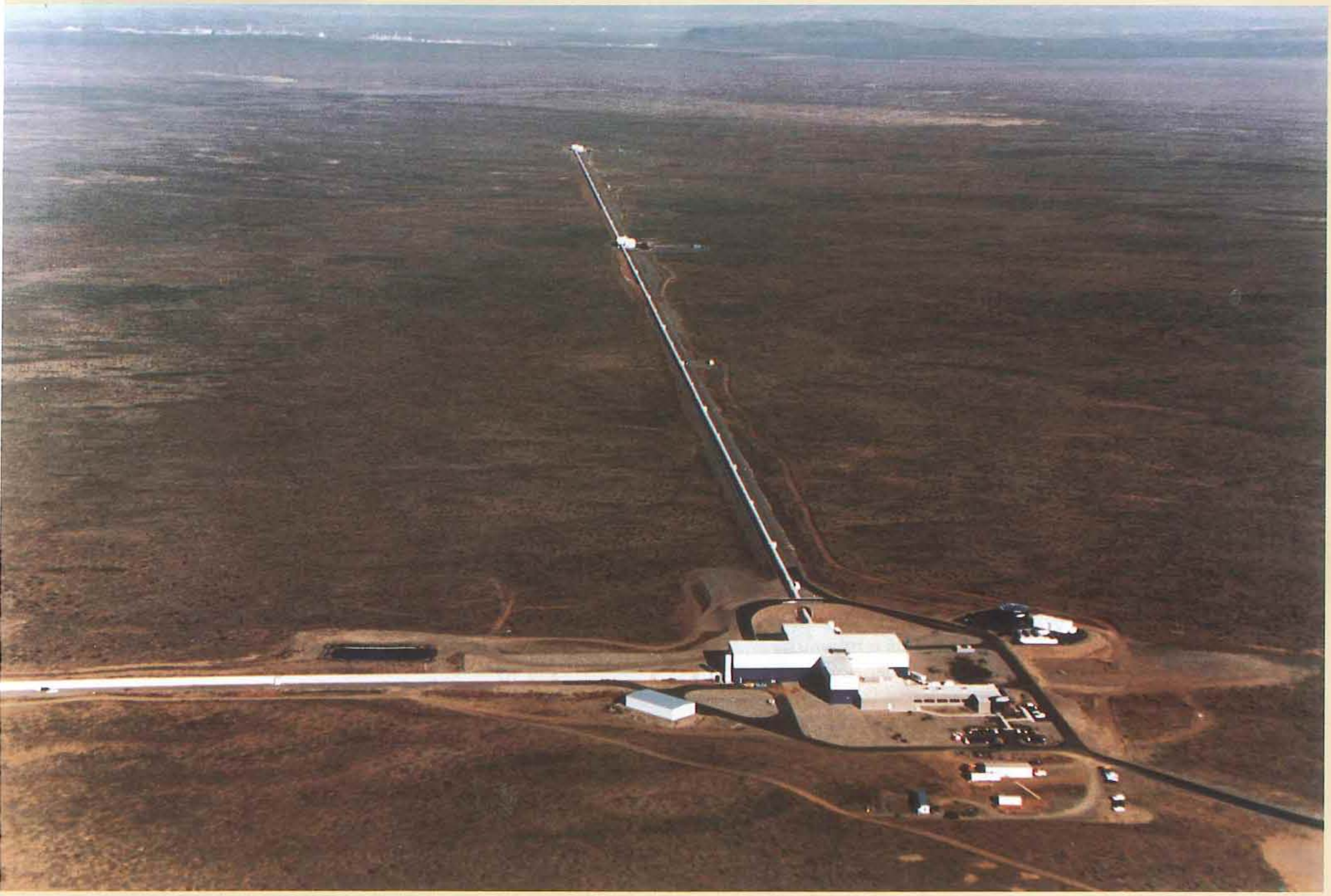
One of the dual instruments of the Laser Interferometer Gravitational-Wave Observatory sprawls across the desert near Hanford, Washington, each arm extending four kilometers and meeting at the corner of an L. The support buildings at the corner house laboratories as well as electronic and optical equipment, 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.

