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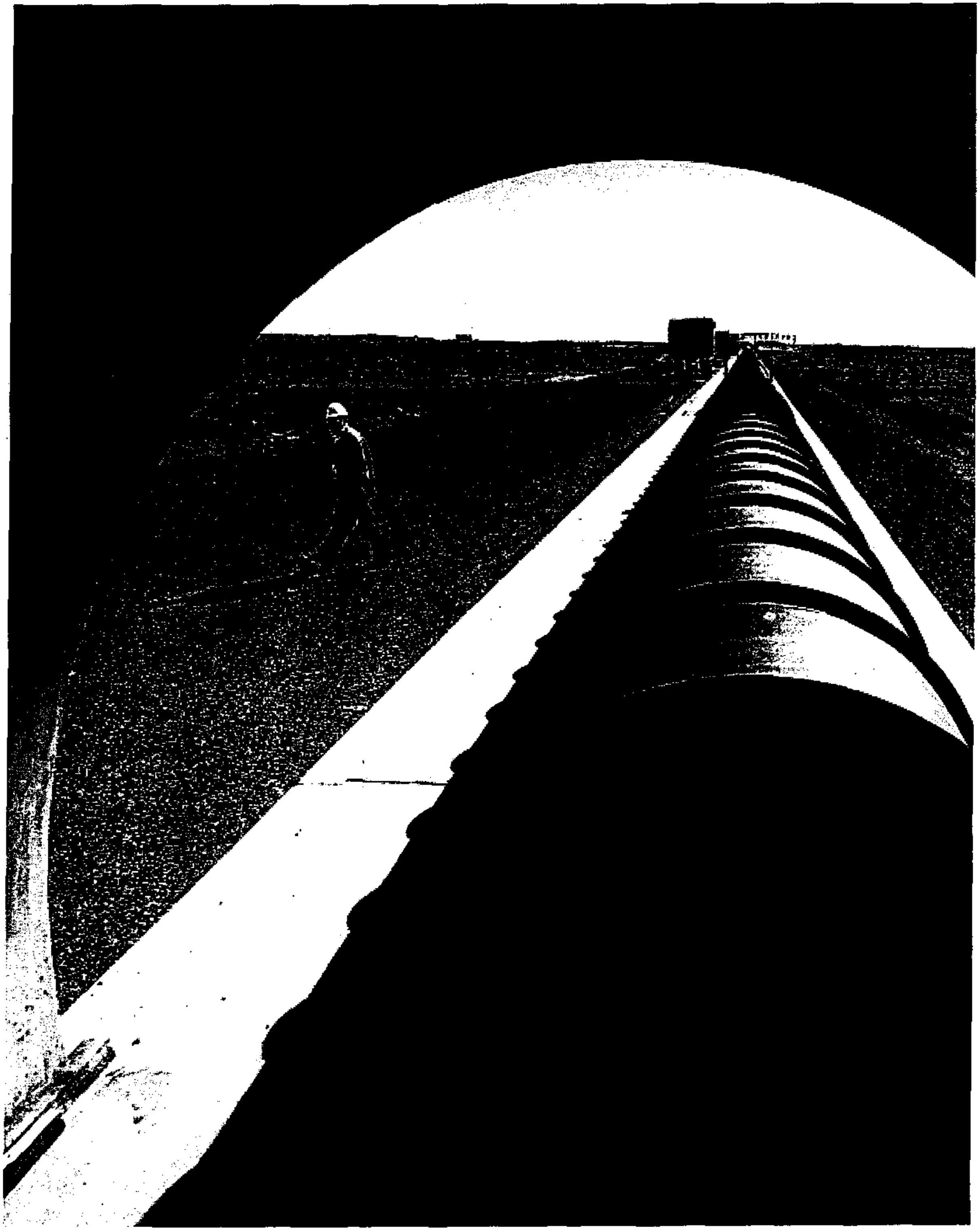
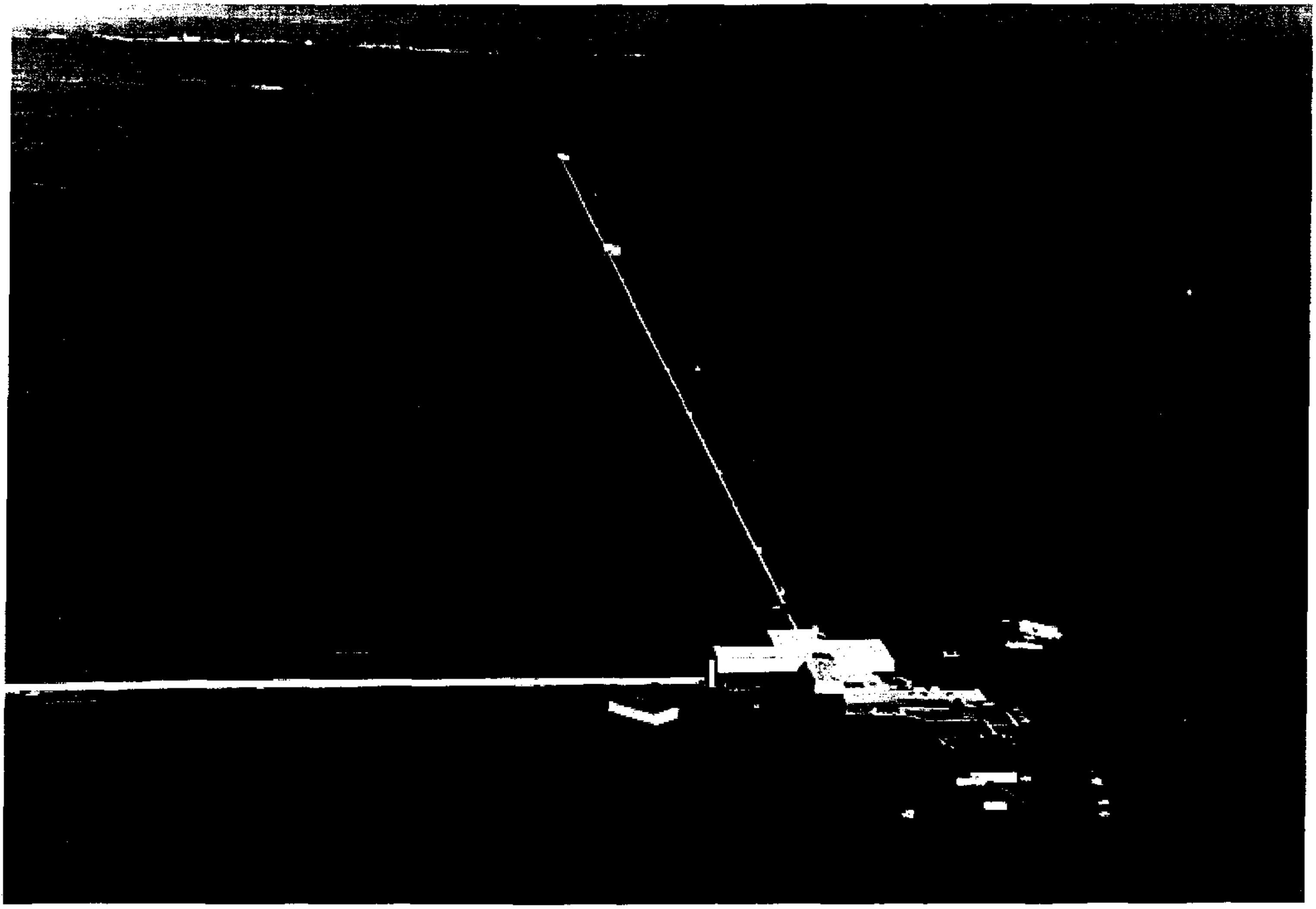


