CHAPTER · 2

Inventing Machines That Discover Nature: Detectors at SLAC and KEK

Most people, when they think of tools for scientific research, think of telescopes and microscopes and X-ray machines; they assume that research equipment clarifies what is remote, small, or otherwise inaccessible to sight, much as eyeglasses help some of us to see the world more clearly.[1] Even accelerators have sometimes been likened to big microscopes. To understand the role of research equipment in high energy physics, one must have some familiarity with the stages of the research process.

It is an ancient idea that the universe is composed of indestructible fundamental elements and, nevertheless, remains infinitely complex and perpetually in flux. Classical Chinese, Hindu, and Greek texts disclose debates about the nature of these raw materials of the universe. In the late nineteenth century the contemporary model of the basic elements (called atoms, after the Greek word meaning indivisible) began to take form. J. J. Thomson proposed that atoms were composed of clusters of particles with negative electrical charge; the particles came to be called electrons (from a Greek word meaning amber, which retains an electrical charge). In 1913 Ernest Rutherford concluded that the bulk of the atom's mass was concentrated in a positively charged core, the nucleus, which is surrounded by orbiting electrons. He identified the positively charged constituents of the nucleus, named protons (Greek for *first* or *primordial*), in 1921; James Chadwick established in 1932 that the nucleus also contains particles without charge, or neutrons.

Even this tripartite model of the atom has not remained stable.

Atoms routinely emit and absorb electromagnetic radiation in the form of photons. A decaying neutron emits a neutrino as well as an electron and a proton. Interacting nuclei exchange pi-mesons. Further discoveries in particle physics have increased the number of "elementary" particles to well over one hundred. Various models have been devised to describe the relationships among these many particles. The classification system devised by Yuval Ne'eman and Murray Gell-Mann in 1961 (named the Eight-Fold Way) organizes the particles according to mass, charge, decay products, spin, and so forth. This system is analogous to the periodic table of the chemical elements developed by Mendeleev in the nineteenth century.

In addition to identifying the basic materials, any theory of fundamental immutable elements must also account for the appearance of movement that the universe presents to us. Historically, in physics this question has been posed in the following way: How do bodies act upon one another across space? Modern physics has identified four forces to account for "action at a distance." Two of these, gravity and electromagnetism, are familiar to classical physics. Two others, the strong and weak nuclear forces, are not.

From the work of Newton, Laplace, and Einstein the force of gravity is rather well understood; it operates from the cosmic to the terrestrial scale. Electromagnetism operates on the astronomical, planetary, terrestrial, and atomic scale. The strong nuclear force was first suggested in 1933 to explain how the positively charged proton and the neutron were bonded together in a stable nucleus on a scale where gravity is weak and electrostatic repulsion ought to force them apart. Physicists are able to manipulate this strong force, but it is not completely understood. The weak nuclear force was proposed in 1933 by Fermi to account for the natural radioactive decay of nuclei. This theory correctly predicted the existence of the neutrino.

Developments in particle theory forced physicists to reevaluate fundamental tenets of classical physics. From the sixteenth century to 1900 physics supported and refined a mechanistic view of nature. Classical physics, furthermore, had as its foundation an experimental method that stressed isolating cause from effect and determining which specific cause produces which particular effect. In 1926 Heisenberg and Schrödinger rejected the notion of strict causality in atomic processes. They concurred that at any given time it is impossible to determine the exact state of a system. If we cannot determine the exact state of a system at two separate points in time we cannot strictly determine specific causes and particular effects. We can only project *statistically* what effect might succeed what cause. The uncertainty principle was a serious challenge to the mechanistic model of classical Newtonian physics, and replaced it with a statistical model of the universe.

Initially in particle physics electromagnetism, gravity, and the strong and weak forces were seen as incommensurable. Then, electromagnetism and the weak force were linked by Sheldon Glashow, Abdus Salam, and Steven Weinberg in a theory of the electroweak force; this theory correctly predicted two new particles, the *W* and *Z*, which were found in 1983. Eventually gauge field theories of the strong force and the electroweak force were combined into a Grand Unification Theory, or GUT. Theoretical efforts are now under way to incorporate gravity with a GUT, and these are called "superstring theories." Physicists are also trying to incorporate superstring theories and supersymmetry into a "Super GUT." The proposed research device known as the Superconducting Super Collider (SSC) is justified as necessary to investigate these new theories.

The SSC is an accelerator, which is a device that impels particles to very high energies and then directs them at "targets" composed of other particles. The collisions of the accelerated particles with the target particles generate energy; most of this energy takes the form of new particles, although some energy is released in the form of radiation. Targets are closely surrounded by diverse devices that record traces of the new particles. The target plus the recording device and the computing system that analyzes the records is called a "detector."

At any laboratory there are many detectors near the accelerator, receiving accelerated particles from it. Since the particles are clustered into discrete pulses, they can be directed—by magnets in the switchyard that bend their paths—to any of the detectors. One detector may be able to accommodate sixty pulses per second; another, ten; yet another, thirty. The full load of the accelerator beam (which may be as much as three hundred and sixty pulses per second) is distributed in this way to the several experiments being conducted concurrently, each using one detector.

The accelerator belongs to the laboratory as a whole, but each of the resident groups of experimentalists conceives, constructs, maintains, and develops its own detector. Detectors are distinctive and serve as the "signature" of the group. These machines are at the heart of the research activity of particle physicists. Detectors—their conception and development, their maintenance, their performance during the precious allotment of beamtime for an experiment—are the stuff of frustration, hope, heartbreak, and triumph for research groups. Discovering a new way to detect and record the traces of elementary particles can bring great honor and influence. A detector that ran perfectly at all times would be considered either obsolete or not daring enough in conception.

The place of detectors in high energy physics contrasts sharply with the role of research equipment in many other fields. In much biological research, for example, laboratory machines are not built or even designed by the scientists using them; they are mass-produced and advertised in catalogs. Their design incorporates theories and laboratory practices so widely accepted that their validity has not been questioned for many years, perhaps decades. Bruno Latour and Steve Woolgar in their study of an endocrinology laboratory vividly describe how such tools represent "reified theory" and are regarded by scientists as useful, but routine and uninteresting.[2] The endocrinologists' research reports never describe the workings of the "black boxes" they use.

High energy physics detectors are not black boxes with unquestioned assumptions hard-programmed into them. In high energy physics inventing machines is part of discovering nature. In this chapter I describe four styles in detector design, represented by three detectors at SLAC and one at KEK. These four styles represent four different strategies for making discoveries: four different strategies for spending money, organizing a research group, and becoming a success in science. Many physicists have claimed that big machines in science determine the organization of scientific research, even that they determine the research questions. By looking closely at how specific machines shape scientific practices and at how scientists regard the machines they are constantly building and rebuilding, we can challenge the claim of mechanistic determination.

Most high energy physics detectors share certain characteristics. A closed container houses a highly sensitive medium. Pulses from the accelerated beam enter the container and collide with particles of the medium; new particles, generated by the collisions, are propelled through the medium, creating disturbances that are meticulously tracked and measured. The record of the pattern of disturbances is then analyzed for clues to the properties of the particles that caused the disturbance. Significant differences between detectors of the same type depend upon how sensitive the initial environment is, how effectively that environment can be controlled, how finely the disturbance of the medium can be differentiated, and how precisely that disturbance can be calibrated. Physicists also want to know how frequently the process can be repeated so as to accumulate as many events as possible during each experiment; this will enhance the validity of their conclusions and increase the probability that a rare event will be "seen."