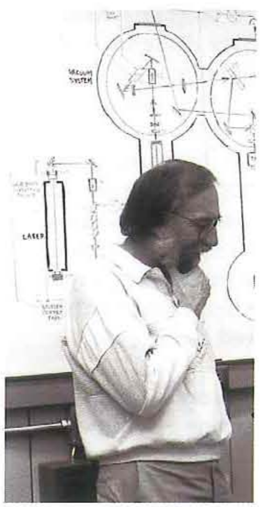
When scientists began their search, they didn't know how strong or how frequent gravity waves would be, and how sensitive their instruments would have to be to observe them. There was no precedent; it was virgin territory. Over the almost four decades after the search began, the need for more and more 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

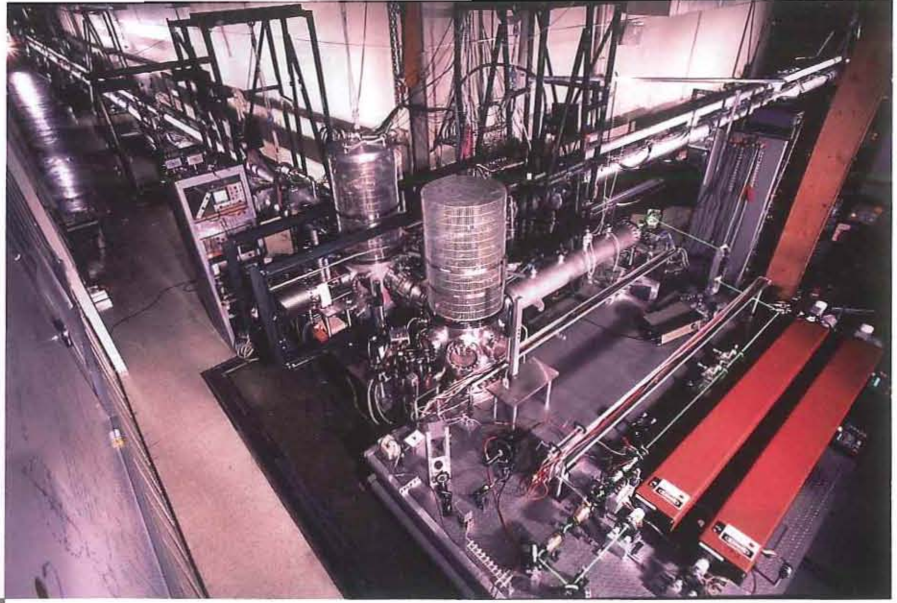


As two black holes orbit each other, in this representation of the curvature of space, they create outward-propagating ripples of curvature called gravitational waves.

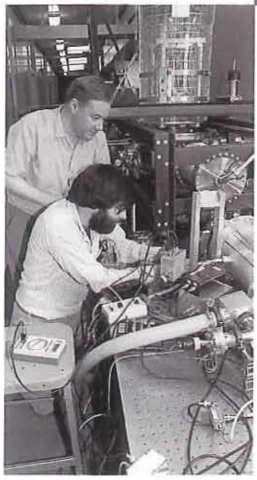
"I thought it was going to be much easier than this."

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."

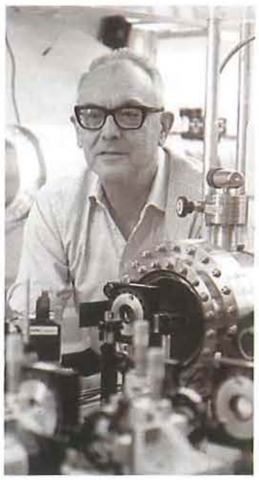
With Drever and Whitcomb building their 40-meter prototype, NSF refused to fund a similar prototype at MIT, but encouraged Weiss's desire to proceed with bigger plans, in space as well as on the ground. Weiss was thinking in terms of kilometers rather than meters. While a meter-sized instrument would 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 an intense week of presentations and deliberations, deciding almost from the beginning that the technical and scientific challenges *were* worth NSF's support. The committee strongly endorsed the project, including the Caltech/MIT proposal to go whole-hog and build two full-scale interferometers at the same time instead of sequentially. (It would be very difficult to detect gravity waves with just one; a coincidence between two is required to separate any real signal from the noise.)

