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COVER STORY

Crunch Time

■No one has ever seen a gravitational wave, but Caltech's Kip Thorne and other scientists are convinced they exist. Now they're weeks away from a huge experiment that could prove them right—or wrong.

BY PRESTON LERNER

Kip Thorne's got chalk skills. *serious* chalk skills.

At the moment, he's blanketing a blackboard with equations so densely packed with Greek letters, mathematical symbols and superscripts that they look more like abstract art than any recognizable form of human discourse. To the nonscientist, the scene has the theatrical, you've-got-to-be-kidding-me feel of an outtake from "A Beautiful Mind"—the manic scientist cranking out arcane formulas while onlookers gaze in wonder.

But this isn't a Hollywood set. It's a lounge on the campus of Caltech, where Thorne is the Feynman Professor of Theoretical Physics and just about every room, restrooms excepted, is furnished with a blackboard. This particular Wednesday evening, the lounge is packed with nearly two dozen graduate students, doctoral candidates and postdocs. Several are members of the research group Thorne runs with fellow professor Lee Lindblom. But most of them are sitting in on the group's weekly meeting simply because they've heard that Thorne is going to be "posing some interesting problems." And they smile when he says, "I had some time on my hands so I thought I'd think about physics."

Thirty-two years ago, when Thorne became one of the youngest full professors in the history of the California Institute of Technology, he was a longhair partial to funky pendants and bell bottoms. Today, as an *éminence grise* in black-hole research and gravitational-wave studies—fields he helped create—he looks like a cross between Santa Claus and a tortured El Greco saint, with a mane of flowing hair and a white beard framing attenuated features, a gaunt face and ruddy complexion. At 62, he's slightly hunched, and he has a vocal tic similar to a hiccup. Yet his students regard him with the respect that martial arts students bestow upon their *senseis*.

Photos

The Ahab of Astrophysics
(MARK HANAUER)

Kip Thorne
(MARK HANAUER)

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They nod knowingly when he explains, "I'm not concerned about delta H over H. I'm interested in delta H over G, where G is a typical metric coefficient." They listen attentively as he delivers a characteristically gentle rebuke: "I think you might want to look more closely at the problem. It's not just the spin-supplementary condition. It's also radiation-reaction averaging." They jot down notes when he asks them, "So how do we get past the standing-wave problem to the real problem? That's the question I want to raise as LIGO comes online."

Thorne is a co-founder of the Laser Interferometer Gravitational-Wave Observatory. Big name, big mission: LIGO is designed to detect ripple-like disturbances in the theoretical "fabric" of space and time known as gravitational waves, whose existence was first posited by Albert Einstein in 1916 but which have yet to be observed despite decades of searching. Detecting this great white whale of black-hole physics would verify the underpinnings of Einstein's general theory of relativity. Also, the waves are expected to contain information that would unlock the mysteries of black holes and give us a dramatic new window on the secrets of the universe.

Time out for a quick physics primer: Einstein's theories of relativity hold that space and time are—yep, you got it—relative rather than absolute. According to Einstein, the universe is best thought of in terms of a four-dimensional fabric known as spacetime. Gravity can cause this fabric to warp, contort, oscillate and basically do anything short of the lambada. But nowhere does spacetime undergo stranger, stronger distortions than in and around the stellar phenomena known as black holes—dead stars that have collapsed to form masses so dense their gravitational pull prevents even light from escaping, therefore rendering them invisible.

Black holes are ciphers by definition; we infer their existence from the powerful effect they have on the space around them. But while they emit no light, radio waves or X-rays, they *do* send out waves made of the same stuff as the holes themselves—warped spacetime. These so-called gravitational waves are undulations in the fabric of space-time, like the ripples caused by dropping a stone in a pond. The biggest waves are produced by the most cataclysmic events—a supernova, say, or the collision of two black holes. These waves contain the story of their own creation, and we could play them back like high-fidelity tapes—if only we could detect them.

"I and many other relativity theorists have spent much of our lives working with the mathematics of general relativity, trying to understand what it predicts—for example, predictions it makes about black holes," Thorne says. "But we have almost no experimental data to support these predictions. And when we get to the most interesting situations—where space and time are oscillating, twisting, vibrating, distorting—we don't know how to solve the equations. Gravitational waves will allow us to *watch* space-time distort rapidly, in large magnitudes. Then we can go back and forth between theory and observation to finally figure out how everything hangs together."

Like a brainy, genial Ahab, Thorne has been chasing gravitational waves for nearly a quarter-century. Thanks largely to his tireless efforts, two enormous observatories have been built, one in Louisiana and another 2,000 miles away in Washington state. Housed within these odd structures are devices called interferometers that are designed to detect gravitational waves by measuring movements of almost incomprehensible smallness.