One of the dual instruments of the Laser Interferometer Gravitational-Wave Observatory sprawls across the desert near Hanford, Washington, each arm extending four kilometers and meeting at the corner of an L. The support buildings at the corner house laboratories as well as electronic and optical equipment, which will send a laser beam, split in two, back and forth down the two arms to intercept the infinitesimally small signal of a gravitational wave.



> "LIGO represents the transition of a field from small science to big, and as such is an important case study. It was a transition done largely internally at Caltech—and, in the end, done very successfully."

Realizing LIGO

by Jane Dietrich

Stretching across flat, empty desert in central Washington State (where it's easily seen on commuter flights), and mirrored on Louisiana's timbered coastal plain, a pair of gigantic L-shaped structures lie in wait for something that no one has ever seen. Along their two-and-a-half-mile-long arms run tubes containing one of the world's largest vacuum systems (the volume equivalent of about 15,000 kitchen refrigerators), in which laser beams will bounce back and forth anticipating the slightest jostling that would indicate the arrival of a cosmic signal. The tubes, four feet in diameter—you could walk through them crouched over—are constructed of a ribbon of 1/8-inch-thick stainless steel, rolled up like a toilet-paper roll and spiral welded along the seams. Continuous arches of six-inch-thick concrete cover the beam tubes, protection from the rattling desert wind as well as hunters' stray bullets; tumbleweeds pile up along the arms and must be harvested regularly with a hay-baling machine lest they ignite a conflagration.

This is LIGO, the Laser Interferometer Gravitational-Wave Observatory, at $371.3 million ($296.2 million for construction alone) the National Science Foundation's most expensive project, and one that comes with no sure-fire guarantee. When it turns on in the year 2002, LIGO will be searching for a signal as small as a thousandth of the diameter of a proton.

What are gravitational waves and why should we spend hundreds of millions of dollars to try to see them? Deduced by Albert Einstein in 1916 as a consequence of his general-relativity laws of physics, gravitational waves are ripples in the curved fabric of space-time, generated when huge masses precipitate violent events—when supernovas explode or black holes collide, for example. The gravitational energy released squeezes the warp and stretches the woof (or vice versa) of that fabric as it ripples outward, weaving a legible tapestry of the universe's cataclysmic events. But by the time the edges of this ripple reach Earth, the signal is extremely faint—near the edge of detectability by today's human technology.

If scientists can detect the signal, they may be able to discern some of the 90 percent of the universe that is hidden from the view of current instruments—optical and radio telescopes, X-ray and gamma-ray detectors—all of which explore only the electromagnetic spectrum. Deciphering gravity waves could show how two black holes engulf each other and reveal the mechanisms of a collapsing star. The gravitational equivalent of cosmic background radiation, created when the universe was less than a billionth of a second old, could help us decipher the details of the birth of the universe.

But do gravitational waves even exist? How do we know Einstein was right? Scientists interested in the phenomenon got lucky in 1974, when Joseph Taylor and Russell Hulse at the Arecibo Radio Astronomy Observatory in Puerto Rico observed two neutron stars (very dense balls of neutrons, the remnants of dead stars) orbiting each other. One of this pair was a pulsar, sending out a regular radio beam that allowed Taylor to measure precisely the drifting period of the signal and to calculate that the drift was exactly what should come from the orbit's losing energy by radiating Einstein's gravity waves. By 1974 the search for gravity waves was already under way, but Taylor's discovery reinforced the conviction among the searchers that they were indeed looking for something real.

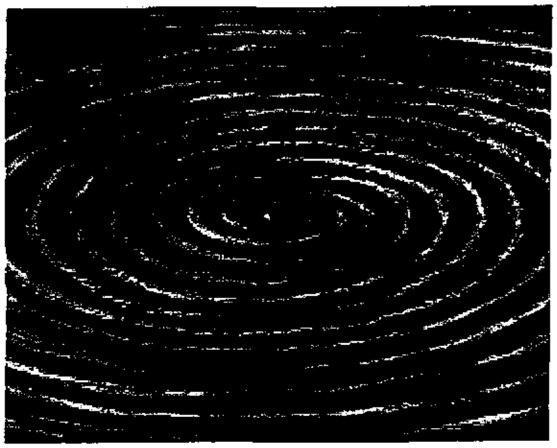
When scientists began their search, they didn't know how strong or how frequent gravity waves would be, and how sensitive their instruments would have to be to observe them. There was no precedent; it was virgin territory. Over the almost four decades after the search began, the need for more and more sensitive detectors eventually took it out of the laboratory and transformed it into "big science"—perhaps too big, some have said, for an institution like Caltech. The transformation was not accomplished without growing pains, as different scientific styles clashed and management methods were superseded, and as the difficulty of the task challenged some of the traditional ways of doing science, producing culture shock on a campus where most science has been done in small groups.