Other aspects of the ambient environment, besides the particles generated by the controlled collision, also disturb the medium and trigger the measuring and recording equipment. These undesired disturbances are "noise." A fine detector should enable physicists to identify and measure the noise generated in any specific experiment. A highly sensitive medium, capable of finely differentiated disturbance, associated with a system that can measure those minute fluctuations, adds up to a delicate piece of machinery, quite vulnerable to high levels of noise, some of which will be unpredictable. Experimentalists strive to maximize sensitivity and speed while minimizing noise, especially unpredictable noise. In the high energy physicists' view a mass-produced detector would necessarily have an unacceptably large margin of conservatism built into it. Once one of their own detectors begins to work with great regularity and predictability, it becomes a candidate for manufacture and distribution to scientists in other fields; it is obsolete for high energy physics. A detector can be discarded (or never even built) for another reason: cost. The price of achieving the sensitivity, calibrating the noise, or "reading" the data can become prohibitive.

Given these common features and problems, detectors are rated by the extent to which they maximize one of the component variables: sensitivity in identifying the presence of particles, speed of data collection, capacity for distinguishing noise, and efficiency of data analysis. Bubble chambers provide the most elaborate data on particle behavior; but they collect data much more slowly than other detectors, and since the data are recorded photographically rather than directly in computers, analysis involves human scanners and is therefore lengthy and costly. At the other extreme are

"counters," which merely signal that some particle has passed through a sensitive grid of wires at a specific point; this sort of information can be recorded immediately in computers and analysis can begin while the experiment is still running so that the experimentalists can judge the quality of data they are gathering and alter the experiment accordingly; this is "on-line" or "real-time" data analysis. Experimentalists always search for new ways to collect complex data quickly so that information can be recorded directly into computers for on-line data analysis.

Ancestral Machines

There have been nine detectors in the SLAC research yard, fed from the SLAC accelerator: three bubble chambers, a spark chamber, a streamer chamber, a large aperture solenoid spectrometer, a group of three spectrometers, and two detectors associated with a colliding beam facility. The bubble, spark, and streamer chambers represent refinements of decades-old innovations. The others are examples of more recent developments. Before turning to a discussion of the four styles of detector design I came across during my research in the 1970s, I will briefly describe their forerunners.

Bubble chambers were developed by Donald Glaser at the University of Michigan in the early 1950s; in 1960 they brought him the Nobel Prize.[3] He is quoted as saying that he decided to persevere in his studies on bubble chambers because of a conversation over a few beers with fellow physicists:

> After several pitchers of beer we began to wax philosophical about physics. One of the boys, looking dreamily into the pitcher of beer before him, saw the usual streamers of bubbles and remarked, "You can see tracks in nearly everything." Just for fun I actually exposed some beer to gamma rays the next day in the laboratory. Nothing happened.[4]

Bubble chambers usually contain hydrogen, which has a comparatively simple structure. Liquid hydrogen in a very smooth vessel is put under increasing pressure; under certain conditions, it can be "superheated" beyond its boiling point without boiling. In this state it is highly sensitive to any fluctuations in temperature. Then, a bunch of particles from the accelerator is allowed to enter the vessel. Each collision between an accelerated particle and a particle of the superheated liquid generates heat, causing the liquid to begin to boil at the point of collision; the pressure is lowered just enough to allow an initial bubble to form. The energy created by each collision re-forms into new, short-lived particles, which scatter away from the original collision; the heat generated by their movement causes the liquid to bubble along their trajectories. The entire vessel is surrounded with strong magnets, which are turned on just as the initial interaction occurs. This causes any new particle with an electrical charge to be attracted toward one or the other of the magnetic fields; its bubbling track bends accordingly. The angle to which that particle's trajectory is bent by the known force of the magnetic field is a measure of the particle's momentum. If a particle disintegrates or decays into other particles while in the medium, the trajectory will split. The whole array of bubbling tracks in the bubble chamber is photographed from three directions so that the trajectories can be reconstructed in three dimensions. Then the pressure must be further reduced to allow the bubbles to recondense back into the liquid; if the whole liquid in its superheated state were to start to boil, the vessel might well explode. When the liquid regains its stability, the whole process is repeated. Bubble chambers vary in how often this process can be repeated and in the quality of the pictures that are produced. (One bubble chamber at SLAC, the eighty-two-inch chamber, took 24.3 million pictures over a five-and-a-half year period, pulsing twice a second during its experimental runs.)[5] The pictures are then scanned to measure and classify all the tracks, and this information is recorded in computers and analyzed for "significant events"—tracks with particular configurations of interest to the current experiment. Two advantages of bubble chambers are that resolution of the particle track is very good and that the liquid can be changed to provide alternative target particles.

Spark chambers and streamer chambers are similar to bubble chambers in that a sensitive medium is used to signal the presence of a particle and its path.[6] Both spark and streamer chambers rely on a stack of two-dimensional grids of fine wires aligned in the sensitive medium; when the grids "fire" in sequence, the inference is that one particle and its decay products, passing through the grids, caused the series of signals. Spark chambers can operate much faster than bubble chambers, and they can be set up so that photographs will be taken only when significant events occur; this

reduces the time and cost of data analysis. Streamer chambers represent an attempt to combine the advantages of bubble and spark chambers—selective triggering on the one hand, and fine resolution of tracks on the other—by turning a series of isolated sparks into a stream of dots, as in a bubble chamber picture. The result is a set of discontinuous signals as in a spark chamber, not a continuous track, as in a bubble chamber: the grids of fine wires can never be placed close enough together to replicate the density of signals possible in liquids.

SLAC's spark, streamer, and bubble chambers are fine examples of their kinds. The eighty-two-inch bubble chamber was built, in fact, at the Lawrence Radiation Laboratory in Berkeley in 1959, as a seventy-two-inch chamber. In 1967 it was brought to SLAC, with most of its operating crew, to take advantage of the special characteristics of the accelerator beam there. The chamber was dismantled, modified, and rebuilt as an eighty-two-inch chamber. It was dismantled finally in 1973 because the cost of analyzing its photographic data, relative to other detectors, had become prohibitive. The director of the laboratory also argued that, although the eighty-two-inch chamber was a detector that still produced very fine physics, it was no longer sufficiently distinctive. His strategy was to maximize the laboratory's access to funding by concentrating on research equipment and processes that could not be duplicated at other laboratories. I attended the party held in the fall of 1973 in honor of the chamber, just before it was finally dismantled.[7] The twenty-five-foot-high structure housing the chamber was decorated with streamers from reels of film which had been used in recording its data. Among the people present were those who had been involved in building, maintaining, and modifying the chamber and many of the physicists who had designed it and used it for experiments. Seventeen new particles and resonances had been discovered in the course of its long and honorable career.

The physicists and operators of the eighty-two-inch chamber were disturbed and saddened by its impending demise. We stood in the metal shed, gathered around the machine, drinking beer (of course) and listening to tales of the glories and quirks of the fourteen-year-old machine. The technicians at the chamber had been among the first at the lab to befriend me and explain their detector to me in detail; I had long been impressed with their ingenuity in simultaneously modifying the detector and keeping it working so well. It looked like a Rube Goldberg contraption and made a lot of noise while it was operating. The pressurization system was built partly with Navy surplus materials from submarines, partly with the most sophisticated special-purpose fittings available. The cameras used to record the tracks had had to be rebuilt at SLAC because the specifications could not be met by any supplier. The group members were proud that they had expended money and time selectively, only when needed, and used experience and ingenuity to find workable shortcuts.

I had especially enjoyed standing above the chamber while it was operating, peering inside its windows and watching the tracks form and re-form as the whole structure shook with each pulse of the pressurization system. The structure felt rickety and looked worse, but the chamber itself, encased in all its supporting equipment, was gleaming, smooth, and elegant. The events in the chamber gave me the impression I was actually seeing the fundamental constituents of nature at work, as if through a gigantic microscope. It was not easy to remember that I was looking at signals produced by a machine designed to react in a stylized way to the debris from a collision occurring under highly controlled and artificial conditions. I was not looking through a window on the world of subatomic particles; I was doing something more like reading dinosaur tracks. It was the "real-time" activity in the chamber that created the impression of seeing.

