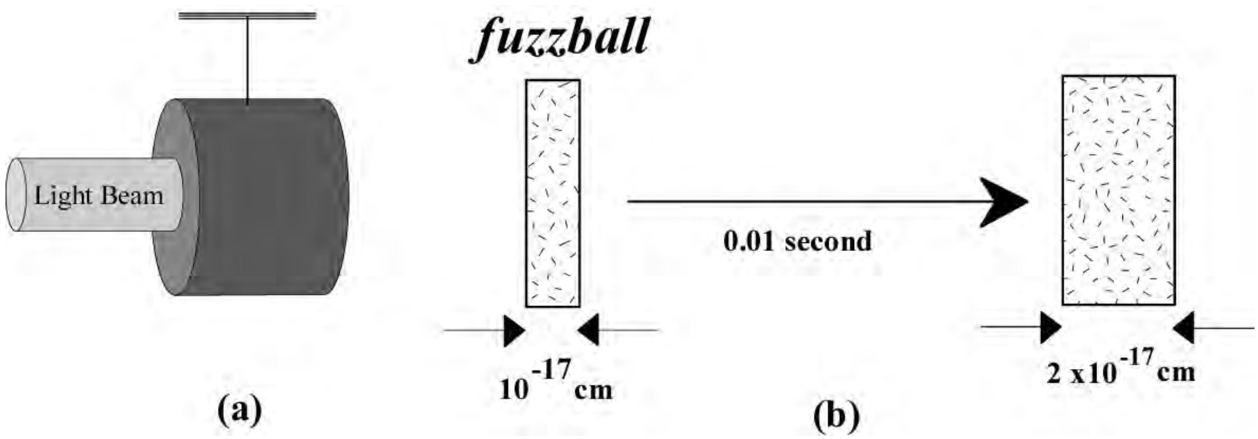


Figure 17: Consequences of the uncertainty principle for successive measurements of the center-of-mass of an advanced LIGO mirror.

of-mass. In effect, the mirror in this measurement behaves like a single particle weighing 40 kilograms, instead of like a conglomerate of 10^{28} atoms banging around against each other.

The light beam does not measure the center-of-mass location in all three dimensions, but in only one: along the beam's direction. In 2008—2010 it will measure that location with exquisite accuracy: about 10^{-17} centimeters — 1/10,000 the diameter of an atomic nucleus; 1 billionth the diameter of an atom; 10^{-13} (1 ten trillionth) of the wavelength of light. This fantastic precision will localize the mirror's center-of-mass into the 10^{-17} centimeter thick fuzzball shown in the middle of Figure 17. If that fuzzball did not grow between measurements, then by successive 10^{-17} centimeter measurements, we could detect gravity waves that move LIGO's mirrors by distances as small as $\Delta L = 2 \times 10^{-17}$ centimeters. However, the uncertainty principle forces the fuzzball to grow: The first measurement, with its extreme accuracy, induces a velocity uncertainty large enough to double the fuzzball thickness in half a gravity wave period (about 1/100 second). This growth will hide the effects of any gravity wave as small as $\Delta L = 2 \times 10^{-17}$ centimeters — unless we can find some way to circumvent the uncertainty principle.

In 1968, my close Russian friend Vladimir Braginsky identified the uncertainty principle as a potential obstacle for gravity-wave detectors and other distant-future, high-precision measuring devices, and in the 1970s Braginsky had the foresight to begin inventing ways to circumvent it — ways to which he gave the name *quantum nondemolition*, meaning "don't let the uncertainty principle demolish the information you are trying to extract from your measuring apparatus." I and my students joined Braginsky in this quest for a few years in the late 70s, and we recently renewed our collaboration with vigor, when we realized that LIGO must confront the uncertainty principle in 2008. Thanks to ideas from Braginsky and his Russian colleagues, and to recent work by Alessandra Buonanno and Yanbei Chen in my own group, we will be ready in 2008: We now know viable ways to protect the gravity waves' information from the uncertainty

