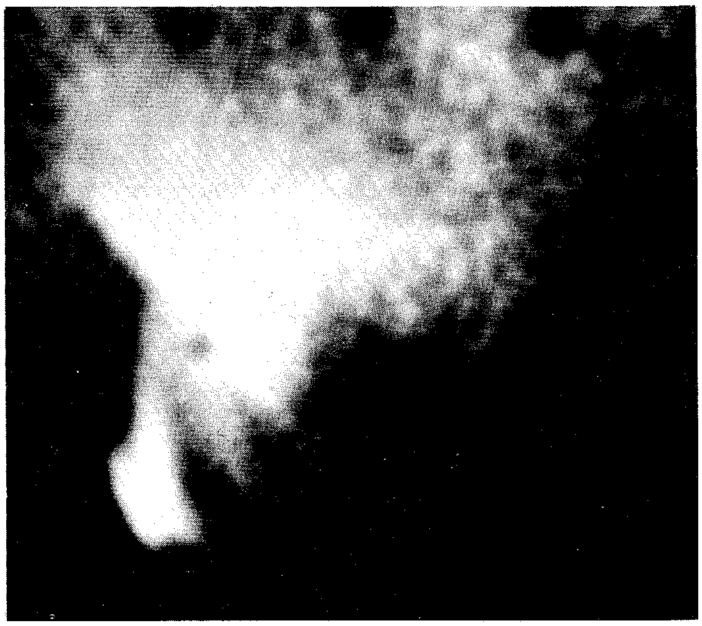
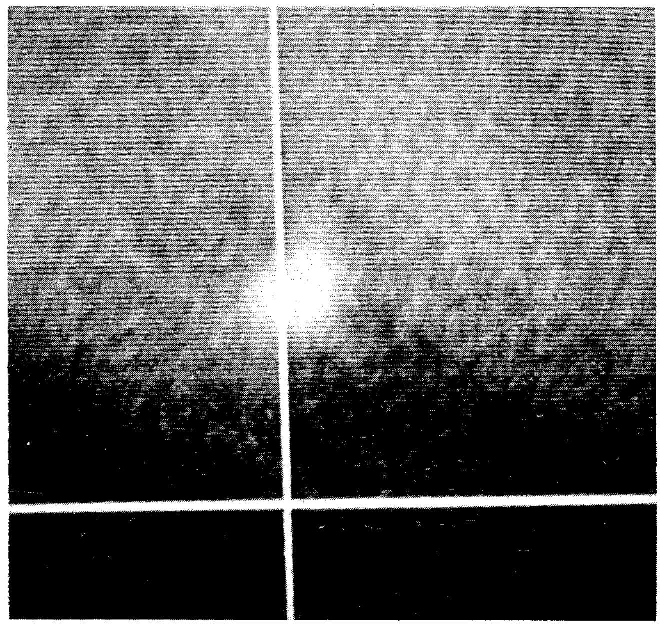
SLAC BEAM LINE

We dance round in a ring and suppose,
But the Secret sits in the middle and knows.
—Robert Frost

Volume 15, Number 3 March 1984





"2/04/84. 0450. The latest round of measurements gave us 3E-5 rad-m in horiz. We're there!!!!"

A MILESTONE FOR THE LINEAR COLLIDER

At 5 o'clock on the first Saturday morning of February, the Linear Collider passed a major technical milestone as physicists accelerated an electron beam with the high intensity and high quality needed in the collider. The quote above, which was taken from a computer logbook, shows how the group working on the test felt about it.

These two photographs are images of beams striking a luminescent screen and are enlarged about 20 times. The small spot on the right was produced by an *SLC* beam which had been through the damping ring to reduce its size. The beam which produced the diffuse spot at left had not been damped. The story on page two explains more about this achievement.

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Stanford University operates SLAC under contract with the US Department of Energy.

LINEAR COLLIDER PASSES MAJOR MILESTONE

The Linear Collider is a completely new way to collide electrons and positrons at very high energies. It is not a scaled up version of a smaller accelerator, and there is no laboratory model to compare with. So, there is great interest to find out as soon as possible how well it is going to work. With this in mind, a small group of physicists and engineers recently set up a crucial test of the chief feature of the new machine: accelerating an intense electron beam of high enough quality to be focused into the tiny spot needed at the *SLC*.

Intensity is a familiar idea: it is just the number of electrons being accelerated. Beam quality is more complicated. Roughly speaking, it is like the difference between a laser beam which runs for long distances without spreading out much, and an ordinary penlight, which starts out no bigger around but spreads out rapidly. This property of beams, which depends on both the size of the beam and its tendency to spread out, is called emittance.

The important test, then, is to accelerate an electron bunch with very high intensity and very low emittance. Unfortunately, the two properties do not happily coexist. Intense beams are hard to produce with low emittance and even harder to accelerate without losing it. The collider requires both in order to do good physics at a reasonable rate. Hence, the great interest in this combined measurement.

The collider required a new gun and injector system to get the required high-intensity of around fifty billion electrons squeezed into short bunches a few millionths of a millionth of a second long. These devices are shown as points 1 and 2 in the rough sketch below.

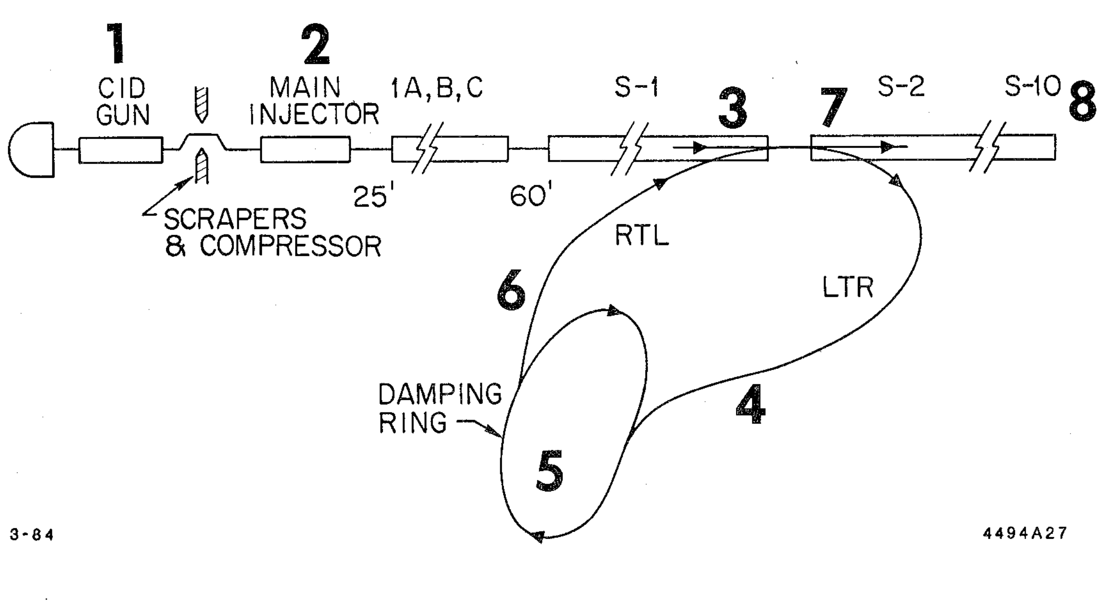
This produces a beam which is intense enough and short enough, but the emittance is too high. This fuzziness can be cleaned up by storing the beam in a ring, where the natural radiation processes damp it down. At point 3 the beam is taken out of the linear accelerator, bent around a long arc, and injected into the damping ring at point 4.

As the beam circulates around the ring (5), it shrinks down to a smaller size. After about 30 thousandths of the second (faster when running at the final design energy), the beam is taken out of the ring at point 6 and reinjected into the linac at point 7. The beam is then accelerated to about the one-third point of the two-mile linac for the final measurements at point 8.

The intensity is determined using a loop which measures the charge of the beam, and hence the number of electrons. The emittance measurement is more difficult, since it depends not just on the size of the beam at a point but also on how it is spreading out. The photograph on the right of the cover shows the beam size at a luminescent screen. The spot is electronically scanned along the two lines to determine the size quickly and accurately. Then a focusing magnet ahead of the screen is varied, changing the size of the spot. In this case, a beam of good emittance is not as sensitive to changing this focusing magnet as one of poor emittance. The emittance value is extracted from a plot of a series of these measurements.

The final measurements came after weeks of studying the effects of changes in the injection system, the damping ring, the transport lines between the linac and ring, and the new precision controls of the accelerator itself.

The result is that the intensity and emittance are both at the desired values for this stage of the project. The collider is well on its way.



SIR JOHN ADAMS — IN MEMORIAM

Sir John Adams, former Director General of the European research center CERN, died early this month at the age of 63. The following description of his illustrious career was written by Albert Hofmann, who worked for many years at CERN. The reflection at right is by SLAC Technical Director Burton Richter.