Now, with the first scientific data runs just weeks away, Thorne is about to see his lifelong vision come into focus. Even so, he suspects that gravitational waves won't be detected until second-generation interferometers are built. "I wish we didn't have to do it in two steps," he says. "I wish we hadn't had to build a $300-million facility to make it happen. I wish we could have done it on a tabletop. But nature just isn't made that way."

no matter what ligo finds—or doesn't find—thorne's reputation is secure. Oddly enough, it has less to do with his own scientific achievements than with creating an environment for others to make award-winning breakthroughs. He's been an evangelist for black-hole and gravitational-wave physics, not only luring nonbelievers but also drumming up donations (a.k.a. federal funding). He's been an effective mediator between traditional scientific adversaries—theorists and experimentalists, for instance, and astronomers and physicists. But most important, he has inspired young scientists to follow his example and imprinted them with his own qualities. Equal parts Mr. Chips and Mr. Wizard, Thorne is the Pied Piper of theoretical physics.

"He's a fantastic mentor. There is a whole cabal of former students who still admire him very, very much," says Clifford Will, chairman of the physics department at Washington University in St. Louis. "Not only did he motivate us to become better scientists, but he also inspired us to be better listeners and teachers." Adds another former student, Richard Price, now a professor of physics at the University of Utah: "Kip was one of the first scientists to take general relativity, which most people saw as an intellectual curio, and apply it to astrophysics. But more than any single theoretical breakthrough, he will be remembered for populating this new field with students. He taught them how to behave—morally, ethically and scientifically."

Thorne is the co-author of one of the only science textbooks long-lived enough to justify being called a classic. (Pirated editions of "Gravitation" are still being printed in Kurdistan 30 years after the book's initial publication.) At the other end of the spectrum, he also wrote the pop-science bestseller "Black Holes & Time Warps: Einstein's Outrageous Legacy," which, along with more serious subjects, detailed his blueprint for a time machine and prompted Caltech President David Baltimore to dub him "Caltech's number-one strange scientist, the prince of counterintuitive science."

Some of Thorne's friends wonder if he might have achieved more personally if he had spent more time on his own research and less on mentoring his charges. But Thorne waves this notion aside. "I feel I've had a deep influence on science through my students," he says. "If you take a look at what my students have done while they were students, forgetting about what they've done afterward, you'll find that they've collectively accomplished more than I could have done on my own."

ligo is big science. capital b, capital s. to date, $365 million has beenspent on two separate facilities in Hanford, Wash., and Livingston, La. An additional $165 million has already been committed over the next five years to upgrade to second-generation interferometers. This makes LIGO the most ambitious project ever funded by the National Science Foundation.

The LIGO facilities look every bit as strange as the gravitational waves they were built to detect. In aerial photographs, they look like giant crop circles left behind by inscrutable aliens. Splayed out at right angles to the angular central structure are two spindly legs that resemble giant pipelines leading to nowhere. Encased within each one of these long halfcylinders—picture Quonset huts 2 1/2 miles long—is a 4-foot-diameter vacuum tube. A mirror dangles from a wire at the end of each leg. When the interferometer is running, a steadily shining laser beam in the central structure is split in two. These beams shoot down the two tubes, bounce off the dangling mirrors and return to the center. There they merge and "interfere" with each other.

Here's where things get tricky. Astrophysicists say gravitational waves are constantly wafting across the universe, causing space to stretch along one axis and squeeze along the other. This distortion is so minuscule that we don't ever notice it. (Ditto, fortunately, for nearly all of the most dramatic effects of general relativity.) The problem, of course, is that it's also too small for scientists to detect.

Enter the interferometer. When an especially powerful gravitational wave from a distant universe passes over a LIGO site, the space around one leg ought to shrink while the space around the other stretches. This should cause the mirrors within to quiver ever so slightly. Less than slightly, actually. *Infinitesimally* hardly begins to describe it. LIGO director Barry Barish pegs the movement at 10 to the minus-18th meters, or ten billionth's the diameter of a hydrogen atom.

Still, this would be enough to nudge the two returning laser beams out of phase, causing their interference to change. This modified interference should reveal the shape, or form, of the passing gravitational wave in much the same way that sound can be charted on an oscilloscope. (Besides mounting the interferometers on exotic shock absorbers, the scientists built *two* LIGO facilities in different parts of the country to rule out seismic vibration or other so-called noise as the cause of any observed movement.)

"If and when LIGO detects gravitational waves, it'll be a big deal," Thorne says. "But our goal has never been detection alone. It's been to use these waves to explore aspects of the universe and fundamental physics that we can't explore any other way. We want to be able to make maps of the warpage of space-time. We want to see how warped space-time behaves when two black holes collide. We should be able to see things unlike anything we've seen before."