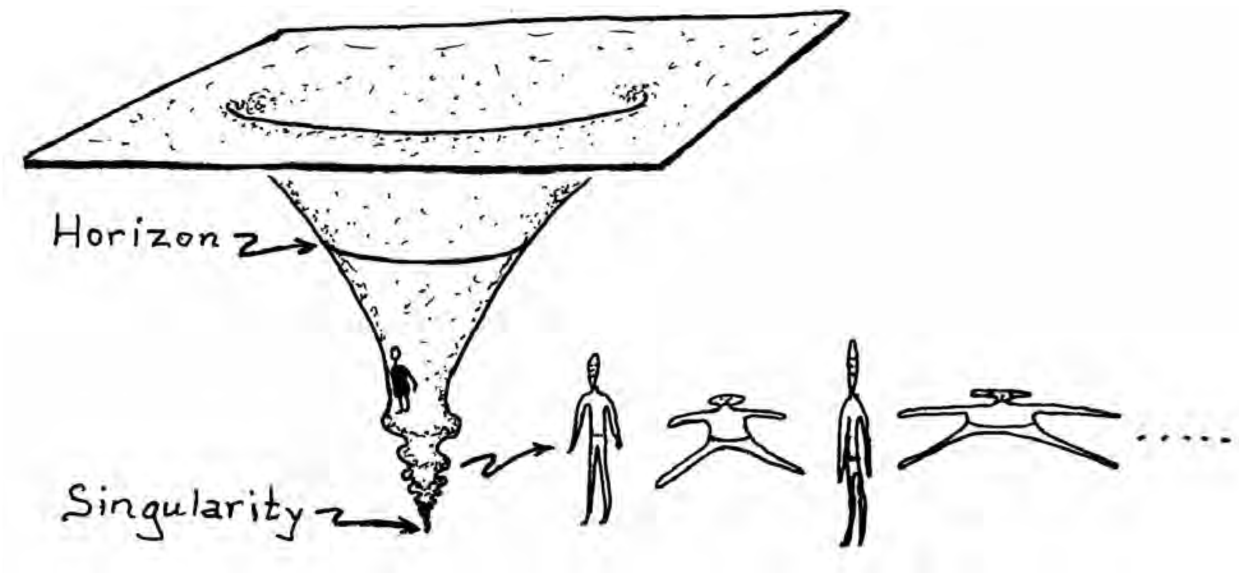


Figure 18: Kip falls into the singularity at the core of a black hole, and is chaotically stretched and squeezed by the spacetime warpage near the singularity.

principle as it passes through LIGO's 40 kilogram, quantum mechanical mirrors..

The keys to this quantum nondemolition are several, and are mostly too complex to discuss here today, but one key idea can be stated quite simply: In the advanced detectors we must *never* measure the locations of the mirrors, nor the separations between them (which would contain location information). Instead, we must only measure *changes* in the separations, without ever measuring the separations themselves. In this way, we can evade the clutches of the uncertainty principle.

****

Early in this talk , I depicted myself futilely trying to send signals out of a black hole as I was pulled into the singularity at its core [Figure 3(a)]. The nature of that singularity is a great mystery, but the spacetime warpage near it is not. In the early 1970s, three Russian friends of mine, Vladimir Belinsky, Isaac Khalatnikov and Yevgeny Lifshitz, probed the singularity's warpage by solving Einstein's equations, and discovered the violent and chaotic behavior shown in Figure 18.[3] When I near the singularity, the warpage stretches me from head to foot while squeezing my sides, then stretches my sides while squeezing me from head to foot, and then repeats, faster and faster, in an ever changing, chaotic pattern. Soon my body gives way and I become spaghettified (to use a technical term coined by John Wheeler). Then my body's individual atoms get spaghettified beyond all recognition, and then space itself gets spaghettified.

[3]More recent research, initiated by my Canadian-South African friend Werner Israel, has shown that, as the black hole ages the warpage around its singularity becomes more tame, and possibly even less lethal. I'm skeptical that it grows less lethal, but must admit my skepticism is not firmly founded. Only the laws of quantum gravity (discussed below) know for sure.

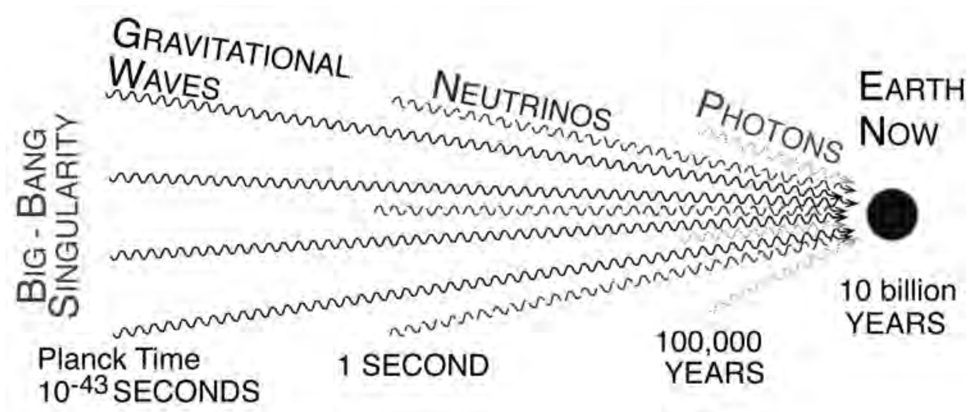


Figure 19: Photons, neutrinos, and gravitational waves from the big-bang creation of the universe.