The group had already begun work on two new bubble chambers. They had "married" a forty-inch bubble chamber to a spark chamber and achieved a pulse rate of six pulses per second. By using the spark chambers to pick out interesting events, they were on average taking only one picture in thirty pulses; the rapid pulsing meant that many more interesting events were observed, and the bubble chamber provided rich data on each. Later the hybrid forty-inch chamber achieved higher pulse rates and was "married" to other devices used to refine its selection of interesting events to photograph. Its pressurization system had been cannibalized from the eighty-two-inch chamber.[8] Groups can cannibalize their own past, but they cannot take over equipment from other groups, no matter how useless the materials may have become to their owners. The same holds for computer software. I found this to be true in Japan, at Fermilab, CERN, and SLAC.

To give a sense of how sensitive a detector is and how a group

is preoccupied with designing, maintaining, and modifying their detector in addition to operating it for experiments, I will quote at length from a report written by a member of the Bubble Chamber Group on the hybrid forty-inch chamber:

> A number of changes were made to shorten the recondensation time and extend the pulse rate. Pressures were raised to cause more rapid condensation. Heat exchangers were positioned to promote convection and prevent bubbles from collecting in pockets. Cracks and crevices, the most copious producers of bubbles, were eliminated wherever possible. There are no longer any bolted joints inside the chamber. Everything has been welded. The main glass window seal, a major source of bubbles, now has a special cast and machined indium sealing surface which is far superior to the conventional indium wire seal.
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> A second problem is to produce accurate and uniform expansions with the hydraulic actuator. The piston must move with a precision of a few thousandths of an inch in space with an accuracy of one ten thousandth of a second in time. The hydraulic system must produce this motion against a three-quarter ton force ten times per second.
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> When everything is in good working order, the expansion system, originally developed by the operations group for the 82-inch bubble chamber, works admirably well at 10 pps [pulses per second]. There are some difficulties, though. At 10 pps mechanical vibrations do not die out between pulses but build up to such a level that parts break from fatigue. In spite of a continuous program of strengthening, a large number of bolts were broken during the experiment. Repairs were often made to the machine while pulsing in order to keep it going. Ten expansions per second require 30 gallons of hydraulic oil per minute under 3000 pounds per square inch of pressure. During the early part of the experiment there were numerous failures of the hydraulic plumbing. With this quantity of high-pressure oil flowing, the leaks were often spectacular.
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> Once the chamber began to run regularly at 10 pps, the pictures began to show that some tracks were disappearing in parts of the chamber and reappearing in other parts. At first it was thought that this was due to incorrect temperatures in some parts of the chamber which prevented the bubbles from growing. This had to be discounted when it was found that the trackless areas varied from pulse to pulse. Furthermore the problem went away if the chamber was pulsed slowly. The difficulty was finally uncovered

in the hydraulic system. At high pulse rates, oil in the exhaust pipe would resonate like air in an organ pipe. A pocket of gas would collect inside the actuator. Each time the chamber pulsed, this gas pocket collapsed causing a vibration that was transmitted to the main piston inside the chamber. The pressure variations in the hydrogen from this piston vibration caused the track bubbles not to form in some parts of the chamber. Once the oil pipe was pressurized to prevent the gas pocket, the vibration disappeared and tracks were visible throughout the chamber.

The entire experiment was done with one Scotchlite reflector. The chamber stayed clean for the whole experiment and the optical quality of the pictures was always good. This experiment would have been impractical in any chamber which became dirty from pulsing.[9]

The other new machine the group was beginning to work on was the fifteen-inch Rapid Cycling Bubble Chamber (known as "the RCBC"). It had an electromagnetic rather than a hydraulic drive system and would ultimately be able to pulse up to sixty times per second. Its powerful magnet, which was nevertheless quite small because it was superconducting, was designed and built by the Cryogenics Research Group at the lab.[10] These newer bubble chambers are smaller than the eighty-two-inch and are contained in more compact supporting structures.

Machine Styles and Strategies for Making Discoveries

The ESA detectors. As one travels beyond the stately central plaza at SLAC, beyond the uniform laboratory offices, beyond the orderly two-mile procession of klystrons accelerating properly aligned electrons, beyond the subterranean, systematic beam switchyard, one descends by road into the huge, paved Research Yard, excavated twenty-five feet to accelerator level. The Yard resembles nothing so much as a big, messy manufacturing business. At one end is a monolithic, windowless concrete structure, seven storeys high. Several corrugated metal one- and two-storey buildings are scattered around the Yard. The rest is a haphazard jumble of massive concrete blocks, large cable spools, stacked lumber, very big cranes, fork lifts, some toilet sheds, and clusters of automobiles. The people working here look a little dirty; some wear

safety helmets. Over the years I have discovered that most nonscientists think of labs as extremely clean, meticulously tidy places where people in immaculate white coats do their work with minute, precise movements, and that scientists work alone, in silence. High energy physics laboratories are not like that.

Walking around this terrain, one is confronted by obstacles in almost every direction—raised wooden burrows housing the electrical cables, thick as a fist, that connect the detectors to power sources and to computers. One crosses these by means of little ladders, much like stiles for crossing country fences.

At the far end of the Research Yard is "End Station A," a massive seven-storey concrete structure with thick walls that move on rails like barn doors. The heavy concrete protects against the radiation produced inside. As with the accelerator and the switchyard, no one is allowed in this building during an experiment; the research devices are controlled remotely during a typical "run" of several weeks. Radiation is a problem at End Station A because the spectrometers there do not retain all the new particles generated from collisions; bubble chambers do retain all the generated particles, so the radiation they produce is contained.

Experiments here can make use of the maximum energy of the beam and up to 320 of the beam's 360 pulses per second. When the incoming accelerated electrons collide with target protons, the electron is said to "scatter" and the proton to "recoil" ("elastic electron scattering"); in some interactions new particles are also generated ("inelastic electron scattering"). In some experiments the electron beam is directed at a preliminary target, generating photons which are used as a "secondary" beam to collide with the usual target protons. In this case (photon-proton interactions) the proton recoils and new particles are also generated; this is "photoproduction"—production of new particles by means of a photon beam. The three spectrometers in End Station A are designed to measure the amount of electrons scattered, the new particles produced, and the recoil of the proton.

Between experimental runs, the usual access to End Station A, unless the walls are open, is through a long corridor opening onto the vast 2,500-square-meter interior space of the building. The most prominent objects in the room are three big concrete boxes, each mounted on one of a concentric set of rails forming nearly a half circle that takes up most of the width of the room. At the center of these rails is the target, a drum-sized metal cylinder mounted on a tall pivot made for a sixteen-inch gun from a World War II battleship. The base of the pivot is in a narrow dark circular pit. The beam from the accelerator comes in along an overhead pipe and meets the target about nine feet above ground. Below that, collars turning on the pivot connect to three bulky, rigid limbs, each one leading its catch of particles from the collisions in the target out to one of the concrete boxes.

The three limbs all look different: each contains magnets that bend and focus the path of electrons and new particles. The amount of resistance to these constraints is the first indication the detectors receive about the momentum and position of the particles at the moment of collision. The two longer limbs are about two meters wide and high; one is about fifty meters long, the other about twenty-five meters. The concrete boxes open to reveal configurations of detectors, which have changed often over the years. Originally, simple counters were arrayed in the boxes. By 1971, these were supplemented by multiwire proportional chambers, so that the data about the scattered and newly produced particles could be further refined. This added information also makes possible better detection and rejection of data from unwanted sources. The multiwire proportional chamber is a new type of spark chamber originally developed at CERN. In the grid used to detect the presence of particles, wires were placed particularly close together, but in a way that avoided the danger of having the whole system trigger itself. Each wire constricted when fired by a passing particle; when that constriction moved (at a predictable rate) to the end of the wire at the edge of the metal frame, the computer was signaled. In this way, a great amount of very precise information was collected.

The longest spectrometer, called the twenty GeV (billion electron volts), is fifty meters long and weighs two thousand tons; the eight GeV is twenty-five meters long and weighs one thousand tons. The third and shortest spectrometer, the 1.6 GeV, weighs 575 tons.[11] The larger spectrometers analyze scattered and newly produced particles; the smallest spectrometer analyzes the recoiled protons. Large electrical cables spew out of the boxes' detectors and are carried alongside the magnets, down the arms of the spectrometers to the control pit. From there, gathered together, they are guided along the floor and up the wall, where they enter the Counting House, End Station A's control room and computer facility.