In the beginning was Joseph Weber of the University of Maryland, the acknowledged father of the field. In the early 1960s he built a detector based on a multi-ton aluminum bar, which may or may not (all experts now agree, not) have oscillated to incoming gravity waves in 1969, but his experiment inspired groups of physicists around the world, many of whom are now united in LIGO.

In 1963 Kip Thorne, then a graduate student at Princeton, met Weber and became fascinated with gravity waves. Thorne was a member of the theoretical relativity community, a field that theorized about black holes but had little contact with experiment. Arriving at Caltech in 1966, Thorne began spearheading an effort among theorists to convert his field into an observational one. We had "this beautiful theory of black holes," he says, "and no experimental data on the black holes themselves." Thorne considered gravity waves an ideal tool for observing black holes. To further that goal, he became "house theorist" for a talented group of experimentalists building bar detectors in Moscow under Vladimir Braginsky, who had been inspired by Weber.

Ron Drever, at the University of Glasgow, had also heard Weber lecture and decided to try to build better detectors. (Three decades later, Drever admits that if he had known how difficult it was going to be, he might never have gotten into gravity-wave detection; "but I thought it was going to be much easier than this.") Rainer (Rai) Weiss at MIT was also excited by the new field, and in 1970 had already come up with the concept of an interferometer-type detector (which was very much along the lines of what is now stretching across the flats of Washington and Louisiana). Weiss analyzed these detectors—figured out the noise sources the interferometers would have to confront and devised promising ways to deal with them. "Rai saw, right from the beginning, all the noise sources that today constrain LIGO," says Thorne. "His prescience was remarkable." Weiss, however, couldn't sell his ideas to MIT or NSF and was not able to get funding to build a prototype of his detector.

Kip Thorne

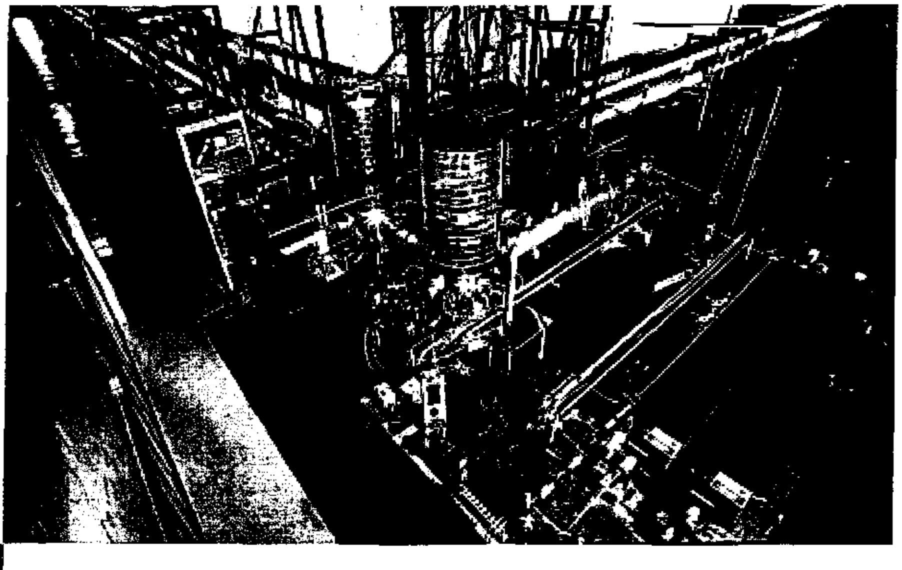


As two black holes orbit each other, in this representation of the curvature of space, they create outward-propagating ripples of curvature called gravitational waves.

"I thought it was going to be much easier than this."

Meanwhile, back at Caltech, Thorne (who is now the Feynman Professor of Theoretical Physics), decided to urge the Institute to get into gravity waves. His 1976 proposal was supported with enthusiasm by a faculty committee consisting of Barry Barish, Alan Moffet, Gerry Neugebauer, and Tom Tombrello, and was ultimately endorsed by the Division of Physics, Mathematics and Astronomy and by the administration. The decision was made to mount a strong effort in this new field—to build a prototype detector and to bring in an outstanding experimental physicist. The call went out to Drever, whom Thorne described as "highly creative, inventive, and tenacious," qualities that were deemed necessary to the project. Drever, who was known for his skill at designing things that work, had grown pessimistic about the capabilities of bar detectors and was starting to experiment with interferometers. He was loath to abandon his work in Scotland, but he saw the possibility of building a larger prototype in Pasadena. Before making the decision to move permanently to Pasadena, he agreed to a five-year arrangement: half time at Caltech and the other half in Glasgow, where he was building a 10-meter prototype interferometer. (After the five years he became a full-time professor of physics at Caltech.) When the design of Caltech's 40-meter interferometer got under way, "I did most of the drawings on the plane flying over the pole," says Drever.