I am convinced, by arguments due to Wheeler in 1957, that the end point of spaghettification — the singularity itself — is governed by a union or marriage of the laws of quantum mechanics with those of spacetime warpage. This must be so since the warpage spaghettifies space on scales so extremely microscopic that they are profoundly influenced by the uncertainty principle.

The unified laws of spacetime warpage and quantum mechanics are called the *laws of quantum gravity*, and they have been a holy grail for physicists ever since the 1950s. In the early 60's, when I was a student of Wheeler's, I thought the laws of quantum gravity so difficult to comprehend that we would never discover them in my lifetime, but I now am convinced otherwise. An approach to understanding them called *string theory* looks tremendously promising.

String theory has a bad reputation in some circles, because it has not yet made predictions that are testable in the laboratory or by astronomical or cosmological observations. Singularities, being quantum gravitational objects, might rectify this, if we can observe them.

Now, the singularities inside black holes are not of much use, since they can't be seen from earth. If you see them, you die without publishing. Are there other singularities that we *can* observe without dying? Yes, there is at least one: The big-bang singularity that gave birth to our universe, and gravitational waves are the ideal tool for probing it.

The big bang produced three kinds of radiation: electromagnetic radiation (photons), neutrino radiation (neutrinos), and gravitational waves; see Figure 19. During the first 100,000 years of its life, the universe was so hot and dense that photons could not propagate; they were created, scattered, and absorbed without traveling hardly any distance at all. Finally, at age 100,000 years, the universe had expanded and cooled enough for photons to survive, and they began their journey to earth. We see them today as a *cosmic microwave background* (CMB), arriving from all directions and carrying a picture of the universe at age

100,000 years.

Neutrinos are much more penetrating than photons. Someday the technology of neutrino detectors will become good enough to detect and measure the neutrinos from the big bang. When that happens, they will bring us a picture of the universe at age 1 second; before then the universe was too hot and dense for neutrinos to survive.

Gravitational waves are far more penetrating than neutrinos — so penetrating, according to calculations by my Russian friends Yakov Borisovich Zel'dovich and Igor Novikov, that they should never have been absorbed or scattered by the universe's matter. They should have traveled unscathed by matter, from the universe's earliest moments — from the big-bang singularity itself. They therefore might bring us a picture of the universe's birth throes — birth throes which, over a time of about 10^{-43} seconds (the *Planck time*), destroyed the singularity and created space, time, matter, and radiation.

The big bang's gravitational waves, no matter how weak and few, should have been amplified strongly in the first one second of the universe's life. This amplification (predicted by my Russian friend Leonid Grishchuk in the mid 1970s) is caused by nonlinear interactions of the waves with the universe's spacetime warpage, and it gives hope that the waves are strong enough to detect. This leads to my next prediction — really an informed speculation, since I'm less confident of it than of the things I call predictions:

- **Informed Speculation 6:**[4] **Sometime between 2008 and 2030, gravitational waves from the big bang singularity will be discovered. There will ensue an era, lasting at least until 2050, in which great efforts are made to measure the spectrum of the primordial gravitational waves (their intensity as a function of wavelength) from wavelengths of 10 billion light years down to 100 meters, and to map out the waves' intensity pattern on the sky. These efforts will reveal intimate details of the big-bang singularity, and will thereby verify that some version of string theory is the correct quantum theory of gravity, and they will also reveal a great richness of phenomena in the first second of the universe's life.**

Why am I so uncertain about the date to discover waves from the big-bang singularity (2008 to 2030)? Because we are extremely ignorant of the singularity's properties and the universe's first second of life. The physics establishment likes a model for the first second called *inflation*, which predicts big-bang gravitational waves so weak that to detect them may require the technology of 2030. However, I'm skeptical of this establishment prediction because its inflationary model does not take detailed account of the (as yet unknown) laws of quantum gravity. An initial attempt to incorporate string theory (our best guess at quantum

[4]I have modified this speculation from the version in my talk at Kipfest, due to new insights in the months from then until this book went to press.

gravity) into the big bang has been made by Gabriel Veneziano in Switzerland and others. Their stringy big-bang model predicts waves that might be strong enough for detection by LIGO in 2008 or LISA in 2010 — but string theory is still in its infancy and the stringy model is necessarily crude and tentative, so I have little confidence in its predictions. Nevertheless, they are a warning that the big bang and its gravitational waves may be quite different from the establishment's pessimistic inflationary views; the big-bang waves might well be detected before 2030.