Each of these three spectrometers is very limited in the characteristics it can identify and the particles it can capture. Particles scatter from the target in all directions; the spectrometers can monitor only those particles whose paths coincide with the three limbs. However, they have two important advantages: first, at 320 pulses per second, an extremely large number of events can be analyzed; second, all three spectrometers can be moved. They can rotate through a total of 165 degrees around the target.

The pervasive grey of the concrete at End Station A (or ESA) and the large, lumbering detector boxes, with their supporting equipment reaching toward the pivot pit, always look to me like great mechanical elephants with their trunks plumbing a watering hole. The room and the spectrometers seem massive, mechanical, and clumsy. It is difficult to remember that this is the fastest detector at SLAC and the site of more than one experiment of major theoretical consequence. The scattering experiments have served to arbitrate between theories on the internal structure of the proton. The design and integration at ESA of the polarized electron beam source called "PEGGY" and a target with polarized protons has enabled experimentalists to design an experiment from which it was concluded that time reversal invariance is maintained—that is, these particle interactions proceed the same whether "time" is going forward or backward.[12]

LASS. Nearby is a building containing another kind of detector, the Large Aperture Solenoid Spectrometer, known by its acronym, LASS. As I described earlier, particle activity in a bubble chamber can be detected in three dimensions because the medium in which the initial collision between accelerated particles and target particles occurs is also the medium of detection. The difficulty with bubble chambers, however, is their slow rate of data collection and the expense of analyzing data from visual records. The hybrid systems minimize these problems, but do not eliminate them. LASS represents another approach.

In an earlier incarnation of this detector, several different kinds of recording devices, including both counters and spark chambers, were aligned behind the target, which is at the core of a very large magnet. As in the bubble chambers, the purpose of the magnet is to alter the path of charged particles and provide a measure of that particle's mass and lifetime. Several characteristics of those fast-moving particles which emerged in a "downstream" direction from the initial collision, continuing the direction of the beam, could be identified. This detector was called the neutral K meson wire chamber facility (the K^0 or the "K-zero"), after the altered particle beam of mesons it used. The group leader was very proud of the degree of resolution achieved in the multiwire proportional chambers. The group leader also noted to me that the construction of these "magnetorestrictive" spark chambers and the Cerenkov counters used with them, which identify particles by their characteristic light emissions, included techniques he had developed as a young physicist.[13]

The K-zero was incorporated into LASS, much as the hydraulic drive system from the eighty-two-inch bubble chamber was incorporated into later bubble chambers built by the same group. The added features were designed to identify the slower-moving particles that had emerged from the initial collision at wider angles than the K-zero could detect. This diverse array of magnets and detecting devices means that a great deal of information can be gathered about each particle path, even though LASS is not a three-dimensional detector. All of the information is recorded by computers, and complex data analysis can be conducted during an experiment. Considerable computing power is required for operating the detector, data collection, and analysis, especially given the speed at which LASS is designed to operate: while the eighty-two-inch chamber recorded 24.3 million events in five-and-a-half years, LASS could record one hundred million events in one year. These massive computing requirements eventually led to the acquisition of a major new computer for SLAC, the IBM 3081.

LASS was designed to investigate interactions analogous to those explored at End Station A. In the ESA scattering experiments, accelerated electrons collided with target protons, generating new particles and causing the electron and proton to recoil. LASS would be able to study the same kind of scattering process, but between different kinds of particles. In particular, LASS would analyze hadron-hadron interactions. Electrons have charge, which means that they belong to a class of particles interacting by means of electromagnetic force. Hadrons are particles that interact by means of the strong nuclear force.

LASS is about twenty meters long, and three to five meters high. Each of the components, aligned in series along the beam path, has a distinctive configuration. The four separate successive coils of the superconducting magnet, three meters in diameter, are smooth, thick, and bright. Sandwiched between these coils are the multiwire proportional chambers; almost all that is visible of them

is their long electrical cables. This whole section rests on a system of rails and jacks so that it can be aligned and dismantled easily. All this is straddled by a long-legged rigging, which supports the refrigeration system for cooling the magnets. The rigging looks like a giant daddy longlegs insect embracing a metal and plastic caterpillar.

Next is the conventional magnet. After that the fast-moving particles enter what is essentially the old K-zero detector. Its magnetic coil is wrapped into a configuration that looks like giant lips surrounding the particle path for a meter of its length. Next are the twelve flat, one-meter square wire spark chambers with their mass of electrical cords, hung on bright metal frames. Each frame looks like a vertical loom, and the spark chamber is like a rug with its threads still attached to the frame on all four edges. Seeing a dozen of these frames with chamber and cords attached, arrayed in series, brings to mind a textile mill. The physicists move around and between the frames, adjusting the chambers and tinkering with the cords, like loom operators. The buildings are not heated or well lit, which enhances the image of a nineteenth-century mill. The closely spaced chambers covered with plastic sheeting resemble the bellows of a huge plate camera. At the end of the entire tract is a dark box, five meters long, containing the Cerenkov counters, which extract the final data from the event by analyzing the light emitted by the particles. Hovering over all this, near the ceiling and moving on rails that run along two opposing walls of the building, is a seven-and-a-half-ton-capacity crane. The crane is used to dismantle and rearrange the components of the detector.

LASS took several years to design and construct; the final stages included many setbacks, especially in construction of the magnets. During this time, doubts were raised at the lab and in the larger physics community as a whole about the viability of this detector, and whether the physics it was designed to do would prove worth the resources that had been allocated to it. Some physicists thought that the design was impossibly reliant on engineering precision; others thought that the physics questions being asked were state of the art but that the detector was undistinguished in conception. Doubts like these, I came to realize, beset any project, especially once it is funded. Part of the responsibility of a group leader is to defend the group's project (and budget) against all efforts to diminish it. Years later the technology for on-line data analysis developed for LASS had been incorporated into many other detectors.

Shortly after the LASS magnets began operating, a party was held in its honor. The research group played host in the building housing LASS to all who had contributed, directly or indirectly, to the existence of the detector. The party for LASS included huge kegs of beer; the group was known to have gathered often at a nearby tavern during the long struggles of funding and construction, to discuss physics and their LASS. Each group member could be seen, holding a half-quart paper cup of beer, pointing to parts of LASS and talking animatedly or sitting in the control room bringing up interesting graphics on the video screens about LASS's sensitive self-monitoring system.

SPEAR. North of LASS and beyond the bulwark of End Station A is a facility which almost failed to be built. It is called SPEAR, an acronym for Stanford Positron Electron Asymmetric Rings. The original design called for two pear-shaped rings; the final design has one symmetric ring, but the name remains. SPEAR is one of a growing number of "colliding beam" facilities at high energy physics laboratories, in which two accelerated beams of particles are made to collide with each other, thereby doubling the center-of-mass energy available at the moment of collision. For example, if each beam had an energy of 4.5 GeV, the center-of-mass energy available at the moment of collision would be nine GeV. Collisions between an accelerated beam and a stationary target have a much lower interaction energy, because the recoil of the original particles is so much energy lost. It would take a conventional accelerator capable of accelerating a beam to fifty GeV to produce nine GeV center-of-mass energy. A significant tradeoff, however, is that the accelerated particles actually collide much less often in a colliding beam design than in the conventional configuration, because a beam is less dense than a stationary target.[14]

A special feature of colliding beams is that usually one beam is composed of the antiparticle of the other beam. For example, at SPEAR, one beam is composed of electrons from the linear accelerator. The other beam, also from the accelerator, is composed of antielectrons, called positrons. An antiparticle has most characteristics in common with its particle, but not its electrical charge, which is reversed. A positron is a positively charged electron. Positrons are generated in the accelerator by causing a partially accelerated beam of electrons to strike a tungsten or copper target inserted about one third of the way down the two-mile accelerator.