But the committee chairs also took note of the profound management problems and, as urged by Weiss and others, demanded a new organizational structure: a cohesive team with a single strong leader who had the authority to make decisions without consensus. Enter Rochus (Robbie) Vogt, the Avery Distinguished Service Professor, former provost, former division chair, former chief scientist at JPL (where he continued to lead the Voyager cosmic-ray experiment team), and former acting director of the Owens Valley Radio Observatory. After months of pleading by Drever, Weiss, and Thorne, Vogt finally agreed to sign on as the project's director and principal investigator. "Without Weiss or Drever, this thing would never have even started," says Thorne, "but without Robbie it would never have taken off."



Robbie Vogt

The project that Vogt took command of in 1987 was still in reality two groups, which had developed completely different research programs with much duplication of effort and no common design. Said one member of the project, "Every time somebody wrote a working paper, somebody from the other institution wrote a dissenting working paper." This stopped under Vogt, who became a hands-on manager with a vigor that shocked some, but shook new life into the project. He made some hard decisions and shut down some research activities at MIT (he chose Drever's optical design and Drever's type of laser), but within a couple of years he had organized everyone into working toward a common goal. Not *just* a manager, Vogt was intimately involved in the scientific and engineering design of the project.

"It's Caltech's great fortune that Robbie was able to pull something together that could go forward," says Whitcomb, who had left the project in 1985, believing it could not happen under the conditions that prevailed at that time. Whitcomb returned as deputy director in 1991 after Vogt had resurrected what had now been christened LIGO. "Basically, he brought together a group of scientists who had never built something on this scale and led them to a conceptual design that was down-to-earth, quite practical, and used real technology," says Whitcomb. "He had to educate scientists without much practical real-world experience in what it means to design a piece of scientific hardware on a reasonable scale and have something that's practical to build."

Under Vogt's firm guidance, the new organization submitted a proposal for a full-scale interferometer that—after strong endorsement by outside reviewers—NSF accepted (see *E&S* Summer 1991). But while NSF could approve projects, an undertaking of this size and cost also required the blessing of Congress, which had to vote on providing the funds. Vogt then took on Washington. Admittedly a relative novice in government appropriations, Vogt in 1991 linked up with Hall Daily, Caltech's director of government relations (although "government" then most often meant Pasadena city hall), and the two set out to convince Congress to give them $47 million for the next fiscal year. The House appropriations subcommittee promptly zeroed it out, to the shock of NSF, which had expected the battle to come later, in the Senate. The project stayed alive on a fortuitous appropriation of $500,000, and in the winter of 1992, Vogt and Daily, along with newly hired consultant April Burke (to be their

Above: The vacuum tanks arrive at Hanford in August 1997. Right: By February 1998 the vacuum equipment is installed at the point of the L. The center vertical tank houses the beam splitter. At right one of the beam tubes takes off into the desert.

"eyes and ears" in Washington), set to work in earnest. Resistance in the House remained strong. There was philosophical opposition to the NSF's involvement in big-science projects. In comparison to the Superconducting Super Collider and the space station, LIGO wasn't really "big," but NSF had never attempted anything on this scale before. In addition, some in the scientific community opposed it. Some doubted that an instrument capable of doing the job could be built with 1990s or 2000s technology; and others, particularly astronomers, were disturbed by the risk that LIGO's first interferometers would see nothing, and thought the money could better be spent on electromagnetic telescopes, where success could be far better assured. Though NSF insisted that shifting the money to electromagnetic telescopes was not an option, many doubted that claim.

Vogt had in the meantime worked out a realistic budget, now totaling $220 million ("really an economy price," says Vogt), a budget that was embraced by NSF, which had been skeptical of previous estimates. Finally, there was a real, legitimate, bottoms-up estimate for what this thing would cost. It was divided into stages, with a "ramp up" period as construction demanded most of the funds, and a "ramp down" stage as construction costs tapered off and operations and advanced research and development that would require less money took center stage. The Caltech team also needed a strategy. To succeed in Washington, according to Daily, "you have to grab personal attention, tell a true story, and make a case that there's value attached to spending taxpayer money for some purpose." And Vogt became a master at selling his story. "Robbie was astounding," says Daily, at persuading people and delivering clear explanations of what gravity waves were all about. "He treated congressmen and staffers alike with respect and didn't talk down to them."

"It was a delight to talk to [Sen. Johnston]. . . . He was genuinely interested in science and cosmology." He was also chairman of one of the 13 appropriations subcommittees. . . .