For virtually all of human existence, our knowledge of the cosmos has been limited to what we could observe with our own eyes, either unaided or through optical telescopes. But the 1940s brought the development of radio telescopes and, soon after, other alternative observational devices that expanded the distances we could see and gave us our first glimpse of phenomena such as pulsars and quasars. Despite these advances, our vision is still limited to objects that emit electromagnetic waves—light waves, gamma rays, X-rays and so on. This accounts for only a puny slice of the universe. Gravitational waves, on the other hand, should allow us to observe black holes and other matter that remains shrouded from our sight.

Astrophysicists have already produced reasonably firm evidence of gravitational waves. In 1993, the Nobel Prize for physics was awarded in part for this discovery. But the waves themselves remain elusive. And if it turns out that they don't exist, then there's a serious problem with the concept of relativity.

In 1905 and 1916, Albert Einstein published his special and general theories of relativity. With these two papers, he demolished the foundations of Newtonian physics and reimagined our universe. By 1919, with the publication of proof that an extremely large mass, in this case our sun, caused light to bend, general relativity was confirmed and Einstein was hailed as a genius. But for several decades, some of the more implausible implications of general relativity—the existence of gravitational waves, for example—were ignored or dismissed as mathematical oddities.

Before physicists could tackle gravitational waves, first they had to puzzle out black holes. But because astronomers couldn't see them, black holes were regarded with skepticism, if not outright derision, until the late 1950s.

by happy coincidence, this was when student kip thorne arrived atCaltech, a scientist both by nature and nurture. He is the eldest child of two academics: His father was a professor of soil chemistry at Utah State University, where his mother later founded the women's studies program. (Two of his four siblings are professors.) His interest in science was fired at age 8, at a lecture about the solar system. "My mother and I worked out calculations for building our own model of the solar system," he recalls. "The model consisted of drawing a 4-foot-diameter sun on the sidewalk near our house. Then we drew all the planets to scale [and] marched down the sidewalk to put them in the right place. The shock was finding that Pluto was in the next town!"

After earning an undergraduate degree from Caltech, he pursued his doctorate at Princeton University under relativist John Wheeler. Besides being a titan of mid-century physics, Wheeler was an inspirational mentor. Teacher and pupil were well matched, and they became two of the architects of a heady period known as the golden age of black-hole research. During this remarkable period, between the early 1960s and the mid-1970s, Wheeler coined the term black hole and the first such object—Cygnus X-1—was identified. Meanwhile, Thorne returned to Caltech to teach and put together his own ambitious, impassioned research group.

"I called it the Children's Crusade of general relativity," says William Press, a student of Thorne and Wheeler who's now deputy director of science and technology at the Los Alamos National Laboratory in New Mexico. "Except for John Wheeler, almost everybody in the field was very young, and it was a period of endless promise. At Caltech, if you were interested in general relativity, you studied with Kip. He couldn't take on enough graduate students."

But by 1975, after a decade of spectacular progress, theoretical physicists ran up against an experimental roadblock. As Thorne puts it: "We had pretty much done all we could do in terms of mathematical solutions or approximation techniques, and the only way to make major progress was either through computer simulations or through observations, or both. Only now, in 2002, thanks to supercomputers and LIGO, are we on the verge of both approaches coming to fruition. But there's been a long period of building the right tools."

One November night in 1976, Thorne wandered the streets of South Pasadena, seeking direction. "I was sure that if we were successful in detecting gravitational waves, it would have a profound impact on our understanding of black holes and the universe," he says. "But the waves are so weak and the task of detecting them was so daunting that I wasn't sure the odds of success were high enough that I should urge Caltech to get involved in the business."

In the end, he decided that the potential reward outweighed the risk. He subsequently became part of a triumvirate with two experimentalists—Rainer Weiss of MIT, who invented the gravity-wave interferometer, and Ron Drever of Caltech, who refined it—and set about trying to sell the program to the National Science Foundation, the federal agency created to support blue-sky research on the frontier of pure science. Twice they failed. In 1989, on their third try, with former Caltech provost Robbie Vogt as LIGO director, they finally came up with a winning plan. Even then, they had to run a five-year gantlet of reviews before getting the foundation's ultimate go-ahead in 1994.

These days, Thorne and his students are designing second- and third-generation interferometers. He's also organizing a Caltech supercomputer effort to simulate colliding black holes and other cosmic cataclysms. He stresses—forcefully and repeatedly—that he's not involved with the day-to-day operation of LIGO, and he insists that the bulk of the credit for the program belongs to the experimentalists who built and run the interferometers. "I'm just a theorist," he says, "and I'm quite concerned that my role not be overplayed."

Thorne's colleagues chuckle when they hear this assessment. "That sounds just like Kip," says Sandor Kovacs, a former student-turned-physician who teaches at the Washington University School of Medicine. No less an authority than Thorne's longtime friend Stephen Hawking has said, "I don't think [LIGO] would have happened if he hadn't pushed it so hard."