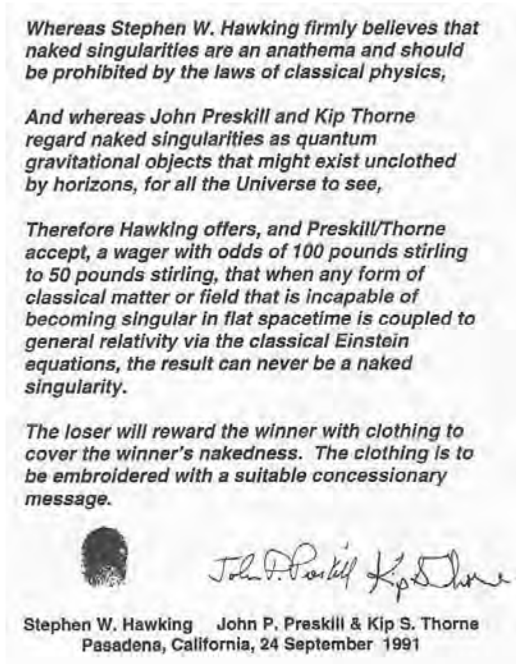
The establishment also tells us with much confidence that during the universe's first second of life, there must have been a rich variety of activity. For example, as the universe expanded, it cooled downward from an initial, unbelievably hot temperature. Initially, all the fundamental forces — the gravitational force, electromagnetic force, weak nuclear force, and strong nuclear force — were unified into a single force. Thereafter, at discrete moments in the expansion and cooling, each force suddenly and violently acquired its own identity, perhaps producing strong gravitational waves in the violence. For example, the electromagnetic force is predicted to have acquired its own identity last, by splitting off from the weak nuclear force when the universe's temperature was about 10^{16} degrees and its age was about 10^{-15} seconds (a thousandth of a trillionth of a second, also called a femtosecond). The gravitational waves produced in this *birth of the electromagnetic force* should lie in LISA's wavelength band today, and might be strong enough for LISA to detect and use to watch the birth of electromagnetism.

Though gravitational waves from the big bang singularity may be a promising way to probe the laws of quantum gravity, they are far from a sure bet. It would be much nicer if we had other singularities to probe.

Is there any hope ever to find and study singularities in the present day universe? The establishment's answer is "probably not" and is embodied in Roger Penrose'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. There are *no naked singularities*.

In 1991 Stephen Hawking, and John Preskill and I made a bet about cosmic censorship. The bet is displayed on the left side of Figure 20. Hawking as defender of the establishment (he has even been anointed "companion of honor to her majesty the Queen of England"!) insists that "naked singularities are prohibited by the laws of physics", while Preskill and I, tweaking the establishment, maintain that naked singularities are "quantum objects that may exist unclothed by horizons, for all the universe to see".

Now, Preskill and I were far from confident we would win, but Hawking conceded in 1997 (Figure 21) — though not gracefully. Our bet specified that "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." The clothing Hawking gave us was a politically incorrect T-shirt that Preskill's wife and my wife forbade us to



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

Figure 20: 1991 bet in which Hawking upholds the Cosmic Censorship Conjecture, and Preskill and Thorne oppose it.

Figure 21: Left: Hawking concedes he has lost our cosmic-censorship bet, as Thorne bows with pleasure and Preskill looks on with glee. Right: The politically incorrect T-shirt that Hawking gave us. [Left photo, taken at Caltech, is courtesy Irene Fertik, University of Southern California.]

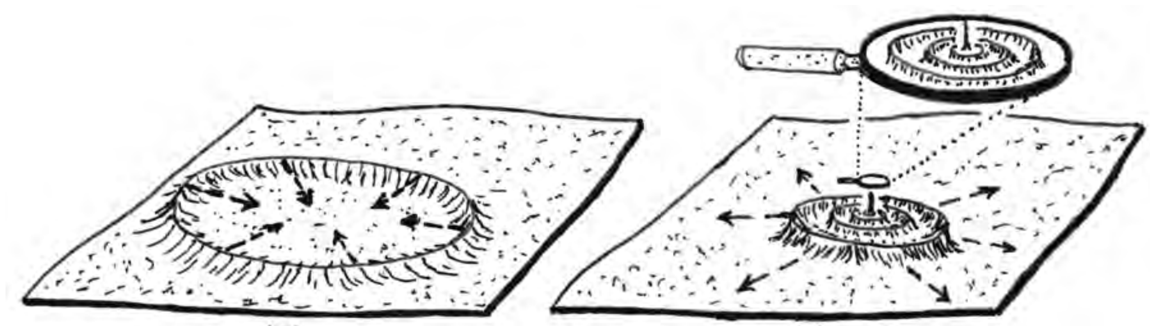


Figure 22: The supercomputer simulations of imploding waves, which triggered Hawking to concede that the laws of physics permit naked singularities, at least in principle.