He began his scientific career with radar development in England during the war, and later worked at the Atomic Energy Research Establishment at Harwell. In 1953 he joined the newly founded center at *CERN* in Geneva, becoming Director of the Proton Synchrotron Division.

John Adams was an excellent project leader and not only completed the machine ahead of schedule but brought its performance to a level beyond the original expectations. This success brought him wide recognition and gave a big boost to the young organization. In 1960 he became Director General of *CERN* at age 40.

He later accepted a position as Director of Culham Laboratory in England, doing plasma physics research. Meanwhile, *CERN* had begun planning a much larger accelerator named the Super Proton Synchrotron *(SPS)*, and called him back to lead the new project.

From 1969 to 1975, he was Director General of *CERN II* and led the center through the construction and successful operation of the new machine. By 1976 the two *CERN* laboratories were combined with John Adams serving as Executive Director General until 1980.

He was an outstanding leader for scientific projects and laboratories. He combined excellent technical knowledge with a great ability for management and administration. In technical crises his good judgement and calm, firm leadership always led to a solution. He was able to choose the best people for the different tasks of a project and unite them in an efficient team. His sense of humor often helped to discharge a tense situation. He served in many panels and committees advising government agencies or promoting international collaborations.

His achievements brought him many honors from honorary degrees to Knighthood, but perhaps the most significant tribute to his work is *CERN* itself, which as an international organization and laboratory owes so much of its success to Sir John Adams.

–Albert Hofmann

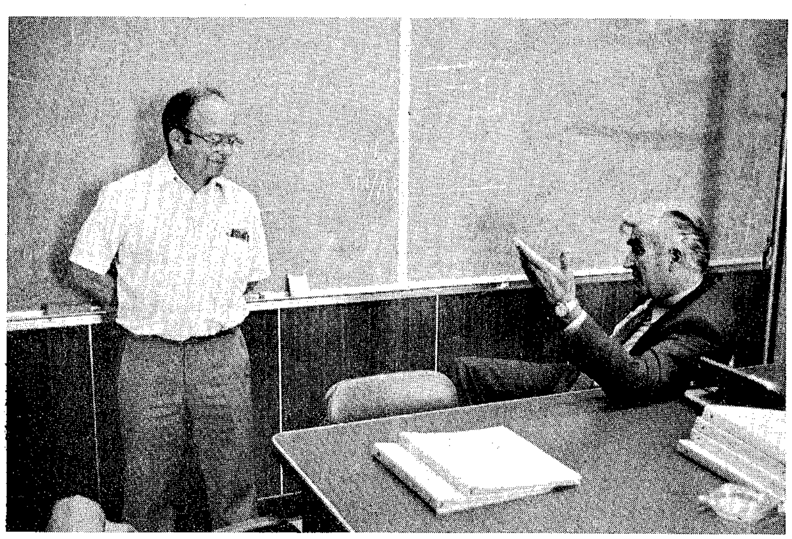
I knew John Adams for many years and have always had the greatest respect for his abilities as an accelerator builder and as an organizer of great projects.

The machines at *CERN* and the experiments that have been done with them are monuments to those abilities.

With his death, high-energy physics has lost one of its important leaders. We shall all miss him.

–Burton Richter

"...originator and devoted constructor of powerful accelerators which have made fundamental discoveries in elementary particle physics possible, in the framework of collaborations of which he has always been a strong advocate." — from the Doctorate Honoris Causa awarded to Sir John Adams by the University of Milan in 1980.



Sir John Adams, right, chatted with W.K.H. Panofsky during his visit to SLAC in 1981.

20

TWENTY-YEAR SERVICE AWARDS

DICK ALLEN
BOB BAKER
JACK BEARDSLEY
ROY BORTLE
MICHAEL BROWNE
JOHN CAREY
JOHN COCKROFT
JIM COOK
GEORGE CRUICKSHANK
JEAN FRANCIS
CHUCK HALE
MURRAY HARGAIN
CLARENCE HARRIS
HAROLD ITO
BILL JOHNSON
WALTER KAPICA
RON KOONTZ
HELEN MORRISON
JAMES MOSS
ROBERT PEDERSEN
MARTIN PERL
DARYL REAGAN
FRED ROUSE
DUANE SINCERBOX
VERN SMITH
BILL TOMLIN
BOB VACCAREZZA
DIETER WALZ
DICK WILSON
WALTER ZAWOJSKI

Ten years ago, Sid Drell honored the largest group ever to receive awards for completing ten years of *SLAC* service. Incredibly, two-thirds of that group were present at the ceremony held on January 27, 1984, this time for serving *SLAC* for twenty years. Once again *SLAC* Deputy Director Drell was the guest speaker while Dr. Panofsky presided over the awards presentation. The 60 honorees were feted at the Stanford University Faculty Club, enjoying cocktails and dinner with their fellow workers and spouses. Pief highlighted their history at *SLAC* by saying, "Collectively they represent the contributions of those employees who remained with us for a long time and literally made this successful laboratory and our achievements possible. There have been triumphs and anxious moments that we have shared in these two decades, but the net result speaks well for all of those who participated."

GORDON BABCOCK
JIM BASKETT
MARY ANN BLACKMAN
ADAM BOYARSKI
FATIN BULOS
BILL CLAYTON
TED CONSTANT
DAVID COWARD
IDA DONALS
FINN HALBO
ROBERT HANSELMAN
VIRGINIA HARMON
DALE HORELICK
DAVE JENSEN
JIMMY JUE
FRANK KARAS
BOB LAUGHEAD
GEORGE MOSLE
NICK PAPPIS
FRED PEREGOY
BILL PIERCE
BENNY REVILLAR
WALLY SCHMIDT
JIM SIROIS
WARREN STRUVEN
DAVE TSANG
NICK VASSALLO
HERB WEIDNER
LARRY WOMACK

Ginny Hale, Bob Laughead, Hedi and Ed Loens, Liz Laughead and Chuck Hale toast the completion of twenty years of dedication to the Laboratory. Award recipients and spouses celebrated the evening with fellow long-timers and each SLAC'er was given an engraved silver keychain with the SLAC logo. At the right, John Cockroft and his wife, Barbara, display the booklet which outlines the accomplishments of each awardee. Photographs by Casey James.

SLOW ROAD IN CHINA

Helen Morrison, Gwen Bowen and Janet Zhang went out into the Chinese countryside near Beijing (Peking) to visit the ruined gardens of the Summer Palace (Yuan Mien) which had been destroyed by the British and French during the Opium Wars of 1860. They wandered among those fanciful pavilions and pillars, imagining the Manchu court strolling there on just such a blue and gold afternoon.

By the time they were ready to depart no transportation was available — the taxi had not waited, the buses did not come. The three started bravely walking down the road to Beijing. The scenery was charming, bullocks plowing in the fields, farmers bringing in the crops in horse-drawn wagons, wide-eyed children gazing at the foreign ladies and their Chinese friend. But there were firm dinner plans in Beijing and not enough walking time. They then tried to stop trucks and buses heading in their direction — no luck at all.

At this point Helen, recalling her hitchhiking years in the Navy, took a position in the middle of the road and stopped a big green truck full of farm workers by waving her hands and just standing there. The driver and his passengers jumped out, explaining excitedly that his truck was too dirty, already full and was not a proper place for foreign ladies. After much argument, interpreted by Janet, Helen and Gwen were welcomed into the cab and Janet was helped onto the truck bed, and away they went to Beijing. The truck deposited them near the West Gate of Beijing University, a 10 minute walk from their hotel, and returned to its work after many thank-you's from Helen, Gwen and Janet.

–Gwen Bowen

Where was the horse when needed?

Helen Morrison retired in 1980 after nearly 20 years of service as Secretary to the Director of the Research Division. Helen has been a life-long student of Chinese art and culture.

Gwen Bowen has been SLAC's housing coordinator for 15 years. She shares Helen's enthusiasm for Chinese art and culture.

Janet Zhang (Zhang Ying-Xian) spent 4 months in 1981 as an apprentice to Shirley Livengood in the Technical Data Library. She returned to Beijing to help set up a similar library at the Institute of High Energy Physics.

SLAC BECOMES AN ENGINEERING LANDMARK

In a ceremony here on February 29, the two large engineering societies in the United States designated *SLAC* a national historic engineering landmark. Many of the laboratory's engineering alumni and the present engineering staff were present to hear their accomplishments praised by representatives of the American Society of Mechanical Engineers and the Institute of Electrical and Electronics Engineers.

W.K.H. Panofsky, who accepted the award on behalf of the laboratory, spoke on the great importance to *SLAC* of its engineers.

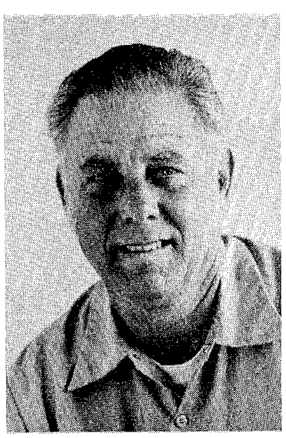
A brochure describing *SLAC*'s engineering accomplishments and the landmark program was prepared by the *Beam Line* and is included as a special supplement to this issue.