This thought is echoed by Vladimir Braginsky of Moscow State University, who's been working with Thorne since long before the end of the Cold War. "LIGO could not have gone forward without Kip Thorne. It will be his legacy. This project will live in the memory of mankind for centuries."

in his narrow, nondescript office at caltech, thorne grabs an old notebook from a bulging bookcase and opens it at random to a page filled with meticulously neat, handwritten formulas not unlike the ones he'd scrawled across the blackboard at the weekly meeting of his research group a few days earlier. These are his own notes, taken when he was a student struggling to keep up with the ferocious competition.

"When I arrived at Caltech, I took a bus to the freshman orientation camp," he recalls. "On the way, all the kids were quoting their IQs, and mine was 10 points below everybody else's. I had a pretty rough time keeping up that first year. So I started identifying the important ideas that were being taught and writing my own analyses of where they came from and how they related to each other. So instead of having textbooks with some underlining as my major source of information, I had my own summaries. I think this process enabled me to understand things more deeply than other people and allowed me to make connections that they didn't see."

These days, Thorne does most of his serious thinking at a getaway on the wild Oregon coast and in the north Pasadena home he shares with his second wife, Carolee Winstein, a professor of biokinesiolgy and physical therapy at USC. (Thorne has two grown children from a previous marriage.) His office was designed by his son, an architect. It's filled with exquisite woodworking crafted by his brother, who builds artisanal furniture. In this airy room ringed with windows, he pores over calculations for four or five hours at a stretch—a grinder, he insists, who succeeds by doggedness rather than genius.

Self-effacing to a fault, Thorne waffled mightily when he was offered the Feynman chair at Caltech. "Feynman was a close friend, somebody I admired and idolized," he says. "But it was difficult because I'm obviously not in his class scientifically. Of course, not many people are." Thorne laughs. "My genius, if you can call it that, has been picking areas where there was a lot of elbow room and something to be learned, and I've carefully avoided areas where there was a lot of activity by a lot of good theorists."

In one field, actually, Thorne has emerged—much to his amusement—as the world's most celebrated thinker. His friend Carl Sagan once asked him to vet the time-travel section of the manuscript that would eventually be published as "Contact" and then filmed as a movie starring Jodie Foster. Thorne immediately dismissed Sagan's hypothesis. But while driving on the I-5, west of Fresno, he had an epiphany: It might be possible to use a wormhole—a shortcut through the fabric of space-time—as a time machine.

Most scientists would have dismissed such speculation as pointless. Not only was the subject highly speculative, but it also carried the whiff of ridicule. Nevertheless, Thorne examined it with the same rigor he applies to any other subject, and he and two students published a paper titled "Wormholes, Time Machines, and the Weak Energy Condition." To this day, Thorne remains a hero to science-fiction cultists because of that and other papers.

Thorne's own hero, of course, is Einstein, the patron saint of relativity. And so, this afternoon, before teaching his own class in gravitational waves, he is himself a student at a Caltech lecture being given by one of his former pupils. The subject is "Einstein and the Astronomers: Testing Relativity 1914—1933." Forty professors, researchers, administrators and students listen while Daniel Kennefick, dressed incongruously in shorts, traces the journey by which Einstein arrived at his general theory of relativity.

In the middle of the presentation, a research scientist challenges the figure Kennefick has cited for an orbital anomaly of Mercury—an anomaly that baffled astronomers until Einstein explained it.

"Kip?" Kennefick asks hopefully of his one-time graduate advisor. Thorne digs into his briefcase and pulls out a pen. While the lecture continues, he scribbles calculations on a manila folder. Then he announces: "It's 43 seconds of arcs per century, not 0.43."

After the lecture, Thorne deconstructs his parlor trick in a way that would make sense to precious few people on the planet: "Well, I knew in order of magnitude that the size of the sun divided by the size it would have if it were a black hole is about 100,000. So the typical magnitudes of relativistic effects near the surface of the sun are about a part in 100,000. Mercury's orbit is out maybe something like 30 solar radii from the sun. So relativistic effect on Mercury's orbit ought to be a factor of 30 times smaller, or about 3 parts in 10 million. So the perihelion shift per orbit ought to be about 3 parts in million of a circuit. Then I just had to convert this into an angular shift per century." Thorne smiles sheepishly. "I should have known the number off the top of my head, but my memory is lousy."

As he strides across the campus to his own lecture hall, Thorne pauses to chat briefly with an old man sitting on a bench. "That was Jerry Wasserburg," he explains later. "He showed that the solar system is 4.58 billion years old. He won the [equivalent of] the Nobel Prize for geology. He's a wonderful man, approaching 80 now but still doing wonderful research."

Twenty years from now, chances are somebody will be saying the same thing about Kip Thorne.

Preston Lerner last wrote for the magazine about car designer Freeman Thomas.