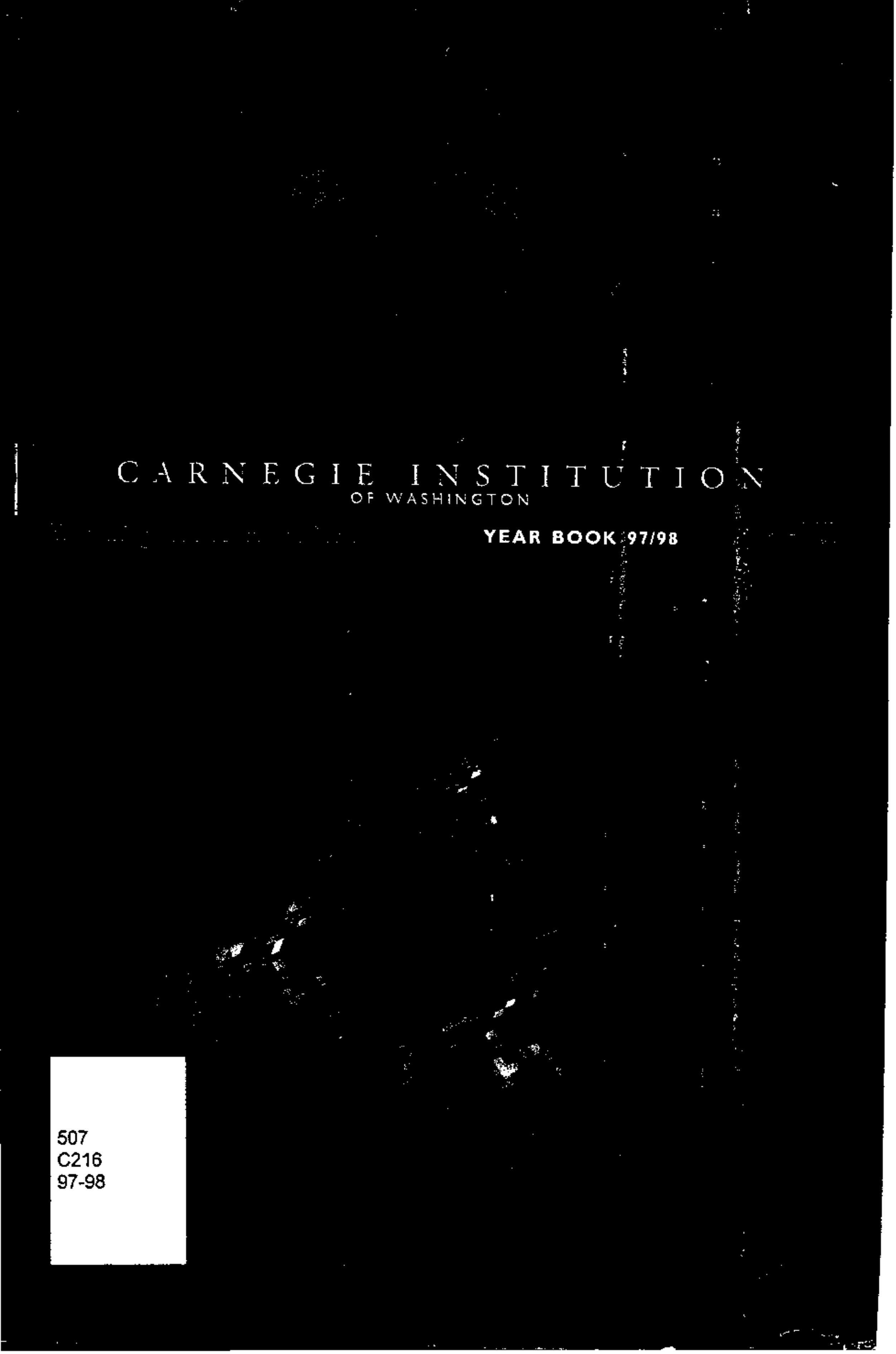
CARNEGIE INSTITUTION
OF WASHINGTON

YEAR BOOK 97/98



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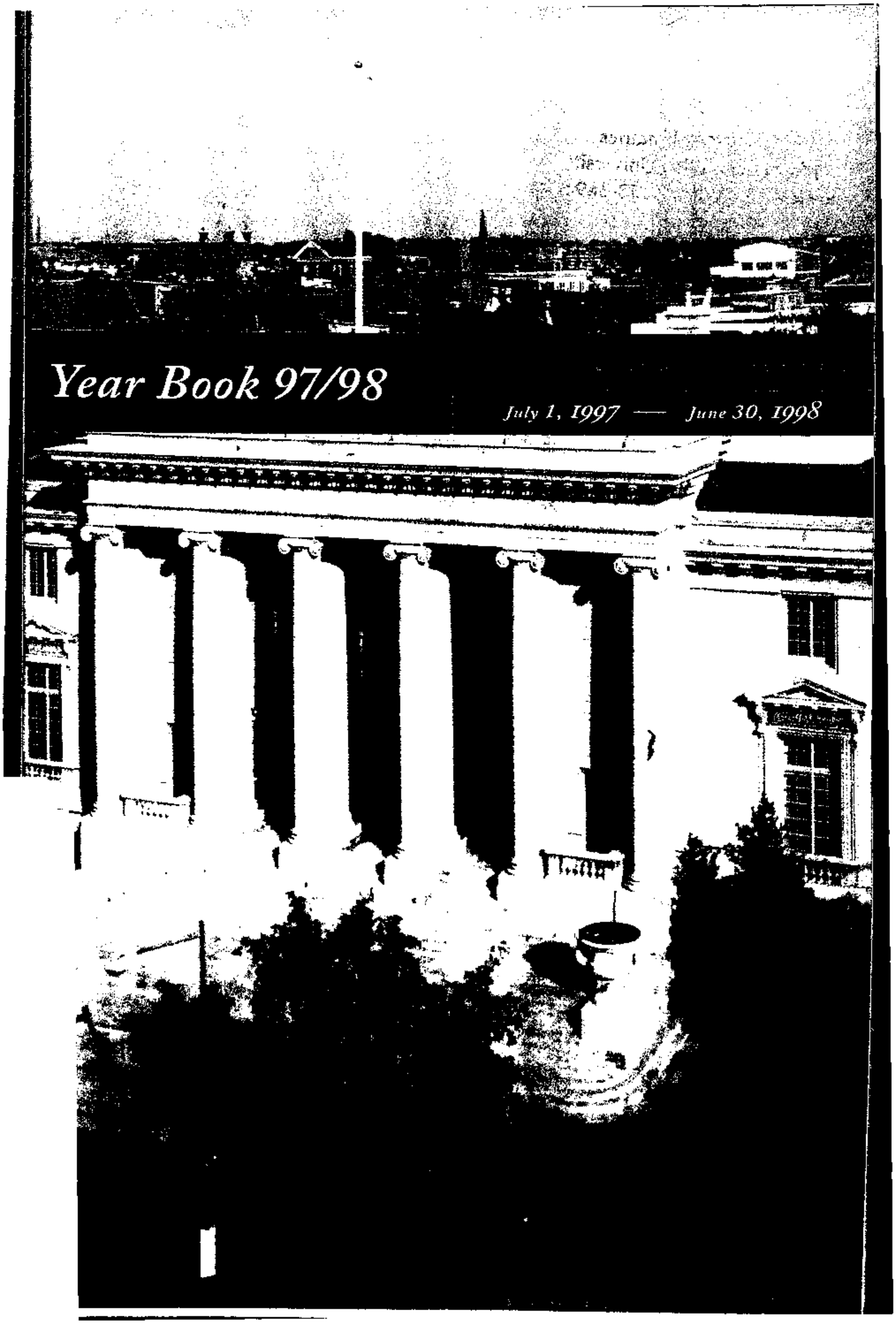

Year Book 97/98

July 1, 1997 — June 30, 1998

ABO [illegible]

. . . TO ENCOURAGE, IN THE BROADEST AND MOST LIBERAL MANNER, INVESTIGATION, RESEARCH, AND DISCOVERY, AND THE APPLICATION OF KNOWLEDGE TO THE IMPROVEMENT OF MANKIND . . .

The Carnegie Institution of Washington was incorporated with these words in 1902 by its founder, Andrew Carnegie. Since then, the institution has remained true to its mission. At five research departments across the country, the scientific staff and a constantly changing roster of students, postdoctoral fellows, and visiting investigators tackle fundamental questions on the frontiers of biology, earth sciences, and astronomy.

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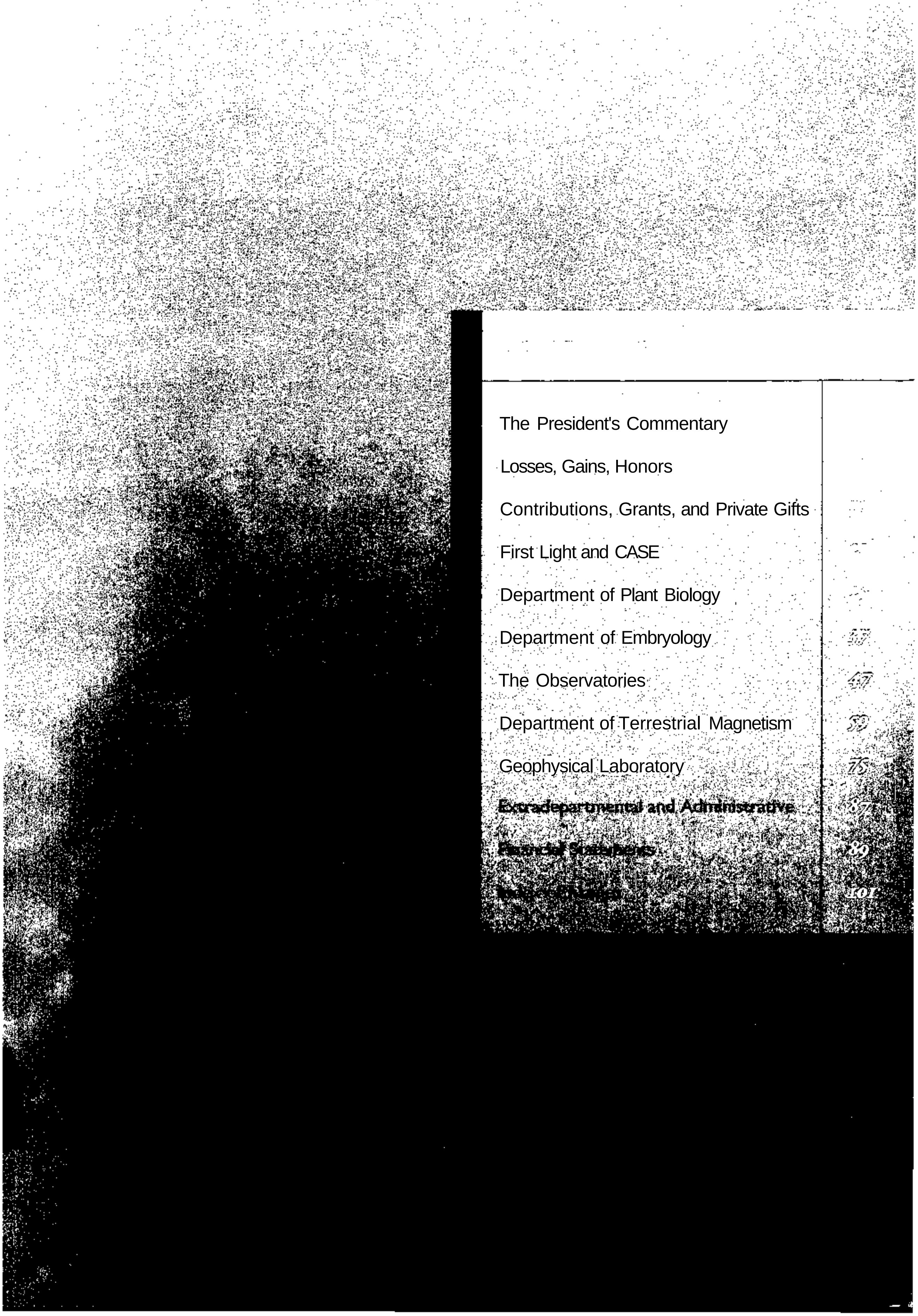

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[illegible] DAPI [illegible] DNA [illegible] Carnegie Department of Embryology [illegible]

THE EYE IS NEVER SATISFIED WITH SEEING;
ENDLESS ARE THE DESIRES OF THE HEART.
GATES OF REPENTANCE. THE NEW UNION PRAYERBOOK FOR THE DAYS OF AWE.

Central Conference of American Rabbis.
New York, 1978.

Last spring I attended a meeting about that perennial question, the state of university education. Scholars concerned with the humanities spoke about their own undergraduate experiences with classical philosophers and authors. Many decades later, they could still reach easily into their considerable memories and find there pertinent quotations and fresh ideas. Their university educations are the living foundations of their current efforts. My own educational memories, as least as many decades old as theirs, are somewhat different. Aside from several fundamental matters in the physical and biological sciences, few specifics that I learned in college or university are relevant to today's science and a lot have since been proven wrong. Scientists must continually revise the scientific ideas stored in their heads. I pointed out that while they had been trying hard for as much as half a century to *remember* what they had learned as students, I had been working to *forget.* They were astounded and certain I must be wrong, until another scientist in the room concurred with me.

After the meeting I wondered if I had exaggerated. As I was also thinking then about my tenth anniversary as president of the Carnegie Institution, the two questions merged in a consideration of the past decade. Marking the changes in research directions and methods is an essential window on the health of a scientific institution.

To begin to assess the changes in Carnegie science over the last decade, I asked each staff member to send me a copy of her or his most significant paper of the past year. Several general impressions emerged from reading them. For one, Carnegie scientists are collaborating more., both with their colleagues within the institution and with scientists from around the world. For another, their research has come to depend increasingly on centralized, often government-sponsored national and international facilities, such as synchrotrons, space telescopes, satellites, computer networks, and data banks. A good example is DTM's Selwyn Sacks' ongoing investigation of the rate of convergence of the Nazca and South American tectonic plates along the western coast of South America. Collaborating with Sacks are scientists from Peru and several U.S. institutions. The geodetic data they used were obtained from a national system of global positioning satellites.

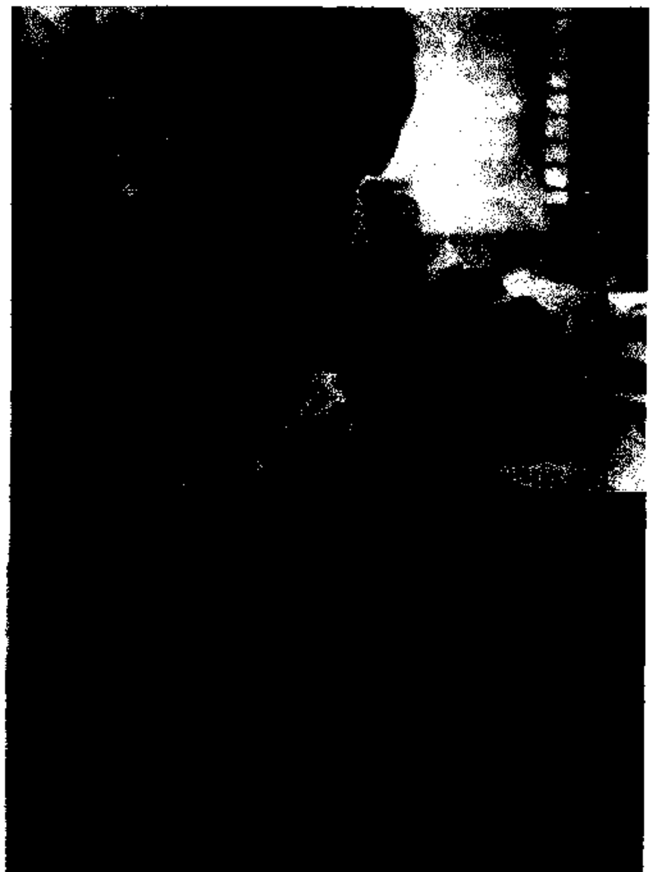
Among all the changes that impressed me, three have particularly profound and interdependent effects on the science carried out across the Carnegie departments. All three reflect the capacities of computers. One stems from the implications of large data banks. Another concerns the basic scientific tool of model building. And the third is the revolution in the ability to generate images. It is commonplace to note that computers are altering the foundations of human culture and society. Less widely appreciated are the influences that novel science, generated with computers, will have on those altered foundations.

THE NEW COLLECTIONS

Natural history museums all over the world store a wide range of preserved specimens, bones, and rocks. Scholarship still focuses on these often haphazard or eclectic collections, and continues to yield essential information on the evolution of the biological and physical Earth. In its early years, the Carnegie Institution started its own collections.

The Department of Embryology's unique human embryo collection is now carefully housed at the National Museum of Health and Medicine of the Armed Forces Institute for Pathology in Washington D.C., where it is available to scholars. The large collection of photographic plates from the Mount Wilson Observatory is accessible at the Observatories' headquarters in Pasadena. These plates remain useful by providing, among other data, benchmarks to chart changes in the sky.

The newest scientific collections are not concrete entities. Their sizes are not limited by available physical space or curatorial resources. They consist of vast amounts of information that reside in computer data bases, not museum shelves. They can be accessed from anywhere on Earth, and even from space. Some of these data bases are constructed from painstakingly gathered and recorded information. Others represent the direct input of data acquired by instruments. Thus, computers not only permit the storage of large bodies of data: they spur the making of collections.



▶ Astronomers no longer use photographic plates to study the sky but rely instead on computers that can rapidly access data stored in large memory banks. Above: Carnegie astronomer Edwin Hubble (1889-1953) examines one of the plates from the Mount Wilson collection. Below: the Observatories' Patrick McCarthy examines his data using a computer.

Examples abound. In genetics, the sequencing of individual genes necessitated the development of data base storage techniques. This in turn stimulated the development of tools to access and manipulate the data. Large-scale projects to sequence whole genomes foster improved methods for computer-dependent data acquisition, recording, and retrieval. In astronomy, modern instrumentation often provides more data than is of interest to the astronomer who collects it. Similarly, vast amounts of data are collected by satellites and space probes and by the increasingly sophisticated and sensitive instruments used for experimental earth science. Placed in data bases, the information tangential to a particular project is thus stored for future research.

Collecting vast amounts of data is one thing. Being able to use the information in the service of science is another. Today, the genome data banks can be queried about various aspects of gene and protein structure and used to search for similarities between genes within an organism or among different organisms, or to identify single active genes. In a series of experiments at the Department of Plant Biology, Krishna Niyogi, OUe Bjdrkman, and Arthur Grossman used such tools to advance understanding of the way plants protect themselves from excess light. Winslow Briggs applied the tools to a problem that has long intrigued him: the mechanism by which plants respond to blue light. Don Brown and Alejandro Sánchez Alvarado at the Department of Embryology depended on data banks to identify genes that are turned on or off in response to major physiological upheavals: metamorphosis in toads and regeneration in planaria, respectively. And the data banks they used weren't restricted to toad and planaria genes. Because of the remarkable similarity among genes in different organisms, planaria and toad genes can often be characterized by referring to data banks for fly, human, or yeast genes.

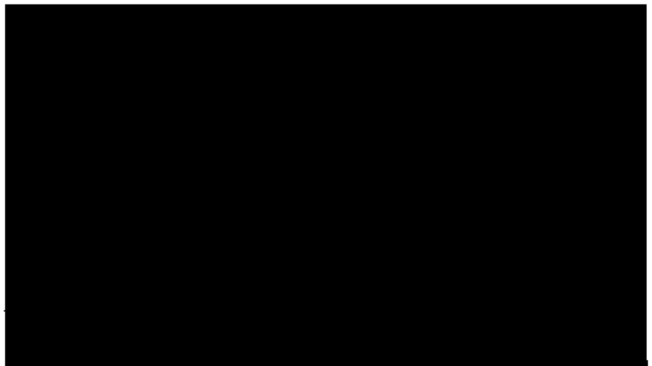
In all of these studies, computers played a secondary role. The questions were posed by the scientists. Answers were obtained by a lot of hard, experimental work. The computers only assisted. And the investigations necessarily proceeded one gene or at most a few genes at a time.

Scientists now recognize that unexpected questions are likely to emerge from experimentation with the data banks themselves, if only sufficiently intelligent and innovative tools can be developed to manipulate them. Christopher Somerville and Shauna Somerville, among others, have been thinking about this issue in relation to biology (see this Year Book, pp. 27). One challenging task is to design the data bases so that they are maximally useful in the future. This itself may produce novel science because it requires trying to imagine what new questions may emerge. Another task is to develop techniques that encompass more than one or a few genes at a time. Shauna Somerville, for example, is working on methods that will, in single experiments, obtain and store data on entire networks of plant genes that respond to particular environmental stimuli, both internal and external, in individual cell types. The next task, the province of the new field of bioinformatics, is to develop techniques that will synthesize the many simultaneous discrete responses into a coherent and comprehensive understanding. Such tools will also be useful to developmental biologists like Brown and Sanchez Alvarado. The capacity of computers to handle simultaneously a large number of variables will undoubtedly permit new insights on a variety of complex questions.

BUILDING MODELS

One approach to mining the depths of the data banks for the solution of complex problems is the time-honored scientific practice of making models. Models are plausible explanations for poorly understood phenomena. Computers have enhanced the range and detail of model construction over earlier paper-and-pencil techniques. Computers can also test models against relevant banked data. Some models will be discarded. Others, perhaps only one, will fit the data and can be adopted, at least tentatively, as an explanation. A good example of this approach is Sean Solomon's work on the ridged lava plains observed on the surface of Venus by the Magellan mission. Solomon and his collaborators used computers to construct and test models for ridge formation. The analysis suggests that the ridges arose in response to great fluctuations in the atmospheric and surface temperatures of the planet, not through purely tectonic processes.

At the Department of Plant Biology, Joe Berry, Chris Field, and collaborators used computer models to analyze the effect of a doubling of atmospheric carbon dioxide on large ecosystems. They coupled a general model for atmospheric circulation with a terrestrial biosphere model that they derived using extensive banked experimental data on the nutritional status of the plant species, the exchanges of heat and water between plants and atmosphere, and various environmental factors, including temperature and water levels. The combined models predict that at some latitudes, temperature will rise more than one degree over and above that predicted by the greenhouse effect of increased atmospheric carbon dioxide. The Berry and Field results will need to be refined with additional data. But without access to satellite-acquired data on the



DNA micro-array technology is designed to measure the expression of large numbers of genes simultaneously. In this microarray image from the Department of Plant Biology's Shauna Somerville representing 192 genes. DNA from each gene was spotted onto a glass slide using a high-precision [illegible] [illegible] to the [illegible]. The intensity of the fluorescent signal—shown as variations in color—depends on how much mRNA was present in the tissue sample for that gene, [illegible] indicates high [illegible], [illegible] is low.

type, density, and color of vegetation, and the computational power of modern computers, such models could not be tested or refined.

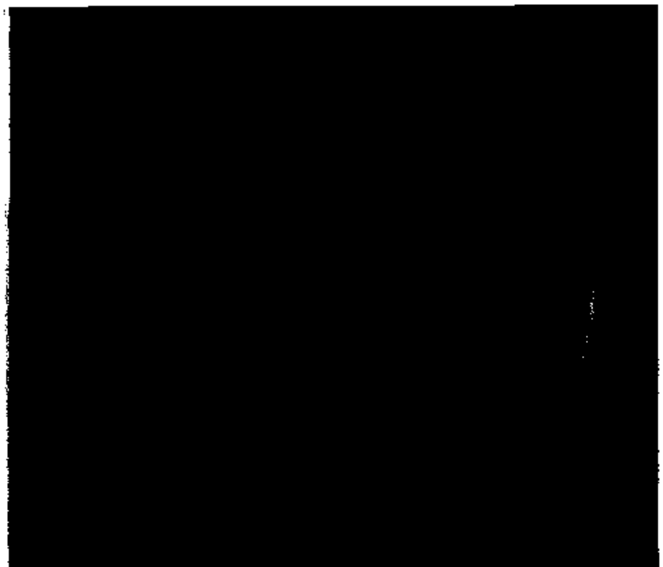
Similarly, powerful computers enable DTM's Alan Boss and George Wetherill to model and test theories about the origin of solar systems, our own and those around other stars. And François Schweizer points out that computers are the experimental tools with which models for evolution of galaxies and complex galactic interactions can be simulated, providing blueprints for the data needed to test the models.