This one-foot by two-foot bronze plaque, which commemorates SLAC's landmark award, will be mounted for public view in a suitable place at the laboratory.

JIM NOLAN RETIRES

It's time for Jim Nolan to throw away his alarm clock. After more than 18 years at *SLAC*, he's retiring.

Jim came here from Food Machinery Corporation in San Jose in 1965. He joined Crafts Shops in the Plant Engineering Department as a rigger-operator.



Jim later became rigging supervisor. During his days in the rigging department Jim used his knowledge and talents all over *SLAC*. His help was sought by those who had large apparatus to move or delicate instruments to install. Jim was directly involved with procuring, maintaining and operating all the heavy moving equipment now in use here.

He went to Texas to attend school for the operation of the 40 ton LeTourneau forklift and in turn taught other operators to use this indispensable machine. In October of 1978 Jim joined *EFD* as coordinator of IR-6 at *PEP* which became home for the Free Quark Search and the High Resolution Spectrometer (*HRS*).

He was instrumental in the move of the old 2000 ton 4-meter bubble chamber magnet from Argonne National Lab to *SLAC* for use in *HRS*. The convoy which carried the 105 ton superconducting magnet coil across the country made the national news. Jim managed the loading and unloading of the coil, the assembly of the magnet and detectors and the move into the interaction region.

Early in 1982, Jim took a brief 'vacation' from *HRS* to assist in the move of the Crystal Ball from *SLAC* to *DESY* in Hamburg, Germany. It was flown there by the Air Force in a C5-A and Jim went along to supervise the rigging and the installation at *DESY*.

In his career Jim has faced many unique rigging problems and has provided some elegant solutions. He has a marvelous ability to get along with people and to gain their respect and confidence. He leaves a host of friends and admirers at *SLAC*.

Jim and his wife will retire to Sonora, California, to pursue the good life — fishing, hunting, and caring for their ranch. His many friends wish him well. Good Luck Jim!

–Ed Keyser

CHARLES J. KRUSE RETIRES

Charlie Kruse retired from *SLAC* on January 4, 1984 after almost 22 years of service. For almost 20 of those years, Charlie was head of the RF Drive Group in Accelerator Physics and at the same time took care of the administrative tasks of the Accelerator Physics Department. In addition, in the early 1970's, Charlie inherited responsibility for the linac laser alignment system from Bill Herrmannsfeldt.

During all these years, what characterized Charlie was his loyalty to *SLAC,* his dedication to whatever he was responsible for, and his good will toward people. I think it is fair to say that he leaves only friends behind him. More than eighty people attended the luncheon in his honor on February 13.

It was both gratifying to honor him and sad to see him leave after so many years. I am excerpting a few of the tongue-in-cheek remarks I made about him at this luncheon. Those who know Charlie (most people at *SLAC* !) will realize that these were just vignettes.

"Charlie Kruse was born to *SLAC* in the M-1 Building on Lincoln's Birthday, 1962. He arrived that day at 8:06 AM and continued, with one exception, to arrive at that time for the next 22 years. The exception happened in 1973 when one morning, as he was bicycling to work he discovered that he had a cold and pedalled back home to pick up a handkerchief. That day, he arrived at 8:16 AM. The rest of Charlie's $\sim$ 1600 hours of sick leave was wasted!

"As head of the RF Drive Group, Charlie's biggest job was probably to procure and then to install the two-mile main drive line and the thirty sub-drive lines.

"Like most of us, Charlie survived the mid-sixties, the turn-on of the linac, the Beatles, beam breakup and all the other turmoil. But then, in April 1968, the Forces of Evil descended upon the Klystron Gallery, and one fine morning, the entire main drive line broke down. This was a major catastrophe which brought *SLAC* to a grinding halt. As Charlie's family assembled here can probably testify, for three weeks Charlie, with Dick Wilson and his crew, lived, breathed, ate and slept with the drive line. As Winston Churchill would have said, 'This was his finest hour,' for after three weeks of blood, sweat, tears and a bit of Rhodium plating, the war was won and *SLAC* together with the Main Booster came back on triumphantly!

"Then somewhere in the late 1970's, back in the Business Division, Gene Rickansrud asked Charlie to become the *SLAC* Patent Administrator, and in a moment of weakness he agreed. ... What most people do not know is that in this position Charlie had to read through thousands of pages of Renormalization Theory, Quantum-chromodynamics and all the other mundane stuff we write!

... "But let me abandon the curricular and switch to the extra-curricular. What would Accelerator Physics Christmas parties have been without Charlie's Irish Coffee? What would *SLAC* families have become without Charlie organizing *SLAC*'s Family Day? And what would Santa Claus have done at *SLAC* all these years without Charlie's cookies?"

Now we are all going to miss Charlie very much, on the job and off. The only consolation we have is that some of his social skills will now become useful to his wife Marge and to their kids. Think about all the Family days and Christmas parties he can have at home now!

–Greg Loew

OSCAR FLEISHER — IN MEMORIAM

Oscar Fleisher passed away on March 1, within a few days of his 58th birthday. Oscar joined us in August 1969 as the Associate Purchasing Officer. He retired in March 1981, but returned in the last few months of 1983 to help out as a part-time consultant, due to an upsurge in the Purchasing work load. He brought *SLAC* a wealth of business and purchasing experience at a time when we really needed the help.

His background included inventory management; duty as Purchasing Superintendent at the Charleston Naval Shipyard; support services on the USS Proteus; head of Contracts Division in the Naval Plant Representatives Office, Lockheed, Sunnyvale; and Director of Purchasing Division, Navy Purchasing Office, Washington, D.C. He was a graduate of Pennsylvania State University.

Oscar was a very enthusiastic and devoted person. He would always roll up his sleeves and get into the job himself. He was particularly adept at training people and enabling them to take on increased responsibilities.

Oscar is survived by his wife Ruth, son Andrew, and daughter Beverly who reside in Cupertino. Burial was at Arlington National Cemetery, Arlington, Virginia. Friends may contribute to the American Heart Association, Santa Clara County, in his memory, if they wish. We shall miss a dear friend.

–Ralph Hashagen

SLAC GOLFERS

For several years a *SLAC* golf league existed quite happily but faded away under a pile of paperwork. There is now a good possibility that a new set of volunteers can be found if enough people are interested in forming a new league.

The rules of the old league were approximately as follows:

- A nine-hole tournament played each week on the front nine of the Stanford Course any afternoon Tuesday through Friday.
- Round must be played in the company of one or more other members of the league.
- League membership will be divided into two flights.
- Weekly prizes will be as follows:

  1 ball for low net high handicap flight
  1 ball for low net low handicap flight
  1 ball for closest to hole on Number 8

If you are interested in participating, please contact Bob Eisele (ext. 2582, Bin 60).

CO-ED SOFTBALL

Sign-ups have begun for the newly formed *SLAC* Co-Ed Slow Pitch Softball team. Please contact Tom Kamakani at *SLAC* ext. 2371 for registration information and practice times.

TO CONTRIBUTE TO THE SLAC EMERGENCY RELIEF ASSOCIATION (SERA), PLEASE INDICATE YOUR CHOICE ON THE FORM BELOW.

\- - - - - -

I WANT TO DO MY PART TO HELP.

☐ MY CHECK IS ENCLOSED. I WOULD LIKE TO DONATE $______ TO SERA.

☐ I AUTHORIZE PAYROLL DEDUCTIONS OF $______ PER MONTH FOR SERA, TO CONTINUE UNTIL FURTHER NOTICE.

____
(Signature)

____
(Please print name)

____
(Date)

____
(Employee number)

ALL CONTRIBUTIONS TO SERA ARE TAX DEDUCTIBLE

mail to BIN 70

BOOKMOBILE

The Bookmobile which has been coming to *SLAC* for many years now is in danger of being discontinued due to lack of patronage. If you are interested in keeping this service to the laboratory, visit the Bookmobile on alternate Wednesdays from noon until 1:00 beginning March 7th. It is conveniently parked near the firehouse.

FIRST ANNIVERSARY

Pictured above is a partial group of those who celebrated one-year-less-one-day of running of the damping ring. The damping ring is a major component of the *SLAC* Linear Collider and figured prominently in the milestone test which was passed in February (see story, page 2).

SLAC EMERGENCY RELIEF ASSOCIATION

The *SLAC* Emergency Relief Association, *SERA*, is a personal assistance organization formed in 1968 by *SLAC* employees to aid those of the *SLAC* community whose financial condition has become desperate due to emergencies beyond their control.

Unlike most assistance groups, *SERA*'s operating expenses are less than one percent! This is possible because the entire effort is carried on by volunteers. *SERA* is a charitable corporation whose three directors, elected semi-annually by the membership, together with a secretary and treasurer do the necessary work.