Besides eyes and ears, LIGO needed a champion for its cause in Washington. It found one first in Sen. George Mitchell of Maine, and later, in 1993, after Maine had lost out in its bid for a LIGO site, in Sen. J. Bennett Johnston of Louisiana, whose state had been more fortunate. (The winning sites were Hanford, Washington, and Livingston Parish, Louisiana—both sufficiently remote, quiet, and above all, flat.) When Burke wangled a 20-minute audience with Johnston, Vogt so intrigued the senator with his cosmology tales that Johnston canceled his next appointment, and the two of them ended up sitting on the floor with Vogt drawing pictures of curved space on the senator's coffee table. "It was a delight to talk to him," Vogt says. "He was genuinely interested in science and cosmology." He was also chairman of one of the 13 appropriations subcommittees (and remained the ranking minority member after 1994). Although Johnston was unable to save the Superconducting Super Collider, which he had also championed and which Congress shot down in 1993, he was successful in getting LIGO through the Senate.

Louisiana turned out to be providentially well positioned in the House as well as in the Senate. Congressman Bob Livingston, in whose district the LIGO site lay (before it was redistricted out) and whom Vogt had already converted into a cosmology fan, became chairman of the House Appropriations Committee after the Republicans acceded to the majority position in Congress in 1994. LIGO continued on a roll, and its full funding looked assured.

For Vogt, Washington was a good experience. "I came back with a much more positive view of Congress than I ever had. And the reason is, I met many good people who worked very hard, who were idealistic and wanted to make things work—staffers in particular, but also congressmen and senators, who had absolute integrity and worked very, very hard under difficult conditions. I came back with much more respect for the system than I had before."

Meanwhile, however, back at Caltech, LIGO was outgrowing Vogt's team. The rules for big science, or even sort-of-big science, were changing, and NSF now favored a different kind of structure, one akin to the large, management-intensive organizations that built accelerators for high-energy physics. Vogt's project was lean on management; he likens its style to that of Lockheed's famous Skunk Works: "You basically build a project and you build a wall around it and say, 'Throw the money over the wall.' And in *n* years, I break the wall down and deliver a beautiful thing—an airplane or a LIGO." In 1994, NSF let Caltech know that it wasn't too keen on just throwing money over Vogt's wall, and Caltech's president, Tom Everhart, responded with another change in leadership.

(Vogt's close-knit and intense research group had also developed internal problems. Drever, whose research style some thought incompatible with the ever-larger-growing project, was separated from the project, triggering outrage and controversy among the Caltech faculty. When the dust finally settled, Drever had been promised his own independent laboratory, funded separately from LIGO.)

Barry Barish, the Linde Professor of Physics, succeeded Vogt. The end of the Vogt era was painful for just about everybody, but today Vogt waxes philosophical about his departure. Barish,

As seen from inside (above), a beam tube, at four feet in diameter, is almost big enough to stand in, hunched over. The tubes are laid out in sections on a concrete slab (right) and then covered with sections of concrete arch, six inches thick, seen here partially finished at the Louisiana site. The completed tunnel, in the less verdant expanse of Washington (above right), has access entrances every 250 meters.

he says, "represents what today is politically acceptable, and I represent what is politically no longer acceptable. That doesn't make him right and me wrong or vice versa. It just is a fact that life has changed, and some of us refuse to change—because maybe someone ought not to compromise, and some of us are in the fortunate position of being able to decline to do so." Vogt remained with LIGO until the summer of 1997, setting up the organization and methods for designing and constructing LIGO's first interferometers, initiating the design, doing cost reviews, and acting as mentor to a group of SURF (Summer Undergraduate Research Fellowship) students working on LIGO. Now he talks about doing something completely different—perhaps indulging a long-time desire to become a "gentleman scholar." He's also coteaching a course in the fall, with Associate Professor of History Diana Barkan, on the development of big science in the 20th century and the technological, social, and political factors that have altered the way science is practiced.

Recast in the image of a high-energy physics project, LIGO has thrived. Barish happens to be a genuine experimental high-energy physicist, and in 1994 had just recently returned from the biggest science of all—the $3-billion-plus SSC, where he was leader of one of the SSC's two detector groups. Barish also had roots in gravity waves, having been a member of the original committee that first recommended that Caltech get involved.