NEW EYES

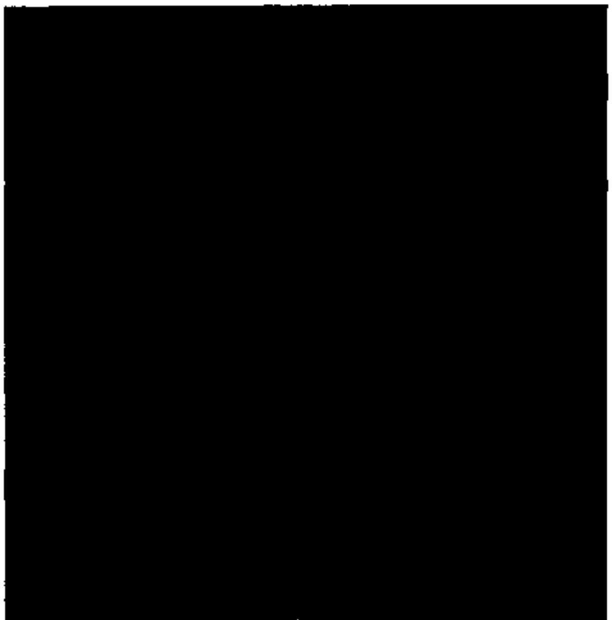
The abundance and clarity of images in current scientific papers is remarkable. This revolution in data presentation hails from the ability of computers to convert digitized information into images—on paper or the internet. Many of these visual experiences were unimaginable even a few years ago. In September of this year, for example, I watched over the internet from my home in Washington, D.C., as the glass for the Magellan II mirror melted inside the spinning oven at the University of Arizona. But even more extraordinary is that we now routinely see what was previously invisible. Computers have given us eyes that evolution, for all its elegance and competence, did not. There is even a site on the web that displays images as seen by a honeybee!

Our computer-given eyes accomplish three especially wonderful feats. They see images at wavelengths outside of what we call the visible region of the electromagnetic spectrum. They see hidden things. They see images constructed out of data that have little or nothing to do with light at any wavelength.

Seeing invisible light. The visible region of the electromagnetic spectrum—the region our eyes detect—includes wavelengths for the familiar red, orange, yellow, green, blue, and violet colors and also accounts for the white we see when light at all these wavelengths arrives together on our retinas. Much larger regions of the spectrum are invisible



▶ Equatorial view of a protoplanetary disk, simulated by DTM's Alan Boss using a program that calculates the three-dimensional flow of gas and dust. The disk is undergoing a phase of gravitational instability leading to spiral arm formation. A solar-mass protostar lies unseen at the disk's center.



◀ Three-dimensional view of the deformation and pressure distribution in a diamond-anvil cell deduced from "finite-element" calculations performed on a supercomputer (100 GPa = 1 million atmospheres pressure). The view shows a cross-sectional cut through the diamond and the metal (or gasket) being compressed. The calculations show that diamond bends elastically like rubber under these ultrahigh-pressure conditions, in agreement with experimental observation. (Courtesy of Sebastien Merkel and Russell J. Hemley, Geophysical Laboratory.)

to human eyes, including, at wavelengths longer than that of red light, infrared (heat) and radiowaves, and, at wavelengths shorter than that of visible light, ultraviolet, gamma, and x radiation.

Carnegie astronomers are making extensive use of the invisible parts of the electromagnetic spectrum. Infrared and radiowaves are now collected by ground- and space-based telescopes. Space telescopes above Earth's atmosphere record x-ray and ultraviolet wavelengths. By scanning across a galaxy with appropriate detectors, light of particular wavelengths can be sensed and the spectra beamed to Earth-based computers. The computers then convert the spectra into graphs and false-color images, with the colors representing light intensities at invisible wavelengths. The pictures show the distribution of material and energy. For example, they illustrate the diffuse gas that exists around stars, nebulae, and galaxies, and thus provide a more complete picture of the stuff that is out there. Without such computer-generated images, we would have no way to see light outside of the visible region of the spectrum, even if we journeyed into space ourselves. As Gus Oemler points out in his essay (see pp. 47), we are no longer limited to seeing just starlight.

The last upgrade of the Hubble telescope provided a camera capable of taking images from the near-infrared part of the spectrum. This is important because it allows astronomers to image light emitted from very distant, ancient objects which, because of the Doppler effect, is shifted into the infrared by the time it reaches Earth. Using the infrared camera, Ray Weymann, Pat McCarthy, and their postdoctoral colleagues at the Observatories found that the number of galaxies per unit area of the sky gets bigger as galaxies become fainter and smaller. This makes sense if, as believed, closer (and newer) galaxies formed from mergers of gravitationally interacting smaller (and older) ones.

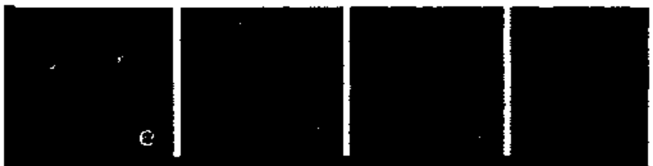
Seeing hidden things. The invention of microscopes in the 17th century led to the discovery of cells and chromosomes. Since then, advances in microscopy have continued to transform biology. The electron microscope, for example, magnifies objects a thousand times more than traditional light microscopes, which expand images only up to about several-hundred fold. Scanning electron microscopy gives three-dimensional images. Video cameras attached to microscopes yield dynamic rather than static images. Videos are now even part of published papers; in these instances, the reader is guided to web site addresses for viewing.

A "true-color" image of several faint galaxies, made by combining an infrared image from the Hubble Space Telescope with blue and green images from the Keck 10-m telescope in Hawaii. The red galaxies are seen only or primarily in the near-IR images, and are most likely a cluster of massive galaxies at large redshifts. The blue galaxies are closer to us. (Courtesy of Lin Yan, Lisa Storrie-Lombardi, Ray Weymann, and Patrick McCarthy, all of the Observatories.)

Clever, insightful interpretation of cellular structures seen in microscopes gives important but inconclusive clues as to function. In the past decade, however, ways have been found to couple the structural information seen in the microscope with definitive functional data obtained from biochemical experiments. The key is to associate the presence of particular proteins with specific, intracellular structures. The dependence of the structure on the protein's function can then be experimentally confirmed by inhibiting or destroying the gene that specifies the protein.

Two different techniques mark the presence of a particular gene product or protein in microscopic images. In one, the sample is treated with an antibody that binds to that protein and no other, the antibody itself is chemically marked with a fluorescent tag. In the second technique, the protein's gene is first reconstructed to include the genetic code for a naturally fluorescent protein; whatever cell types naturally express the gene will then fluoresce. Especially productive application of these methods derives from their use in conjunction with what is called a confocal microscope. Confocal microscopes use laser light of particular wavelengths (chosen to match the fluorescent tag). The light is focused on a single plane of the sample and scanned across that plane, making individual images at various points. The digitized images are computer-synthesized into a picture across the plane.

The extraordinary insights afforded by confocal microscopy are illustrated by the work of Joe Gall and his colleagues at the Department of Embryology. They have revisited what were, before their recent experiments, enigmatic structures within cell nuclei called coiled bodies. These bodies were described as early as 1913 and first caught Gall's attention in 1954. The new confocal microscope pictures readily distinguish coiled bodies from other nuclear bodies by shape, size (up to 10 micrometers), and the presence within them of a spherical structure. In experiments, Gall and colleagues mark the cells with specific antibodies to two different proteins, coilin and Sm. Each of the two antibodies is associated with a tag that fluoresces at a distinctive wavelength. The confocal microscope detects the two different fluorescent markers simultaneously. The resulting pictures show, by arbitrary colors, the distribution of each protein separately and together. The photograph (below) shows that coilin is in the coiled body itself but not in the small, associated structures, while Sm occurs in all the visible structures. There is no coilin in the spherical inclusion inside the coiled body, but there is Sm. The experiments allowed Gall and colleagues to conclude that coilin is important for the maturation of particular messenger RNAs that encode proteins called histones, a process known to occur in the coiled bodies.



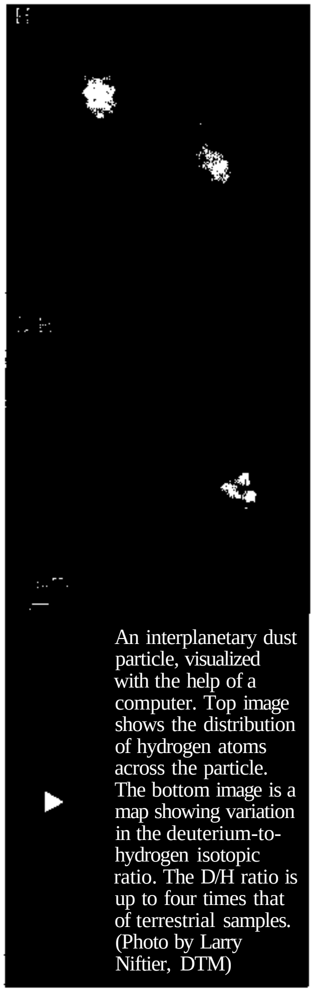
A coiled body from a *Xenopus* oocyte [illegible] photographed by Joe Gall and Michel Bellini [illegible] Panel e shows a coiled body with [illegible] attached associated structures [illegible] photographed by differential interference contrast. Panels f–h shows the same field imaged with the confocal microscope. The coiled body is stained for both coilin (green) and Sm (red) proteins. Because these proteins fluoresce at different wavelengths, the confocal microscope can detect them simultaneously. In h, they are colocalized. (Reprinted from Mol *Biol.* Cell 9, 2987-3001, with permission.)

"Seeing" what is not light at all. Computers display radiation by converting digital data into images, regardless of where in the electromagnetic spectrum the light waves originate. Computers can also construct images from data that have nothing whatever to do with light, as long as the data represent a scan over a surface or a body. Such pictures are not what we usually mean when we think of "seeing," that is, the perception of a distribution of light.

In Erik Hauri's studies of volcanic rocks at DTM, the focus is on tiny inclusions that originated in magma from Earth's fluid interior mantle. Conel Alexander is interested in special small inclusion grains in meteorites; these presolar grains represent material formed before the sun and planets took shape. Both scientists use an extraordinary new instrument, which produces beams of ions that sweep across a rock's surface and shoots tiny samples from precise locations on the surface into a mass spectrometer for determination of chemical and isotopic composition. Computers run the ion microprobe and the mass spectrometer, as well as the connection between the two. Computers also collect and store the raw data, and calculate visual maps of the abundance of the different atoms and isotopes across the surface, all on a scale of micrometers. Visualization of the data yields an appreciation of its significance which would otherwise be difficult to perceive.

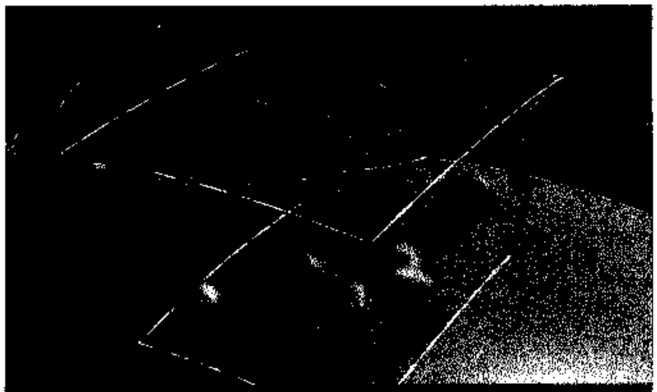
Not long ago, we could not even imagine seeing the inner structure of a living human brain. Tomography, a consequence of the computational power of computers, has changed that. The word originally referred to an x-ray scan at a chosen plane through a living brain. Computers are necessary to perform the complex mathematical calculations that convert the scanned data to cross-sectional pictures. Such tomographic images show concentrations of structures as areas that are electron dense or deficient. Seismic data, too, can be visualized—by converting them into a seismic tomograph, a picture of the distribution of particular properties, such as seismic velocity, in a cross-section or column of the Earth's interior (see, for example, Sean Solomon's essay in Year Book 96/97).

At the Geophysical Laboratory, Yingwei Fei, Constance Bertka, and Larry Finger experiment with materials believed to be in the iron-rich cores of Earth and Mars. Iron is surely present and sulfur may also occur, accounting for densities known to be less than that of pure iron. Better estimates of the temperatures in the planets' cores depend on understanding the nature of the iron-sulfur compounds that may be present. In their recent experiments, these scientists used x-rays to map the distribution of iron and sulfur over samples ranging from 25 to 50 micrometers in size. The mixtures had been treated at high temperature (over 800°C) and pressure (10 gigapascals and higher). The data were converted into false-color maps showing the distribution of metallic iron (Fe), iron **sulfide** (FeS), and, at 14 gigapascals, an unexpected intermediate, **Fe_3S_2**. The images thus made it possible to "see" the three materials and their juxtaposition in melted and unmelted samples.



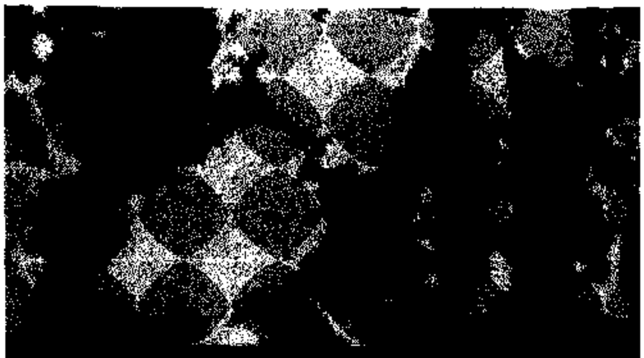
An interplanetary dust particle, visualized with the help of a computer. Top image shows the distribution of hydrogen atoms across the particle. The bottom image is a map showing variation in the deuterium-to-hydrogen isotopic ratio. The D/H ratio is up to four times that of terrestrial samples. (Photo by Larry Niftier, DTM)

Molecules would probably be visible, and may one day be so, if sufficiently powerful microscopes could be built. But for now, in spite of the fact that molecules are everywhere, we can't see them directly and in detail. Students used to be introduced to molecules through two-dimensional and later three-dimensional schematic drawings in textbooks. Rarely were the diagrams accurate descriptions of the relative sizes of the atoms, the lengths of the bonds between them, or the space they filled. The illustrations were further limited by the inability to show very large molecules. Even 100 atoms were a challenge to the artist and the budget manager for the book or journal. That was the past. Today, students and working scientists routinely see images of even huge protein molecules on computer screens or printed pages. Everything is three-dimensional, and color coding emphasizes different aspects of the structure. On a computer screen, the molecules can be turned every which way at will. Different views show distinct aspects of the molecules. It is even routine to view two interacting molecules, for example an enzyme and its substrate, and evaluate the "fit" between them. Investigators in search of drugs or inhibitors of particular enzymes can try out the "fits," tweak the structures, try again, and thus come to a rational decision about what kinds of substances are worth synthesizing in the laboratory.



Three-dimensional image of seismic velocity anomalies in the Earth's mantle beneath southern Africa, modeled by former DTM fellow John VanDecar from a computer-generated tomographic inversion of seismic data. The material with the highest velocity is enclosed in blue regions, the lowest in red. (The gray sphere underlying the model is at 1000-km depth; the yellow lines at the surface represent political borders.) The high-velocity anomalies near the top of the mantle (100-km depth) lie beneath ancient Archean cratons. The low-velocity anomaly at the bottom of the model may correspond to the upper part of the low-velocity anomaly seen in lower-resolution global tomographic images, and may represent a large-scale, buoyant upwelling of the deep mantle (see pp. 66).

Here, again, the input digitized data do not originate in images. Massive tabulations of fundamental information on the size of atoms and the length and directions of bonds between particular kinds of atoms are mined. This information, together with data on how **crystalline** forms of the material scatter x-rays, is fed into powerful computational pro-



▶ Sulfur x-ray map prepared by Yingwei Fei and colleagues at the Geophysical Laboratory shows a mixture of iron and iron-sulfur subjected to 14 GPa at 850 C. Under these conditions, the iron (black) does not melt, but a new compound, Fe S (yellow) appears.

grams. The end results are elegant sculptures of three-dimensional molecules containing a few or thousands of atoms.

BEYOND OUR SENSES

Science and technology have for centuries expanded human competence beyond the limits imposed by biological capacities. By now, the abilities to float, fly, explore the deep sea with submarines or the shallows with scuba gear are so accessible that they are recreational as well as scientific and commercial activities. These technologies all extend human physical capabilities. Enhancements of the human senses are of more recent origins. Radio and telephones enable our species to hear sounds otherwise out of reach of our ears. Movies, television, and now the internet, let us see light originating out of sight of our eyes.

This essay has described extraordinary ways through which novel images have, in the last decade, enabled new science. Carnegie Institution scientists, like their most productive colleagues in other institutions, have been quick to adopt and adapt the innovative technologies. Scientists should now recognize that the general public will also respond enthusiastically to these marvelous pictures. Imaging tools represent a very special opportunity to improve public understanding of and confidence in science.

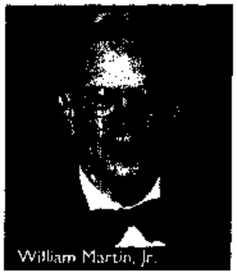
This computer-simulated image, modeled by Ronald Cohen of the Geophysical Laboratory, illustrates what happens to magnetic metal ions in cobalt oxide as pressures increase. Magnetic collapse is a change in electronic configuration from non-spherical magnetic "high-spin" ions to more spherical, low-magnetic moment "low-spin" ions, and is shown here as the contrast between solid and more transparent areas. The colors represent the local magnetic moments (spin density.) ◀

A great deal of evidence confirms that the public-at-large has only a minimal knowledge of modern and even not-so-modern scientific insight into the natural world. Yet, we also know that many people are interested in science. The Discovery Channel thrives. Millions connected to NASA's web site when Pathfinder's robot roamed Mars. Congress this year gave a $2 billion boost to the NIH budget. Each month almost 400 people fill the Root Auditorium in Carnegie's administration building to hear a Capital Science lecture. Together, the high interest and yet lack of understanding suggest a failure in communication. Scientists speak and write. The public listens and reads, but only occasionally comprehends. It finds scientists' beloved charts, tables, and graphs confusing and dry. But people readily remember images. The new imaging power can be a key to enhanced public understanding.

Centuries ago, the invention of the telescope revealed the moons of Jupiter and focused minds on the universe beyond Earth. Later, the microscope uncovered the unsuspected world of microbes and cells, engendering new wonder at the natural world. "Seeing is believing* is a phrase that does not wear out. Science has new and marvelous things to show.

— *Maxine F* Singer*
November 1998

LOSSES


William Martin, Jr.

Former trustee William mcchesney Martin, Jr. died on July 27, 1998. He was 91. Mr. Martin served a 16-year term as trustee (1967-1983) and three years as chairman of the board (1974-1976), remaining a trustee emeritus until his death. He is most remembered by the public for his role as chief of the Federal Reserve Board, from 1951 to 1970, the longest-held tenure in that position since 1913. Little known is that he earlier served as the first salaried president of the New York Stock Exchange and later, after service in World War II, he was the president of the Export-Import Bank.


William Hiesey

William HIesey, a longtime staff member at the Department of Plant Biology, died on August 8,1998, at the age of 95. Hiesey joined the department in 1926 as a transplant assistant. After earning his Ph.D. at the University of California, he was appointed a staff member, and remained so until his retirement in 1977. Hiesey was a member of the classic Hiesey-Keck-Clausen trio that established the concept of ecologically adapted races as an initial phase in the development of distinct species. The institution published the group's studies as the five-volume *Experimental Studies and the Nature of Species* series, between 1940 and 1982. The work is also to be found in any major text dealing with plant evolution.


Elburt Osborn

Eiburt Osborn, former staff member and distinguished professor of the Geophysical Laboratory, died on January 19, 1998, at the age of 87. Osborn was an internationally recognized authority on petrology, mineral technology, and mineral education. He joined the Lab in 1938 and remained there until 1945, when he became dean of the College of Mineral Industries at Penn State University. He went on to direct the Bureau of Mines and, finally, returned to Carnegie in 1973 as distinguished professor. Although he retired in 1977, he retained emeritus status until 1983, when he returned to Penn State to continue research.

Norman Heydenburg, a DTM staff member from 1935 until 1962, died on March 20,1998, in Tallahassee, Florida at the age of 90. Heydenburg was involved in work measuring the nuclear component of the force between proton and proton, demonstrating that the proton-proton force was identical to the neutron-proton force, a theory that has remained the basis for all nuclear structure theory. He later worked with Merle Tuve on the proximity fuze.

James W. Boise, former bursar of the Carnegie Institution, died on April 29, 1998, at the age of 72. Boise began his career with the institution in 1952 as an accountant. In 1960 he was appointed bursar, and he remained in that position until his retirement in 1984. Boise was instrumental in developing the institution's retirement plan.

Charles Little, electronics and machine specialist at DTM from 1940 until 1977, died on December 10,1997.

Sherman Johnson, hired in 1955 as a chauffeur at P Street and retired in 1990 as payroll supervisor, died on June 4,1998.

Mary Coffeen, who spent 32 years as research assistant and librarian at the Observatories (1932- 1964), died in March 1998.

Milton Taylor, DTM instrument maker (1970-1983), died on January 12,1998, at the age of 80.

Dawlcf Weinrlb, DTM fiscal assistant since 1988, died on September 14,1998, at the age of 75.

RETIRING

Two long-time staff members retired this year, and both remain at their respective departments as staff members emeriti. Allan Sandage began his appointment as staff member at the Mount Wilson and Palomar Observatories in 1952, three years after he arrived on Santa Barbara Street as a Caltech graduate student. He spent the rest of his career at the Observatories, contributing to a wide range of subjects. He is perhaps most well known for his 50-year pursuit of the fundamental cosmological parameters. As Gus Oemler writes in his essay (see p. 47), Allan has had a profound influence on several generations of astronomers. He officially retired on September 1,1997.


Allan Sandage

?oyad Tera, a staff member at DTM for 20 years, retired on December 31,1997. Tera is known for his innovative applications of analytical chemistry to a variety of geo- and cosmochemical topics, including defining the age of the Earth and Moon, detecting ^{10}Be in island arc volcanic rocks (thereby proving the deep subduction of surface sediments), and providing a high-precision time scale for meteorite and planetesimal formation.


Fouad Tera

Also retiring this year was Las Campanas resident scientist Wofciech Krzeminski. Krzeminski first came to the Observatories in 1992. He also served as administrator of the Las Campanas Observatory for several periods. His research focused on the properties of close binary stars.

Michael Seenrsann, design engineer-mechanical, retired from DTM on July 1, 1998, after nearly 40 years of service. He participated in the development of many new scientific instruments, especially in the area of seismology, and was for many years responsible for the smooth operation of the DTM campus.

Hary Eileen Hogan, senior technician at the Department of Embryology, officially retired in April 1997 after 23 years of service, but she remains at the department as an employee of Howard Hughes.

joe Vokroy retired on January 31,1998, after 19 years as facilities manager at the Department of Embryology.

Charles **Townes** became a trustee emeritus in May 1998. He has been a trustee since 1965.

Charles T. **Prewitt** stepped down as director of the Geophysical Laboratory after 12 years of service. He remains a member of the scientific staff. During his tenure as director, he led the Laboratory to world-class recognition in high-pressure physics research.