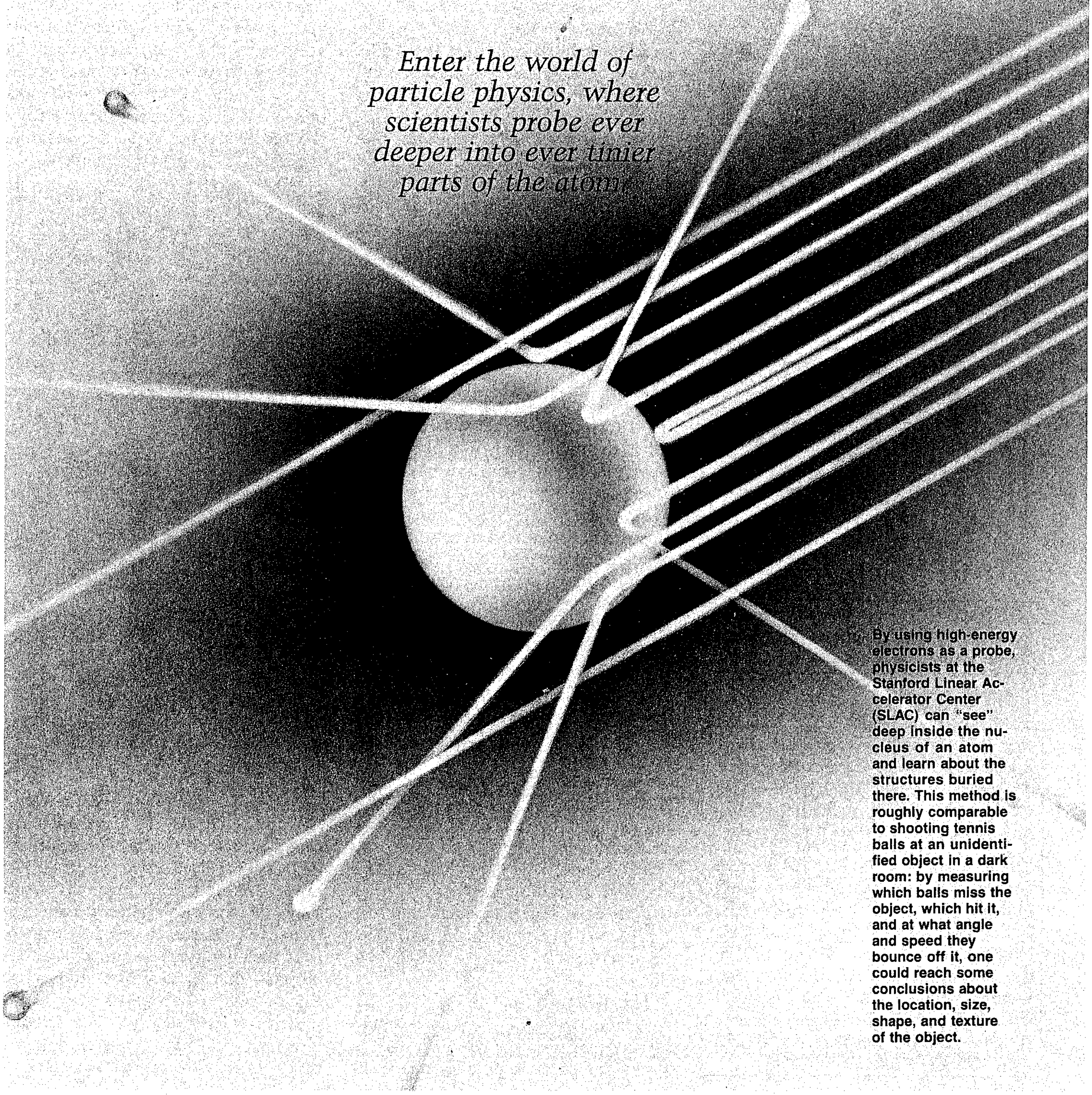
In these hard times disbursals have increased and there is a greater need for your support. *SERA*'s income is primarily from the donations of its members. A payroll deduction of 50 cents or more per month will make you a full voting member. You may, of course, wish to make the $6 fee a lump sum donation or authorize a larger monthly donation (our current average is $1.47). In any case, we hope you will join us in this worthwhile enterprise.

Please indicate your donation on the adjoining form and drop it in the mail today.

OF QUARKS, ANTIQUARKS, AND GLUE

BY HELEN R. QUINN
ILLUSTRATIONS BY WALTER ZAWOJSKI

Enter the world of particle physics, where scientists probe ever deeper into ever tinier parts of the atom.



By using high-energy electrons as a probe, physicists at the Stanford Linear Accelerator Center (SLAC) can "see" deep inside the nucleus of an atom and learn about the structures buried there. This method is roughly comparable to shooting tennis balls at an unidentified object in a dark room: by measuring which balls miss the object, which hit it, and at what angle and speed they bounce off it, one could reach some conclusions about the location, size, shape, and texture of the object.

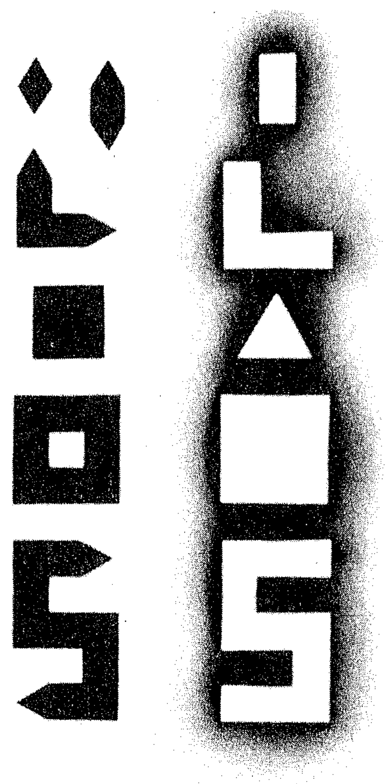
What is the world made of? That simple question has fascinated mankind since the earliest recorded philosophers. The ancient answer of "earth, water, fire, and air" does not satisfy us today. Particle physicists seek a modern answer to this age-old question, using sophisticated tools to study matter at ever finer resolution. As these tools have been developed we have learned that all matter consists of structure within structure—molecules within cells, atoms within molecules, and further structure within the atoms.

We have also found that, to understand the structures at each level of detail, we need to ask two kinds of questions. First, what are the building blocks from which the structures are made? Second, what are the rules that govern how these building blocks fit together? These two questions—the building blocks ("constituents") and the rules governing their interactions—are intimately linked in the study of particle physics. An improved understanding of either one allows progress in learning about the other. Until we find a theory that satisfactorily explains both, we cannot say that we understand the structure of matter.

To get some idea of the type of thinking involved in particle physics, try to solve the puzzle shown at right. The black pieces represent some of the "allowed objects" in the two-dimensional world of the puzzle. The white objects, however, have never been seen. Now, the challenge of this backwards jigsaw puzzle is to figure out the answer to the two questions: What are the constituent pieces (shapes) from which all the allowed objects are made? and What are the rules for putting them together? There are only two types of constituents in this puzzle and the rules are very simple. (The answer is given on page 31 for you to check yourself.) You will find when you try to solve this puzzle that the set of white shapes—those that do not exist—tell you as much about how the pieces are put together as do the black shapes. This is also true in the study of particle physics: sometimes the physicist learns as much from the things that do *not* occur in an experiment as he does from the things that *do* occur.

The two-mile-long Stanford Linear Accelerator, which sits in the Stanford hills not far from the main campus, is a tool for particle physics research. Think of it as a gigantic microscope. By using high-energy electrons as a probe, physicists at the Stanford Linear Accelerator Center (SLAC) can "see" deep inside the nucleus of an atom and learn about the structures buried there. This method is roughly comparable to shooting tennis balls at an unidentified object in a dark room: by measuring which balls miss the object, which hit it, and at what angle and speed they bounce off it, one could reach some conclusions about the location, size, shape, and texture of the object.

Our understanding of the structure of matter has grown enormously in the years since SLAC began operations in the early-1960s. SLAC and other accelerators around the world have played a crucial role in confirming some earlier theories about matter and in generating some important new developments.



THE FIRST STEP INSIDE THE ATOM

All atoms consist of a central core, called a nucleus, that is surrounded by a cloud of particles called electrons. The nucleus of an atom is made up of two kinds of particles, protons and neutrons. The neutrons, as one might guess from their name, are electrically neutral objects—that is, they have no electric charge—while the protons each carry a positive electric charge. The circling electrons each have a negative charge that is exactly the opposite of that of a

ERRATUM: The phrase "three quarks for Muster Mark" appears in James Joyce's *Finnegans Wake*, not *Ulysses*.

Permission to reprint this article granted by The Stanford Magazine. The report is being circulated as a special issue Number 6 of the Beam Line, March 1984.