When Barish took over LIGO, he applied a lesson learned from the SSC—that two simultaneous sets of management, one for the construction and one for the scientific laboratory, only clashed with each other. "I wanted to make it as simple as possible," says Barish, "and the first task was just to build the thing. So I wanted a simple project management, a structure that was as unimaginative as you could possibly be—the kind of organization that builds a bridge." Barish assumed the title of LIGO's principal investigator, but left the title of laboratory director vacant until such time as the "bridge" was finished.

Everyone's favorite word to describe Barish's organization seems to be "robust" (as opposed to Vogt's Skunk Works, which was termed "fragile"). When LIGO, at full ramp-up, reached a certain size, it needed, says Thorne, "a robust management and a robust organization that could deal simultaneously with the construction of facilities, the R&D and planning for detectors, the pressures from the funding agencies, the pressures from the Caltech and MIT administrations and faculty, the continual reviews that the funding agency feels are necessary to insure success, and so forth." Barish's capacity to juggle all these things stems from his ability to delegate great amounts of authority, which consequently demands a larger management staff—not so "lean and mean" as its predecessor. This would cost more money, but NSF and Congress, realizing that it was necessary for the success of the project, accepted the increased costs without a whimper.

From the SSC Barish brought in Gary Sanders, another experimental high-energy physicist, to be project manager of LIGO. As project manager for one of the SSC's detectors, Sanders is, like Barish, one of a fairly small group of scientists who have had the unique experience of running big projects. As Sanders describes it, "A few of us have learned how to act like builders for a few years, and then stop and act like scientists for a few years, and then maybe go on and be builders again."

To act like a builder can often mean not acting like a scientist. A construction project, says Sanders, "is driven by schedules, the need not to fall behind—and the need *not to be too clever* and try to improve things. You have to think: this is what you're going to build; it's good enough to do the job; it's what you promised to build; build *this* and not a new idea that you just had yesterday. This is antithetical to what you do in the laboratory when you're doing research. There you strive each day for the best possible thing."

In June 1996, the contractor Chicago Bridge & Iron moved onto the Hanford site, in less than a year erected the total of eight kilometers of beam tubes in clean-room conditions (the stainless steel itself is so clean that it doesn't leak hydrogen into the vacuum inside the tubes), and then moved on to do it all over again in Livingston Parish, where it should be finished this summer. The support buildings are basically finished at both sites, and at Hanford the resident staff of 12 (and growing), under the direction of Fred Raab, has moved in, grateful for flush toilets at last. Operating funds (separate from construction funds) are already paying the utility bills. Recently, the high-precision seismic isolation system to shield the suspended mirrors from vibration has arrived at Hanford.

Gary Sanders, above; Barry Barish, right.

Besides containing scientists' offices and labs for optics, electronics, and vacuum systems, the main buildings (which are virtually identical at both sites) have a multipurpose area for lectures and visitor programs. The Livingston site, under the direction of Mark Coles, will put particular emphasis on educational outreach, with a museum and interactive exhibits.

All this construction represents the bulk of the expense of building LIGO, and although the technical achievement of creating one of the largest ultrahigh-vacuum systems on the planet is no mean feat, the real excitement and the intellectual challenge of the interferometer itself is just beginning. The vacuum equipment is currently being installed and tested. The detectors, being designed and built under the direction of Stan Whitcomb, are about a third of the way through fabrication. The first parts of the laser system have arrived at Hanford, but other detector bits are scattered at assorted manufacturers and institutions—including MIT and the University of Florida, as well as Caltech—in various stages of fabrication. About half the optics were finished as of this summer, many of the pieces residing in basements on the Caltech campus. The first mirrors, 10 inches in diameter and 4 inches thick, got their final coating in May. Some of the electronic components, such as the control systems and data-acquisition systems, are still in the final design stages. The integration of all these parts—pulling them together and getting the whole thing to work with the sensitivity it's been designed for—over the next couple of years is going to be the most challenging and the most difficult part of building LIGO, according to Sanders.

During the transitional phase, as construction is completed and operation begins, Barish and Sanders wear two hats—as builders *and* scientists; soon their builder roles will wither away, as the ramp-down period ends and LIGO settles into its long-term life with a budget of about $20 million annually for operations and another $2.5 million for advanced R&D. Last fall the LIGO Project officially became the LIGO Laboratory, a scientific undertaking, with Barish as director and Sanders as deputy director, and with a Caltech staff of about 80 people. Most have offices in Bridge Lab, but those responsible for data analysis and simulation of the detectors' performance moved this summer to the sixth floor of Millikan Library. The LIGO Laboratory also includes Weiss's substantial group at MIT and those being established at Hanford and Livingston Parish.