Charles T Prewitt

GAINS

Euan Baird, chairman of the board, president, and CEO of Schlumberger Limited, was elected a trustee of the Carnegie board of trustees at the board's May 1997 meeting. Baird joined Schlumberger, an international technical service company to the oil industry, in 1960 as an engineer, after receiving an MA in geophysics from Cambridge University. He worked in various capacities before assuming his present position in 1986.


Euan Baird


Wesley T. Huntress, Jr.

Wesley T. Huntress, Jr. was appointed director of the Geophysical Laboratory, beginning his tenure on September 28, 1998. Before joining Carnegie, Huntress had been NASA's associate administrator for space science, responsible for programs in astrophysics, planetary exploration, and space physics. Previously, from 1990 until 1993, he was director of NASA's Solar System Exploration Division and, from 1988 to 1990, he was special assistant to the director of the Earth Science and Applications Division. From 1968 until 1988 he was a research scientist at Caltech's Jet Propulsion Laboratory. Huntress, who studies fundamental chemical processes in comets, planetary atmospheres, and the interstellar medium, will be involved in the astrobiology program at the Laboratory.

Luis Ho is a new staff associate at the Observatories. Ho, who received his Ph.D. from Harvard University, studies active galactic nuclei, emission-line galaxies, supernovae, extragalactic star formation, and young star clusters.

Two new staff associates joined the Department of Embryology in July 1998. Jim© Borjigin (Ph.D., Tohoku University) studies the vertebrate brain. Erika Matunis (Ph.D., Northwestern University) studies *Drosophtla* spermatogenesis.

HONORS

DTM's George Wetherlil was elected to membership in the American Philosophical Society in April 1998. He received a National Medal of Science from President Clinton on December 16, 1997.

DTM director Sean Solomon was selected to receive the 1999 Arthur L. Day Prize and Lectureship of the National Academy of Sciences. Solomon will be the third Carnegie recipient of this prize, which is named after the founding director of Carnegie's Geophysical Laboratory. (The Geophysical Laboratory's Hatten S.Yoder, Jr. and David Mao received the prize in 1972 and 1990, respectively.)

Asteroid 5726, discovered January 24, 1988 by Carolyn and Eugene Shoemaker, was named "Rubin" by them in April 1997 in honor of DTM's Vera Rubin. Rubin delivered the Halley Lecture at Oxford University on May 19,1998. She was awarded an honorary D.Sc. by Ohio State University at its September 1998 commencement.

Minor planet *7225* was named in honor of Wesley Huntress, new director of the Geophysical Laboratory, in recognition of his leadership at NASA. He was also given the second Carl Sagan Award by the American Astronautical Society. He delivered the Carl Sagan Memorial Lecture in November 1998. He was also elected president of the American Astronautical Society and was recently appointed a distinguished visiting scientist at Caltech's Jet Propulsion Laboratory.

Christopher Somervilie, director of the Department of Plant Biology, was awarded an honorary D.Sc. From the University of Wageningen in the Netherlands in March 1997.

Chen-HIng Fan, staff member at the Department of Embryology, received a Damon Runyon Scholar Award.

DTM's Paul Silver and Steve Shirey were elected felows of the Geological Society of America in May and October, 1997, respectively.

Robert Hazen of the Geophysical Laboratory received the Elizabeth Wood Science Writing Award at the July 1997 meeting of the American Crystallographic Association.

Marilyn Fogel of the Geophysical Laboratory was selected to be a 1999 Loeb Fellow of the Smithsonian Environmental Research Center. The Loeb Fellowship, inaugurated this year, recognizes accomplishments in applying physical science research tools to ecological problems.

Observatories staff associate **Luis Ho** received the 1998 Robert J. Trumpler Award from the Astronomical Society of the Pacific, given for outstanding dissertation research in astronomy.

Geophysical Lab's **Charles T. Prewitt** was honored at the Fall 1997 meeting of the American Geophysical Union with a special symposium. The twelve Trewitt sessions" focused on aspects of mineralogy and crystallography to which Prewitt has made significant contributions.

Hatten S. Yoder, Jr., director emeritus of the Geophysical Lab, received the 1998 History of Geology Award at the Geological Society of America's annual meeting, and was the 1998 Distinguished Scientist Lecturer at the Forum for the History of Science in America.

High school students Caleb Fassett and Andrew Waterman, summer interns at DTM, were named semi-finalists in the Westinghouse Science Talent Search in January 1998. Their reports were based on their internships with John Graham and Vera Rubin, respectively. In July 1998, Fassett won seven awards at the Montgomery Area Science Fair.

Former Embryology staff member Robert DeHaan (now at Emory University Medical School) received the Thomas Jefferson Award from Emory University. In December 1998, he received the Bruce Alberts Award for Distinguished Contributions to Science Education from the American Society for Cell Biology.

Monir Humayyn, a former Barbara McClintock Fellow at DTM now at the University of Chicago, received the Clarke Medal of the Geochemical Society in August 1998.

Lars StixrucJe, former postdoctoral associate and visiting investigator at the Geophysical Lab, received the 1998 Macelwane Medal of the American Geophysical Union.

Maxlne Singer received the 1998 Georgeanna Seegar Jones Award in June 1998 for Lifetime Achievement in Women's Health Research. She received the Outstanding Educator Award from San Francisco's Exploratorium at its 21st annual awards dinner in May 1998.

Trustee William Golden received an honorary degree from the Graduate School and University Center, City University of New York

Gary Ernst was awarded the first Geological Society of Japan Medal at the Society's annual meeting in Tokyo on March 28.

Frank Stanton received an honorary degree of Doctor of Humane Letters from Muhlenberg College in May 1998.

Frank f¥e» was awarded the Lomonosov Medal of the Russian Academy of Sciences, its highest award.

Charles Towntts was elected to the National Academy of Engineering.

The Carnegie Institution received gifts and grants from the following individuals, foundations, corporations, and government agencies during the period from July i, 1997 to June 30, 8998.

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Thinking is a Field Trip

I DO NOT KNOW WHAT I MAY APPEAR TO THE WORLD, BUT TO MYSELF I SEEM TO HAVE BEEN ONLY LIKE A BOY PLAYING ON THE SEASHORE AND DIVERTING MYSELF IN NOW AND THEN FINDING A SMOOTHER PEBBLE OR A PRETTIER SHELL THAN ORDINARY, WHILST THE GREAT OCEAN OF TRUTH LAY ALL UNDISCOVERED BEFORE ME.

SIR ISAAC NEWTON
FROM *MEMOIRS OF NEWTON*, VOL. II

We have all experienced a moment, a question, the beginning of a pathway, something that draws us toward what we later recognize as understanding. It happened to me during a recent hike I took with my First Light kids along the Potomac River. Earlier in the day, the children and I had discussed what science means to them, and how they like to learn about their world. As I walked, I began to understand what they had been saying.

It was a crisp autumn day. We had left the designated hiking trail some time earlier. Each of the kids had now chosen his or her own path. Some children hiked alongside others, some were widely scattered, yet all were totally engaged with their surroundings. Their bodies were like so many question marks popping up over the landscape. Small pools of water, abandoned trolley tracks, a hole, a rock ledge, shells in the sediment and the creek were invitations to explore. The path each child selected was full of unknowns. All of them moved with excitement at the freedom and promise of possibility.

By selecting their own paths, each child had selected entry into a unique world of discovery. For the most part, adults lead children to places where they have already been. Children, however, prefer blazing new trails. They know that it is the new trail that fills their senses and exercises their curiosity. First Light focuses on the development of science activities that recognize children's great affinity for exploration. The Carnegie Academy for Science Education (CASE) extends these activities to the children's teachers, who learn in summertime institutes how to carry out the activities in their classrooms. In the process, many find themselves becoming like children again.

As adults, it is easy for us to believe that a child fails to think scientifically because of some shortcoming. As parents, we worry when our own child seems unmotivated, or uncaptivated by any scientific subject. If we were to step back, however, and look at the choices we give our children, we might find the real answer in the paths we allow them to explore.

Left: During a study of wetlands, First Light participants raised North Carolina tree frogs.

Textbooks make science seem very durable and opaque, open to few questions. In truth, it is the *process* of science that is durable; the *ideas* of science are constantly evolving. But what do the children think of the science and the methods by which they are taught? After years of teaching science and developing an intuition as to how children feel about doing science, I wanted to find out what children really had to say about science and the First Light experience, I led my kids into a simple discussion of what makes science important, and what they do that is scientific.

Picking apples, part of a First Light unit on plants. Some of the apples were donated to a homeless shelter.

The results were illuminating. Children view science as simple tasks with complex possibilities. In their words, science has "easy things to do but lots of hard questions/' "Whenever we do something we never seem to get to one end...it*s never really finished." Mixing ingredients, measuring sand, building towers, sorting pebbles, searching under rocks, and watching life were things children said they liked to do. One child said it best: "I know how much better the stuff is to learn when no one tells me about it first. I like being the first to learn something. It's like the teacher's always in front...always the boss." Another added that "teachers talk too much." The implications of these statements clearly challenge the cleanly choreographed science lessons we offer our children.

The basics of science and math, as currently offered by texts and worksheets, do not create real science. By prescribing paths of investigation, these formats may present a great deal of knowledge, but they encourage very little original thought. Thinking is basic to science; the freedom to think must therefore be paramount.

Science is a blend of thinking and being informed (knowledge). Thinking, said one child, is like a "field trip. You just take off and when you get someplace and look around, that's like the science." Children want to spend time exploring. At First Light, exploration has led to some interesting discoveries. One of the older participants said: "We were trying to wire the robot completely wrong. You never said a word except to say * make sure it makes sense'—the order we were doing things. When we finished we hadn't put together the battery holder. No power!" Another chimed in that building a rock box was difficult but rewarding. "Making something for the first time is so hard...then yours comes out so neat and different even after you had to start some parts over." The freedom to think helps make the mental "field trips" that children take much more likely to result in great scientific conclusions. This helps explain why First Light is so appealing to youngsters and why, at CASE, instruction is harder than it is elsewhere: the path isn't set.

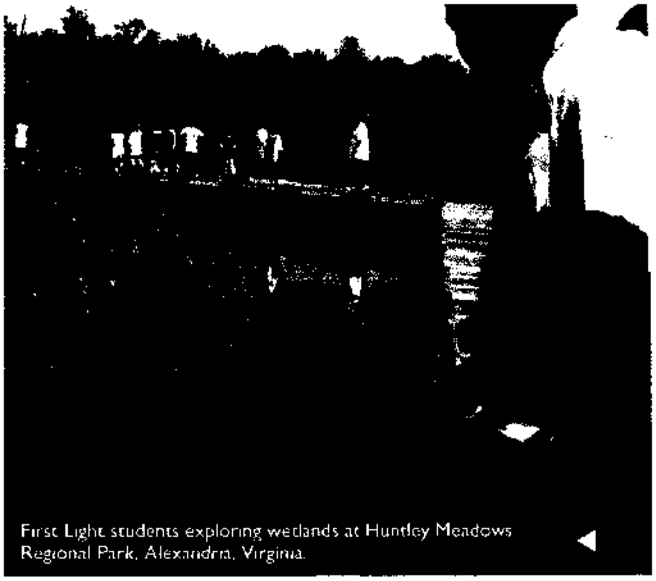
The hike along the Potomac reminded me that everything is captivating to children. Grasshoppers in billows of grass, crumbling walls, rocks, shards of old china, and absolutely anything alive. How often do we provide opportunities for exploration to our children? How important are these childhood pleasures and of what value are they to a child's developing sense of science? It seems that the diligent child who spends countless moments exploring seemingly simple tasks with great interest is being very true to his or her nature. How true to that essence are our classrooms?

Not especially, if you listen to the children. Children believe they can understand things if they are given time. "I bet most kids could figure science out if they had money and computers and time," said one participant. "But we always are getting rushed. It takes some time to warm up. I like the activities we do that take a couple of weeks. We can go on with something we know." Children believe that the world is understandable and that each person can explore to find answers to reach understanding. The great loss to science is that this confidence disappears from the conversation of older children. As one eight-year-old said: "Science is important when you are an adult, because maybe you liked it and learned all about it when you were a kid...but my brother hates science in high school."

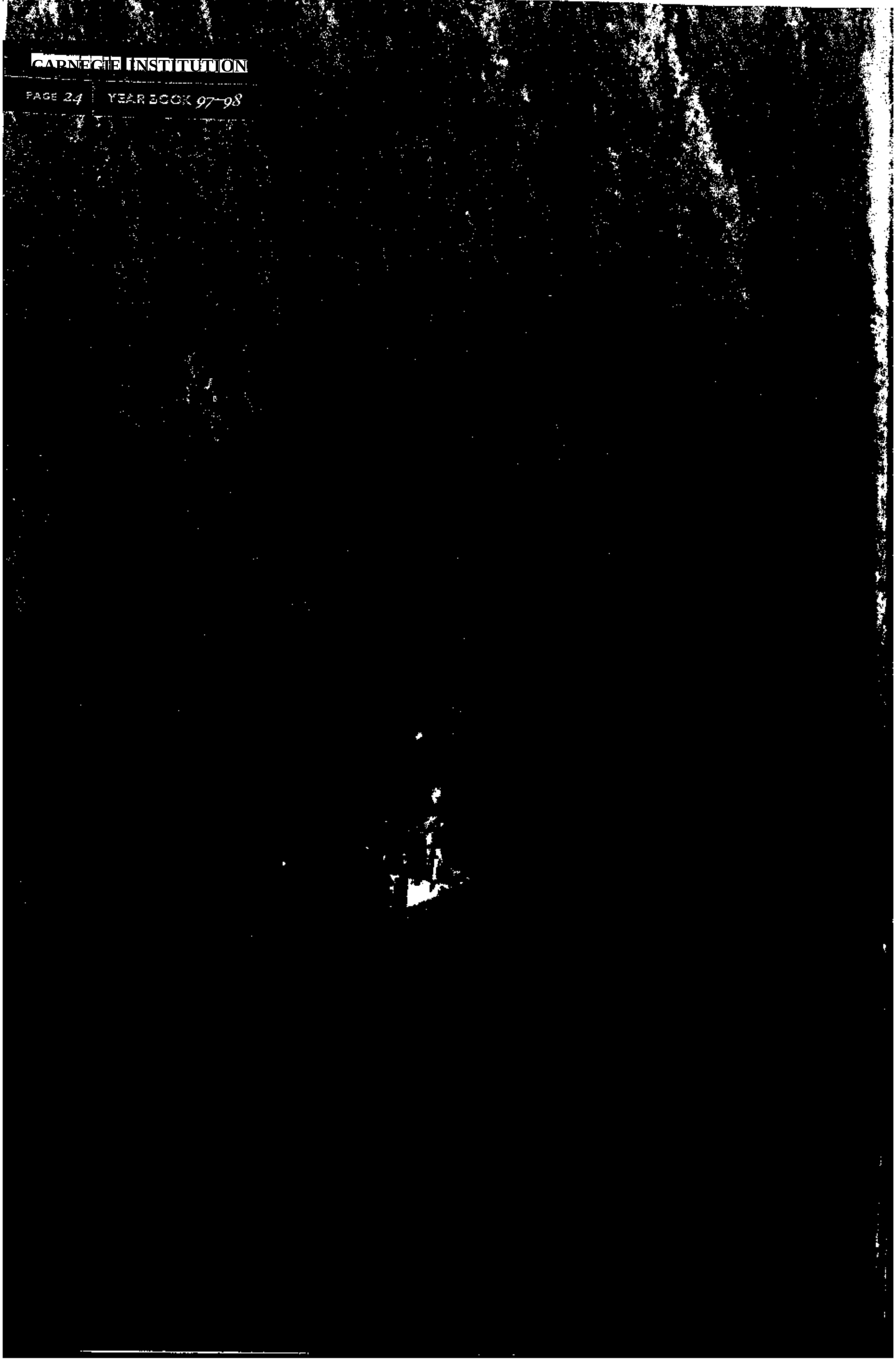
But how do we reconcile our adult views of science with those of our children? For children to enjoy and learn science two requirements seem crucial: time for exploration and the materials to explore. The children agreed that there were never enough materials around to use. From the children's perspective, ideal materials included "magnifying things, containers, building stuff, water, and supplies for putting things together." The children also wanted real things like "rocks, shells, teeth, and bones, but nothing dead." One comment was especially insightful. "You don't need a lot to teach with. Remember when we did that map about where pencils came from? But when we are learning science ourselves, it's fun to have a lot of stuff around."

During our hike, there were fascinating things everywhere to learn about. I was comforted that the children were so curious about what they were experiencing. But as I talked about the history of the rocks and the complexity of the local plants, I realized that most of the children didn't know how to connect the animals, plants, people, and places to their lives and hometown. As I talked on about the city at large, I realized anew that the children's world was only as far as they could see, touch, and question. Dynamite holes and rusting relics of trolley tracks, fish bones, abandoned nests, evidence of fire, and a lost shoe became the history lessons. Each find became a mental field trip. Questions of origin and purpose connected the things we found along the river to the children's lives.

Where we find suitable materials for our thinking is largely determined by the "hikes" we are allowed to take. The trails we offer children determine the whats, hows, and whys they are challenged to answer. The paths they experience become the passions that mold them mentally. This conclusion emerges from the reflection of children who have experienced science both ways—in First Light and in their classrooms. If, as they have suggested, we try letting them choose the path and hike behind them instead of always in front, than we as parents and teachers may discover the child's truth, that "thinking is a field trip."


First Light students exploring wetlands at Huntley Meadows Regional Park, Alexandria, Virginia.

—Charles James



THE DIRECTOR'S ESSAY:
Computers and Biology

> EVERYTHING SHOULD BE MADE AS SIMPLE AS POSSIBLE, BUT NOT SIMPLER.
>
> —ALBERT EINSTEIN (1879-1955)

When I was a teenager, my friends and I completely disassembled a car and then put it back together again to understand how it functioned. I believe that scientists will ultimately take much the same approach to understand the mechanistic aspects of life. Indeed, until he was distracted by the prospect of sequencing the entire human genome, Craig Venter, the founder of the Institute for Genome Research in Rockville, Maryland, had initiated experiments to recreate a bacterial cell from components obtained from disrupted cells. Venter's basic idea was to first learn how to recreate a living cell from its parts, and then substitute an increasing proportion of those parts with chemically synthesized components until eventually a completely synthetic cell was created. The theatrical quality of the experiment aside, Venter's approach would allow the analysis of many combinations of many different genes rather than the current practice of studying the effects of genes singly or a few at a time.

Although it is not yet possible to put a date on it, at some point in the foreseeable future we will know a great deal about the function of every gene in a bacterial or yeast cell. Shortly thereafter, we will have some degree of understanding of the function of every gene in first one, and then many, multicellular organisms. This will come about in a series of parallel discoveries. First, all the genes in a large number of organisms, from bacteria to humans, will be sequenced. This phase, which is rapidly approaching completion for many species, will afford us the complete chemical structure of all the hereditary information in these organisms. Once a gene's structure is known, a large amount of information about its function can be determined simply by comparing its nucleotide sequence (or, correspondingly, the sequence of its encoded protein) to the sequence of all other known genes or proteins. In practice, this is made possible by internet access to extremely powerful computers at national facilities. These computers are capable of rapidly comparing particular

Left: Joe Berry, standing on a tower erected in the Canadian forest canopy. Berry and colleagues gathered information about the primary productivity of the boreal forest to incorporate in models simulating photosynthesis and stomacal responses.

nucleotide sequences against a database of known sequences from all manner of organisms and finding the best matches. An example of the results from such a search is shown in Figure 1, where the amino acid sequence of the alcohol dehydrogenase gene from the plant *Arabidopsis thaliana* is compared with the sequence of alcohol dehydrogenase from humans. It is readily apparent that, at many locations along the length of the primary sequence, the two proteins contain the same amino acids. In contrast, two proteins of unknown function would show little or no sequence similarity, even if they came from the same organism. The fact that the two sequences have many amino acid residues in common implies that they have similar or identical function. Thus, if we were to isolate a new gene from an organism and find that the protein encoded by that gene also shared a high degree of sequence similarity with these two proteins, there would be a high probability that the new gene is also an alcohol dehydrogenase. By this and related kinds of analysis, it has been possible to assign general functions to about 40% of all the plant genes sequenced to date solely by computational methods. As more genes are studied, the proportion of genes that can be assigned function by computer analysis will expand until at some point all genes will be assigned to a class of known function.

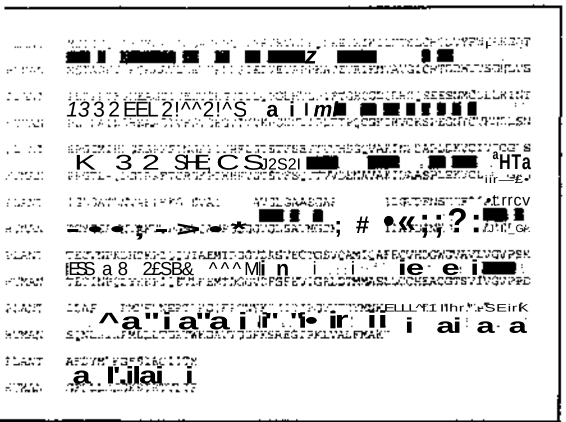
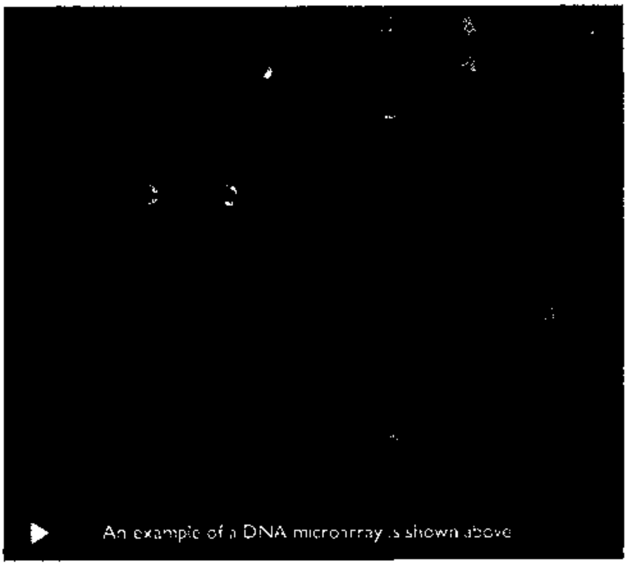


Fig. I. Map of the amino acid sequences of the alcohol dehydrogenase gene from human and plant. The large degree of sequence identity (marked as solid) or similarity (shaded areas) implies the two genes have similar function.

Unfortunately, knowing that a protein carries out a certain function usually conveys very little about what role the gene plays in the intact organism. For example, it is now estimated that of the approximately 20,000 genes in *Arabidopsis,* at least 1,200 are transcription factors, i.e., genes that control the expression of other genes. Knowing that a *gene* encodes a transcription factor, however, tells nothing about which genes it controls, nor when and where in the organism it acts. Until recently, information about when and where a gene is expressed could be obtained only by extracting RNA from source tissues in different organs or from the same tissues exposed to different environmental conditions. The RNA could then be labeled with radioactivity or a fluorescent molecule and hybridized with the gene of interest to obtain a rough quantitative measurement of the abundance of the RNA corresponding to that gene. Knowledge of the amount of mRNA is useful in understanding where and when the corresponding gene acts and what, if any, environmental factors influence its action. Because there are more than 20,000 genes in a higher plant, many different cell and tissue types, and hundreds or thousands of environmental conditions, it is not surprising that little or nothing is known about how the expression of most genes changes in response to the many possible variables.