The Stanford Linear Accelerator Center, *SLAC*, is a national laboratory for basic research in high-energy physics. Its facilities are used by scientists from universities and other laboratories in this country and abroad. Stanford University operates *SLAC* under contract with US Department of Energy through the Department's San Francisco Operations Office in Oakland.

HOW SLAC WORKS

"In high-energy physics you have to have bigger and bigger machines to see smaller and smaller things."
Wolfgang K.H. Panofsky, director of SLAC

The heart of the Stanford Linear Accelerator Center (SLAC) is a pieced-together copper tube four inches in diameter and two miles long. This is the "linac" itself, the conduit down which electrons (the particles that normally swirl around the nucleus of an atom) travel before colliding with a target in an experiment area, where the results of the collisions are studied.

SLAC separates electrons out of their atoms and propels them in a way not much different from the way an ordinary television set does. In a television set, an electron gun at the back of the picture tube shoots a beam of electrons forward while magnets direct the beam around to make pictures on the screen. SLAC's electron gun in the foothills behind Stanford evaporates electrons out of the atoms in a filament of hot tungsten and shoots them straight down the two-mile linac. The electrons travel in bunches or pulses, up to 360 pulses per second, with billions of electrons in each pulse. Magnets surrounding the first ten-foot section of the linac act as lenses to steer and focus the beam of electrons. Radio waves piped into the linac from devices called klystrons carry the electrons along. (The two-mile-long building visible above-ground at SLAC is only the shed housing the series of 240 klystrons. The linac itself is in a tunnel 25 feet underground.) The electrons ride the radio waves and gather energy from them in much the same way surfers ride ocean waves: a cluster of electrons travels with each peak of the radio wave energy. The farther along they travel, the faster they go, approaching ever closer to the speed of light.

It takes two millionths of a second for an electron to reach the end of the linac, where powerful magnets steer it into any of several research areas. In one research area, End Station A, the electron enters a stationary target such as a tank of liquid hydrogen or deuterium. Like all atoms, those in the target consist mostly of empty space, so the electron bullet may pass clean through the atoms of the target, missing any subatomic particles altogether. If the negatively charged electron does come close to any charged particle, the electrical interaction between them will cause it to change course. A detector records what happens, counts how many particles go in which direction, at what speed, and so on. Computers analyze this information.

Two other research areas, SPEAR (Stanford Positron Electron Asymmetric Ring) and PEP (Positron Electron Project) are both based on the principle of colliding moving particles head-on, thereby achieving higher-energy density than is possible with a stationary target. This can reveal phenomena that could never have been seen before.

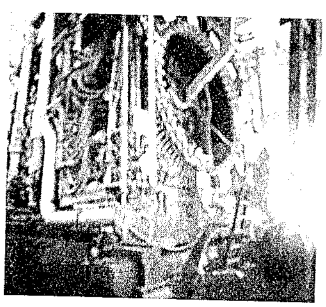
SPEAR, the older of the two research areas, is a 200-foot-diameter oval-shaped ring at the end of the two-mile linac. SPEAR works with both electrons and their antimatter equivalents, positrons (which SLAC can also accelerate). Magnets steer electrons into the SPEAR ring to run one direction, and steer positrons to run in the opposite direction.

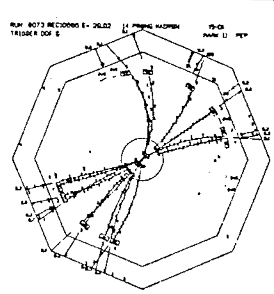
The beams of particles are kept circulating at high energy, and made to cross where detectors can record what happens. Millions of electrons and positrons meet each second. Sometimes they simply deflect one another. Sometimes they collide and annihilate one another, thereby creating a burst of pure energy that lasts for only about one ten-trillionth of a trillionth of a second, before it rematerializes into a shower of all kinds of subnuclear particles and antiparticles that register in large electronic detectors.

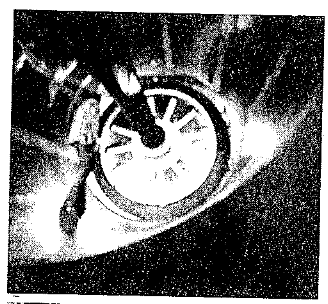
Successes at SPEAR and the desire for even more powerful collisions led physicists at SLAC and the Lawrence Berkeley Laboratory to build a ring ten times larger, called PEP. It works on the same principle as SPEAR, but because it is larger (one and a half miles in circumference), electrons and positrons with much higher energy can be stored in this ring and therefore collide with greater force. Hence PEP allows physicists to explore regions inaccessible at SPEAR.

Plans are now under way to build the Stanford Linear Collider (SLC), which will collide electrons and positrons at energies much higher than can be stored in PEP, but without putting them first in a storage ring. This will require new developments in accelerator technology, something SLAC has continued to produce along with its contributions to basic physics research.

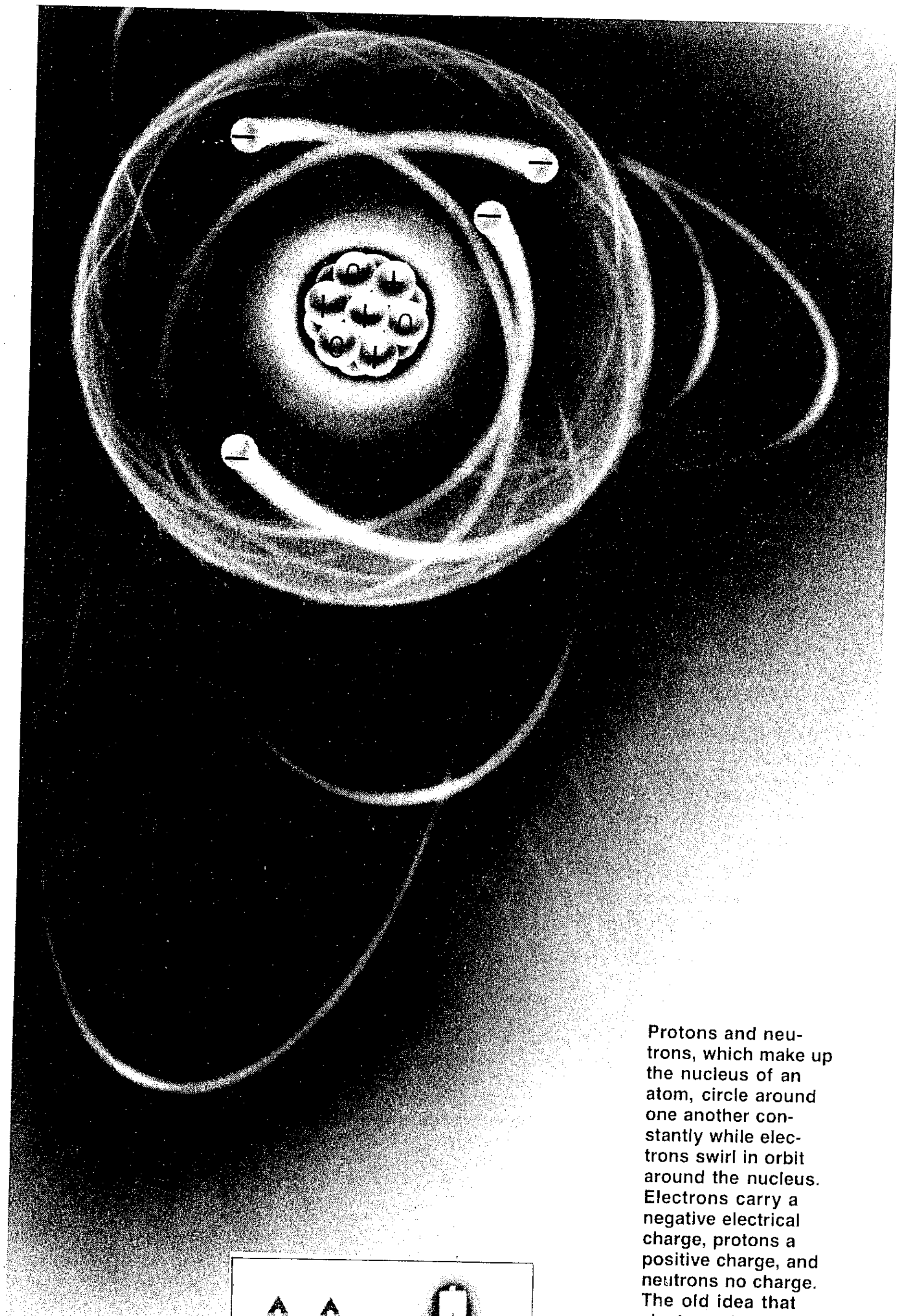
SLAC is the most powerful electron accelerator ever built. Though operated by Stanford, it is a national facility owned by the Department of Energy.