In addition, Barish has established the LIGO Scientific Collaboration, which includes, along with members of the LIGO Laboratory, also Thorne's theory group and his old friends in Moscow, Drever's new laboratory and his former colleagues in Glasgow, and groups of scientists from Stanford, the universities of Colorado, Florida, Michigan, Oregon, and Wisconsin-Milwaukee, and Northwestern, Penn State, and Syracuse universities, as well as two groups from Germany, and one from Australia. The Germans and Scots together are building their own GEO interferometer near Hannover, smaller and less sensitive than the U.S. duo, but likely to be turned on sooner, as is a similar Japanese device. The Australians have a design for another large interferometer, on the scale of Hanford and Livingston Parish, but as yet no funds. And near Pisa, France and Italy are building VIRGO, equivalent to one of LIGO's interferometers, which they expect to turn on around the same time—the year 2002. "We have a good working relationship with them," says Barish. "We collaborate on some technical things, and we expect to compare data, as data come in."

And when will the data come in? After the interferometer is finished will begin what Barish calls the learning period. "Everything will be built. Nominally we'll have light bouncing around, but we think it will take us two years (until 2002) to get the kind of sensitivity we've proposed and designed and to actually do science." No one is promising that the first gravitational wave will be seen in 2002. Says Barish, "From the experimental point of view, we'll do *our* part. From nature's point of view, there's always an uncertainty. But that's what happens when you look in a new direction where nobody's ever looked before."

Sanders is an optimist, the consequence of having survived other big projects. "Most of those efforts found new physics; many of them found physics that was different from what they set out to find." But while an optimist as to the outcome, he's also a realist about how difficult it's going to be to make it work. "It's going to be harder than we thought to actually make it work—that will take the next two to three years."

"From the experimental point of view, we'll do our part. From nature's point of view, there's always an uncertainty."

"This is the first of a kind, a tremendously ambitious device, so any troubles will start after we build it. I don't think we will have any major problems building it, but making it work is going to be the challenge," adds Barish.

Thorne, who back in 1976 thought the search for gravity waves might take 10 years, has been forced by LIGO's travails and many delays to lengthen his time horizon somewhat. He's not sure that LIGO's first searches will sight gravity waves—and he so told all reviewers of LIGO proposals from 1984 onward, a confession that helped ignite astronomers' opposition. However, he says, "I'm very optimistic that we'll be seeing waves by the middle of the coming decade, when enhancements of the first interferometers have increased their sensitivity 10-fold." For LIGO, as Sanders points out, was not built as an "experiment," but as a "capability" to do experiments, a platform for successive generations of detectors, which will continue to scan the universe to unravel its mysteries—just as electronic advances have enabled the 200-inch Hale Telescope on Palomar Mountain to keep its big eye on the sky for 50 years. Drever, as well as other members of the LIGO Scientific Collaboration, is already at work on the next generation of advanced detectors. Drever's lab's role, he says, is to "develop new ideas that are going to work—more sensitive instruments that can fit into the LIGO facilities to get much higher performance than we currently know how to do."

In hindsight, should a small campus like Caltech, where most science is done in small groups, have attempted to manage such a large project? Some critics along the way have insisted that it properly belonged in a national laboratory like Los Alamos or in an organization like the Jet Propulsion Laboratory. Thorne, who began it all, disagrees. "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. We even learned how to keep small-science groups like mine and Drever's healthy, alongside a huge project. Caltech could have just spun LIGO off like JPL was spun off, or have turned it over to JPL. But then our campus would not have nearly the degree of exciting gravity science and measurement technology that we will have with LIGO firmly ensconced here. Biologists face similar issues, as technology and science opportunities drive some of their science bigger and bigger. It would be unfortunate for Caltech not to learn how to do these things in ways that keep the intellectual ferment and payoffs right here on campus." □

If there are trees, this must be Louisiana. Otherwise the two LIGO sites are essentially identical. Two interferometers are necessary to single out a gravity-wave signal from the noise.