DNA Microarrays. Recently, a new technology called DNA microarrays has emerged that offers the potential to greatly facilitate the acquisition of information about gene expression and gene function. The technology is superficially simple. For each gene in an organism, a fragment of DNA can be purified and stored in a multiwell plate consisting of a regular array of closely packed tubes each of about 20 microliters volume. A robotic arm equipped with one or more very finely machined quills is then used to transfer DNA from the wells of the storage plate onto the surface of a glass slide that has been chemically treated so that the DNA

▶ This high-precision robot that was made for the Department of Plant Biology represents a qualitative change in our ability to study gene function.



▶ An example of a DNA microarray is shown above

binds to the glass. Each time the quill touches the surface of the slide, it deposits a tiny droplet of DNA as a round dot. The robot is sufficiently precise so that approximately 10,000 distinct dots of DNA can be placed within a three-square-centimeter area to produce a DNA microarray. When a solution containing fluorescently labeled total cellular mRNA is incubated with the microarray, each of the DNA fragments binds to its cognate mRNAs; the amount of mRNA bound to a single DNA dot is proportional to the amount of the corresponding mRNA in the total mixture. Thus, by measuring the amount of fluorescence associated with each DNA dot, one can determine how much of each type of mRNA exists in a complex mixture of mRNA, such as that normally found in whole-cell extracts. The importance of this method is that it permits the simultaneous measurement of the expression of all the genes in an organism with a relatively simple procedure. This represents a qualitative change in our ability to study gene function.

DNA microarrays were invented several years ago by Dari Shalon, Pat Brown, Ron Davis, and colleagues at Stanford University. With the benefit of their generous advice, and support from the U.S. Department of Energy and the Carnegie Institution, staff member Shauna Somerville commissioned the construction of a gridding robot at the Department of Plant Biology in 1997, and

Shauna Somerville (right) and Pam Green, Michigan State University. ◀

implemented the technology for use in understanding plant gene expression. Since that time, Shauna has become the lightning rod for interest about the technology in the plant biology community. She received more than 100 inquiries within a two-month period following a well attended symposium talk in early 1998, and has since then hosted many dozens of visitors to the department.

Although Shauna's interest in the technology is related to its use in understanding the changes in gene expression following the infection of a plant by a pathogen, she also considers it her responsibility to help the community acquire access to the technology. As part of this effort, Shauna and colleagues Pam Green, John Ohlrogge, and Ken Keegstra (Michigan State University), Michael Sussman and Rick Amasino (University of Wisconsin), Steve Dellaporta (Yale University), and Mike Cherry (Stanford) recently received a three-year, $8.7 million grant from the National Science Foundation to make DNA microarrays and a collection of insertional mutants available to the community. The Carnegie and Michigan State groups will print DNA arrays consisting of more than 10,000 different *Arabidopsis* genes and provide them free of charge to the academic plant biology community. Upon request, they will also perform the hybridizations for hundreds of experiments each year. Because the instruments used to measure fluorescence are not yet widely available, they will also analyze the results of hybridizations for anyone who needs assistance. In return for providing this service, they expect to receive a copy of the data obtained from each experiment- After a short delay, they will release the data to a public database that is being developed at the Department of Plant Biology. Since each of the hundreds of users of the technology will likely be pursuing a unique question, the conditions used to make the different RNA preparations associated with the various experiments will represent a broad range of inherent possibilities. In this way, by combining the individual experiments on a common technology platform, significant progress will be made toward the goal of understanding the topology of plant gene expression.

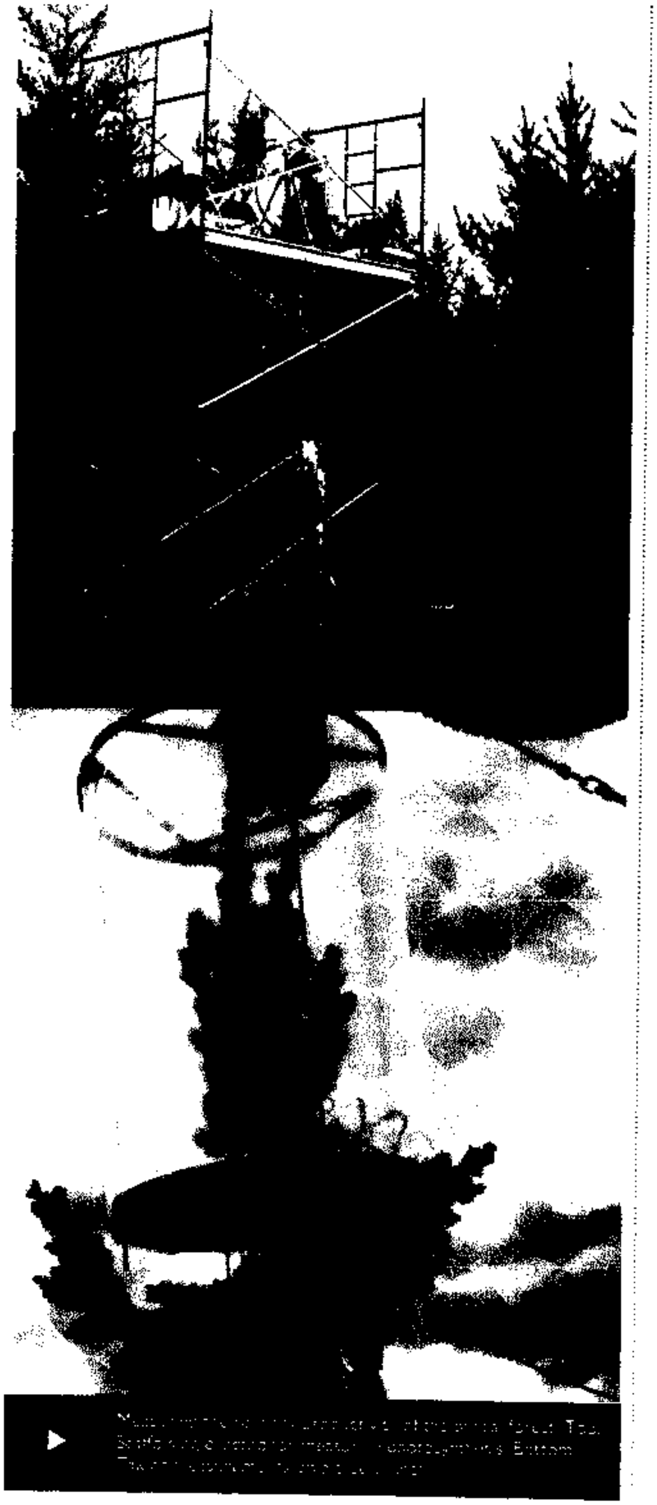
Since each data point of each experiment will contain information on more than 10,000 genes, the computational problems associated with this approach to biology are significant. The problem is not in storing the data, but in deciding how to interrogate it. There are many different aspects to the problem, but perhaps an example will best illustrate the issues. Suppose that at some point in the future we have a database in which RNA from *Arabidopsis* plants subjected to 100 different treatments has been used to measure the expression of 10,000 genes over an average of five different tissues and four time points. As an example of such a treatment, we might treat a plant with a chemical that, for unknown reasons, causes an effect on growth. We would extract RNA from the plant and use it to measure the chemical's effect on the expression of all the genes. We would then compare the treatment pattern to all previously observed patterns in the database to determine if the treatment mimicked any other effect of known cause. Here is where the complexity arises. It is unlikely that an exact match will be found. Rather, each of the data sets may have some responses in common with the treated sample but other responses that don't match at all. The solution to the problem—determining which responses are informative of the underlying cause and which are not—will require the development of novel analytical tools at the interfaces of biology, computing, and mathematics. Similarly, it is already possible to envision many other kinds of experiments whose complex queries can be answered only with new computer tools.

Characterizing mutations. Yet another large-scale strategy that can be used to obtain information about the function of all the genes in an organism is to characterize a mutation in each gene. In the simplest case, this can be accomplished by insertional mutagenesis using a transposable element, such as the maize *Ac* element. Ideally, it should be possible to produce a large collection of insertional mutants such that for every *gene* in the organism at least one plant in the population has an insertion in that gene. By sequencing a few nucleotides of the DNA region adjacent to the insertional ele-

▶ Members of the combined labs of Chris and Shauna Somerville, summer 1998.

ment in each plant, and then comparing the nucleotide sequence to the complete genomic sequence, it should be possible to identify which gene had been altered in each mutant line. Since higher plants are thought to contain only about 20,000 genes, ultimately, only about 20,000 mutant lines would be required to inactivate each gene in a flowering plant such as *Arabidopsis.* The information on these 20,000 lines could be linked in a database to information on *gene* sequence and patterns of gene expression, information on the function of related genes, and finally to information on the experimentally determined phenotype of each mutant (the latter to be contributed by the world community of scientists). In the case of *Arabidopsis*, there are thought to be about 3,000 people working with the organism. If we assume that the analysis of each *Arabidopsis* mutant would require about one person/year, it seems likely that the complete analysis could be completed within the next ten years. In order to initiate this kind of analysis* Shauna's collaborators, Mike Sussman, Rick Amasino, and Steve Dellaporta, will take responsibility for disseminating approximately 110,000 mutant lines of *Arabidopsis* containing insertional mutations. Although their distribution model does not as yet involve sequencing all the inserts, preliminary experiments by Jonathan Jones and colleagues at the Sainsbury Institute in Norwich, UK, have indicated that this would be a productive and efficient next step.

In summary, the path to some degree of comprehensive knowledge about the informational basis of various life forms is within reach. It seems likely that additional high-throughput experimental methods will be developed and will contribute other forms of information. For example, various known protein modifications, such as the phosphorylation/dephosphorylation reaction, may be amenable to high-throughput approaches. However, I believe that as the amount of information grows, and as the sophistication of our computational tools improves, we will find an increasing number of experiments driven not by direct observations of an organism, but by computer-gen-



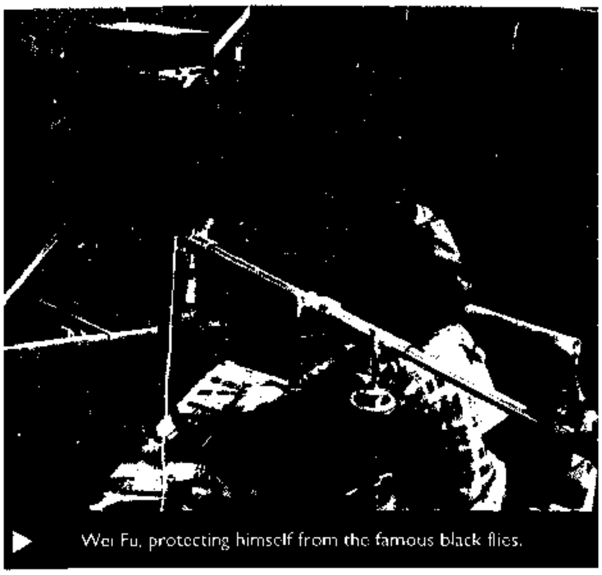
▶ [illegible] Top. [illegible] Bottom [illegible]

erated hypotheses. One last gedanken experiment may illustrate the point.

The available evidence suggests that genes encoding proteins which act together in some fashion have a common mode of regulation, i.e., they form a regulon. Thus, it seems likely that if one measured the level of expression of all the genes in a plant under a very large number of different developmental and environmental conditions, one would find that all of the genes involved in, say, lysine biosynthesis would have a pattern of regulation more similar to each other than to any gene not in the pathway. If this is generally true, then the function of many unknown genes could be discovered simply by identifying which other genes they most closely resemble based on patterns of gene expression. In all those cases where at least one gene in a regulon is of known function, the function of the other genes could be inferred. Experiments to test the proposed function could then be carried out in an efficient manner.

Computational Ecology

Carnegie staff member Chris Field has remarked that the ecological equivalent of a genome project is global ecology. Indeed, this seems an apt comparison by many criteria, including the dependence on computational methods to extract information from large volumes of data. However, whereas molecular biologists have not yet really begun to understand how cells function as molecular ecosystems, Chris, Joe Berry, and colleagues have made significant progress in developing predictive computer models for terrestrial ecosystems. Their approach has been to summarize individual plant responses to environmental variables into models that simulate ecosystem exchanges of carbon, water, and energy at the global scale. These models synthesize surface data on climate and soils and satellite data on vegetation type and canopy development, and draw functional generalizations from physiology and ecology. Ultimately, they help test hypotheses that lead to a better understanding of the future status of terrestrial ecosystems, especial-



Wei Fu, protecting himself from the famous black flies.

ly the responses to and influences on such global change factors as increased atmospheric carbon dioxide (CO_2), habitat destruction, and altered climate.

Although useful models have been developed, the quest for more robust models continues. Over the past decade, Joe Berry and colleagues have developed largely mechanistic models to predict how the rates of photosynthesis and transpiration of water by leaves of higher plants are controlled by environmental conditions, such as light intensity, temperature, water availability, and CO_2 concentration. They first formulated these models at the scale of the fundamental metabolic unit, a leaf cell. They are now developing methods to apply these models at ever larger scales, with the ultimate goal of simulating the responses of forest canopies. The difficult part of this work is not in writing the models but in testing them against reality. This year, postdoctoral associate Wei Fu developed a model that simulated photosynthetic and stomatal responses of a tree canopy. He based the model on long-term measurements of real responses using instruments placed high in a forest canopy. Photosynthesis and stomatal conductance are maximal in the early morning of each day and fall during mid-day with partial recovery during the afternoon. At night, CO_2 production by respiration continues. The result is an apparent negative rate of net photosynthesis. Wei Fu successfully simulated these responses using only information on environmental conditions experienced by the aerial parts of plants and physiological information obtained from studies of leaf responses to light intensity, temperature, and CO_2 concentration.

At a larger scale, the CASA2 biosphere model is a spatially-resolved modeling environment used to extrapolate ecophysiological and biogeochemical principles to the global scale. The CASA2 model was developed at Carnegie, the NASA Ames Research Center, and Stanford University. Its main advantage is its reliance both on satellite data (for the parameterization of its net primary production, NPP, model) and on mechanistic plant and soil carbon and nitrogen data (for the modeling of carbon flow through terrestrial ecosystems). CASA2 has been used to test the assumptions not only of current theory in the global carbon cycling community but also the usefulness of the satellite data on which it relies. The model calculates the seasonal flow of carbon between the atmosphere and the terrestrial biosphere on a number of different time steps and with a multitude of spatial resolutions. It explores relationships between different assumptions about the terrestrial biosphere and the activity of the global carbon cycle.

During the past year, Chris Field and colleagues used CASA2 and related tools to explore a number of global-scale questions. In one project, described in a paper published in *Science* (Vol. 281, pp. 237-240, 1998), the group coupled CASA2 with the VGPM ocean primary production model to develop a new estimate for total annual growth, or net primary production (NPP*), of land and

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For both terrstnii and Deems; rrudds, £ cannot be instil mezurert *fi.m -.ict x> 1 ·>- m^T to z.'j^r eterized with field measurements. Marine systems can be parameterized from thousan 'J G biiedf-ed ^e^uremenfc r/NPP Teirtctmi »'i!ue: ire levj J w tint 'A'th'iAL-xceptions ocean NPP models estimate it solely as a function of sea-surface temperature [illegible] [illegible] urable levels of temperature, nutrients, and water ocean plants, using satellite data and parallel algorithms for the terrestrial and marine components. The basic approach was to calculate NPP as a function of the driving energy for photosynthesis and the average light utilization efficiency E. The driving energy for photosynthesis is the absorbed, photosynthetically active (400-to-700 nm) solar radiation (APAR). APAR depends on the amount and distribution of photosynthetic biomass as well as the fraction of downwelling solar radiation that is in the visible (photosynthetically active) wavelengths. Field *et al.* calculated oceanic APAR from satellite-derived measurements of surface chlorophyll (Csat). They calculated terrestrial APAR from satellite-based estimates of vegetation greenness, which is often referred to as the normalized difference vegetation index (NDVI). (Csat and NDVA are the primary sources of variability in the model.) £ is an effective photon yield for growth that converts the biomass-dependent variable (APAR) into a flux of organic compounds (NPP).

The analysis by Field and colleagues highlighted the nearly identical magnitude of total land and ocean annual plant growth, but it also pointed to important differences between land and ocean plant biology. For instance, only 7% of the photosynthetically usable radiation incident on the ocean surface is absorbed by phytoplankton, with the remainder absorbed by water and dissolved organics. In contrast, leaves of terrestrial plants on land without permanent ice cover absorb about 31% of the photosynthetically usable radiation. Although primary producers in the ocean are responsible for nearly half of the biospheric NPP, they represent only 0.2% of the global primary producer biomass. This uncoupling between NPP and biomass is a consequence of the more than three orders of magnitude faster turnover time of plant organic matter in the oceans (average 2 to 6 days) than on land (average 19 years).

Another series of studies, led by predoctoral fellow (and recent Stanford Ph.D.) Jim Randerson, used atmospheric tiiti as a probe for terrestrial processes. Focusing on recent increases in atmospheric CCX concentration at high northern latitudes, Jim concluded that the patterns are consistent with increased plant growth in the temperate and boreal zones in recent years. The atmospheric patterns also imply an earlier start to the growing season, with an average shift of about four days since 1980. He found, however, that the patterns are not consistent with a recent hypothesis put forward by others—that most of the northern hemisphere sink reflects the regrowth of previously harvested forests.

Approaching recent changes in the carbon cycle from a different perspective, sabbatical visitor Ruth DeFries (University of Maryland) combined traditional vegetation maps, new satellite-based vegetation maps, and a carbon-cycle model to quantify the cumulative effect of human activities on terrestrial carbon storage and plant growth. Ruth's approach indicates that human activities have decreased terrestrial carbon storage by about 180 billion tons, or about 10% of the current total. Her concurrent estimates of changes in plant growth underscore the challenges of land management, especially in tropical climates. On average, she found that human modification of the Earth's surface has decreased annual plant growth very little, only about 5%. But the impacts are far from uniform. Across much of the tropics, for example, human-induced changes in vegetation type often decrease plant growth by more than half. Some of this reflects degradation from grazing, fuelwood harvesting, erosion, etc. But when the effects of agriculture alone are considered, the pattern is striking. In the temperate zone, total plant growth in regions converted to agriculture is usually equal to or greater than that before clearing. In the tropics, however, conversion to agriculture often decreases plant production substantially, especially in countries with the least resources to invest in land and crop management.

The future development and application of whole-biosphere models, such as those described here, can play a major role in the emergence of integrated, comprehensive perspectives on the function of the Earth system. Measurements of NPP are critical to these efforts, because NPP is central to carbon and nutrient dynamics and links biogeochemical and ecological processes. The global carbon cycle and the ecological processes that contribute to it are not in steady state but are highly dynamic. Current capabilities to interpret these dynamics and their implications for the future of the biosphere are constrained by gaps in the data record, limitations on data quality, and incomplete understanding of some of the mechanisms. The successful launch of the Sea-viewing Wide-Field-of-view Sensor (Sea WiFS) in September 1997, along with other forthcoming remote-sensing missions, will provide marked improvements in the quality of APAR measurements for both land and ocean. These programs need to be paralleled by efforts to improve the characterization of spatial and temporal variations in carbon flux and to learn the fate of carbon once it is fixed in photosynthesis.

Education in Biological Computing

Unfortunately, there are very few scientists who have the level of knowledge in biology, mathematics, and computing required to develop computational tools for the new frontiers in biology. Those with the requisite skills generally elect not to work in the academic sector because of the relatively low level of compensation or because of the grudging academic recognition accorded computational biology by many bench scientists. Because of the limited employment opportunities facing recent Ph.D.s in biology (see Year Book 96/97, p. 27), I believe that support and encouragement for additional training of biologists in computer science and certain aspects of mathematics would both accelerate the growth of biological knowledge and provide rewarding career opportunities. Because Carnegie departments do not have the constraints on staff composition associated with most university departments, this is an area where the institution may be able to help catalyze the growth of a critical new discipline. During the coming year, for example, the current staff of the *Arabidopsis* database, AtDB (http://genome-www.stanford.edu/Arabidopsis/), will move from the Stanford medical school to the Department of Plant Biology. It is my hope that this group will find common ground with the ecological modeling groups here and that something novel will emerge from this new frontier.

—*Christopher* ***Somerville***

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THE DIRECTOR'S ESSAY:

Cyclopia: From Monsters to Mutants

> THE PROGRESS MADE IN RECENT YEARS ON THE STUDY OF TERATOLOGY HAS BEEN SO MARKED THAT IT IS NOW POSSIBLE TO RECONSIDER THE WHOLE SUBJECT AND TO PLACE IT UPON A PERMANENT SCIENTIFIC BASIS. FOR THIS PROGRESS WE ARE INDEBTED ALMOST EXCLUSIVELY TO THE EXPERIMENTAL EMBRYOLOGISTS.
>
> —R P. MALL (1917), CIW PUBLICATION NO. 226, p. 5.

Humans have always been both fascinated and repelled by the occasional appearance of stillborn embryos with grotesque malformations. When the Department of Embryology was founded 84 years ago, such spontaneous "monsters" were recognized as rare resources where the effects of altered development could be studied in mammals. Among the most striking are "cyclopean" embryos, in which a single eye develops along the midline, as in the Cyclops of mythology. Partial or complete cyclopia is a relatively common developmental defect in humans, livestock, and many if not all other vertebrates. True cyclopia is now recognized as a particularly severe manifestation of a syndrome of related defects in craniofacial and brain development called "holoprosencephaly." In 1917, Franklin P. Mall, founder and first director of this department, summarized contemporary knowledge in his monograph "Cyclopia in the human embryo" (CIW publication no. 226). In attempting to explain the origin of cyclopean monsters, MaU grappled with issues central to the understanding of embryonic development. Many of these issues remain relevant today.

Mall's first conclusion, quoted above, is that virtually all progress in understanding developmental mechanisms comes from experimental studies on model organisms. In the case of cyclopia, the most informative studies carried out by 1917 were those on amphibian embryos by future Nobel prize winner Hans Spemann, and on fish embryos by C. R. Stockard at Woods Hole and Warren Lewis, a Department of Embryology staff member who made several landmark discoveries both before and after the department was founded. While Spemann used a fine hair to ligate embryos at a very early stage, forcing embryonic cells into two groups (each forming a separate, cyclopean head), Lewis's technique was far more precise. With the help of the low-power microscope, which he pioneered for embryological manipulation, Lewis was able to prick developing embryos at a specific site, thereby releasing and killing a small defined region. His treatments often produced cyclopia. The most astonishing results, however, were those of Stockard. When Stockard placed intact fish

lefts Production of a specific mutation in mice using embryonic stem cell technology. The father- (dark with white spots! was generated by combining host albino embryos (white) with engineered donor embryonic stem cells (dark)* which contained the desired mutation. When the father is mated to an albino mother, two kinds of offspring are produced whose cost color is determined solely by the genome of the father, Sn this case, the father Is made of two types of cells, albino (normal) and dark (contairortg *tht* mutation). Mis brown offspring will thus contain the desired mutation since they are derived from the »n*tfc&f!y modified emlryonic stem cetlt. (Generated by Noah Hay In the laboratory of Chen-Hing Fan; photographed by Kris Beichner.|

embryos in a magnesium chloride solution, more than half developed cyclopia. Studying the experimental manipulations that caused cyclopia seemed likely to provide deep insight into the mechanisms that regulate normal head and brain development.

In his monograph, Mall noted that regular rules governed the effects of experimental manipulations. Cyclopia could be induced only by treating very young embryos, before any visible evidence of eyes. Lewis found that pricking a precise location on the midline of the developing head region was effective; pricking just off the midline resulted in unilateral eye defects. Even the seemingly uniform effects of the magnesium bath were only manifest very early in embryonic development, and were most effective in embryos containing from just 8 to 32 apparently identical cells. Cell growth in general was retarded by the magnesium solution. Mall believed that specific groups of embryonic cells, including perhaps the same midline cells targeted by Lewis, might be unusually sensitive to growth arrest at certain times and thus be particularly susceptible to damage. Clearly, highly detailed events were taking place in early embryos long before the appearance of recognizable adult structures. These events were specific to particular locations within the embryo and changed over time. Seemingly identical cells were already "fated" to produce particular body parts, so that interfering with a specific embryonic region at a particular time disrupted a predictable structure and process.