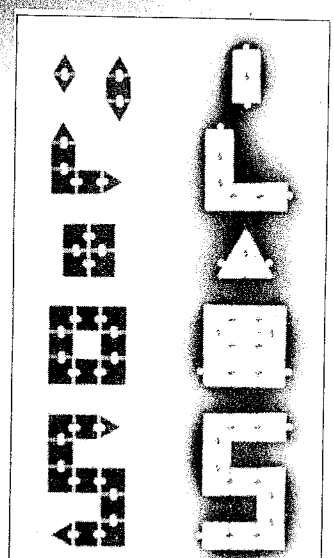




When particles at SLAC's highest-energy research area, PEP, collide and shatter, detectors such as the one at left, top, record what happens. Left, bottom is a typical computer plot of a resulting scatter pattern. This particular plot would be interpreted as two jets of particles, produced by a quark and an antiquark. Particle jets from lower-energy facilities than PEP are not as narrow or well-defined, so they cannot be as easily interpreted. Right, top and bottom: different portions of one huge detector at SPEAR. People are not around while detectors are operating.



Protons and neutrons, which make up the nucleus of an atom, circle around one another constantly while electrons swirl in orbit around the nucleus. Electrons carry a negative electrical charge, protons a positive charge, and neutrons no charge. The old idea that electrons travel around the nucleus in neat symmetrical orbits (like planets around the sun) is incorrect. Electrons travel in irregular orbits, sometimes passing through the nucleus, sometimes straying out of the atom entirely.
The scale in all these illustrations is necessarily quite distorted. If the nucleus were the size shown here, the electrons would be invisibly small and on an average of one and a half miles away.



SOLUTION TO PUZZLE: Each figure is, of course, made up of triangles and/or squares. In allowed objects, triangles connect (as indicated by hooks) to any other piece, but on only one side; squares connect on any two sides but always exactly two sides.

proton. Matter viewed on this scale (or the even smaller scales we will discuss shortly) is never static. The electrons are constantly in motion around the nucleus, and the protons and neutrons are in motion around one another *within* the nucleus. The electrons are held to the nucleus rather weakly by the attraction of the protons' opposite electrical charges.

In the early twentieth century, scientists regarded the atoms themselves as the smallest building blocks of matter, hence they named the set of possible atoms "the elements." In fact, scientists thought it would be impossible to split an atom—that is, to break apart an atomic nucleus into smaller pieces. We now know, however, that this is exactly what happens naturally in radioactive decay.

Once they understood the structure of atomic nuclei, physicists thought that the proton, neutron, and electron might be elementary particles. These did seem to provide a very satisfactory answer to the first question, What are the building blocks?—three types of particles from which all types of atoms (all the "elements") can be made. But investigation into the second question, the nature of the forces between protons and neutrons, led us to conclude that the situation was in fact much more complicated. Rather than having three elementary particles, we found a considerably larger number — a hundred or so, which had to be regarded as at least as fundamental as the proton or neutron.

Particles play two distinct roles in physics. Some are the constituents of matter, as already described, but others can be viewed principally as the *carriers of interactions* between constituent particles. The "carrier" particles travel back and forth between the constituent particles. Particles that have electrical charges interact with each other because of those charges. For example, it is the electrical attraction of the positively charged nucleus that binds electrons to it to form an atom. The electrical interaction between protons in the nucleus and electrons can be viewed as a continual interchange of particles called photons—the carriers or, more correctly, the quanta of the electric field. (The true meaning of the much-overused term, "quantum jump," is here. When an atom makes a transition from one possible configuration to another lower-energy configuration, it does so by emitting a quantum of electromagnetic energy—a photon. This is a quantum jump and it is, despite the popular usage, a very tiny though sudden change in energy, not a large one.)

WHAT HOLDS THE NUCLEUS TOGETHER?

Electromagnetic interaction explains how electrons are held to the nucleus but does not explain how the nucleus itself is held together. In fact, the electromagnetic interactions might be expected to push the like-charged protons of the nucleus apart and have no effect on the neutrons. Yet the protons and neutrons do hold together. Why? It is because a much stronger force overpowers the electromagnetic interaction. Unimaginatively, physicists call this the "strong interaction" or the "strong force."

A theory of this force was first proposed in 1935 by the Japanese physicist Hideki Yukawa. He predicted the existence of some particles about a tenth the mass of protons and neutrons, called pions, which would play the role of the quanta of the strong force. The discovery of pions during the early 1940s not only verified Yukawa's ideas, it also touched off the rash of discoveries of "elementary particles" mentioned earlier. The search for pions was complicated by the fact that pions are unstable. When they decay they produce another particle, which we now call the muon. The muon is like an electron, in that it has no role in the strong interaction, but it is much heavier, almost as heavy as the pion. In fact, when physicists were searching for Yukawa's pion, the first new particle they found was the muon. The fact that the muon's mass was close to that predicted by Yukawa for pions led to some initial confusion. No one had expected the muon, and to this day we know of no reason why this "heavy electron" exists.

Many additional particles were discovered in early accelerator experiments in the 1950s and 1960s. Some were heavier cousins of the pions. Pions and all their cousins are generically called mesons. Similarly, heavier cousins of the proton and neutron were found. Protons, neutrons, and all their cousins are generically called baryons. (I call these particles cousins because even as they were discovered physicists recognized that the particles could be grouped together on the basis of certain properties. In particular, all the particles of a given group have the same spin—a property that can be roughly thought of as an internal rotation of the particle. The spin of mesons can be 0 or 1 unit; the spin of baryons is $\frac{1}{2}$ or $\frac{3}{2}$ units.)

SHORT-LIVED PARTICLES

Many of these particles are highly unstable. This means that they do not normally exist in nature. There are probably no muons anywhere in the room where you are reading this. They come into existence only in high-energy particle collisions such as those produced by an accelerator, or in radioactive decays. You can think of them as being like music, which is not there until you turn on the radio. A fraction of a second later the unstable particles themselves decay; that is, they fall apart into lighter particles. Most unstable particles are not constituents of any normal matter; they are not around long enough for anything lasting to be made of them. Nonetheless, they are just as real as more stable particles.

Many of these unstable particles can be "seen" at SLAC—that is, their effects can be recognized in experiments here. For example, at SLAC we may fire a beam of electrons into a target that is a container of hydrogen. (See the sidebar on page 30.) The electrons that pass close by a hydrogen nucleus (which consists of just a single proton) will interact electrically with that proton. Energy is transferred from a passing electron to a proton. By observing the energy and direction of the electron emerging from the target, we can reconstruct what energy and momentum were transferred to the proton. Or we may turn our attention to other particles produced by the encounter, such as pions. Noting the pattern of energy and angles at which these particles come out of the target is another way we can reconstruct what went on in the target. For example, if just the right amount of energy is transferred to the proton, we may transform it into a particle called a Δ^+—a delta plus. This particle is very unstable. After a tiny fraction of a second (10^{-23} seconds to be more precise) it decays into other particles. Accelerator experiments of this type were responsible for the discovery of many of the unstable particles now known to exist.

THE QUARK REVOLUTION

By grouping particles into families, one sees a pattern emerge. In the mid-1950s this pattern led Caltech physicists George Zweig and Murray Gell-Mann to make a proposal that, at the time, seemed quite revolutionary: that the mesons and the baryons were all composites, made from objects they called "quarks." Gell-Mann picked the name from the phrase "three quarks for Muster Mark" in James Joyce's book *Ulysses*. (In German, quark is something between sour cream and cottage cheese—which of course is a poor choice for the building blocks of anything.)

Zweig and Gell-Mann suggested that quarks come in three types: up, down, and strange. Each of the three different types of quark has its own pattern of charges and strangeness. (We particle physicists have a bad habit of taking everyday words and giving them technical meanings that bear little relation to their usual meaning. "Strangeness" is one such word. When particles with this property were first found, some of their behavior was hard to understand, so we called them strange particles. Later we realized that their behavior could be understood and quantified, so we assigned them a label or quantum number. The name "strangeness" was later attached to this quantum number.)

For each kind of quark there is also an antiparticle, called an antiquark, which has opposite charge and strangeness from the corresponding quark. From just the three types of quarks and their antiquarks, Gell-Mann and Zweig showed that they could describe each of the known particles as a different combination of quarks. For example, in their quark model, mesons (such as the pion) are all made of combinations of one quark and one antiquark. The baryons (protons and neutrons and their cousins) are combinations of three quarks; antibaryons are made of three antiquarks.

Why was the quark idea revolutionary? After all, the history of particle physics was to look for structure within structure. The idea was revolutionary because, in order to equal the charges of each known particle by adding up the charges of its quark constituents, one had to assume that the quark charges were $\frac{2}{3}$e and $-\frac{1}{3}$e (where e is the charge of the proton). No particle with charge other than integer (whole) multiples of e had ever been observed. If fractionally charged particles exist, they exist only in those combinations that add up to integer charges, never any others, or alone.