The resulting gamma rays, striking another target, generate electrons and positrons in pairs. The electrons are pulled aside by means of magnets, leaving a beam of positrons which then are accelerated the remaining length of the accelerator.[15] Colliding beam facilities use particle and antiparticle beams because in particle-antiparticle interactions no matter survives and there is no recoil: both particles are annihilated, with only energy remaining. This energy then re-forms into new particles, some leptons and some hadrons.

The first colliding beam facility was built at the Stanford University High Energy Physics Laboratory (HEPL) in the late 1950s and early 1960s. The leader of the group that designed, constructed, maintains, and does experiments with SPEAR was a member of the Stanford-Princeton team that built the HEPL ring. He joined SLAC in 1963 and submitted his first proposal for a high energy colliding beam facility at SLAC in 1964. That and subsequent proposals were rejected until 1970, when a relatively modest version was accepted; it still seemed to many a wildly implausible concept. Actually, SPEAR was not funded through the usual channels. The Atomic Energy Commission, the federal agency that then funded particle physics research in the United States, merely allowed SLAC's director to bypass his own Program Advisory Committee and shift five million dollars from other projects to finance the construction of SPEAR.

The man leading the SPEAR group had done important work in the 1950s on electron-positron interactions, establishing that the current analysis of the electromagnetic force was correct at extremely short distances (10^{-13} centimeters). He had decided he wanted to study hadrons, which interact by means of the strong nuclear force:

> It seemed to me that the electron-positron system, which allowed one to produce these particles in a particularly simple initial state, was the right way to do it . . . That was the beginning of the long struggle to obtain funding for the device.[16]

In spite of the precariousness of funding worldwide for high energy physics since the early 1970s and the difficulty of funding SPEAR, a report by this group circulated in 1972 at SLAC projected the following timetable:

> In 1972—conceptual design and physics studies; 1973—begin detailed engineering studies and writing of proposals; 1974—submit official proposal to the AEC, asking authorization for construction to begin in FY 1976. With such a timetable, a PEP accelerator [a much expanded colliding beam facility on the model of SPEAR] would be operating about 1980.[17]

With small perturbations, this timetable's predictions were fulfilled. It is typical for a lab's new projects to enter the design stage immediately after other projects have been funded, so that there is a continuous cycle of ideas seeking funding. Of course, many projects never make it beyond the design and proposal stage.

The main approach to SPEAR is by a narrow bridge over the ring, which is about seventy-five meters across. To a visitor driving over the makeshift bridge into the circular paved parking area occupying most of the middle of the ring, SPEAR looks like a series of concrete boxes closely arranged in a circle. At the edge of the parking area is a corrugated metal building; scattered around the paved lot are some metal sheds for supplies and a trailer used for office space. Interrupting the ring at opposite sides are two more corrugated metal buildings. Walking inside one of these two buildings, one is confronted by a deep, paved rectangular pit surrounded by a narrow walkway with a metal railing. Sunk halfway into the pit is a 150-ton octagonal object standing on edge, fifteen feet thick and fifteen feet high, with people crawling around it and inside it. This is one of the SPEAR detectors, called MARK I. It looks like a huge mechanical model of an eye, with a hole for the lens and eight concentric rings of alternating grey metal and black plastic for the iris, all outlined by black metal. Masses of little wires link the rings. Radiating from the outer ring are about twenty-five light grey metal rods, alternating with pairs of protruding tubes. Thick wires extend out of two sockets sunk into each of those tubes and converge into fat electrical cables. The rods and the tubes are framed by eight grey metal bars. Each bar is echoed by two behind it. These bars look like retracted eyelids, and the cables drape over them like tangled eyelashes.

What we are seeing is a series of concentric wire chambers, sheaves of tubular scintillation counters wrapped in a magnet, all surrounded by more counters. The hole in the center is for the flattened ten-by-two-inch pipe, which carries the two beams of electrons and positrons traveling in opposite directions around the

ring. When the beams are at the appropriate energy and density, they are deflected toward each other while they are passing through the section of beam pipe that is surrounded for fifteen feet by this detector. Paths of the particles created from the energy of the electron-positron annihilation are recorded as they scatter through the detector.

Retracing our steps to the parking lot, we enter the metal building housing the Sigma 5 computer that runs SPEAR and MARK and collects and analyzes data from the experiments. Watching the computer graphic display on CRT screens, one can again imagine that one is actually seeing the tracks of particles created from the annihilation. It is a rather tame experience, compared to standing on top of a shaking bubble chamber, but in fact the spectacle is less predictable: within three years after SPEAR and MARK I were completed, two entirely new particles and several resonances were discovered.[18] The weekend that the first new particle manifested itself, a lot of champagne was drunk in the control room at SPEAR, and many people crowded in to see the data reconstructed on the CRT. This experimental result confounded some existing theories and led to a Nobel Prize for the group's leader in 1976.[19] The prize was shared with another physicist at Brookhaven National Laboratory (BNL), near New York City on Long Island, who produced similar results, using a different type of detector, almost simultaneously. The working styles of the two groups were considered by physicists to be diametrically opposed: the SPEAR group did "horseback" physics—aggressive and daring, with charismatic leadership; the BNL group was said to be "finely tuned," meticulous and cautious—and its leadership was known as fiercely authoritarian.

The different names that the two separate groups gave to the same particle reveal their claims of ownership. The SPEAR group at SLAC called the particle *psi* because the highly prized computer graphics of the data produced by their detector generated a visual pattern that strongly resembled the shape of the Greek letter *psi*. Calling the particle *psi* called attention to their distinctive data collection process. The Brookhaven group named the particle J because that capital letter in the Roman alphabet strongly resembles the Chinese character of the group leader's name. In one case, the name evokes nature's presumed signature as revealed by a specific detector; in the other, the name evokes the signature of a human being. The perpetual repetition of these signatures in the data continually reiterates both groups' claims to its ownership.

Gossip was intense: exactly how could the two groups have made the same discovery at the same time? Attention focused on "leaks"; some were sure that rivals of either the SLAC or BNL leader had told former students or research associates at the other lab where to look for the important new data. Many were startled that groups with such different styles should have produced the same results independently. The scientists' disbelief contrasts sharply with the response of the lay person, for whom recurring instances of simultaneous discovery seem to endorse the truth of scientific results.

There was surprise, too, at the awarding of a prize for such recent work; some physicists at the lab said that, since funding in high energy physics had declined drastically worldwide, the Nobel committee had been urged to make an award in particle physics soon, in the hopes that funding would be stimulated. In both these cases physicists responded with a mass of hypotheses to what struck them as anomalous information: "simultaneous" discovery by two groups having disparate styles of physics, and early award of a Nobel prize.

The physics community also responded with a mass of hypotheses to the data generated by the experiments at SPEAR and BNL. There were so many interpretations that *Physical Review Letters* declined to publish them for a period. "Phys. Rev. Letters," as it is called, publishes brief articles on important issues rapidly, on the presumption that more expanded work will be published later in *Physical Review*.[20] A satire on the proliferation of theories to account for the new particle was submitted to *Physical Review Letters* by Marty Einhorn and Chris Quigg of Fermilab, who named their own theory "Pandemonium."[21]

The KEK detector. Soon after my arrival at KEK in summer 1976, a Japanese physicist whom I had met at SLAC offered to show me the accelerator and the research areas. The accelerator is only a short walk from the main laboratory building. The physicist showing me the accelerator explained the beam characteristics that had already been achieved.[22] I was startled to realize that there were no detectors arranged around the usable beam. It was explained to me that no research group was permitted to use the beam because the accelerator department did not want it used when it was only partially completed. I had not been at any other

laboratory in which accelerator physicists had the power to overrule experimentalists, but I had never been at a lab at its inception: I know that accelerator physicists are only in command of a laboratory until the accelerator is running efficiently; then the experimentalists take over. At KEK, the accelerator physicists had managed to convince the director that theirs was the correct policy. Still, this did not resolve my feeling that here was something deeply strange: I had never seen a laboratory which was not trying to "get physics results" as quickly as possible. I had become attuned to the sense among American particle physicists that time is a precious commodity. I strongly suspected that at SLAC an experimentalist would have argued that he needed to test his detector, and then surreptitiously done physics research. If the physics results were interesting, he would be lauded for his cunning and enterprise.