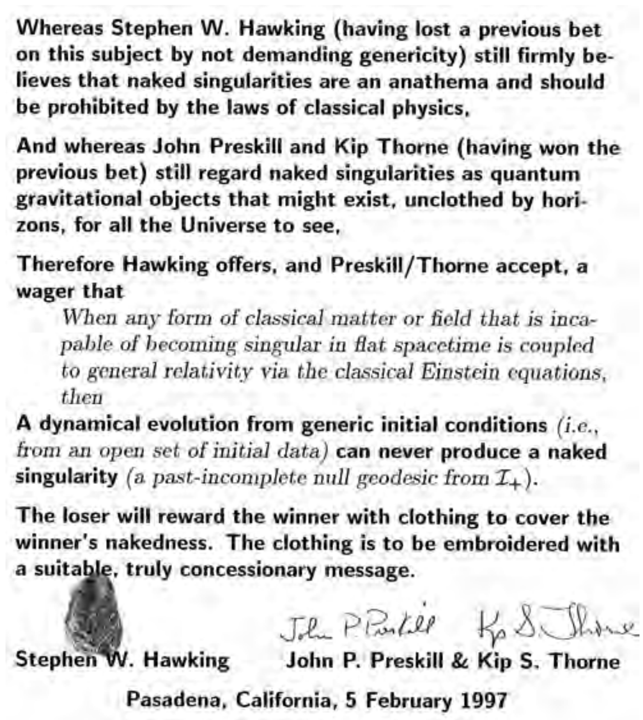
wear in public, but I show for all the world to see in Figure 21. Although Hawking was conceding that the laws of physics permit naked singularities, the woman's towel on the T-shirt insists — as Hawking still insists — that *Nature abhors a Naked Singularity*. This was hardly a "suitable concessionary message".

To explain Hawking's insistence, I sketch in Figure 22 the evidence that triggered his concession. That evidence came from supercomputer simulations of an imploding, spherical pulse of waves [diagram (a)]. The original simulations, by Matthew Choptuik at the University of Texas, were a tour de force in numerical relativity — far more accurate than any previous numerical relativity computations — but they involved a simple type of wave that might not exist in the universe: a *classical scalar wave*. Later simulations, by Andrew Abrahams and Chuck Evans at the University of North Carolina, involved imploding gravitational waves and gave the same results.

When the imploding waves were given a big amplitude, so they contained lots of energy, the implosion's dynamical nonlinearities produced a singularity clothed by a black-hole horizon, as all gravitational physicists had expected. When the waves were given small a amplitude, so they contained only a little energy, the waves went inward, passed through each other unscathed by any nonlinearities, and reemerged as outgoing waves. This was also expected.

The big surprise came when the waves' amplitude was carefully tuned to infinitesimally less than enough to make a black hole. Then, as depicted in diagram (b), the imploding waves interacted with each other dynamically and nonlinearly to produce a boiling froth of spacetime warpage from which outgoing waves continually leaked. Close examination of the boiling's core showed the waves shrinking in wavelength, continually and quickly and with a surprisingly regular pattern, until they created an infinitesimally small, naked singularity, that (we suspect) lives for an infinitesimally short time before destroying itself.

With these simulations as a guide, we were able to look back at previous pencil-and-paper studies of Ein-



Whereas Stephen W. Hawking (having lost a previous bet on this subject by not demanding genericity) still 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 (having won the previous bet) still 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 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, then*

A dynamical evolution from generic initial conditions *(i.e., from an open set of initial data)* **can never produce a naked singularity** *(a past-incomplete null geodesic from* $\mathcal{I}_+$*)*.

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.

Stephen W. Hawking **John P. Preskill & Kip S. Thorne**

Pasadena, California, 5 February 1997

Figure 23: The new, 1997 version of the bet in which Hawking upholds the Cosmic Censorship Conjecture, and Preskill and Thorne oppose it. The italicized thin type makes the bet more precise using the technical jargon of theoretical physics.

stein's equations by Demetrios Christodolou (a former postdoc of mine, now a professor of mathematics at Princeton University) and see them confirm that the implosion could produce a naked singularity. It is a tribute to numerical relativity that, only after numerical simulations revealed the full details of the imploding waves' froth, were we able to understand clearly what Christodolou's mathematics was trying to say. What a wonderful tool computers have become, thanks to people like Choptuik, Abrahams and Evans!

So why does Hawking insist that nature abhors naked singularities? Because, to make their naked singularities, Choptuik, Abrahams, Evans, and Christodolou had to adjust very precisely the amplitude of the imploding waves [diagram (a)]. With a slightly higher amplitude, a singularity would form but would be hidden by a black-hole horizon; with a slightly lower amplitude, the waves would interact and boil, then reexplode without making any singularity at all. Only one, very delicately chosen amplitude would produce a naked singularity, and that singularity would be infinitesimal in size and energy, and (presumably) in lifetime. Such fine-tuning of amplitudes is extremely unlikely ever to occur in Nature — though highly advanced civilizations might achieve it in their laboratories. Regrettably, human civilization is utterly incapable of producing and fine-tuning the required waves today, or next year, or next century, or probably next millennium.