Franklin P. Mall

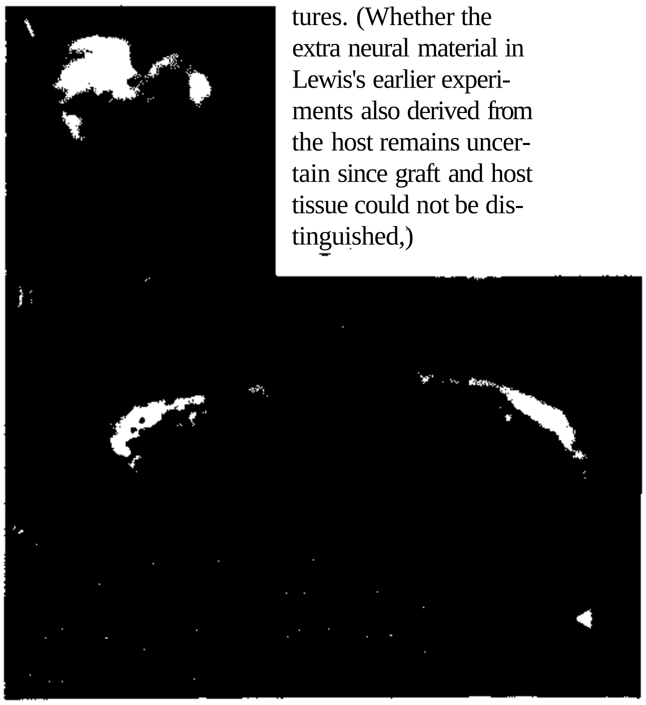
Embryology Beginnings


A normal embryo, number 417 from the Human Embryo Collection

What cells and processes might underlie the appearance of cyclopia? By 1917, embryologists had established that the eyes develop as outpocketings that originate just off the ventral midline of the embryonic brain. At these early stages the brain is no more than a simple "neural tube" underlain anteriorly by the prechordal plate and more posteriorly by the notochord, a transient rod of cells characteristic of the Chordate phylum that includes all vertebrates. Lewis's experiments suggested that the neural cells lying along the midline between two lateral eye primordia were the critical target for cylcopia induction. If these cells were lost, the normally separate primordia would fuse together and form a single median eye. The forebrain itself is reduced in cases of human cyclopia, but experimentally Lewis could produce cyclopia in fish with nearly normal brains, ruling out brain size per se as the cause. This analysis implied that the behavior of embryonic cells depended critically on the nature of their neighbors. In the presence of the midline tissue, both eye primordia generated complete and separate eye structures. When midline tissue failed to form or was destroyed early in development, however, eye-forming cells could reassess their surroundings and change their behavior to produce a single, well-proportioned eye, or partially fused "hourglass" eyes, regardless of the exact number and position of the surviving progenitor cells.

The full significance of this regulative ability, however, was not realized until later. The smoothly integrated tissues in cyclopic and partially fused eyes strongly imply that the progenitor cells differentiate in harmony with their neighbors, at least locally. Today we recognize that this could not occur without extensive communication via signals between developing cells. However, the true significance of intercellular signals only began to be appreciated in 1924, with the publication of embryological experiments by Hans Spemann. Earlier, Lewis had grafted a region from the frog embryo known as the dorsal lip of the blastopore to a different site in a host embryo of the same species. A large amount of neural tissue developed at the location of the graft, leading him to conclude that the growth rate of the transplanted dorsal lip was greatly increased in the new location. By transplanting dorsal lip tissue to a different species of frog (one differing in pigmentation), however, Spemann discovered that the dorsal lip, at the appropriate time and location, actually functioned differently. A small amount of dorsal lip tissue induced nearby host tissues to take on completely new fates, forming a second embryonic brain and axial structures. (Whether the extra neural material in Lewis's earlier experiments also derived from the host remains uncertain since graft and host tissue could not be distinguished,)

A cyclopean "monster."' Drawing of a **cyclopean** human **embryo.** The major structures of the face are identified Note that the ears have moved toward the midline* and lie below **the** cyclopean eye. **From** G.L Streeter (I 922),. **Contributions** to Embryology, Vol 14, pp. S 11-138, Carnegie Institution of **Washington..**



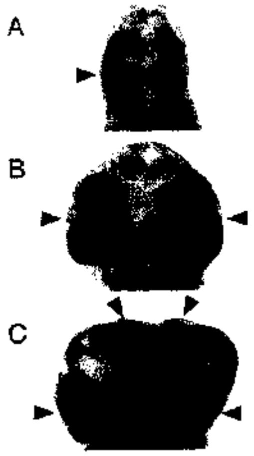
Members of the Department of Embryology, October 1998: First row (from left): Tong Tong Liu.Jie Deng, Donald Brown, Stacey Hachenberg, Kim Dej, Horacio Frydman, Eleni Goshu, Maggie de Cuevas; Second row: Jacques Michaud, Jimo Borjigin, Cathy Mistrot, Brian Calvi, Rachel Fasnacht, Eileen Hogan, Ben Remo, Bruce Hodess, Pat Englar; Third row: Ellen Cammon, Iijun Zhang, Shika Laloraya, Joe Gall, Ona Martin, Laura Buttitta, Brigitte Lavoie, Susan Parrish, Sofia Lizarraga, Ru Gunawardane, Amy Rubinstein, Jamie Fleenor, Pat Cammon; Melissa Pepling; Fourth row: Yixian Zheng, Valarie Bertogiio, Alejandro Sanchez Alvarado, Kristine Funkhouser, Tim Mical, Rejeanne Juste, Michelle Macurak, Shannon Fisher, Catherine Lee, Jenny Hsieh, Nicole Mozden, Erika Matunis, Nicole Greider; Fifth row: Chris Wie.se, Allen Strause, Allan Spradling, Andy Wilde, Scott Nowak, Michel Bellini, Alex Schreiber, Steve Farber, Noah May, Zengfeng Wang, Andy Fire, Ting Xie; Sixth row: Chen-Ming Fan, Vinny Guacci, Bob Skibbens, Bill Kelly, Zheng-an Wu, Debby Berry, Phil Newmark, Jenny Liang, Lisa Timmons, Steve Kostas, Paul Megee, Rick Elinson

In revealing the astonishing potency of embryonic signals, Spemann's experiment for decades remained the most famous in embryology. Today we know that embryonic cells send a wide array of signals at specific times and locations that keep development on course despite inevitable environmental perturbations and embryo-to-embryo variation. For cyclopia, the existence of widespread signaling during development implied that the critical midline tissue might not be made up of neural cells serving as a passive spacer. Instead, the underlying cells of the prechordal plate might actively signal the neural midline thereby causing eye-forming cells to develop in two separate groups.

Mall felt that the ready production of cyclopic embryos by environmental factors vitiated the need to search for a genetic cause of the spontaneous human cases of cyclopia he had characterized. Genetic knowledge in 1917 was still primitive, and since the cyclopic embryos they studied did not survive, most researchers could not understand how a gene causing cyclopia could even be propagated. In fact, genetic studies would turn out to be the key to further progress in understanding the signals controlling the early differentiation of the vertebrate brain and eyes. Since each of the tens of thousands of genes in a vertebrate genome controls the production of a specific protein molecule, identifying the relative handful of genes that can cause cyclopia should reveal those few proteins that are critically important to the development and signaling of midline cells during eye development. To identify such genes, one needs organisms in which mutants can be readily induced, scored for their effects on embryos, propagated (as heterozygotes) in genetic stocks if they produce cyclopia, mapped to specific chromosomal sites, and molecularly cloned (based on their chromosomal position) to identify the nature of the encoded protein. It is only in recent times that a few model organisms have been developed to the point where each step in this long process has become routine.

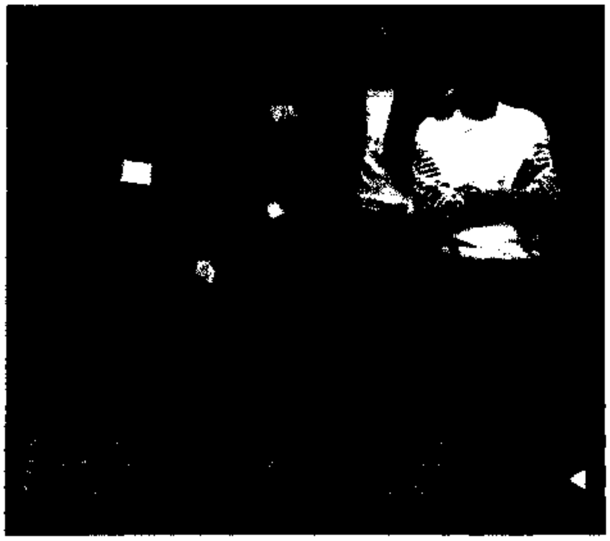
The first gene implicated in cyclopia, *Sonic hedgehog (Shh),* was characterized by former Embryology staff associate Phil Beachy shortly after he started his own lab at the Johns Hopkins University School of Medicine. Beachy initially cloned the Drosophila *hedgehog* gene, because in this genetically tractable organism *hedgehog* had been shown to send signals within the early embryo. He and other researchers subsequently found that the mouse and human genomes harbor three hedgehog-related genes, including *Shh.* Early in development, prechordal plate and notochord cells express high levels of the protein encoded by *Shh.* To investigate the protein's function, the scientists generated mice completely lacking a functional *Shh* gene. £M~deficient mice did not come to term, but the embryos frequently developed cyclopia. These and other observations led to a model in which *Shh* signaling from the prechordal plate programs the differentiation of the overlying neural tube, and causes neural cells competent to form eyes to divide into two groups separated by midline cells. In the absence of the *Shh* signal, the cells fail to separate at all or remain too close together, leading to the production of a perfect or partial median eye, much as Mall proposed. It is now known that some human cases of holoprosencephaly are caused by the inheritance of defective *Shh* genes, as well.

The zebrafish is another vertebrate in which sophisticated genetic analysis is possible. This year, staff member Mamie Halpern, her colleagues Amy Rubinstein and Jennifer Liang, and their collaborator Chris Wright and his colleagues at Vandcrbilt University and in Singapore, identified the molecular nature of the zebrafish *cyclops* gene, adding an important new piece to the puzzle of cydopia. (Former Embryology staff member Igor Dawid and his colleagues at NIH also reported similar results.) *Cyclops* encodes a signaling molecule from the transforming growth factor beta family. Members of this family are potent regulators of growth and differentiation that act at many times during development, sometimes in conjunction with hedgehog family members, Haipem and colleagues found that events critical for eye separation actually begin much earlier than the postulated prechorda! plate signal, at a time when *cyclops* is strongly expressed, and while the embryo is still in the process of separating into individual layers, before a neural tube, prechordal plate, or notochord have even formed. Most likely, *cyclops* mediates signals between the precursors of these cells, which are needed for the growth or maintenance of the ventral midline cells that will much later signal to divide the eye precursors. Disruption of these initial signals may explain why very young embryos were the most sensitive to the experimental induction of cyclopia in the experiments summarized by Mall.



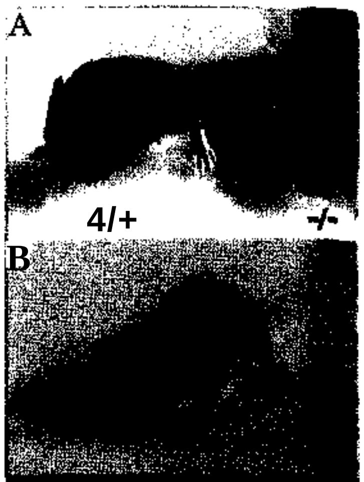
Cyclopean zebrafish.. Image shows the head region of zebrafish embryos expressing too little (A), normal (B), and too much (C) amounts of Cyclops protein. A fused cyclopean eye has formed in A,, while two partially fused additional eyes have developed in C. Arrowheads indi- [illegible]

The Halpern group's research also has important implications for understanding more generally how the brain is patterned. Current thinking has focused extensively on the *Shb*-mediated signals



sent by the notochord to pattern the overlying neural tube posterior to the eye-forming region. However, the Carnegie group's study of *cyclops* reinforces previous evidence from the Halpern lab that instructive signals for brain patterning begin much earlier, and are already flowing between neural and notochord precursor cells. The orderly formation of the immensely complex tissues and organs of the adult organism likely require a continuous sequence of such signals, only a small minority of which are currently known. *Cyclops* appears to function at multiple points. For example, after eye specification, cyclops protein accumulates to very different levels on the left and right sides of the brain, suggesting that it also mediates differences between left and right brain development.

The continued importance of signaling along the midline for proper neural development is further supported by research carried out by staff member Chen-Ming Fan and his colleagues Jacques Michaud and Noah May, and collaborator Thomas Rosenquist (SUNY, Stony Brook). Fan's group is analyzing the role played by two mouse genes, *Siml* and *Sim2*$_y$ that are expressed in precise regions of the developing mouse brain, including the hypothalamus, a key midline structure that is often absent in cyclopia. As with *Shby* interest in the *Sim* genes originated with a *Drosophila* homologue, ^*single-minded (sim).*^{n} The absence of Sim protein causes *Drosophila* brains to lose a key subpopulation of midline cells that are required to form the major neural connections between the left and right sides of the brain. By generating a mouse strain that lacks a functional *Siml*, Fan's group demonstrated that *Siml* is essential for the development of a critical subgroup of neural cells located in three reports of the hypothalamus. Normally, based on information collected by the brain, the hypothalamus coordinates the activity of various body tissues by controlling the secretion of peptide hormones from the pituitary gland. A least five types of secretory neurons, including those expressing the hormones oxytocin, vasopressin, thyrotropin-releasing hormone, corticotropin-releasing hormone, and somatostatin, are absent in the *Siml* mutant. Fan's group showed that *Siml* acts quite late during the differentiation of the critical neurons. Without these important hormones, mice lacking *Siml* die shortly after birth.



Sim 1 mutant mouse. (A): Mice from the same litter that contain (+/+) or lack (-/-) functional *S\m* I genes are shown. The small size and abnormal posture (B) are associated with defects in hypothalamic development. ◀

This work is important not only in defining the genetic control of hypothalamic development, but in elucidating new general mechanisms that control neural differentiation. *Siml* is a member of the PAS-domain family of proteins, which are structurally related regulators of gene transcription and include genes that control arcadian rhythms. The activity of at least one family member, the dioxin receptor, can be regulated in laboratory experiments by a small molecule, much like a hormone receptor. At present, however, very little is known about molecules that interact with PAS-domain proteins during normal development. Fan has postulated that ligands exist for other PAS-family members, including the *Sim gtnts.* Thus, further study of how *Siml* controls hypothalamic development may reveal the existence and mode of action of a new class of developmental hormones.

Hormonal effects on development have long been a topic for study in the department. (In fact, progesterone was discovered by former Embryology director George Corner.) Given our long familiarity with hormones, however, we know surprisingly little about the molecular mechanisms by which they work "We do know that when developing cells receive a hormonal signal, they respond initially by altering the pattern of genes they express. But exactly which genes are affected? Donald Brown's group has approached this question by studying how *Xenopus* tadpoles respond to the thyroid gland hormone thyroxin, which controls their metamorphosis into frogs. (In mice, the thyroid-stimulating hormone thyrotropin is one of the pituitary hormones whose production depends on *Siml* function.) Using a powerful, general method they developed to answer such questions, Brown's group has now extensively characterized more than 30 specific genes that are turned either on or off following the release of thyroxin.

The biggest problem Brown faces is to learn the function of each specific change in gene activity. The critical experiment would be to observe the process of metamorphosis in 30 strains of frogs that each lacked one of the responding genes. Unlike zebrafish or mice, however, this type of experiment is impractical in *Xenopus* due to the frog's two-year generation time. Can we afford to limit the detailed analysis of gene function to only a handful of model organisms? Brown thinks not. He and his colleagues, Nick Marsh-Armstrong, Haochu Huang, and Ben Remo, are using an approach they have dubbed "F0 genetics" to circumvent the problem. In this approach, they inject specially designed genes into *Xenopus* sperm or newly fertilized eggs. The added gene produces a protein that interferes with the activity of one of the metamorphosis genes they wish to study. A great advantage of the technique is speed and simplicity. The consequences of disrupting the target gene are observed as soon as the injected and fertilized eggs grow into tadpoles and attempt metamorphosis. In contrast, a classical genetic approach would require multiple generations before function could be tested. However, the current F0 approach also has several disadvantages. Genes that interfere with a specific target gene cannot always be constructed, and not all the cells express the introduced gene uniformly. Nevertheless, Brown's group has already used the method to interfere with the function of thyroid hormone in vivo, and to rule out a postulated role for growth hormone in metamorphosis.

Recent work by staff member Andy Fire and his colleagues Sequin Xu, Mary Montgomery, and Steve Kostas, with collaborator Craig Mello (University of Massachusetts) and his colleagues has the potential to greatly expand the scope and power of F0 genetics. Using the nematode *C. elegans,* Fire and his colleagues discovered a new way to potently and specifically inhibit gene expression in a single generation. Their approach, which is called "RNA interference," or "RNAi," appears to be effective with a large number of genes, and seems likely to function in other organisms as well. To carry out RNA interference, the researchers simply inject into the worms (or feed them) a small segment of double-stranded RNA corresponding in sequence to part of the target *gene* they wish to inhibit. As a result, the activity of the targeted gene declines drastically in the animals and their progeny. The use of RNAi can potentially save so much time compared to conventional genetics that it has already been widely adopted for experiments utilizing *C. elegans,* where extensive genetic technology is already available. The potential of the method in organisms that lack conventional genetics, such as *Xenopus,* is enormous.

"F0 genetics." A young *Xenopus leovis* tadpole containing two introduced genes. One causes a green fluorescent protein to be produced in the eyes so that transgenic individuals can be recognized. The other expresses the protein whose functional effects are to be tested.

A better understanding of how the injected RNA interferes with *gene* expression will be required to fully realize that potential, however. The method almost certainly does not mutate the *gene* itself, since the inhibition is not permanent. Mature messenger RNA is thought to be the ultimate target,

because gene regions that are spliced out as the gene transcript is processed are completely ineffective. One exciting explanation is that worms (and probably many other organisms) possess a previously unrecognized defense mechanism designed to inactivate gene transcripts that appear in double-stranded RNA form. (Normally, only messages belonging to a virus or invading parasite would be expected to appear as double-stranded RNA.) If true, the mechanism might be widespread, and allow RNA interference to be applied in a wide range of animals and plants. The Fire group and many others are attempting to extend the method, both in the worm and to other species, and to investigate its many biological and medical implications.

Clearly, studies of vertebrate embryology continue to thrive in the department more than 80 years after Mall's review. Moreover, the focus is still on questions that would be familiar to the workers of his day. Today, however, researchers need not wait for "monsters" to appear spontaneously. Molecular genetic methods provide the means to produce and study an almost unlimited number of embryos with specifically programmed developmental alterations tailored to any question of interest. Not surprisingly, by basing experiments on the solid function of specific genes and genetic pathways, the depth of our knowledge is increasing enormously. Perhaps, most exciting of all, is that we can begin to glimpse the methods of tomorrow which promise to expand the scope of our investigations beyond a few favorable laboratory organisms and into every corner of the biological world.

News of the Department

Two new staff associates were appointed during the year. Jimo Borjigin carries out research on the vertebrate brain that will help continue the traditions discussed in this essay. Her recent focus has been the pineal gland, the key center in the brain where circadian behavior is modulated, Erika Matron's studies *Drosopbila* spermatogenesis. The generation of male gametes represents a fundamental biological process that is still not well understood. Because sperm have very different functional requirements than eggs, they present opportunities to study a wide range of cellular mechanisms that are uniquely required for this process.


Jimo Borjigin


Erika Matunis

Our seminar program was highlighted by the twenty-first Annual Minisymposium, entitled "Genomic Instability." Nancy Craig (Johns Hopkins School of Medicine), Meng-Chao Yao (Fred Hutchinson Cancer Research Center), Andrew Murray (UCSF), Christoph Lengauer (Johns Hopkins School of Medicine), Stephen Warren (Emory University School of Medicine), and Leonard Guarente (MIT) presented one-hour talks.

Support of research in the department comes from a variety of sources besides the institution. Doug Koshland and I, and various members of our labs are employees of the Howard Hughes Medical Institute. Others are grateful recipients of individual grants from the National Institutes of Health, the John Merck Fund, the G. Harold &, Leila Y. Mathers Charitable Foundation, the American Cancer Society, the Jane Coffin Childs Memorial Fund, the Damon Runyon-Walter Winchell Cancer Fund, the Pew Scholars Program, the Alfred P. Sloan Foundation, National Science Foundation, and the Arnold & Mabel Beckman Foundation. We remain indebted to the Lucille P. Markey Charitable Trust for its support.

—Allan Spraiiimg

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[1] To December [illegible]
[2] To June 3[illegible]
[illegible] 1997
From January [illegible]

Updated through December I, 1998

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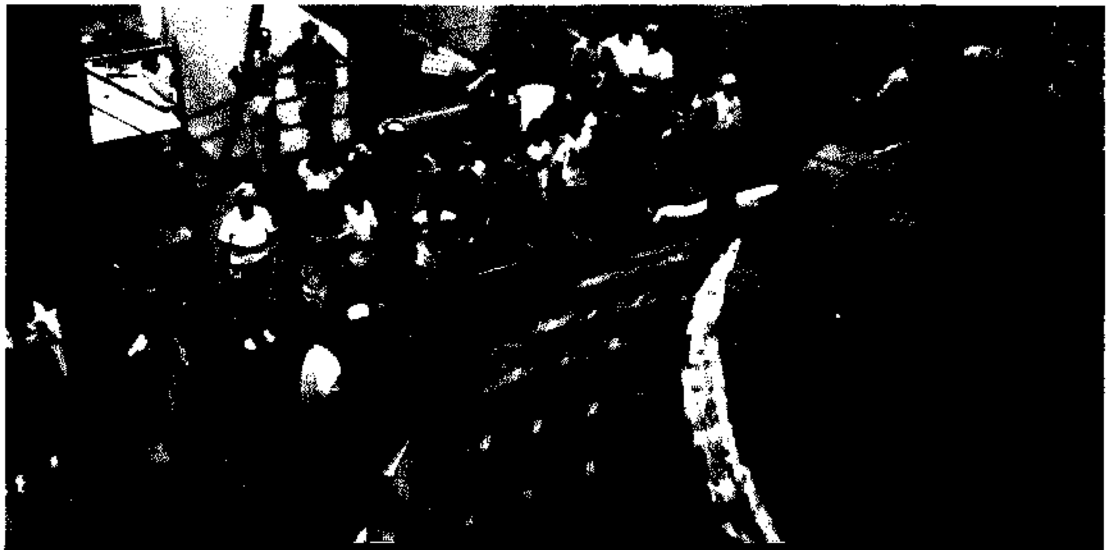
THE DIRECTOR'S ESSAY:

The Unseen Universe



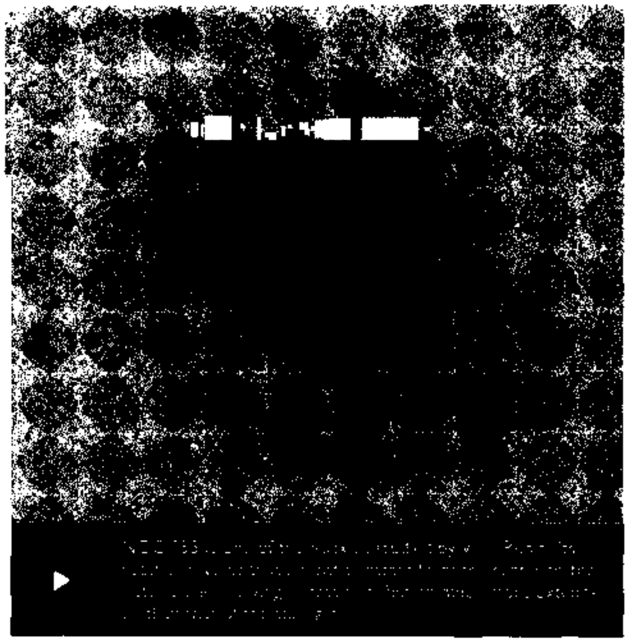
An elementary school class watches the casting oven spin at the University of Arizona, September 14, 1998. Inside is the mirror for Magellan II. (Photo: Matt Johns.)