I asked a Japanese physicist who had worked in the United States for many years and was then visiting various groups in Japan how he would explain this situation. He replied that he was very skeptical about the whole operation of KEK, especially because of the caution about doing physics immediately. I set out to understand why the press of time did not dominate decisions at KEK, to explain why there were no detectors using that beam.

I arranged to meet with a young physicist who I knew had responsibility for an important section of a detector for a powerful research group. I found him in his research area, which was a space about the size of End Station A at SLAC. The room was being used to house a complex array of activities. A trailer was being used for computer equipment. A target stood in one corner. There were storage areas, work areas, and construction areas. Everything looked temporary and makeshift. The young physicist, in jeans, a tank top, and tennis shoes, was in the process of trying to organize and rearrange the area in order to be able to set up the equipment for his detector. He pointed out that the first priority in the laboratory workshop was accelerator development, so it was very difficult for him to get people's work time allotted to his project. He was also having difficulty getting access to the workshop himself. Consequently, he was rearranging the research area so he himself could work there. He was very busy, and eager to get the detector built, but he was working almost alone.

When I spoke to senior physicists, they began to talk of delicate arrangements still under way in the organization of the laboratory.

They also mentioned the severe limitations on the laboratory funding. The absence of detectors seemed to be related not so much to factors within the lab as to KEK's relations to both the government and the rest of the Japanese particle physics community, an issue to which I will return in Chapter 5.

One day a KEK research group leader said he wanted to show me something that was very important for his group. He took me into a room in which a group of young men were arranging lights and cameras in a professional way, preparing to photograph the only other thing in the room: a computer. The physicist explained to me that an international group had recently judged this computer system to be one of the year's one hundred best . . . well, he could not remember exactly best what. Nevertheless, he knew that these one hundred achievements would be exhibited soon at the Chicago Museum of Science and Technology. He searched around and found two eight-and-a-half-by-eleven-inch glossy photographs of the system which he wanted to give me. I asked who designed it. He responded that he and his staff had drawn up the general specifications and then tried to interest a computer company in the project. He said all were reluctant, but Toshiba finally agreed. He smiled, and added that now Toshiba is very glad to have done the project because the publicity will be valuable to them. He expected that Toshiba's award would help him to interest other manufacturing companies to bid on his research equipment contracts in the future.

When I asked about the construction of the KEK bubble chamber, I learned that—as in the case of the computer—the group had made the general design specifications and then looked for manufacturers to produce the components. The body and the supercooling system were built by Nippon Sanso Company, the expansion system by Kayaba Company, the magnet and power supply by Hitachi, the window by Ohara, and the photographic equipment by Canon. Nippon Sanso also took the contract to construct the chamber from these components. This physicist said with a shrug that the process of finding and choosing manufacturers is difficult.

When another physicist at KEK was showing me a special target his group had designed, I asked about the components. He said that some of the parts were from the United States, France, and England. He pointed out that each purchase from a foreign manufacturer must be made through a Japanese representative of that firm, according to government regulations concerning all expenditures at KEK. All funding is "line by line," and closely watched by government bureaucrats; any expenditure over five hundred dollars must be approved by the government. When I commented that this must be very time-consuming, the physicist laughed and said that after a while one learns whom to approach, whom to call about the progress of a request, and so on. With a smile, he added, "It is important, when applying for purchase of duplicate items, not to photocopy old requests, but to have each new request typed nicely." The implication was that the bureaucracy was annoying, but it was possible to learn their habits and humor them.

Yet another physicist told me of an international conference on governmental expenditures for science which he had attended. At this conference, Japan was congratulated for having the most effective science expenditures. He said he thought to himself that the organizers of the conference did not know what they were talking about. In his research group, he estimated that at least 75 percent and probably 90 percent of the budget was paid to private industries for components and fabrication of research equipment for this detector. The government had encouraged the Diet, Japan's parliament, to pass KEK's annual budget, apparently, because of an understanding that a very large proportion of the money would be an indirect means of subsidizing research and development in private industry.

Experimentalists at KEK, conceiving of an experiment, first define their physics question, formulate their hypothesis, and outline how the hypothesis could be tested experimentally. The design of the research equipment is only sketched. Then the engineers from the appropriate industries are invited to join the discussion. When KEK physicists and company engineers have come to an agreement about the general design specifications of the detector, the companies build the detector components and another company assembles the parts at KEK.

This explained another absence I had noticed in 1976 at KEK: the experimentalists did not have the means to make and unmake their own equipment, even if they wanted to. Their own training had not prepared them for dismantling and rearranging detectors, but for overseeing the work of engineers. The funding system in Japan led to large initial outlays of money to construct research equipment, very little subsequent funding for modifying their detectors, and little hope of new funding for decades. This meant that the Japanese physicists were inclined to design all-purpose, durable detectors and to push for the most sophisticated technology available for each component. The lack of workshops and technicians also meant that they wanted reliable detectors. Like a house in Europe, a Japanese detector is expected to outlive its builders.

As I walked around the research areas the few technicians I did see all seemed, compared to those at SLAC, very young—probably under thirty years old. A physicist explained that most of them had been hired directly from technical high schools. When I asked why none had been "raided" from private industry, or from other government laboratories such as the Electrotechnical Laboratory or the Institute for Solid State Physics, the physicist explained that all potential government employees must take a stringent examination, and that this examination is "valid" only for three years; to request another position or transfer, after three years have passed, the applicant must take the examination again. This routine creates an effective barrier against midcareer changes. No such reexaminations are required for academic positions.

Technicians at KEK can be promoted to the position of research associate and even associate professor, but "that gate is very narrow." At KEK in 1976 there was one associate professor (in the accelerator department) who was a former technician, and one research associate (in the bubble chamber group) who was still a technician—he was someone the bubble chamber group had wanted to hire who declined to retake the exam. Hiring him as a research associate circumvented the problem.

Another research group had had the option of hiring a technician or research associate, and chose a research associate because the training of the technician would have required too much of their time. Almost everyone assumes that KEK must hire high school graduates and completely train them to the requirements of research science technology. A leading physicist at KEK asked me many detailed questions about the role and status of technicians at SLAC. He said that in Japan all very good university-trained technicians work in private industry and cannot be lured to KEK because there are no real opportunities for advancement. He believes that KEK will never excel in experimental physics until this situation changes.

I had learned why the KEK experimentalists had not surreptitiously pushed an unfinished but functioning detector in front of a usable beam. They were not only abiding by the policies of the accelerator physicists, they were also dependent upon the companies building their detector, and the companies determined when the equipment was finished and ready to be turned over to the lab. I had also learned why the experimentalists preferred reliable, durable, and technologically sophisticated detectors. The special constraints on their funding, independent of the amount, and the government civil service constraints on their hiring decisions had led them to a certain style of detector design. I was told by a European experimentalist at SLAC that similar constraints exist in some labs there, with similar consequences. Circuitously, their durable precision equipment is consistent with an emphasis on experiments designed to collect precise measurements of phenomena first identified elsewhere, in more innovative and flexible detectors.

There are many ways to design a detector. LASS was designed to provide data for meticulous analysis. It was focused on a specific class of particles, for the purpose of clarifying the fine structure of a sketchily understood part of a widely accepted theory. The detector itself stretched existing technology in order to analyze certain patterns in very large numbers of events. It has strongly influenced subsequent detector design, even though its physics results were not startling. The LASS group's leader said that a detector should be seen not as an end in itself, but as a piece of equipment designed to "resolve a philosophical question." He sees the strength in his group and its detector as the power to correlate data analysis with deep physics questions.