Hawking, Preskill and I are persistent our pursuit of truth and fun, so we have renewed our bet (Figure 23). Hawking now insists that, if we rule out fine tuning (in the words of the bet, for “generic initial conditions”), naked singularities cannot be made, which means they cannot arise naturally. Preskill and I again disagree, and require that next time around the clothing be embroidered with a *truly* concessionary message.

I will venture a prediction about the outcome of our bet:

- **Prediction 7: Before Hawking, Preskill and I die, our new cosmic-censorship bet will get resolved. Who will win? Hawking, I fear, but it is not obvious and I won’t undermine our bet by predicting. However, I do predict that the effort to resolve our bet — to find out whether naked singularities can form without fine-tuning — will involve three prongs: pencil-and-paper calculations, numerical relativity calculations, and gravity-wave searches.**

The gravity-wave searches will be part of LISA’s project to make detailed maps of the spacetime warpage around massive black holes (Figures 5 and 7 above). If one or more of the maps comes out different from general relativity’s black-hole predictions, it may be that the central object, into which the small-mass hole is spiraling, is a naked singularity rather than a massive black hole. The odds of this are small, but we will have the tools to search, so search we will.

****

I turn, now, to my final set of predictions, all focusing on the laws of quantum gravity and what they will teach us.

- **Prediction 8: By 2020 physicists will understand the laws of quantum gravity; they will be a variant of string theory. By 2040 those laws will have been used to produce high-confidence answers to many deep and puzzling questions, including:**
  - **What is the full nature of the big-bang singularity in which space, time, and the universe were born?**
  - **What came before the big-bang singularity, or was there even such a thing as a “before”?**
  - **Are there other universes? and if so, how are they related to or connected to our own universe?**
  - **What is the full nature of the singularities inside black holes?**
  - **Can other universes be created in black-hole singularities?**
  - **Do the laws of physics permit highly advanced civilizations to create and maintain wormholes for interstellar travel, and to create time machines for backward time travel?**

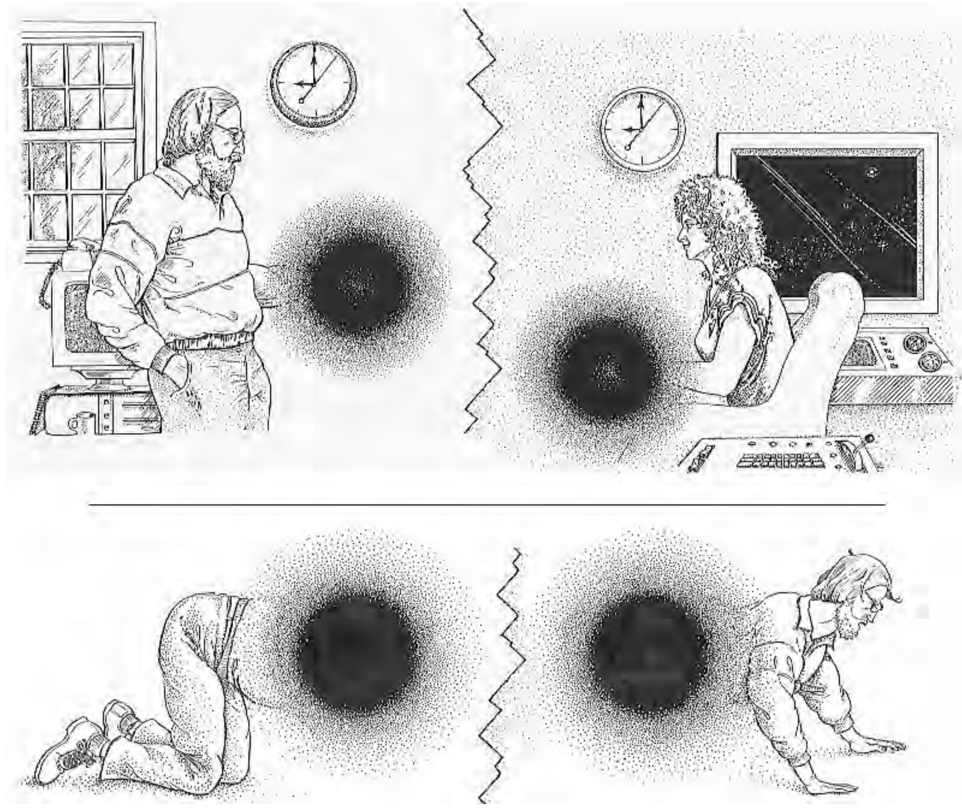


Figure 24: Top: Carolee travels out through the universe in a space ship, I remain at home on earth, and we hold hands through a wormhole. Bottom: I crawl through the wormhole from earth to the spaceship. [Adapted from drawings by Matthew Zimet in my book *Black Holes and Time Warps: Einstein's Outrageous Legacy*.]