The universe of the traditional astronomer is a universe of stars. When we look out from Earth with our eyes, or photographic plates, or CCD detectors, we see only stars or objects—such as planets and gaseous nebulae—that are illuminated by stars. The tools of the optical astronomer are devices for collecting and analyzing starlight, and most of what we know about the universe comes from such analysis.

This is no accident. Our eyes evolved to detect radiation from the nearest star, and most other stars radiate in similar parts of the electromagnetic spectrum. Fortunately for astronomy, that radiation bears an enormous amount of information about the universe. The detailed spectral energy distribution of stellar or nebular light reveals the chemical composition, temperature, density, and velocity of the material that emits it, and of any non-luminous gas through which the light passes on its way to our telescopes. Furthermore, its velocity is an indicator of the gravitational forces acting on the material, and therefore is a measure of the distribution of mass.

As astronomy progressed into the 20th century, the universe revealed by starlight seemed to be filled with the same matter, composed of the same elements, as that found on Earth, and most of that matter appeared to be in the form of stars. The mass of luminous and non-luminous gas seemed to be much less than that of stars, and the mass of solid matter—dust, planets, asteroids—seemed to be even less. The motions of stars and galaxies suggested that the mass in the universe was concentrated where the stars were, and in rough proportionality to their number. This conclusion was not only logical, it was comforting: since we could study only what we could see, it was convenient to be able to see most of what there was, especially if stars and galaxies were composed of the same stuff as that found in earthly laboratories.

Unfortunately, the work of recent decades has overthrown that comforting picture. Astronomy has been forced to confront the possibility that most of the universe is unseen, and much of it indeed may be unseeable. Hints of this possibility were raised as early as the 1930s by Caltech astronomer Fritz Zwicky, but were generally ignored. Not until the 1970s, due in large part to the work of DTM astronomer Vera Rubin, did it become clear that the universe is dominated not by stars but by *dark matter.* By analyzing the rotational motions of spiral galaxies, Rubin showed that the distribution of mass in galaxies extends far beyond the stars themselves. In fact, stars contribute only a very small fraction to a galaxy's total mass* The situation in clusters of galaxies is even more extreme: most of the mass in clusters lies not in the galaxies at all, but smoothly distributed in the spaces between them*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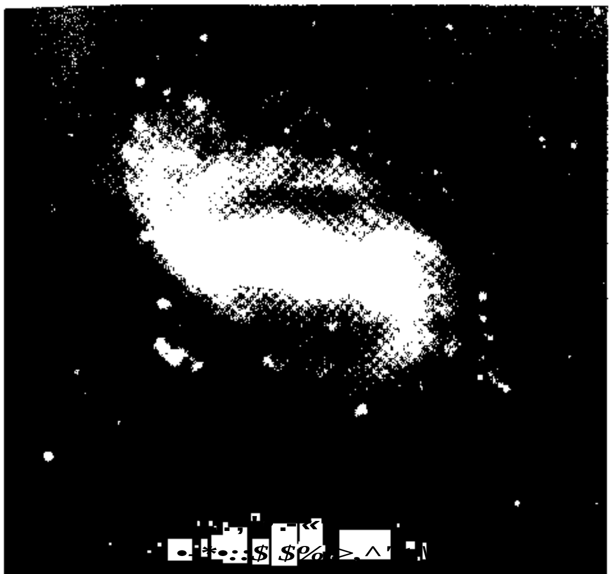
It gets worse. Various lines of argument suggest that most of the unseen matter in the universe cannot be the ordinary stuff of the periodic table—baryons, in the language of physics—but must rather be some exotic form of non-baryonic matter. Observations at other wavelengths, x-rays in particular, show that most of the baryons are not in stars, but in hot, diffuse gas. Finally, recent work suggests that even a significant fraction of the stars themselves may lie hidden beneath the glow of the night sky, in very dim, diffuse systems. Thus, at the very end of the 20th century, one of the major tasks of astronomy is something that was thought completed half a century before: cataloging the contents of the universe.

Mapping Dark Matter

The relative distribution of baryons and dark matter, and the question of where and how baryons form visible stars, are among the most pressing issues in astronomy today. One clue is provided by the way stars and dark matter are distributed within galaxies. Models for the growth of structure in the universe make predictions about those distributions, but they are difficult to test. While Rubin showed that dark matter dominates the outer parts of galaxies, her observations were incapable of untangling the relative contributions of stellar and dark matter to the *cores* of galaxies, where both make up a significant part of the total mass.

Now, two elegant techniques pioneered by Observatories fellows are at last making galaxy cores more accessible for study. One approach targets the class of exceptionally dim, diffuse galaxies that are barely visible on the night sky—the very-low-surface-brightness galaxies. Because these galaxies have such a low density of stars, dark matter should dominate throughout, even in their centers. Rubin's technique to map the distribution of mass by measuring galaxy rotations is able to reveal directly the distribution of dark matter in these galaxies, from their centers to their peripheries. In an effort to test this hypothesis, Hubble fellows Julianoe Dalcanton and Rebecca Bernstein are mid-way through a large project using that technique to map the distribution of stars and dark matter in 30 low-surface-brightness galaxies. In fact, the orbital velocities in many of the galaxies imply that the underlying dark matter fills a spher-



The motions of stars and gas within the central bar of NGC 4123 have been used by Carnegie fellow Ben Weiner to probe the distribution of dark matter within the galaxy.

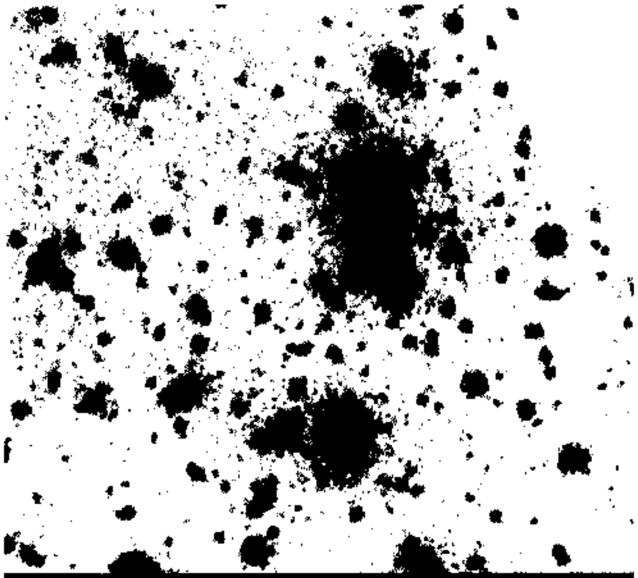
oid of almost constant density. Even though stars make a minor contribution to the total mass in those galaxies, Dalcanton and Bernstein find unusually tight relations between mass and stellar populations. These galaxies must be exceptionally pristine and undisturbed (such fragile objects could not survive much jostling) and may preserve fundamental relationships that have been erased in galaxies with more turbulent histories.

A complementary technique applicable to more common types of galaxies has been developed by Carnegie fellow Ben Weiner in collaboration with Jerry Sellwood and Ted Williams (Rutgers) and Jacqueline van Gorkem (Columbia). Although the majority of galaxies exhibit rotational symmetry, a significant fraction of spiral galaxies do not. These galaxies contain elongated structures, called bars, in their centers. The dynamics of such features are reasonably well understood, and it is clear that the bars are structures only of the stellar mass; the dark matter in these galaxies remains axisymmetrical. Weiner and his collaborators have been studying the motions of gas in the centers of several barred galaxies. The degree to which these motions are influenced by the bar is a measure of the degree to which the stars, rather than the dark matter, dominate the mass distribution in the galaxies' centers. The observations indicate that, in contrast to what Dalcanton and Bernstein observed in low-surface-brightness galaxies, stars rather than dark matter dominate the central regions of barred galaxies.

The two results together support models in which a galaxy's structure and final destiny is determined by the mass and amount of spin of the initial protogalactic gas cloud. (As a protogalactic gas cloud collapses to form a galaxy, centrifugal force keeps the material in more rapidly spinning systems spread out over a greater area than it does in those systems with less rapid rotation; see Dalcanton's essay about low-surface-brightness galaxies in Year Book 95, p. 31.) Eventually, both observational programs should help astronomers determine the size of dark matter halos as a function of galaxy properties. This knowledge is critical for understanding galaxy formation.

Clusters of Galaxies

Although our understanding of the distribution of stars and dark matter within galaxies is still imper-



A supergiant cD galaxy dominates the center of the cluster Abel 2218. its luminous envelope extends well beyond the edge of this photograph feet, it is far more complete than what we know about the environment outside of galaxies. In addition to the starlight observed in individual galaxies, we know that a significant amount of starlight hides within clusters of galaxies. Many rich clusters are dominated by central *cD* galaxies, which are supergiant ellipticals surrounded by enormously extended envelopes of stars. The great extent and total luminosities of these envelopes are often greater than that of all the other galaxies in the cluster, suggesting that they belong as much to the cluster as they do to the central galaxy.

The origin of this sea of stars is poorly understood. As far as we know, all stars are born in galaxies. Thus, if the stars in a cD envelope are bound to the central galaxy, they were most likely born in that galaxy. Alternatively, if the stars are bound instead to the cluster, they are much more likely to be the remnants of disrupted galaxies, torn apart by encounters with other galaxies in the cluster. Early work by Alan Dressler in the 1980s indicated that the velocities of the stars in the very outer envelopes of cD galaxies are more similar to the velocities of stars in the outer galaxies than they are to cD galaxies in the center, supporting the latter idea—i.e., that the stars are remnants of disrupted galaxies. Now, Observatories fellows Scott Trager and John Mulchaey, DTM fellow Dan Kelson, and UC Santa Cruz astronomers Ann Zabludoff (a former Carnegie fellow) and Michael Bolte have used the Keck Telescope to confirm Dressler's finding. They have also measured the metal abundances of the envelope stars, an important indicator of the stars' origin. (The heavy elements, what astronomers call "metals," are all products of the life cycle of stars. The metal content is thus an indicator of the past history of stellar populations.) Trager, Mulchaey, and colleagues find that metal abundance falls as one moves outwards through a cD envelope, as is typical in the outer parts of galaxies (outer stars tend to be older and more metal poor). But then, in the very outer reaches of the envelope, the abundance rises again. This suggests the dominant presence in the outer envelope of a population of younger stars, perhaps those from disrupted galaxies that were once part of the cluster.


▶ Observatories fellows, left to right: Ben Weiner, Scott Trager, Rebecca Bernstein

Another significant component of clusters is hot gas. This gas, spread throughout clusters at temperatures of millions of degrees, is seen only by its x-ray emission, and, until recently, was detectable only in dense clusters. Its total mass is as much as a factor of ten greater than the mass of all the stars, both those within the galaxies and those in any cD envelope. Recently, Mulchaey and his collaborators showed that hot gas is present in great quantities not only in populous clusters, but in groups of galaxies containing only a few dozen galaxies—groups that are a tenth the size of the typical cluster. This is most important. Clusters are exceptional environments and only a very small fraction of galaxies inhabit them; most galaxies are in small groups. Thus, if gas is the dominant component of the more common environment, it may be much more prevalent than astronomers had thought, perhaps adding appreciable amounts of baryonic mass to the universe. Even more recently, Mulchaey and Zabludoff found individual isolated elliptical galaxies that contain envelopes of hot gas as large as those associated with cD galaxies in groups. They speculate that these envelopes may be remnants from former populations of smaller galaxies that were swallowed by the isolated ellipticals, leaving only the gaseous envelopes behind.

Clusters and groups of galaxies provide the starkest example of how much the contents of the universe differ from our naive conclusions of a half century ago. The galaxies by which we recognize and define a cluster represent an almost insignificant fraction of its contents. Most of a cluster's stars are not in galaxies but in a smooth surrounding sea; most of its baryons are not in stars but rather in a sea of gas, and most of its mass is not in baryons but rather in a sea of dark matter.

The Gas Content of the Universe

If the abundance of gas in clusters and populous groups is an indication of the general inefficiency with which the gas originally filling the universe was turned into galaxies, then large quantities of gas should lurk everywhere. In densely populated environments, gas is hot enough to be luminous in easily detectable x-rays. However, in less populous environments, the gas is presumably much cooler, less luminous, and therefore more difficult to detect. Much work has been devoted to searching for cool gas in nearby groups of galaxies, with little success. Now, astronomers are beginning to wonder if the long-sought gas might be right under our noses, in the Local Group of galaxies of which our own Galaxy is a part. In addition to the large and well-understood mass of gas which fills the Galactic disk, a number of gas clouds are observed whose velocities and positions are inconsistent with belonging to the disk. These "high-velocity clouds" have long been thought to be material falling back into the Galaxy after being ejected in supernova explosions. It has recently been suggested, however, that at least some of these clouds are not associated with our Galaxy at all but are more distant inhabitants of the Local Group.

Determining the distance to an object is one of the most fundamental, and maddeningly difficult, problems in astronomy. There is little to tell whether these high-velocity clouds are small and nearby, attached to the Galaxy, or large and far away members of the Local Group. Weiner and Stuart Vogel (U. Maryland) have used the du Pont Telescope to make extremely sensitive searches for hydrogen emission from high-velocity clouds. If the clouds are nearby, they reason, then radiation from the Galactic disk should excite the gas within them and produce an observable amount of emission; if the clouds are far away, there should be little or no emission. The results suggest that the largest clouds, which show significant hydrogen emission, are attached to the Galaxy, but that some of the smaller clouds, which produce no emission, may be true intergalactic clouds.

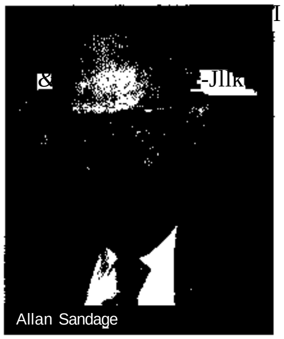
The Observatories participated in the national Earthwatch Student Challenge program during the summer of 1998. Above, high school students who received Earthwatch Challenge Awards, with their advisor, postdoctoral fellow Randy Phelps. Left to right: Sarah Ramer, Colin Trail, Phelps, Ryanne Putnam, Jill Sahajdack, Megan Rogers, Jason LeFebvre, and graduate student assistant Marc Kassis.

A more powerful, but difficult to interpret, probe for intergalactic gas clouds is provided by spectroscopy of quasi-stellar objects, QSOs. The ultraviolet spectra of QSOs contain absorption lines from gas clouds scattered along their lines of sight. The nature of these intervening objects is complex, and uncertain. Some may be gas clouds within the QSOs' host galaxies, analogous to the large, high-velocity clouds attached to our Galaxy. Some may be intervening galaxies along the lines of sight. Others, particularly those producing the weakest absorption lines, are thought to be intergalactic, primordial gas clouds, perhaps similar to the small, high-velocity clouds observed in the Local Group by Weiner and Vogel

Recent theoretical models by several groups indicate that the distribution of gas in the universe is very complex. These models suggest that many of the gas clouds seen in QSO spectroscopy may not be actual physical clumps, but may instead represent "velocity caustics," in which gas, while spread out over vast distances, appears to pile up at certain velocities along the lines of sight. New research by Ray Weymann and Buell Jannuzi (KPNO) addresses this issue. They have completed their ultraviolet analysis of absorbers detected by the Hubble Space Telescope in the HST Quasar Absorption Line Key Project. These absorbers provide by far the best probe of gas distribution at low redshifts, i.e., at recent epochs. (The ultraviolet radiation of QSOs cannot penetrate the Earth's atmosphere and can only be observed from space with HST. From the ground, we can only observe very distant objects whose spectra have been redshifted into the visible.) Comparing the HST observations with ground-based observations, it is clear that the number of absorbers has plummeted with time, as structure in the universe evolved. However, Weymann and Jannuzi show that the abundance levels off at low redshifts (recent epochs), particularly in those producing the weakest absorption features. These results are very similar to those predicted by at least some of the velocity-caustic models, lending weight to this new interpretation of gas distribution.

Additional support for the new theoretical models may be found by testing the properties of some of the nearby absorbing systems. This can be done by looking at galaxies in which individual absorption features are present. While past studies have successfully ascribed strong low-redshift features *to* particular galaxies, the real test is to do the same *in* the weakest low-redshift features. In collaboration with John Stocke, Michael Shull, and Kevin McLin (*U*. Colorado), Weymann *has* begun a survey with the du Pont telescope to search for very faint galaxies which may contain weak features. Failure to find them would lend strong support to the velocity-caustic models.

This year, like every year, saw the arrival of new people and the departure of others from the Observatories. Each coming and going makes a significant difference in the life of the department. This year, a milestone was passed of uncommon significance: the retirement of Allan Sandage. Allan first arrived on Santa Barbara Street in 1949, as a new Caltech graduate student sent up to work with Edwin Hubble. He was appointed a staff member in 1952, even before he received his Ph.D, and, except for brief visits elsewhere, he has been here ever since.

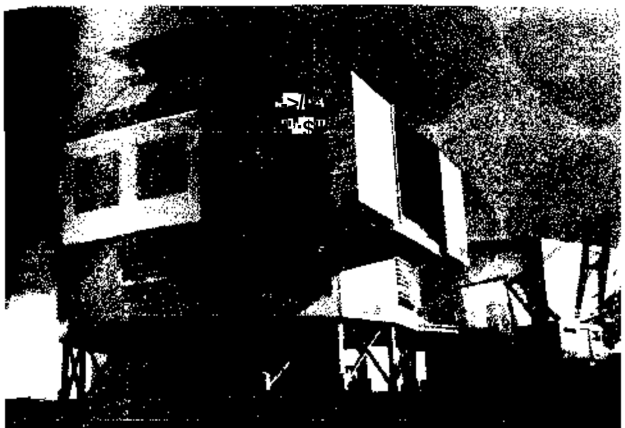


Allan Sandage

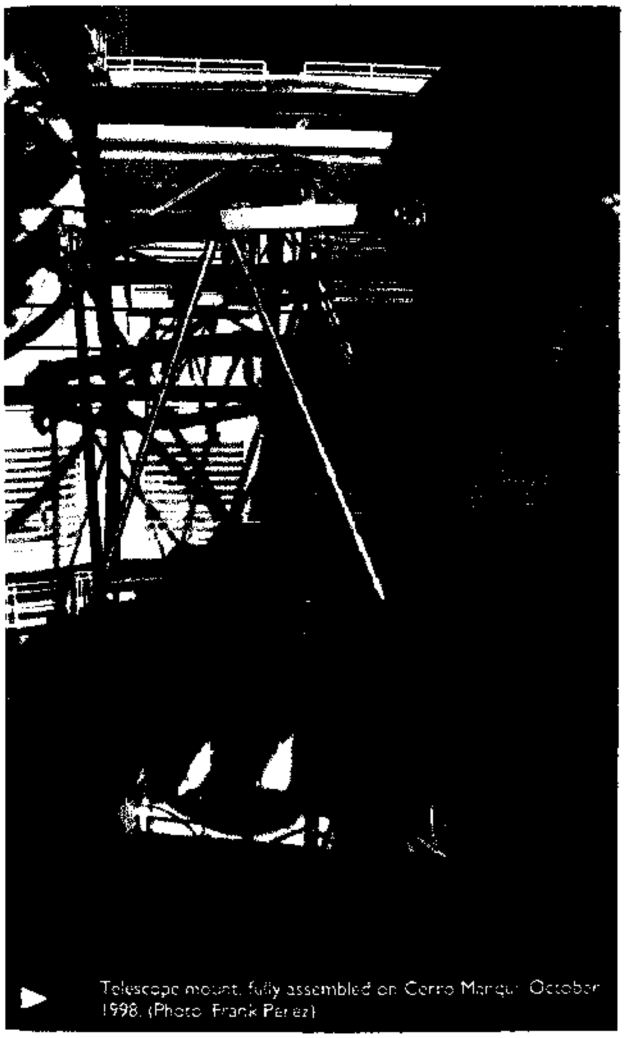
The history of astronomy in the first half of the 20th century was written by a handful of people, many of whom worked at Carnegie's Mount Wilson Observatory. The history of the second half of the century has been the work of a multitude, but if one name stands out from the rest, it is that of Allan Sandage. The range of subjects to which Allan has made major contributions is immense: globular clusters, the structure and evolution of stars, galaxy classification, galaxy formation, Galactic structure, radio galaxies, quasars, and x-ray sources, in addition to his 50-year pursuit of the fundamental cosmological parameters.

Allan has received virtually every honor awarded to astronomers. His single-minded pursuit of understanding the universe has had a profound influence on several generations of astronomers. Astronomy is unlikely to see again anyone with his breadth and depth of influence. Happily for us, Allan's retirement was a mere formality and has not diminished at all his presence on Santa Barbara Street. We hope that he will continue to be an active colleague for many years to come.

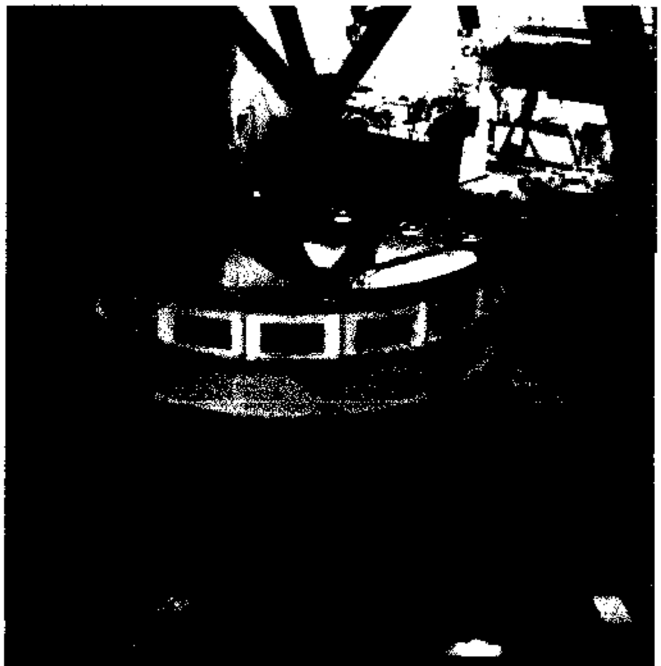
This past year saw the long-awaited signing of the formal Magellan agreement between Carnegie and its partners: Harvard, MIT, and the Universities of Arizona and Michigan. The Magellan Council and Science Advisory Committee, with representatives from all five institutions, have begun their work of guiding the project. The Magellan I telescope now stands fully assembled in its enclosure on Cerro Manqui. Contracts have been let for the construction of the Magellan II telescope mount and enclosure. By mid-1998, polishing of the Magellan I primary mirror was nearing completion at the Steward Observatory Mirror Lab in Tucson, as was the assembly of the mold for the Magellan II primary. The £711 secondary was nearing completion at Contraves, while work on the £715 silicon carbine secondary was progressing slowly at Vavilov State Optical Institute in St. Petersburg.