The group at SPEAR, on the other hand, sees itself as having designed its detector architecturally rather than analytically. This group regards its detector and their physics interests as changing rapidly. The detector is designed so that it can be quickly altered: "We're too stupid to build it right from the beginning, but we can build it so that it can be fixed easily." This physicist means that their group was smart enough to build ways of correcting their "error bars" by fixing the machine itself, refining, deconstructing, and reconstructing it as data analysis improved: "If the detector's architecture is good, new parts will fit in." This detector was designed to search for a wide range of unexpected rare particles interspersed in very large numbers of events. Once the researchers found candidate rare events, they needed to be able to eliminate all possibility that the events were not significant, that they were explicable in any alternative terms. The flexible architecture of the detector enabled them to do this, because they could rearrange the detector to eliminate each alternative explanation systematically. This detector too has had much influence on later detectors.

One physicist constrasted the SPEAR approach to that of ESA: "Our detector was built on much less money, and we are better for it: we built with much more thought and ingenuity. Their machine was built in fat times, and you can still see it in their cupboards. If you wanted three of something, the leader said to order a hundred; we will use them eventually." The implication was that the ESA group was just mechanically rebuilding its detector because it had so many spare parts. This third group made no claim to elegant equipment or subtle architecture. It had built its reputation on quickly getting finely structured results to a specific set of questions. The ESA's detector's results are widely regarded as reliable because the machines are considered to be overbuilt, but other experimentalists have not emulated its design in later detectors.

The differences among these detectors serve as a mnemonic device for thinking about the various groups' models for scientific method: how to elicit traces from nature that are both significant and reproducible. Detectors themselves, then, supply a system for classifying modes of discovery. Each is the material embodiment of a research group's version of how to produce and reproduce fine physics, how to gain a place for the group's work in the taxonomy of established knowledge. Each of the groups' strategies for finding traces is in fact a strategy for dealing with noise. The unfinished detector at KEK was designed to minimize noise at the expense of finding new data. LASS is spare and elegant, meant for refining accepted but little-understood knowledge. SPEAR is ingenious architecture, meant for reconstruction and deconstruction. The ESA is fat and overbuilt, meant to be reliable.

In this chapter I have emphasized the differences between the detectors and the styles they represent.[23] It is important to remember that, in spite of these differences, almost all physicists in American labs have worked at several different short-lived detectors in the course of their careers. In fact, the American physicists' careers often recapitulate detector history. At SLAC the eighty-two-inch bubble chamber, ESA, LASS, and SPEAR emerged in that order; many of the physicists at SPEAR originally worked in the ESA group and the leaders of SPEAR and LASS had worked together in the bubble chamber group. The long-term members of the SLAC community see each other daily, attend the same seminars and policy meetings, and compete for the same recruits, accelerator beamtime, and resources to build their next detectors. Their different strategies for discovery have emerged in the context of a shared perception of how to do good physics and how to maintain a strong laboratory. By contrast, most Japanese physicists work at one detector all their careers and have less contact with other experimentalists; they must pass on their very long-lived detectors to new generations who will ask new physics questions. Across the generations they will share an approach to physics and a commitment to a strong research group. As we turn in the next chapter from the detectors to their makers we find that just as there are different strategies for making research equipment, there are also different strategies for building a career in physics.

Performance," *The SLAC News*, June 2, 1971; Bill Kirk, "End Station A Spectrometers," *SLAC Beam Line*, March 20, 1975, pp. 7–11.

12. S. Kociol, "'Vector Dominance' Works—Or Does It?" *The SLAC News*, April 19, 1971; Charles Oxley, "LASS Construction Underway," *The SLAC News*, April 1972.

13. He believed that his sense of good experimental work had been learned in his teachers' labs in Scotland; he was inspired too by the examples of earlier physicists' experimental equipment that had been displayed in the dining hall of his university laboratory. Scotland has an important history of empirical scientific research. This physicist knew that history through those devices in the dining hall and through his teachers' stories. See for example, Richard Olson, *Scottish Philosophy and British Physics, 1750–1880* (Princeton, N.J.: Princeton University Press, 1975). On multiwire proportional chambers, see Charpak, "Multiwire and Drift Proportional Chambers" (n. 6).

14. Bill Kirk, "An Introduction to Colliding Beam Storage Rings," *SLAC Beam Line*, August 1974, pp. 3–6. See also Martin L. Perl and William T. Kirk, "Heavy Leptons," *Scientific American*, March 1978, pp. 50–57. For a brief history of colliding beam facilities by a physicist active in the design of several of them, see John Rees, "The Last of the Rings?" *CERN Courier International Journal of High Energy Physics*, July–August 1986, pp. 1–3.

15. Bill Kirk, "The Positron Source Job," *SLAC Beam Line*, February 1975, pp. 5–8.

16. Burton Richter, "Burton Richter: A Scientific Autobiography," *SLAC Beam Line*, November 1976, p. 8.

17. "LBL, SLAC Designing Colliding Beam Accelerator," *The Beam Line*, June 20, 1972, p. 4.

18. J.-E. Augustin et al., "Discovery of a Narrow Resonance in e+e− Annihilation," *Physical Review Letters*, December 2, 1974, pp. 1406–1408.

19. J. D. Bjorken, "The 1976 Nobel Prize in Physics," *Science*, 19 November 1976, pp. 825–826, 865–866.

20. Bill Kirk, "Preprints, Publications, and All That," *SLAC Beam Line*, July 1977, pp. 5–8.

21. Martin Einhorn and Chris Quigg, "On the New Narrow Resonances," *SLAC Beam Line*, March 20, 1975, p. 6.

22. For a description of KEK specifications, see *KEK Annual Report 1976*, National Laboratory for High Energy Physics, Oho-machi, Tsukuba-gun, Ibaraki-ken, Japan.

23. In my study of style in detectors I am indebted to the analytic, anthropological work of the archeologist Heather Lechtman. See, especially, "Style in Technology—Some Early Thoughts" in *Material Culture: Styles, Organization, and Dynamics of Technology*, ed. Heather Lechtman and Robert S. Merrill (St. Paul, Minn.: West Publishing Co. 1977; 1975 Proceedings of the American Ethnological Society), and "Andean Value Systems and the Development of Prehistoric Metallurgy," *Technology and Culture*, January 1984.

Walter Vincenti has made a major contribution to my understanding of the relation between tacit, prescriptive, and descriptive knowledge in science and technology in his analysis of innovation, design, and production in engineering in his "Technical Knowledge without Science: The Innovation of Flush Riveting in American Airplanes, c.1930–c.1950," *Technology and Culture*, July 1984, pp. 540–546. On the ethnographic observation and analysis of engineering practices I have been influenced strongly by L. L. Bucciarelli of MIT. See his "Engineering Design Process," in *Making Time: Ethnographies of High-Technology Organizations*, ed. Frank Dubinskas (Philadelphia: Temple University Press, 1988), pp. 92–122.

3. Pilgrim's Progress: Male Tales Told During a Life in Physics

1. Clifford Geertz, "From the Natives' Point of View: On the Nature of Anthropological Understanding," in *Meaning in Anthropology*, ed. Keith H. Basso and Henry A. Selby (Albuquerque, N.M.: University of New Mexico Press, 1976), p. 235.