Wormholes and time machines are discussed at length in the lectures by Novikov and Hawking earlier in this volume, and in the last chapter of my book *Black Holes and Time Warps: Einstein's Outrageous Legacy* — and they are also well known to any consumer of Hollywood films and television. Figure 24 shows a light-hearted example of a wormhole, using drawings adapted from my book.

My wife, Carolee Winstein, and one mouth of a wormhole are in a space ship far from earth, and I am in our home in Pasadena with the other mouth. The distance through the wormhole is very short, so Carolee and I can hold through it, romantically, as she sails around in interstellar space [diagram (a)]. If we want to do more than hold hands, then I can crawl through the wormhole [diagram (b)], into her spaceship.

In my book I explain a crucial consequence of Einstein's laws of spacetime warpage: to hold a wormhole open so that I or anything else can travel through it, one must thread it with "exotic material" — material that, as seen by someone at rest inside the wormhole, has an enormous rubber-band-like tension; a tension larger than its enormous energy density. (I have never explored whether I could crawl through the exotic material with impunity, since we know so little about exotic material.)

We know, as Hawking describes in his lecture and I discuss in my book, that such exotic material can actually exist in tiny quantities and under very special circumstances. However, establishment physicists strongly suspect that physical law will forbid anyone from ever concentrating enough of it together for a long enough time to hold a human-sized wormhole open. One reason for this prejudice is that someone moving through exotic material at high speed, instead of at rest in it, will see a negative energy density. This means it violates the *weak energy condition* discussed in Hawking's lecture, and the physics establishment has an amorous relationship with the weak energy condition.

In the years since I wrote my book, several of my physicist friends have worked hard to try to figure out whether the laws of physics would permit a very advanced civilization to place enough exotic material in a human-sized wormhole to hold it open. The final answer is not in, and might not be fully in until the laws of quantum gravity are fully understood. However, the tentative results, mostly from my former student Eanna Flanagan and my friends Bob Wald, Larry Ford and Thomas Roman, look bad for wormholes.

Despite this, I remain an optimist. If pressed to speculate (as I am pressing myself today), I offer the following

- **Not-so-well-informed Speculation 9: It will turn out that the laws of physics do allow sufficient exotic matter in wormholes of human size to hold them open. But it will also turn out that the technology for making wormholes and holding them open is unimaginably far beyond the capabilities of our human civilization.**

Why am I optimistic about about large amounts of exotic matter? Perhaps mostly because of my skepticism about our present understanding of what kinds of matter can exist in the universe. This skepticism is triggered by a recent cosmological discovery:

Only about 5 per cent of the mass of the universe is in the kind of material from which humans are made — *baryonic matter* (molecules, atoms, protons, neutrons, electrons, ...). Roughly 35 per cent is in some unknown form of *cold dark matter*, which (like baryonic matter) can get pulled inward by gravity to form halos around galaxies, and might also form dark-matter "galaxies", "stars" and "planets" that emit no light. As for the remaining 60 per cent of the universe's mass: It is in some equally unknown form of *dark energy* (as cosmologists call it) that pervades the whole universe and possesses an enormous tension.[5] Is its tension larger than its energy density? Might it thereby be the kind of exotic material that is needed to hold

[5] In the original, oral version of this lecture, I offered a prediction that by 2002 it would be completely clear that dark energy exists. I have deleted that prediction from this written version of my lecture because, as this book goes to press in June 2001, new cosmological observations have confirmed its existence with high confidence. It seems much less daring now to predict that dark energy is real, than it did in June 2000!

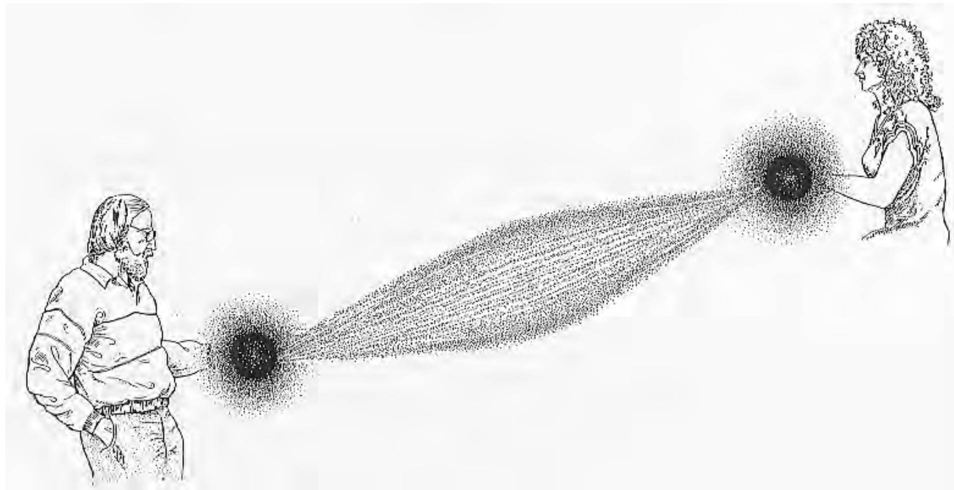


Figure 25: The self destruction of a time machine at the moment it is first activated. [Drawing by Matthew Zimet from my book *Black Holes and Time Warps: Einstein's Outrageous Legacy*.]