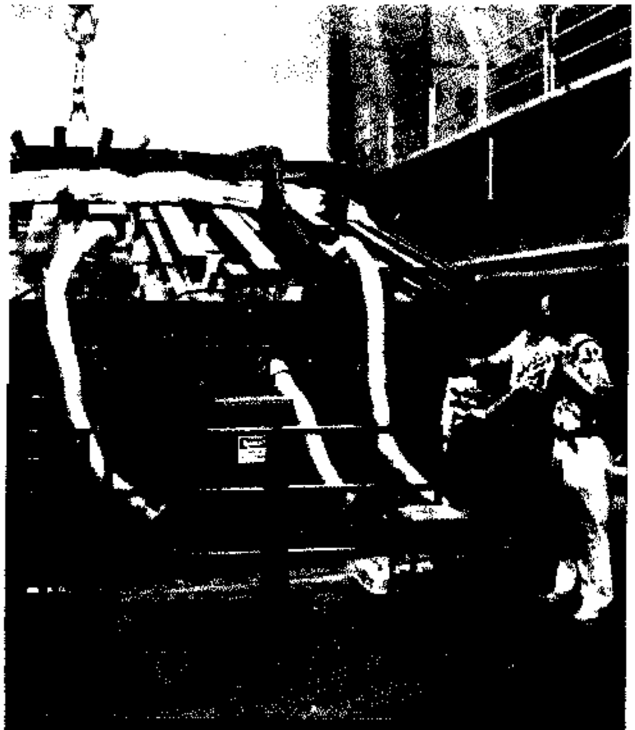
Magellan I dome with doors open, August 1998. (Photo: Matt Johns)



Telescope mount, fully assembled on Cerro Manqui, October 1998. (Photo: Frank Perez)



Magellan I mirror under the test tower at the University of Arizona, September 1998. (Photo: Matt Johns)



frank Perez and Charlie Hull watching the casting oven for Magellan II spin at *the* University of Arizona, September 1998, (Photo: Matt Johns}

As first light for Magellan I approaches, work on Magellan instrumentation continues to accelerate. Considerable progress was made during the year on all three large instruments being constructed by Carnegie astronomers and technicians, though none has *yet* reached the stage of mechanical fabrication. The IMACS (Inamori Magellan Areal Camera and Spectrograph) team now consists of Alan Dressier, Bruce Bigelow, Brian Sutin, and Tim Bond. The optical design is complete, and glass has been ordered for the field lens, collimator, and both cameras. The preliminary mechanical design is expected to converge to a final design by early 1999.

Work on the DDI infrared camera and spectrograph, under the direction of Eric Persson and David Murphy, proceeds in parallel with work on a new infrared camera for the du Pont Telescope, being built in collaboration with Cambridge University. The latter camera, which contains an array of four 1024-square Rockwell detectors, will be an exceptionally powerful survey instrument. Much of the technology being developed for DDI, in fact, is finding a first application in this camera, which is expected to be completed in early 1999.

The Kyocera Echelle spectrograph, under the direction of Steve Shectman and Hubble fellow Rebecca Bernstein, is progressing at a similar rate. The optical design has been completed and the glass ordered, but the mechanical design is not yet finished. Consideration is now being given to adding a multi-object, optical fiber feed to the Echelle. When located at the 30-arc-minute-field Naysmith focus of Magellan, such an instrument would be enormously productive for many projects.

—*Augustus Oemler, Jr.*

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THE DIRECTOR'S ESSAY:

The Stimulus of New Ideas and Enthusiasms

> "...THE BASIS OF [POSTDOCTORAL] FELLOWSHIPS IS THE UNDOUBTED FACT THAT THE STIMULUS OF NEW IDEAS AND ENTHUSIASMS, GROWING OUT OF THE DIFFERENT BACKGROUNDS AND FRESH POINTS OF VIEW OF YOUNG RESEARCH[ERS], IS MORE IMPORTANT TO OUR WORK THAN ANY OTHER FORM **OF SUPPORT."**
>
> MERLE A. TUVE (1939)*

The DTM postdoctoral fellowship program is an essential element of both the research and educational missions of the department. As former DTM staff member and director Merle Tuve noted sixty years ago, our postdoctoral scientists bring a vitality of new ideas and approaches that permeates all of our research activities. Our larger projects benefit from the involvement of multiple collaborators, including scientists at the postdoctoral level, who bring distinct technical or analytical skills to bear on critical questions. The department's investment in advanced instrumentation calls for a vigorous effort to ensure that such tools are effectively used to maximum scientific advantage, and a strong postdoctoral fellow program is the most promising means to achieve such a goal.

A multi-year tenure at the postdoctoral level is an increasingly important career stage in the education of a research scientist. At DTM, whether the Individual's support is derived from the institution's endowment or from a federal grant, a hallmurk of the appointment is the independence afforded *to* pursue research in directions deemed by the individual to be of greatest promise and importance. At the same time, there are ample opportunities to interact with senior staff, at the Geophysical Laboratory as well as DTM, who serve as mentors and potential collaborators. Both of these aspects of our program are highly valued by the postdoctoral scientists who have joined our ranks in recent years.

The DTM postdoctoral fellow program has its roots in the years immediately before World War II. The first postdoctoral scientist listed as a DTM fellow in the Year Book was Richard Roberts, appointed during 1937-1938 to work with the department's atomic physics group. (Roberts later joined the DTM staff and went on to a distinguished career in physics and biophysics; in 1981 a fund to support postdoctoral fellows was established in his honor,) Several additional fellows were appointed in the following two years, with the strong support of staff members such as Tuve. Following the war, Tuve (as DTM director) drafted a detailed outline of a postdoctoral fellowship program for the entire institution, and his plan became the basis for the modern practice.

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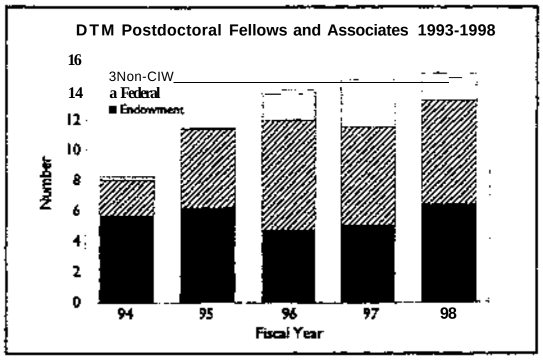
* Letter to DTM director John A. Fleming, 2 April 1939

Left: Postdoctoral scientists at DTM. Top to bottom, left to right: Larry Nittler, Richard Ash, and W [illegible] M*nzr* [illegible] a sample [illegible] the [illegible] for oxygen isotopes. Harri Vanhala, Stephen Kortenkamp, and Kenneth Ch[illegible] discuss [illegible] star [illegible] formation. Catherine Johnson, Patrick McGovern, Emilie Hooft and Andrew Fr[illegible] compare [illegible] *si* [illegible] Di[illegible] and Michael Regan [illegible] *u*n* Hubble Space Telescope images from a pipe?" by Regina and John [illegible] of the Observatories



· of postdoctoral fellows and associates at ed as person years for each of the last five fiscal years. Sources of support for fellows (Carnegie endowment ide funds) and associates (federal grants) are indicated. ctoral scientists with joint appointments at DTM and ysical Laboratory are considered half time at DTM es of preparing this figure.

Over the last five years, considerable effort has been invested in the recruitment of postdoctoral scientists and in raising funds for their support. The number of postdoctoral scientists at DTM, expressed as full-time person years, increased from 9 in 1993-1994 to 16 last year (Fig. 1). Several factors have enabled this increase. First, the staff has raised additional federal grant funds for the support of postdoctoral associates. Second, the department has partnered with the Geophysical Laboratory in an increasing number of joint appointments (there are presently five joint fellows). Finally, the department has benefited from the decision of several individuals who have won national fellowship competitions to carry out their fellowship research at DTM. (In residence at present are one Hubble Fellow and two NSF Earth Sciences Research Fellows.)

DTM postdoctoral fellows and associates last year contributed substantially to the research enterprise of the department. *One* simple statistical measure of the impact of their contributions is seen in the department's bibliography: of the 115 papers listed for the past year, 46% were authored or co-authored *by* present or recent DTM postdoctoral scientists. A richer demonstration of the impact of the post-doctoral program is provided by a look at some of the highlights from the past year of the research programs of individual fellows and associates.

Astronomy and Planetary Science

Research in astronomy and planetary science at DTM spans a broad intellectual reach, from the origin of the solar system to star formation in distant galaxies and galaxy dynamics. Our most recent group of postdoctoral scientists in this area has contributed substantively across the full spectrum of topics.

Theoretician Harri Vanhala employs numerical simulations to test hypotheses for the origin of the solar system. In particular, he is testing the triggered origin scenario, the suggestion that solar system formation occurred as a result of molecular cloud collapse initiated by a shock wave propagating from a nearby stellar source. This hypothesis can account for the presence of short-lived radioactive nuclides in meteorites as products of an explosive stellar event that were then transported to the solar system formation site by the shock wave. It is only in the last few years that computational capabilities have permitted numerical simulations at a resolution sufficient to test this idea. The simulations performed by Vanhala (Fig. 2) show that an

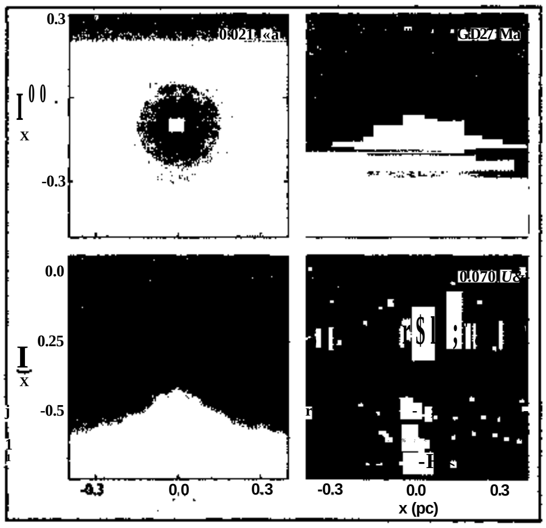


Fig. 2. Interaction between an interstellar shock wave and a molecular cloud core in a three-dimensional simulation by Harri Vanhala. The [illegible] is shown in the x-z plane with the units in parsecs; [illegible] velocity of [illegible] time [illegible] [illegible] of the [illegible] [illegible]

interstellar shock wave can indeed initiate star formation, that material carried by the shock wave can be mixed into the forming system, and that the process is sufficiently rapid for short-lived radioactive nuclides to have survived in detected amounts. His results agree broadly with similar calculations performed earlier by Alan Boss's group with a different simulation method and different approximations. Ongoing work is aimed at the crucial question of understanding mixing in greater detail, and at the broader issue of whether the properties of planetary systems produced by triggered (or assisted) star formation differ from those created through unassisted star formation.

A somewhat later stage of the solar system formation process is the focus of work by fellow Kenneth Chick. Past computer simulations of gas disks around young solar-type stars have demonstrated the spontaneous, rapid formation of density concentrations in the disk. These concentrations may represent the initial phase in the formation of gas-giant planets. Unfortunately, these simulations have relied on numerical techniques that can depict flow in the disk only over tens of years, a brief interval compared with the million-year lifetime of the disk. To determine whether early density concentrations eventually collapse into planets, Chick is working with Alan Boss to develop a disk-simulation code based on a fundamentally different type of numerical technique capable of following the evolution of gas flow over long timescales. A two-dimensional version of the code has been tested successfully against reference solutions with short time scales, such as the propagation of cylindrical sound waves, and further tests are under way for problems with longer time scales, such as the motion of slow tidal waves induced by an external force.

DTM staff on the front steps of the main building, Broad Branch Road campus, October 1998. First row (left to right): Sean Solomon, George Wetherill, Gregory Good, Vera Rubin. Second row: Stephen Shirey, John Lynch, Emilie Hooft, Laurie Benton. Third row: Lianxing Wen, Don Anderson, Janice Dunlap, John Almquist, Mary Horan, Mary Coder, Richard Bartholomew, Georg Bartels. Fourth row: Harri Vanhala, Wenjie Jiao, Richard Carlson, Shaun Hardy, Cecily Wolfe, Timothy Mock, Paul Silver, Kenneth Chick, Louis Brown, Thomas Aldrich. Fifth row: Michael Acierno, Daniela Power, Jane Gore, Teresia Nguuri, Nelson McWhorter, François Schweizer, Daniel Kelson, Brian Schleigh, Fouad Tera, Ben Pandit. Last row: Carol Alexander, Terry Stahl, David James, Randy Kuehnel, John Graham, Patrick McGovern, Alan Boss.

Postdoctoral associate Stephen Kortenkamp is exploring the implications for the growth of the inner planets of our solar system if the gas giants Jupiter and Saturn formed early. In current models for inner planet formation, approximately Mars-size terrestrial planet "embryos" are formed by the accumulation of smaller planetesimals on a timescale of about 10^5 years. Conventional models for the formation of Jupiter and Saturn involve the accretion of a gaseous mantle onto a heavy-element core, a process expected to span a much longer time (about 10^7 years) so that long-range gravitational perturbations would not inhibit the growth of terrestrial planets. Efforts to model the core-mantle formation of Jupiter and Saturn have not yet been successful, however. On the basis of his gaseous-disk calculations, Alan Boss has proposed that giant planets instead form by gravitational instabilities in the disk. Such an alternative model leads to formation times for Jupiter and Saturn of about 10^5 years, nearly simultaneous with the formation of the Sun. Kortenkamp is working with George Wetherill on the question of whether long-range perturbations from early-formed Jupiter and Saturn would preclude the formation of terrestrial planets and asteroids. He has found that, in the presence of gas in the protoplanetary disk, bodies with masses within a factor of about 10 of one another collide with sufficiently low encounter velocities to accumulate into larger bodies. At the Earth's distance from the young Sun, these bodies can continue to grow to the size of Mercury or Mars, and ultimately merge into an Earth-size planet. In contrast, in the asteroid belt the distance between the planetesimals and the giant planets is smaller, the perturbations are much stronger, and formation of planetary embryos is very unlikely unless the giant planets were initially considerably more distant, a result consistent with the absence of an object larger than the asteroids at that solar distance today.

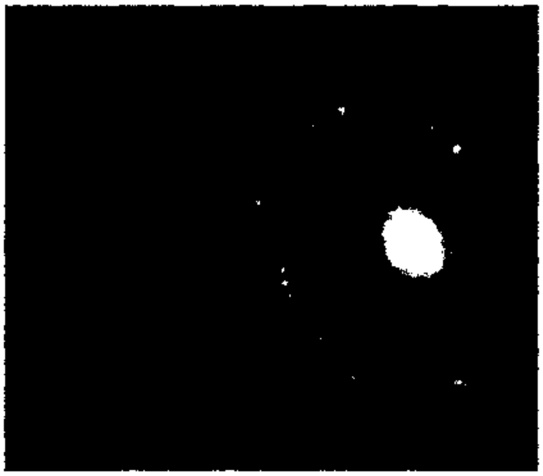


Fig. 3. [illegible] image of the galaxy NGC 3351 [illegible] taken at [illegible] of 1.6 μm with the NICMOS camera on HST. While at this wavelength the images of most galaxies are dominated by older stars, in this galaxy the large amounts of dust and current star formation in the nuclear ring can be seen even at 1.6 μm. The rate of star formation in this ring is several times greater than in the entire Milky Way galaxy.

Although recent observations suggest that massive black holes exist in the centers of most galaxies, not all galaxies display the large amounts of X-ray and ultraviolet emission associated with material falling into a black hole. Why is it that some galaxies exhibit this activity and some do not? One possibility is that some galaxies are better able to drive gas into their central regions. Gas is easily driven into the center of a galaxy if the stars, rather than being evenly distributed, are arranged in an oblong or bar. To look for these bars in active galaxies, Hubble fellow Michael Regan and Carnegie Observatories fellow John Mulchaey have undertaken a survey using the Hubble Space Telescope (HST) and a new HST instrument, the Near Infrared Camera and Multi-Object Spectrometer (NICMOS). By looking in the near infrared, one is better able to see the distribution of stars that are hidden by dust when observed at optical wavelengths (Fig. 3). Regan and Mulchae/s initial analysis of about 100 galaxies reveals no more bars in the active galaxies than in the normal galaxies. Their results lead to the conclusion that whatever determines why one galaxy is active and another is not is controlled very close to the black hole and not by the host galaxy.

Fellow Stacy McGaugh, now on the faculty of the University of Maryland, devoted his attention while at DTM to the measurement and interpretation of rotation curves for low-surface-brightness galaxies. The inference—made a number of years ago by Vera Rubin—that the rotation curves of galaxies cannot be explained on the basis of the mass of their visible portions led to the postulate that dark matter is a significant component of matter in the universe. McGaugh has shown that the rotation curves of low-surface-brightness galaxies show severe mass discrepancies that extend from their centers, unlike high-surface-brightness galaxies where much of the inner rotation can be attributed to the luminous disk. The stars in these low-density galaxies act as accurate tracers of the potential of the hypothesized dark-matter halo, so such galaxies serve as laboratories for testing theories of galaxy formation.

Bryan Miller, a DTM postdoctoral associate with a joint appointment at the Space Telescope Science Institute (STScI) through the summer of last year and now at the University of Leiden, Netherlands, studied extragalactic star clusters as probes of galaxy evolution. Miller's observations with HST, carried out in collaboration with François Schweizer and Brad Whitmore (a former DTM fellow now at STScI), show that large numbers of star clusters display relatively young ages (inferred from spectral color) and likely formed during galaxy mergers. This finding supports the hypothesis, long championed by Schweizer, that elliptical galaxies can be formed by the merger of two spiral galaxies. Miller also began an HST project, with colleagues from STScI, to investigate star clusters in dwarf elliptical galaxies. The relatively large numbers of clusters he has found in dwarf ellipticals suggest that the merging of many such dwarf galaxies may be another way of building giant elliptical galaxies and their large star-cluster populations.

Observations of very distant galaxies provide an opportunity to learn about galaxies at a time when these objects were generally much younger than they are today. Barbara McClintock fellow Daniel Kelson is studying the evolution of galaxies in clusters to redshifts approximately equivalent to half the current age of the universe. For a typical population of stars, the total luminosity fades with time. However, when comparing the luminosities of different galaxies, one cannot know if one galaxy is brighter because it is younger or because it is more massive and simply contains more stars. This ambiguity can be removed by comparing the amount of light per unit mass, referred to as the light-to-mass ratio. A given galaxy's mass can be estimated by studying the random motions of its stars; the faster stars move within a galaxy's gravitational potential, the more massive the galaxy. For high-redshift (distant) galaxies, Kelson has been using HST to measure sizes and brightnesses and the Keck 10-m telescopes to measure internal motions. He has traced galaxy light-to-mass ratios for cluster galaxies as a function of redshift (time). On the basis of models that predict when such galaxies first experienced star-formation, he has shown that cluster galaxies are among the oldest objects in the universe, containing stars that formed when the universe was only a few billion years old. A long-term goal of his work is to understand why we see the myriad of galaxy shapes and morphologies that we do today.

CGSftiocbeniisfry and ***Geochemistry***

The fields of cosmochemistry and geochemistry are often concerned with the elucidation of tracers of ancient events in the history of our planet or solar system. The tools of the trade are sophisticated instruments of high precision, and postdoctoral scientists at DTM made good use of those tools last year to report progress on a wide variety of problems.

Meteorites contain tiny dust grains whose extremely unusual isotopic compositions indicate that they condensed in ancient stars before the formation of our solar system. Detailed studies of these presolar grains have yielded a wealth of new information on galactic, stellar, and solar system astrophysics. However, since presolar grains are very rare in meteorites, investigations of many important questions have been hampered by poor statistics. To address this problem, fellow Larry Nittler developed an automated isotopic-ratio measurement system for use with the DTM ion microprobe. His system allows large numbers of micron-sized particles to be analyzed relatively quickly and rare types of presolar grains to be identified for further study. The first use of the new system to search for presolar oxide grains increased the total known set of these grains by -20% in one week of mapping and resulted in the identification of a previously unrecognized presolar grain type (titanium oxide).

Fellow Richard Ash—a joint appointment of DTM, the Geophysical Laboratory, and the Smithsonian National Museum of Natural

History—employs oxygen isotopes to study the origin and early evolution of the solar system. Working with Conel Alexander and Douglas Rumble in the Geophysical Laboratory's ultraviolet laser fluorination facility, Ash can determine deviations in oxygen isotopic compositions from terrestrial values to the level of one part in 10^5, an order of magnitude better than conventional techniques, on samples as small as 500 ,um in diameter. Ash and his colleagues have focused on chondrules, which are among the oldest solid materials formed in the solar system but whose origin and history remain enigmatic. Chondrules are silicate spheres, up to 5 mm in diameter, found within the most common class of meteorites and formed by the crystallization of a melt floating in free space. The group has shown that the primordial composition of most chondrules is dominated by characteristically nebular signatures, indicating that chondrules crystallized at conditions where isotopic fractionation effects were small. Chondrule formation must therefore have occurred while gas pressure in the primitive solar nebula was sufficiently high that gas-dust exchange dominated over simple evaporation.

Fellow Paul Tomascak, now at the Lamont-Dohcrty Earth Observatory, employs measurements of the isotopic composition of the element lithium (specifically the ^{7}Li/^{ft}Li ratio) to probe both the early history of the solar system and more recent matk processes on Earth. One of the earliest users of DTM's new multi-coUcctor inductively-coupled plasma mass spectrometer, Tomascak has shown that this instrument permits much more rapid measurements of "Li/'Li than were possible with earlier methods. He has demonstrated that TiALi in early-formed meteoritic chondrules is similar to the ratio in terrestrial oceanic crust, a result indicating that the solar nebula ratio was established early in its evolution and was not later perturbed. Because the "Li/" Li ratios of materials that have undergone chemical weathering near the Earth's surface are distinctly higher than mantle ratios, an important question is whether material subducted into the mantle retains this surficial lithium fingerprint Tomascak's data from Hawaiian lavas imply that one component of the materials contributing magma at the Hawaiian hotspot preserves an isotopic memory of Earth surface processes.

NATO postdoctoral associate Harry Becker, now at the University of Maryland, examined the question of how plate subduction at deep-sea trenches may affect the fluxes of selected diagnostic elements into the mantle and the continental crust. So-called "incompatible" elements such as K, Rb, Ba, Sr, and U are depleted in the mantle and in fresh ocean-ridge basalts but become greatly enriched in young oceanic crust through reaction with seawater. These altered basalts, and their thin cover of oceanic sediments that also contain large quantities of these same elements, lose much of their water during the subduction of oceanic lithosphere into the hot mantle. The proportions of water and incompatible elements that are transferred from the subducted plate to the overlying mantle and that are subducted into the deep mantle, however, are not known. Exposed in continental crust are exhumed examples of ancient subduction zones, which include the high-pressure, metamorphosed equivalents of dehydrated subducted basalts. From chemical and isotopic measurements on such samples, Becker has shown that more than 90% of the K, Rb, and Ba contained in altered oceanic crust is lost during subduction at moderate to high temperatures, but that other elements are lost only to a moderate (e.g., U) or minor (e.g., Sr) extent. Becker's measurements provide a new basis to assess the mass balance of incompatible elements at island arc systems and the fluxes of such elements into the converting mantle.

Volcanic rocks generated by partial melting of the mantle are a primary source of information on how the mantle has evolved. Postdoctoral associate and former NSF Earth Sciences Research Fellow John Lassiter has been pursuing the idea that isotopic variations in lavas from a single location may reflect small-scale heterogeneities in the mantle related to the presence of two distinct rock types that melt at different rates. While most of the upper mantle is made of peridotite, a small percentage of the mantle may consist of a different rock type called pyroxenite, which melts at lower temperatures. During melting events, veins of pyroxenite within the more abundant peridotite may be preferentially sampled because they melt to a greater extent. Pyroxenites are of interest because they may reflect ancient crust that has been recycled into the mantle or ancient melts that were unable to escape to the surface but instead were "frozen" into the mantle. Because pyroxenites have much higher Re/Os ratios than peridotites, and because one of the isotopes of Re decays over time into a particular Os isotope, Os isotopes in mantle melts are sensitive to the presence of pyroxenites in the source rock. Lassiter found that the Os isotopes in Hawaiian lavas resemble values found in pyroxenite xenoliths from Hawaii but not those found in peridotites. He also demonstrated that the Os isotopes correlate with the bulk composition (e.g., aluminum content) of the lavas, indicating that the compositions of pyroxenite- and peridotite-derived melts are different. This information should enable the signature of pyroxenite melting in other settings to be discerned and ultimately the abundance and origin of pyroxenite in the upper mantle to be determined.