2. For a study of another culture's organization of emotional states in boys and men during a very long socialization process, see Gilbert H. Herdt, *Guardian of the Flute: Idioms of Masculinity* (New York: McGraw-Hill, 1981). For an analysis of the "psychological adjustments" appropriate to different career stages in America, see Gene W. Dalton, Paul H. Thompson, and Raymond L. Price, "The Four Stages of Professional Careers: A New Look at Performance by Professionals," *Professional Dynamics*, Summer 1977, pp. 19–42. For a study of how affect is linked "to characteristic sorts of activity that change through the life cycle," see Michelle Zimbalist Rosaldo, *Knowledge and Passion: Ilongot Notions of Self and Social Life* (Cambridge: University of Cambridge Press, 1980), p. 63 and passim. For a reevaluation of the anthropological analysis of emotions, see Renato Rosaldo, "Grieving and the Anthropology of Emotions," in *Text, Play, and Story: The Construction and Reconstruction of Self and Society*, ed. by Stuart Plattner, Proceedings of the American Ethnological Society (Washington, D.C.: American Ethnological Society, 1983). The following nonanalytic, anecdotal accounts of elite male socialization in the United States provide data on the cultural construction of emotion: Scott Turow, *One L: An Inside Account of Life in the First Year at Harvard Law School* (New York: Penguin Books, 1978); Charles LeBaron, *Gentle Violence: An Account of the First Year at Harvard Medical School* (New York: Marek, 1981); and Fran Worden Henry, *Toughing It Out at Harvard* (New York: McGraw-Hill, 1984).

3. On analogic thinking in science, see Mary B. Hesse, *Models and Analogies in Science* (Notre Dame, Ind.: University of Notre Dame Press, 1979).

4. Eyrind H. Wichmann, *Quantum Physics*, Berkeley Physics Course, vol. 4 (New York: McGraw-Hill, 1971). See also Thomas S. Kuhn, "The Essential Tension: Tradition and Innovation in Scientific Research," in *Scientific Creativity: Its Recognition and Development*, ed. C. W. Taylor and Frank Barron (New York: Wiley and Sons, 1963), p. 352.

5. On the rhetoric of images and captions, see Roland Barthes, *Empire*

(n. 18); pp. 27–46. See also Richard B. Neal, "SLAC: The Accelerator," *Physics Today*, April 1967, pp. 27–41.

22. Dupen, *Story of Stanford's Accelerator* (n. 3), pp. 70–81, 66–69, 125.

23. Ibid., pp. 53–58, 115. A history of this laboratory is being written by Bruce Wheaton of the University of California at Berkeley. Three laboratory officials have extensive personal collections of documents.

24. *Stanford Linear Accelerator Center 1971 Annual Report* (n. 18), pp. 42–43; "Taming SLAC's Beam," *The Beam Line*, April 23, 1973; Warren Struven, "Computer Control of the SLAC Accelerator," *SLAC Beam Line*, May 20, 1975.

25. "SLAC Plans Anger Neighbors," *The Stanford Daily*, April 22, 1981, p. 3.

26. See Dupen, *Story of Stanford's Accelerator* (n. 3), p. 62.

27. For a discussion of these issues, see Mary Douglas, *Purity and Danger: An Analysis of the Concepts of Pollution and Taboo* (London: Routledge and Kegan Paul, 1978), pp. 55, 115, and passim; and Mary Douglas and Aaron Wildavsky, *Risk and Culture: An Essay on the Selection of Technological and Environmental Dangers* (Berkeley: University of California Press, 1982). See also Bruno Bettelheim, *Symbolic Wounds: Puberty Rites and the Envious Male* (New York: Collier Books, 1971); Edmund Leach, "Magical Hair," *Journal of the Royal Anthropological Institute*, vol. 88 (1958), pp. 147–164; and Raymond Firth, *Symbols: Public and Private* (Ithaca, N.Y.: Cornell University Press, 1975), pp. 262–298.

28. Mary Douglas, *Purity and Danger* (n. 26), pp. 2–5.

29. For a description of the facilities at Tsukuba, see Henry Birnbaum, "Japan Builds a Science City," *Physics Today*, February 1975, pp. 42–48, and "Tsukuba Science City," in *Guide to World Science*, vol. 17: *Japan*, ed. D. B. Forbes (Guernsey, U.K.: Francis Hodgson), pp. 141–147.

30. Personal communication, Thomas Rohlen. For a discussion of the spartan ethos of Japanese elite secondary schools, see Donald Roden, *Schooldays in Imperial Japan: A Study in the Culture of a Student Elite* (Berkeley: University of California Press, 1980).

31. The Japanese novelist Junichiro Tanizaki explores the contrasting values implicit in stark light and subtle shadows in an essay entitled *In Praise of Shadows*, trans. Thomas J. Harper and Edward G. Seidensticker (New Haven: Leete's Island Books, 1977).

32. Kiyonobu Itakura and Eri Yagi, "The Japanese research system and the establishment of the Institute of Physical and Chemical Research"; Hiroshige Tetu, "Social conditions of prewar Japanese research in nuclear physics"; and Yoshinori Kaneseki, "The elementary particle theory group"; all in Shigeru Nakayama, David L. Swain, Eri Yagi, eds., *Science and Society in Modern Japan: Selected Historical Sources* (Tokyo: University of Tokyo Press, and Cambridge, Mass.: MIT Press, 1974).

33. For a description of KEK specifications, see Tetsuji Nishikawa, "The Japanese 12 GeV Accelerator," KEK Preprint 2 (1974), and KEK Annual Reports for 1974, 1976, 1977, and 1980, National Laboratory for High Energy Physics, Oho-machi, Tsukuba-gun, Ibaraki-ken, 300–32, Japan.

34. Liza Crihfield Dalby, personal communication. See her anthropological study, *Geisha* (Berkeley: University of California Press, 1983).

35. Lillian Hoddeson, "Establishing KEK in Japan and Fermilab in the United States: Internationalism, Nationalism, and High Energy Accelerators," *Social Studies of Science*, April 1983, p. 3.

2. Inventing Machines That Discover Nature: Detectors at SLAC and KEK

1. Ian Hacking, "Do We See through a Microscope?" *Representing and Intervening: Introductory Topics in the Philosophy of Natural Science* (Cambridge: Cambridge University Press, 1983).

2. Bruno Latour and Steve Woolgar, *Laboratory Life: The Social Construction of Scientific Facts* (Beverly Hills, Calif: Sage Publications, 1979), pp. 51, 63–69, 242, and 259, n. 15.

3. Donald A. Glaser, "The Bubble Chamber," *Scientific American*, February 1955, pp. 46–50. For another perspective on the development of the bubble chamber and its implications for the organization of work in high energy physics, see Peter Galison, "Bubble Chambers and the Experimental Workplace," in *Observation, Experiment, and Hypothesis in Modern Physical Science*, ed. Peter Achinstein and Owen Hanaway (Cambridge, Mass.: MIT Press, 1985), pp. 353–359.

4. Glaser, "The Bubble Chamber" (n. 3).

5. "'Moratorium' Party for 82-Inch Bubble Chamber," *The Beam Line*, December 4, 1973.

6. Gerald K. O'Neil, "The Spark Chamber," *Scientific American*, August 1962, pp. 36–43; and D. E. Yount, "The Streamer Chamber," *Scientific American*, October 1967, pp. 38–46. For additional information about different types of detectors of this generation, see Georges Charpak, "Multiwire and Drift Proportional Chambers"; William J. Willis, "The Large Spectrometers"; Jack Sandweiss, "The High Resolution Streamer Chamber"; and D. R. Nygren and J. N. Marx, "The Time Projections Chamber"; all in *Physics Today*, October 1978, pp. 28–53.

7. "'Moratorium' Party" (n. 5).

8. "Forty Inch Bubble Chamber—Now World's Fastest," *The SLAC News*, September 1971; "Hybrid 40-inch Bubble Chamber Studies 'Inelastic Muon-Proton Scattering,'" *The Beam Line*, March 7, 1973; "Cerenkov Counter Being Built for New Hybrid Bubble Chamber Facility," *SLAC Beam Line*, December 1974.

9. Gordon Bowden, "Hybrid Bubble Chambers: An Operator's View," *The Beam Line*, February 6, 1973.

10. "Rapid Cycling Bubble Chamber," *The SLAC News*, October 16, 1970; "Rapid Cycling Bubble Chamber TURNS ON," *The Beam Line*, April 5, 1973.

11. "SLAC and MIT Collaboration Studies Proton Structure," *The SLAC News*, February 26, 1970; Steve Kociol, "Does Time Run Backwards?" *The SLAC News*, July 31, 1970; Charles Oxley, "MPC Improves Spectrometer