In an interferometer, free-hanging test masses placed at the corner and ends of an L would theoretically move when a gravitational wave passed by, stretching apart infinitesimally along one arm of the L and squeezing together infinitesimally along the other arm. This motion can be detected by laser light. A laser beam, split in two at the L's corner, travels down each arm and back—a shorter distance along the squeezed arm than the stretched one. When recombined at the L's corner, the two beams interfere, producing a



The prototype interferometer, a hundredth the size of the monster on page 8, was begun in the early '80s on the Caltech campus. The green laser beam generated from the optical setup at lower right enters the system through the horizontal pipe (center), and from the beam splitter in the mesh cage is bounced down the 40-meter arms.

Ron Drever and Stan Whitcomb (foreground) constructing the 40-meter prototype in 1983.

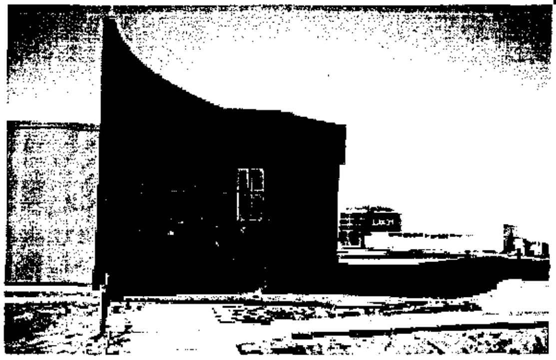
change of light intensity that reveals the arms' stretch and squeeze, and thence the gravity wave. (A vacuum inside the arms minimizes scattering and gives the laser beam the clearest possible path.) To maximize the signal strength, the arms of such an interferometer should be as long as possible, ideally even thousands of kilometers, which of course is not practical—on Earth anyway; in space is a different matter.

Former Weber student Robert Forward and a group at Hughes Research Laboratories built the first laser interferometer detector in the early '70s, but never continued with the project. Also during the '70s, Weiss at MIT and a group in Garching, Germany, were developing approaches and improving techniques in interferometer design. In his seminal 1970 work, Weiss came up with the idea, which the Germans eventually built, of hanging mirrors on the test masses and bouncing the laser back and forth many times between them, in effect "lengthening" the arm. If the light bounced hundreds of times between the mirrors, its total travel distance could be a quarter of a gravity-wave wavelength, with arms just a few kilometers long rather than thousands.

Finding a site on a small, compact campus in Pasadena to build even a prototype (no one knew yet just how big it had to be) posed a problem for Drever's undertaking. It was Robert Christy, then acting president of Caltech, who suggested wrapping the arms (in a sort of lean-to shed) around two sides of the already existing Central Engineering Services building on Holliston Ave. The length of 40 meters for the arms was fixed, says Drever, not by any theoretically ideal number, but by a tree in the way that no one wanted to cut down. Caltech put half a million dollars into the project. The staunch institutional support on Caltech's part, along with strong backing from a blue-ribbon committee convened by the National Science Foundation, swayed the NSF to throw its weight and money behind the project.

Stan Whitcomb, a former infrared astronomer, joined the project as assistant professor in 1980 and directed construction of the prototype, which was largely put together by undergraduates and graduate students (see *E&S*, January 1983). What attracted him to something so speculative as gravitational waves? "The challenge of building a detector that's so sensitive that you can't imagine that it has a hope of being successful," says Whitcomb. "And also the intellectual excitement of seeing something where the theorists don't have a good prediction for what we might see." Like Drever, Whitcomb says he "probably didn't realize how really difficult it was going to be." "In a sense we've been saved by technology developments that occurred after the start of this project," he continues, "things we didn't know about."