wormholes open? We don't know for sure, but establishment physicists have a very strong prejudice that its tension is equal to its energy density, or perhaps a bit smaller, but not larger. I tend to agree: We should be so lucky as to have Nature provide us with exotic material in profusion, everywhere in the universe!

Nevertheless, the dark energy gives me hope that exotic material can, in fact, exist in large amounts. Why? For the simple reason that the dark energy warns us of how very ignorant we are.

And what of time machines? In *Black Holes and Time Warps* I described a universal mechanism, identified by my postdoc Sung-Wong Kim and me in 1990, that might *always* make a time machine self-destruct at the moment one tries to activate it. Hawking discusses this mechanism in his lecture earlier in this volume, using the fancy words "In general the energy momentum tensor diverges on the Cauchy horizon." A more visual, make-believe description is shown in Figure 25:

In my home in Pasadena, the flow of time is slowed a bit by the earth's mass, while in Carolee's spaceship in interstellar space, with no massive bodies nearby, time flows at its normal, faster pace. As Novikov describes in his lecture, after awhile this difference of flow rate transforms the wormhole into a time machine: Carolee can travel backward in time by crawling through the wormhole, and can then climb into another spaceship and fly out into interstellar space and meet her younger self.

There is a first moment, in Carolee's spaceship, when time travel becomes possible — the moment of "time machine activation". This is the moment when the fastest traveling entity of all, a bit of radiation[6] moving at light speed, can pass through the wormhole from spaceship to earth, then travel at light speed back to the

[6]Actually, as is described in my book, it is *vacuum fluctuations* of the radiation field that make this first trip and pile up on themselves.

ship through interstellar space, arriving at the same moment as it started out. The result is two copies of each bit of radiation, the younger copy and the older copy, inhabiting the same spot in space and time. These two copies then travel through the wormhole and back making four copies, then eight, then sixteen, then .... an enormous number of radiation bits, with enormous explosive energy that destroys the wormhole, according to my calculations with Kim.

Our calculations, however, were based on general relativity and quantum theory in their unmarried, ununified forms. In 1990, Kim and I, scrutinizing our calculations, guessed that the ill-understood unified laws of quantum gravity would intervene and halt the explosion before it destroys the time machine. Stephen Hawking disagreed and showed us a more cogent viewpoint — one that convinced us quantum gravity would only intervene at the very last moment, just as the time machine was on the verge of destruction. Quantum gravity, it seemed, would hold the answer tightly in its own grip. We could not know the fate of time machines until we fully understand the laws of quantum gravity.

That was the state of things in 1994, when my book was published. In the past six years, new calculations have given conflicting hints:

On one hand, as Stephen says in his lecture, "One might speculate that there could be quantum states [situations] where the energy density was finite on the Cauchy horizon [where the time machine does not come close to self destruction], and there are examples [of calculations] in which this is the case." By creating such quantum states [situations], an advanced civilization might successfully make and activate a time machine. However, these quantum states look unrealistic; I doubt they can be made in the real universe.

On the other hand, Stephen and his student Mike Cassidy have used a tentative, queasily infirm version of the laws of quantum gravity to estimate what they say about self destruction. This version of quantum gravity predicts an exquisitely tiny probability for a time machine to escape self destruction: one part in 10^{60} — one trillionth of a trillionth of a trillionth of a trillionth of a trillionth. Can we believe this calculation? I don't know. but it is probably our best guide today to the fate of time machines.

All versions of the quantum gravity laws are queasily infirm today. But they are becoming much more firm with the march of time, and by 2020 (if my Prediction 8 is right), they will be fully firm. What will they then tell us about time machines? I offer the following

- **Speculation 10: It will turn out that the laws of physics forbid backward time travel, at least in the macroscopic world of human beings. No matter how hard a highly advanced civilization may try, it cannot prevent any time machine from self destruction at the moment of activation.**

Sadly, Stephen won't bet me on this. We find ourselves on the same side. He has convinced me, but only at the level of informed speculation.

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So there you have them. Ten speculations and predictions about the future. All ten will be proved or disproved long before my next big birthday bash, 60 years hence. The research that probes them will radically change our viewpoint on spacetime warps and the quantum world.