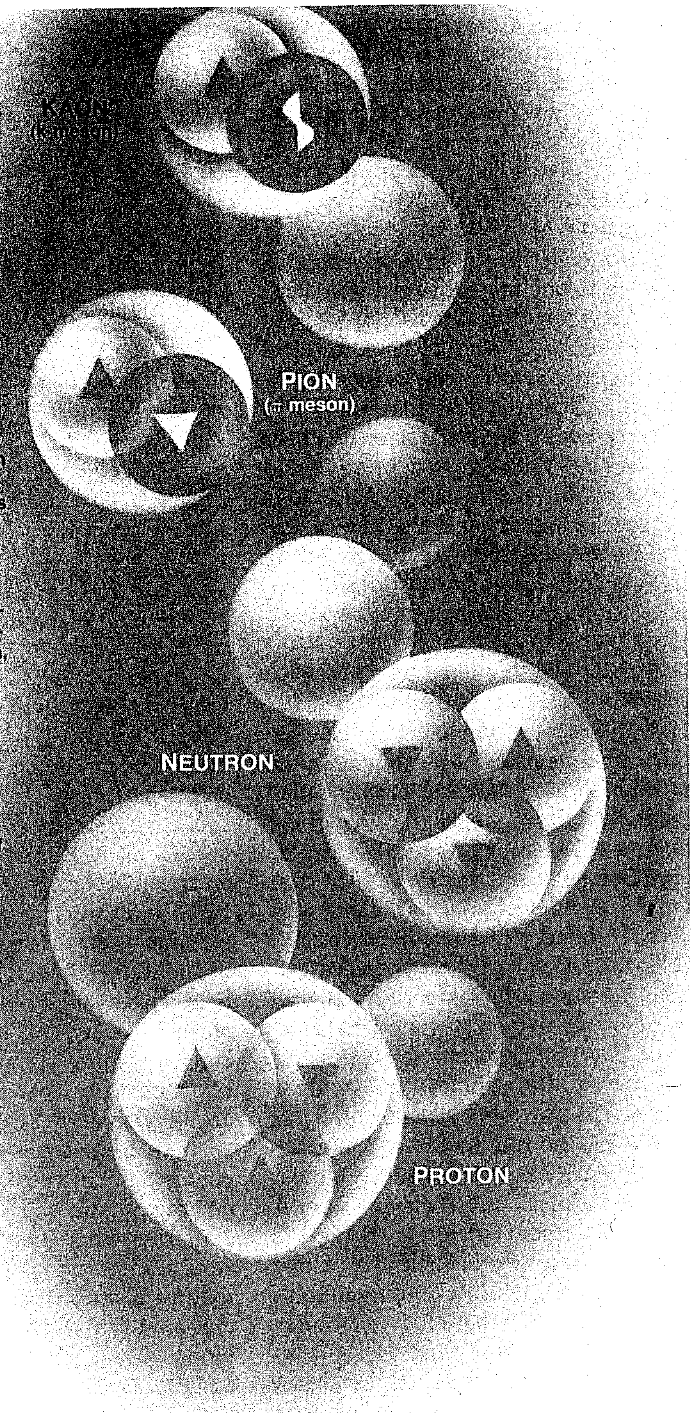
(Only one experiment, performed at Stanford under the supervision of Professor William Fairbanks and published in 1979, claims evidence for isolated particles with charges that are consistent with $\pm\frac{2}{3}e$ or $\pm\frac{1}{3}e$. The question is generally regarded as unsettled. However, if isolated fractional charges do indeed exist, then the rule of combination will need modification to accommodate them.)

At the time the quark model was first proposed, it was believed that protons never fall apart—and in fact no such process has ever been observed. But if a proton *is* made of pieces—quarks—why *doesn't* it fly apart into those pieces if you hit it hard enough? All previous structures had worked that way. So strong was the prejudice against the existence of fractional charges that even the inventors of the quark model were at first reluctant to call quarks real objects. Perhaps, they suggested, the quarks represented only a mathematical device to explain the pattern of the "elementary" particles.

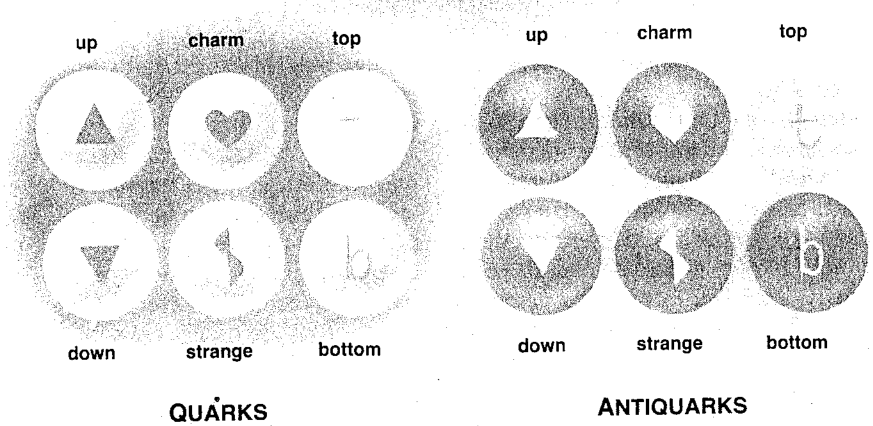
BUT ARE QUARKS REAL?

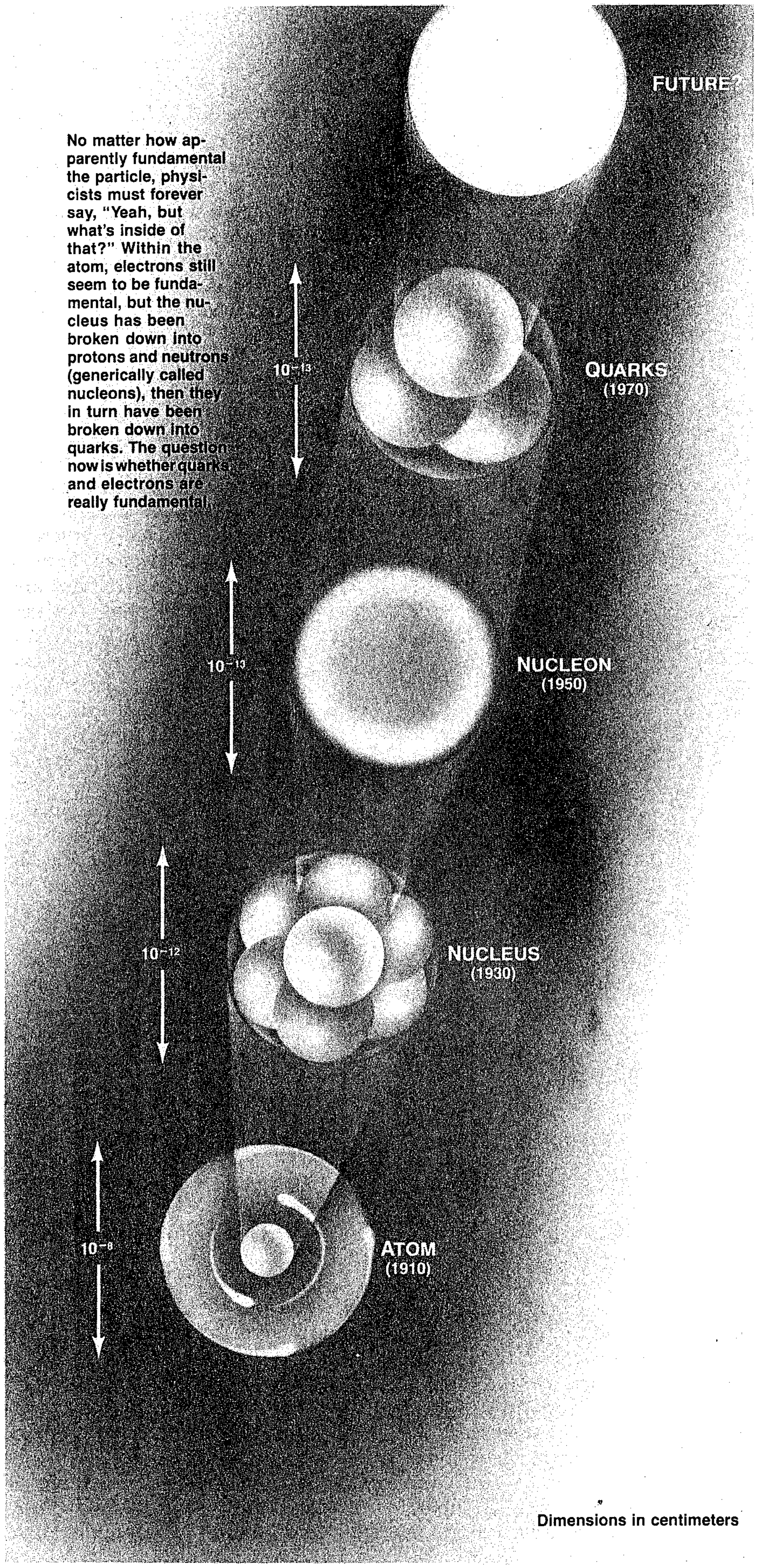
A series of early experiments at SLAC in the mid-1960s provided a major push in the direction of accepting quarks as real physical objects. Carried out by a team under the leadership of Richard Taylor of SLAC and Henry Kendall of MIT, the experiments consisted of shooting high-energy electrons through the accelerator at a target containing hydrogen or carbon. By measuring how many of the electrons scattered off the target in a given direction and with a given residual energy, one could look for evidence of structure within a proton or a neutron. James Bjorken, a theorist at SLAC, showed that results of the Taylor-Kendall experiments could be explained if the proton was assumed to have constituents that, when interacting with the very-high-energy electrons, behaved essentially independently—as if they were separate, free particles, rather than particles tightly bound in a proton. SLAC's evidence, taken in conjunction with later work at proton accelerators in Illinois and Switzerland, gradually made physicists think of quarks as real objects.