In the late '70s and early '80s, according to Thorne, "Ron was generating wonderful ideas—a lot larger share than you would expect for any one individual." Drever wanted to improve on Weiss's mirror scheme, which would need very large mirrors, so he hit on the idea that each interferometer arm should be a Fabry-Perot optical cavity, in which the laser light would bounce back and forth hundreds of times from the same spot on each mirror (instead of the separate, discrete spots in Weiss's scheme). Although this was technically more difficult, it had the advantage of allowing the mirrors to be much smaller. "It seemed to me economical," says Drever. "The mirrors have got to be cheap." Unfortunately, at that time Fabry-Perot interferometers typically worked only over a distance of a few centimeters, because lasers couldn't be made sufficiently stable in frequency to use larger distances. So, even though it was an accepted "fact" at the time that a laser could never be stabilized with the accuracy that the interferometer required, Drever devised a solution. He invented an optical-band technique that locks the laser onto the normal-mode oscillations of a large physical system, a technique similar in principle



Far right: The 4-inch-thick, 10-inch-diameter mirrors at the ends of the beam tubes recycle the laser light. The polished mirrors are coated with up to 35 layers of a purple dielectric coating designed to achieve the right reflectance and transmission of light for the wavelengths used by LIGO. The final coating was put on in May. Right: The front entrance *to the main support* building at Hanford has been landscaped since this picture was taken.

to one that Robert Pound at Harvard had originally developed for microwave frequencies. Now called Pound-Drever locking, it's used widely in laser spectroscopy and other areas of science and engineering.

Drever also (the German group thought of it independently) came up with the idea of recycling the light, so that it actually builds up and becomes more intense as it bounces between the mirrors. "We were very lucky in a sense because we found some wonderful mirrors that had been developed for military applications," says Drever. These mirrors with very small losses were still "kind of semi-secret," but Drever managed to get hold of some samples, which turned out to be perfect for his technique. "With these wonderful mirrors, you don't need to actually lose the light. We could pass the light through the system again and again and again, maybe hundreds of times. The net effect was that you could make a much more sensitive system with the same laser."

With Drever and Whitcomb building their 40-meter prototype, NSF refused to fund a similar prototype at MIT, but encouraged Weiss's desire to proceed with bigger plans, in space as well as on the ground. Weiss was thinking in terms of kilometers rather than meters. While a meter-sized instrument would be fine for testing techniques, it was highly unlikely to achieve the sensitivity necessary to detect gravitational waves. (On the other hand, scaling up by a factor of 100 is not easy; the rule of thumb in experimental physics is to enlarge subsequent generations of an experiment by a factor of 3 to 10.)

In 1983, Drever, Weiss, and Thorne together talked with Richard Isaacson and Marcel Bardon at NSF about building two kilometer-scale interferometers: a Caltech interferometer, and an independent MIT interferometer, which might cooperate in their gravity-wave searches. While Bardon and Isaacson embraced the prospects for such instruments, they insisted that any such project must be a truly joint Caltech/MIT undertaking, with the two groups working together on all aspects of a single, unified design.

The result was a "shotgun marriage"—Thorne's words, though Weiss, realizing that for something on this scale collaboration was necessary and unavoidable, didn't resist. Since MIT's administration had far less enthusiasm for the enterprise than Caltech's, the center of gravity waves moved west to Pasadena under a steering committee made up of Drever, Weiss, and Thorne. This was hardly a perfect union; there were strong disagreements between Weiss and Drever over technical matters in particular and scientific style in general. Drever was generally considered an "intuitive" scientist, while Weiss was deeply analytical. Weiss had worked on large projects with all their sharing and delegation of power; Drever had not, and was more accustomed to individual work. And Thorne, the committee's chair, wasn't an experimentalist at all. Decisions had to be made by consensus, and each was reached slowly, with great debate and agony. Under this rickety (Weiss's word) troika, the gravity-wave project stayed afloat with NSF support for another couple of years, basically as an R&D enterprise. Applications for funding to build the full-scale interferometer were twice turned down due to insufficient referee enthusiasm.

On the enthusiasm front, things started to look even worse in the summer of 1986, when Richard Garwin, an influential physicist who had served on numerous government advisory committees, voiced his suspicions of the grand claims for interferometer technology and demanded that NSF commission a thorough study of the project. A committee of scientific heavy hitters, cochaired by Andrew Sessler of UC Berkeley and Boyce McDaniel of Cornell, then met in November for