Once we reach the point of accepting quarks as real particles, the other question must be asked: What is the nature of the interaction between them? An important clue to the nature of their interaction—and in fact one of the most



Protons and neutrons, once considered fundamental particles, are now believed to be made up of quarks: two up quarks plus one down quark makes a proton; two down quarks plus one up quark makes a neutron. Physicists believe quarks come in at least six types: particles containing combinations of up, down, strange, charm, or bottom quarks have been observed. The sixth quark, called top, has been predicted but no particles containing it have yet been observed. Each type of quark has a corresponding antiquark (shown in black). Quarks and antiquarks combine to constitute particles known as mesons, two of which are shown.





No matter how apparently fundamental the particle, physicists must forever say, "Yeah, but what's inside of that?" Within the atom, electrons still seem to be fundamental, but the nucleus has been broken down into protons and neutrons (generically called nucleons), then they in turn have been broken down into quarks. The question now is whether quarks and electrons are really fundamental.

substantial pieces of evidence for our present theory of matter—comes also from the Taylor-Kendall scattering experiments. The clue is that, to describe these experiments in terms of quarks, one had to assume that the quarks behaved as if they were free while interacting with the very-high-energy electrons fired at them. Most of the particle theories (mathematical structures known as field theories) studied up to that time would not produce such a result. This Taylor-Kendall clue led to a search for theories that would account for this free behavior of quarks. The class of field theories so identified has the general name of Non-Abelian Gauge Theories. (Algebras are classified as Abelian or non-Abelian following the work of the nineteenth-century mathematician Niels Henrik Abel. The charges in these theories have a non-Abelian algebra.)

The particular non-Abelian Gauge Theory that is believed to describe the interactions of quarks is called Quantum Chromo-Dynamics—QCD for short. According to this theory, quarks carry a charge other than their electrical charge. This we call their color charge, or just color. Here is another adoption of an everday word for a totally different meaning. Color charge has nothing to do with the colors we see. It simply means that these particles participate in QCD interactions.

Each type of quark can come with any of three possible color charges. Furthermore, the quantum particles that carry out the interaction of color charges themselves carry color charges. These quantum particles are called gluons because they are responsible for "gluing" the quarks together into combinations that constitute, for example, protons or pions (which have zero net color charge). Whereas *electrical* charges add up according to the rules of ordinary arithmetic, the mathematics of *color* charges is somewhat more complicated (because it is non-Abelian): it turns out that only the combination of quark plus antiquark, or the combination of three quarks can form particles of zero color charge. Two quarks or four quarks can never give zero color charge. Thus, the particles we observe are those that can be understood as combinations for which the total combined color charge is zero.

Quarks exist inside particles, but there is only an extremely small probability that one single quark could ever be observed very far distant from the others. (A comparably improbable event would be finding all the air molecules in a room in one corner while the rest of the room was empty. Such things, though theoretically possible, are so improbable that for all practical purposes one calls them impossible.) Physicists refer to this property as confinement: the quarks are said to be confined to the interior of the zero color charge particles.

DISCOVERIES AND CONFIRMATIONS

I said earlier that quarks come in three types: up, down, and strange. That was the belief until the early 1970s, when particles containing a fourth type of quark, the charm quark, were discovered independently and more or less simultaneously by Burton Richter of Stanford and Samuel Ting of MIT. This was one of the most dramatic particle physics discoveries of the decade. While Richter and his colleagues worked at Stanford, Ting and his colleagues were working on the other side of the country at a proton accelerator at Brookhaven National Laboratory on Long Island. Ting's Brookhaven experiments were actually performed a little earlier than the Stanford experiments, but the group held up the announcement while making careful checks of their results. Finally the two groups, Brookhaven and Stanford, announced their results at SLAC on the same day in November 1975. The two group leaders, Richter and Ting, shared the 1976 Nobel Prize in physics for the discovery. (Particles containing a fifth type of quark have since been discovered by Leon Lederman and his collaborators at Fermilab in Illinois.)

Richter had done his experiments at a new colliding beam research facility built at SLAC under his leadership in the early 1970s, the Stanford Positron Electron Asymetric Ring (SPEAR; see sidebar, page 30). His was not the only exciting discovery at SPEAR. At almost the same time that Richter and Ting were doing their experiments, a group at SPEAR led by Martin Perl discovered another particle, the τ-lepton. Whereas the charm quark had been predicted by some theorists because it was necessary for the theory of some radioactive decays, the new lepton was completely unexpected. It was another copy of the electron and muon, but many times heavier than either. Why this repetition occurs is one of the outstanding puzzles of particle physics today. The discovery of the new lepton was unique to SPEAR, though it has since been observed at other accelerators. As a result of the discovery, Perl shared the 1983 Wolf Prize (with Lederman, the discoverer of the fifth quark).

Other experiments at SPEAR gave further confirmation for the QCD theory of quarks and gluons. Gail Hanson of SPEAR found that the scatter patterns produced when electrons collide with positrons fit those that would be expected according to the QCD theory. It remained for PEP (a later and higher energy version of SPEAR that began operation at SLAC in 1980) and a similar facility in Germany to carry this study of patterns to a level of detail not possible at SPEAR.

Another expectation of the QCD theory is that, in addition to the particles that can be made of combinations of quarks, there should be some particles, called by the silly name of glueballs, that are made of combinations of gluons. Some of the possible glueball particles have properties that could not be achieved from quark combinations. Physicists at SPEAR are currently fascinated by recent evidence for particles that could be glueballs. Further information is needed before they can consider this evidence conclusive, but at present the existence of glueballs seems to be a possible interpretation.

The most widely accepted theory describing the electromagnetic interaction and also the force responsible for some radioactive decays (called the weak interaction) is also a non-Abelian Gauge Theory. It received a very important confirmation from a set of precise experiments made in 1980 by a Stanford group headed by Richard Taylor. They used the original SLAC facility, but with a new particle source capable of producing polarized electrons. As previously mentioned, electrons, photons, and many other particles have a property called spin, which can be thought of as an internal rotation of the particle. The spins of particles in a beam can be aligned or polarized. (Photons, for example, are polarized when light passes through Polaroid sunglasses. You can observe the effect of this polarization by putting another pair of sunglasses at right angles to the first and seeing that no light comes through, whereas when the two lenses are aligned the light comes through both.) In a beam of polarized electrons, the direction of the spin rotation for the majority of the electrons coming down the accelerator is aligned in a predetermined fashion. By detecting a tiny asymmetry in the number of electrons scattered to the left or right (relative to this direction of polarization), the SLAC group demonstrated that the predictions of the non-Abelian weak interaction theory were correct. It was only after these SLAC experiments that the theory was regarded as well enough established to award a Nobel Prize to the theorists who had developed it ten years earlier.

THE FUTURE

We have now reached a picture of matter in which all those particles that have strong interactions are composites of quarks and gluons. The strong interactions are now seen as a residual effect of their internal color charge structure. Other particles, called leptons, have no internal color charge structure and hence no strong interactions; they participate only in the weak, the electromagnetic, and the gravitational processes. The fact that all the interactions, even gravity, are now described by gauge theories has given much impetus to the idea that we can find a single unified theory of all forces—an idea which Einstein pursued without success in the latter part of his research. Perhaps we are now on the verge of formulating such a theory. Certainly, many people are trying. Another equally fascinating direction of research is to try to explain the repeating sets of leptons and quarks by looking for yet another level of structure within them. Perhaps quarks are the fundamental building blocks of nature, perhaps not. Only time and further study will tell.

For SLAC's part, the next major step will be to construct a new higher-energy facility, the Stanford Linear Collider. One of SLC's goals will be to study the particle called the Z-boson, but perhaps other results from SLC will prove as exciting as whatever it can tell us about Z-bosons. When one pushes to a new and unexplored frontier, one often learns more than one can predict.

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