William Minarik, a joint fellow of DTM and the Geophysical Laboratory, has been exploiting the experimental resources of the two departments to understand the distribution of trace elements in the Earth's lower mantle. The most abundant mineral phases of the lower mantle are silicate perovskite and magnesiowüstite, composed primarily of the elements Si, Mg, Fe, Al, Ca, and O. During the formation of the Earth, a large portion of the mantle may have been molten, a consequence of the very large amounts of energy imparted to the Earth by the impacts of large (moon-sized to Mars-sized) bodies late in the history of inner planet accretion. As the magma "ocean" crystallized over a range of depths, all elements would have been variously partitioned between the crystallizing phases and the remaining melt. If we knew the partitioning behavior at lower mantle conditions, particularly for long-lived radioactive elements and their daughter product elements, then the concentrations and isotope ratios of elements in lavas erupted at the Earth's surface could be used to learn whether there are preserved minerals from the early magma ocean, whether there are lavas that formed in the lower mantle, or the extent to which ocean crust subducted into the deep mantle can be recycled and remelted to form new magma. Minarik grows minerals from melts at high pressures and temperatures in a hydraulic press in the laboratory of Yingwei Fei and measures the trace element concentrations in the tiny crystals, only 20-30 μm in size (Fig. 4), with the DTM ion microprobe, in collaboration with Erik Hauri. Minarik's measurements of the partitioning of 21 trace elements among perovskite, magnesiowüstite, and melt will be used by many geochemists trying to understand the evolution of the Earth's structure and composition over time.

Fig. 4. Backscattered electron image of a polished sample in the high-pressure element-partitioning experiments of William Minarik, showing the interface between silicate melt (top) and the silicate minerals magnesiowustite and perovskite

Jie Li, the Grove Karl Gilbert fellow at DTM and the Geophysical Laboratory, has also been measuring the partitioning of elements at high pressures and temperatures, but with a different goal: understanding the composition of the Earth's core and the core-mantle differentiation process. On the basis of seismic velocities and density, the outer core is known to consist dominantly of liquid iron, but a significant fraction of lighter material is also required. To explore the nature of this light constituent, Li studied the partitioning of sulfur, oxygen, and silicon between liquid iron-nickel and liquid silicate at high pressures and temperatures. In collaboration with Carl Agee of NASA Johnson Space Center and colleagues at Harvard University, she has shown that sulfur is the dominant light element in the liquid iron-nickel alloy to the highest pressures of her experiments. In related work with the multi-anvil apparatus of Yingwei Fei at the Geophysical Laboratory, Li investigated the high-pressure, high-temperature partitioning of sulfur and carbon between sold and liquid iron. Her initial findings suggest that sulfur may be a significant component of the Earth's solid inner core.

The Earth's internal dynamics, its seismic structure, and the nature of earthquakes and deformation along major fault zones are closely coupled topics. Postdoctoral scientists at DTM during the past year advanced our understanding of these fields on a number of fronts.

Dynamicist Carolina Lithgow-Bertelloni, an NSF Earth Sciences Research Fellow while at DTM and now on the faculty at the University of Michigan, together with Paul Silver, has produced an explanation for the long-standing mystery of the high elevation of the southern part of the African continent. The ancient and stable cores of continents, or cratons, generally stand about 400-500 m above sea level. The craton in southern Africa, however, stands as a plateau approximately 1200 m above sea level. Attempts by others to explain this anomaly by means of shallow processes, such as higher-than-normal upper-mantle temperatures or thicker-than-normal crust, can be rejected on the basis of other geophysical information. Lithgow-Bertelloni and Silver have demonstrated that the cause may be in the lower mantle. From the most recent images of the Earth's interior produced by seismic tomography, they converted velocity anomalies into density anomalies and computed the mantle flow that would result. Low-density volumes generate upweling flow, while regions of high density produce downwelling. These mantle convection currents tend to deform the shapes of overlying surfaces. Anomalously low seismic velocities (interpreted as regions of low density) extend beneath southern Africa through almost the entire vertical extent of the lower mantle. The upwelling currents predicted for such a region account well for the anomalous topography of the African continent (Fig. 5). This relationship provides a means by which the geological record of the uplift history of southern Africa may yield insight into the upwelling history of the lower mantle.

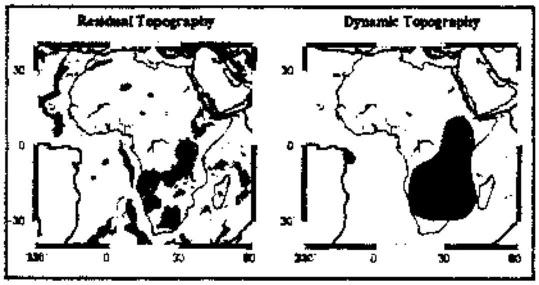


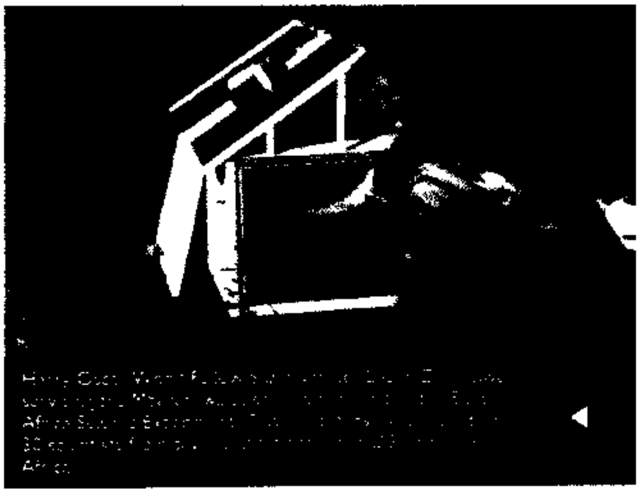
Fig. 5. Comparison of the topography of the African continent and the residual topography of the surrounding oceans (left) with the dynamic topography predicted using the [illegible] Lithgow-Bertelloni [illegible] Africa [illegible]

Current NSF Earth Sciences Research Fellow Andrew Freed has been working on the long-standing question of the forces driving the motions of the Earth's tectonic plates. Candidate forces can be divided between those that arise from density contrasts associated with the plates themselves, called self-driving forces, and those imparted by mantle convection currents not directly associated with the surface plates. Self-driving forces include the push of plates away from mid-ocean ridges contributed by the cooling and thickening of oceanic lithosphere and the pull of subducting slabs of cold and comparatively dense lithosphere at deep-sea trenches. Freed designed a numerical experiment to test whether self-driving forces are sufficient to explain the observed velocities and states of stress of the South American plate and the oceanic Nazca plate to its west. The experiment involved the construction of a mantle density structure from estimates of temperature and pressure, petrology, and experimental thermodynamic data, and a viscosity structure derived from temperature, pressure, laboratory deformation experiments, and observations of post-glacial rebound. He then developed a two-dimensional dynamical model, incorporating these material properties, of a cross-section of the Earth's mantle beneath the Nazca and South American plates and spanning a region from the East Pacific Rise on the west to the Mid-Atlantic Ridge on the east. Freed found that he could predict the observed velocity and stress conditions with models that included only self-driving forces.

The behavior of Earth's geomagnetic field over the past several hundred years is relatively well known on the basis of measurements from satellites, observatories, and magnetic surveys such as those conducted by DTM earlier this century. To investigate the geomagnetic field over time scales of thousands to millions of years, an important window on the dynamics of field generation in the Earth's fluid metallic core, one must turn to paleomagnetic records of field direction and intensity from lava flows or sediments. While the first-order characteristics of the field (its predominantly axial dipole structure, the existence of reversals) have been known for some time, the significance of shorter-wavelength, time-variable features has remained elusive. Such second-order features may relate to properties of the Earth's deep mantle, near the core-mantle boundary, which can influence motions in the outer core. Postdoctoral associate Catherine Johnson (now at the Incorporated Research Institutions for Seismology), along with Catherine Constable of the Scripps Institution of Oceanography, has utilized paleomagnetic data to document geomagnetic field behavior over the past 5 Myr. She has shown that the time-averaged structure of, and the temporal variations in, the global magnetic field are consistent with the influence of a heterogeneous lower mantle on core dynamics, but that improved paleomagnetic data sets are needed to test these ideas further. Her work has included the development of modeling techniques that assist in the selection of optimal new sampling locations to test for specific aspects of field behavior, on the basis of which she helped to establish a multi-institutional paleomagnetic sampling project that aims to improve substantially the distribution of paleomagnetic data from volcanic rocks younger than 5 Myr.

Postdoctoral associate Patrick McGovern has combined numerical models with observations to investigate the deformation of volcanoes, specifically how the mechanical properties of the crust and lithosphere beneath a volcano affect magma ascent paths and volcano growth. The latest data pertinent to the evolution of large volcanoes on the inner planets have come from precise altimetry now being carried out on Mars by the Mars Global Surveyor spacecraft. In contrast to expectations before this latest mission, most large volcanoes on Mars are not surrounded by topographic depressions—telltale signatures of flexure and subsidence of the underlying lithosphere in response *hi* the Ifsad of the volcano—as are many oceanic vulcanic*, on Earth. McGovern deduced that any such depressions must be completely filled by volcanic material, either emplaced as flows (as with most large volcanoes on Venus) or as debris from failure of the flanks (as seen near some oceanic volcanoes on Earth). Circumferential faults around many large volcanoes on Mars had previously been attributed to stretching of the flexed martian lithosphere under the load of the central volcano. New altimetry data from the largest of those volcanoes, however, show that these faults lie well up the flanks of the volcanic edifice rather than in the surrounding lithosphere, as expected for a flexural origin. McGovern has shown that the position of these faults, and the stress field required for their formation, is best met if the volcano was subjected late in its history to uplift from below (e.g., by the intrusion of buoyant material, the development of a low-density mantle following melt extraction, or dynamic support from mantle convection).

Harry Oscar Wood Fellow Suzan van der Lee, now at the Federal Technical University in Zürich, Switzerland, spent much of her time at DTM investigating the structure of the Earth's mantle beneath the continents. For example, she utilized records of regional seismograms from broadband seismic experiments carried out by DTM and other groups to determine the three-dimensional structure of upper-mantle shear-wave velocity beneath central South America. Her analysis method, originated by Guust Nolet of Princeton University, yields particularly sharp images because wave shapes as well as arrival times are employed and both body waves and surface waves are included. Her latest



model (Fig. 6), produced in collaboration with David James and Paul Silver, provides a detailed east-west profile of crust and mantle structure across the entire South American continent. Mantle structure is particularly variable, ranging from the very high seismic velocities of the ancient Brazilian craton in the east, to the moderately low velocities of the central basins, to the very low velocities in the west associated with the subduction of the Nazca plate and the ongoing mountain building of the Andes. The very low velocities beneath the crust of the Andes and above the subducting plate probably indicate that the mantle is partially molten in this region. Such melting is most likely attributable to volatiles, such as water, released from the oceanic crust of the subducting Nazca plate.

Postdoctoral associate EmiHe Hooft makes use of seismic imaging to gain an understanding of magma transport from the mantle to the crust, specifically the process by which magma is focused from a broad source region (e.g., a zone of mantle upwelling beneath a mid-ocean ridge or a mantle plume) to the discrete volcanic systems observed at the surface. Having completed an analysis of seismic refraction data to image the magma focusing geometry at the centers of three segments of the Mid-Atlantic Ridge, she has recently turned her attention to the question of magma transport through the lower crust of Iceland, a ridge-centered hotspot with much higher rates of magmatism and much thicker crust than at a normal ridge. She is making use of earthquake records from a permanent network of seismic stations in southern Iceland, and in particular from the seismic coda, which is the part of the seismogram that follows recognizable arrivals. Energy propagation is complicated for this portion of the seismogram, but with modern seismic arrays and computer processing methods the underlying structure can be resolved and its relation to magma plumbing geometry[7] unraveled.

Shear-wave splitting—an effect similar to the double refraction of light in crystals—is an important diagnostic for anisotropic regions of the Earth. Because the most common source of anisotropy in the upper mantle is the preferential alignment of olivine crystals by mantle flow processes, shear-wave splitting has been an important tool for mapping mantle convection patterns in subduction zones and other oceanic regions. The interpretation of the splitting observations has typically been based on simple one- or two-layer models of the anisotropic structure. Fellow Georg Riimpker, now at the GeoResearch Center in Potsdam, Germany, worked with Paul Silver last year on the effects of shear-wave propagation through more general models of anisotropic media. Using a variety of new techniques, he developed numerical codes to calculate synthetic waveforms, from which he computed shear-wave splitting parameters for comparison with observations. Riimpker demonstrated an important frequency-dependence of the splitting parameters, an effect that can provide information on the fine structure of the anisotropy but one that has usually been neglected in past interpretations. He showed further that depth-dependent anisotropy causes derived splitting parameters to vary with the polarization of the incident wavefront. By documenting these characteristics of more complex anisotropic structures, he

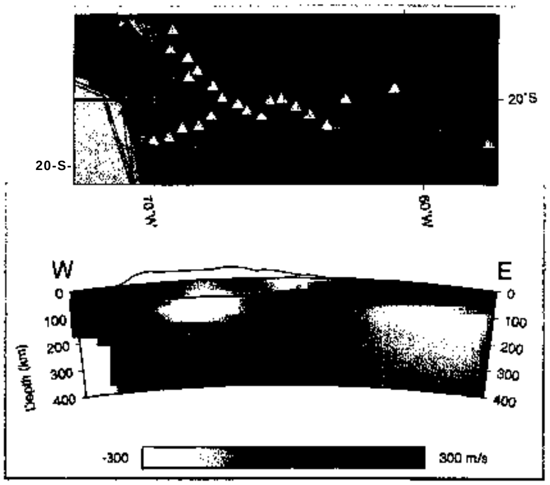


Fig. 6. (Bottom) Profile through Suzan van der Lee's shear-wave velocity model for the central Andes region, where DTM carried out a portable broadband seismic experiment in 1996-1997. The topography along the profile (exaggerated by a factor of 10) and the inferred depth to the crust-mantle interface are also depicted. Earthquake hypocenters from the last 30 years are shown as dots. Gray tones in the cross section represent anomalies in shear wave velocity (in m/s) with respect to a reference model, which has a velocity of 4.5 km/s in the uppermost mantle. (Top) Map view of profile location, including earthquake epicenters (circles), stations (triangles), and wave paths used in the analysis.

has laid the groundwork for testing three-dimensional models of mantle convection with shear-wave splitting observations.

Stephen Gao, a postdoctoral associate at DTM last year and now a visiting faculty member at Arizona State University, made use of records from DTM borehole strainmeters and other geodetic data to study the time-dependent slip of the San Andreas fault system in central California. While it has been known for some time that portions of the fault slip steadily and other sections remain locked for intervals of decades to centuries between major earthquakes, variations in slip at intermediate timescales remain little studied and poorly understood. Working with Alan Linde and Paul Silver, Gao documented a five-year interval during which the slip rate along the San Andreas fault first dropped below normal values for two years and then exceeded normal values for the three years that followed (Fig. 7). The cause of this deceleration and acceleration of fault slip is not known, but Gao and coworkers have speculated that an increase in annual rainfall at the start of the five-year interval may have initially loaded the surface, increasing normal stress across the fault, after which downward percolation may have increased pore pressure in the fault zone, lowering effective stress.

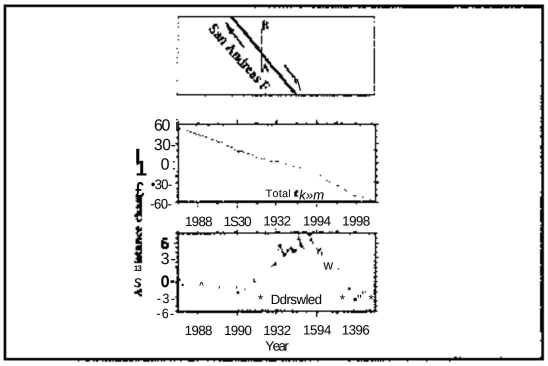


Fig. 7. Distance changes across the San Andreas fault near Parkfield, California, as measured by a two-color laser system, from the work of Stephen Gao. (Top) Sketch map of observation plan: baseline AB, approximately 10 km in length, straddles the fault zone. (Middle) Total changes in distance along line AB [illegible]e same time interval, after removing the best-fitting [illegible] trend.

Wenjie Jiao, a joint postdoctoral associate of DTM and the Geophysical Laboratory, works with Paul Silver and Yingwei Fei on seismological and laboratory tests of proposed mechanisms for deep-focus earthquakes. Motivated by the rupture characteristics of the 1994 Bolivian deep earthquake, the largest deep event known, Silver had proposed that deep earthquakes occur on pre-existing planes of weakness created within the oceanic lithosphere at shallow depths. To test this hypothesis, Jiao compared the distribution of fault orientations of shallow and deep events for the Kurile subduction zone, where the geometry is particularly simple. On the basis of a statistical study of fault-plane solutions for 360 earthquakes in the Kurile subduction zone between 1970 and 1997, Jiao showed that the distribution of fault orientations for the deep events (after rotating by the dip angle of the subducted lithosphere) is indistinguishable from the distribution of orientations for the shallow events. Such an agreement would not be expected if the stress field in the subducted lithosphere, rather than preexisting zones of weakness, controlled fault orientations. While the mechanism of fault reactivation at great depth is not known, one possibility is that the dehydration at depth of hydrous phases concentrated within fault zones at shallow depth leads to some form of instability. It is this possibility that Jiao is now testing experimentally at the Geophysical Laboratory.

These brief summaries illustrate well the generalization that postdoctoral scientists play key roles in all areas of active research at DTM. That the postdoctoral component of the educational mission of the department, too, is achieving its aims can be at least partly demonstrated by the career paths these young scientists followed after leaving DTM. Of the 55 postdoctoral fellows and associates whose appointments ended between 1988 and 1998 and whose professional affiliation could be ascertained as of the fall of 1998, 90% are in academic or research positions at universities, observatories, or national laboratories. Merle Tuve's impassioned plea that the postdoctoral fellowship program should be the highest priority for institutional support remains as valid today as it was when penned sixty years ago.

— Sean C. Soiomon

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Nathalie J. Valette-Silver, *National Oceanographic and Atmospheric Administration*
John C. VanDecar, *Nature Magazine, England*
Elisabeth Widom, *Miami University, Ohio*

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[1] From January 1, 1998
[2] June 1998
[3] Joint appointment with the Smithsonian Institution and the Geophysical Laboratory
[4] To August 2, 1997
[5] From September 1, 1997
[6] From March 1, 1998
[7] From November 1, 1997
[8] Joint appointment with the Geophysical Laboratory
[9] From July 15, 1997
[10] To January 3, 1998
[11] From December 22, 1997
[12] From February 2, 1998
[13] To July 7, 1997
[14] From May 1, 1998
[15] To September 30, 1997, and from May 1 to June 30, 1998
[16] Joint appointment with the Space Telescope Science Institute
[17] To September 30, 1997

To June 30, 1998
From January 5, 1998
Deceased September 14, 1998

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Here updated through November 19, 1998. The list is regularly updated on the DTM web site (http://www.ciw.edu/dtm.html). Reprints of the numbered publications listed below can be obtained, except where noted, at no charge from the Librarian, Department of Terrestrial Magnetism, 5241 Broad Branch Road, N.W., Washington, D.C. 20015 (e-mail: library@dtm.ciw.edu). ordering, please give reprint number(s).

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THE DIRECTOR'S ESSAY:

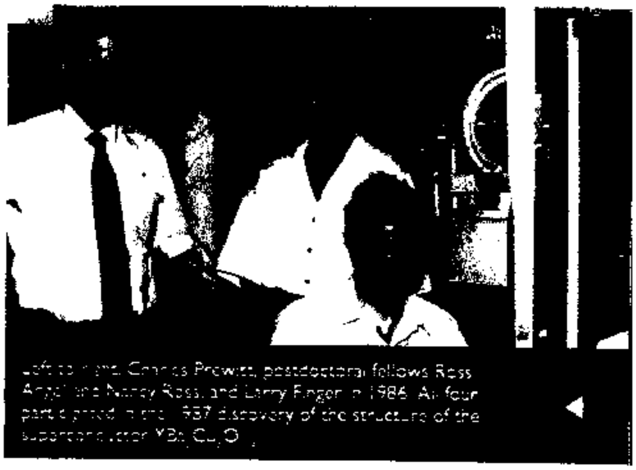
TheGeophysicalLaboratory: Looking Back and Looking Forward

Because this is the last director's essay that I will write for the Carnegie Institution Year Book, I thought I would take the opportunity to reflect on the many things that have happened during my 12-year tenure. I feel privileged to have been director of the Geophysical Laboratory, and I am fortunate to continue to be associated with the Carnegie Institution. As the institution prepares for its first centennial celebration, I have no doubt that it will continue to be a leading scientific contributor for at least the next century.

Upton Street

When I arrived in Washington in the summer of 1986, the Lab was located in its original building on Upton Street in northwest Washington, D.C. The building, 80 years old at the time, was designed to be a research laboratory and was the locale for many important contributions to the geosciences. Although it had many limitations, the staff loved the place. Like the proverbial old shoe, it was somewhat worn down, but very comfortable.

One of the more interesting things that happened during my first few years at Upton Street was the discovery of high-temperature superconductors by Bednorz and Mütter at the IBM Lab in Switzerland and the subsequent synthesis, by Paul Chu at the University of Houston, of another material, YBa$_2$Cui(X.„ with an even higher transition temperature. Chu, a friend of Dave Mao, didn't have adequate laboratory apparatus to characterize this material, so he asked Dave for help. Thus began a very exciting series of events at the Lab. Several of us, including Dave, Rus Hemley, Bob Hazen, Larry Finger, Chris Hadidiacos, myself, and postdocs Ross Angel and Nancy Ross, worked around the clock to perform x-ray diffraction and electron microprobe analyses on the sample. Despite having rather old equipment and being given misleading information about the sample, we were able to determine that Chu's sample actually was two different phases, only one of which was superconductive. As Bob Hazen wrote in his book about the adventure, *The Breakthrough*$_y$ we were the first to report a crystal structure for the material. Unfortunately, it wasn't quite right, and the fine details of structure and composition were eventually worked out by others at Bell Labs and elsewhere. Nevertheless, we learned a lot about the importance of having the talent, apparatus, and resources ready when an important challenge comes along. The fact that we were not very well prepared is one reason that I have made extensive efforts over the years to obtain adequate financial support for new equipment.



Left to right: Charles Prewitt, postdoctoral fellows Ross Angel and Nancy Ross, and Larry Finger in 1986. All four participated in the 1987 discovery of the structure of the superconductor YBa$_2$Cu$_3$O$_7$.

Left; Quenched impact meii in Martian meteorite Alan Hills 7700$ (shergotttte, recovered tn Antarctica) showing skeieal magnesan divine crysals· The irtterstieatj regvons between the divine crystals contain clinopyroxene and a residua! ftIdspathic **{bis.** White regions are iron suS-fidc **The** impact melt was produced at shock pressures tn excess of 80 GPa. fPhoto and interpretation courtesy of NlabiJ Boctor)

The year before I arrived at Carnegie, the president and trustees had begun to consider how to combine the Geophysical Laboratory and the Department of Terrestrial Magnetism in some way, perhaps moving everyone to another location. Invitations had been received from several leading universities to relocate on or near their campuses, and some of these options were very attractive. However, at the trustee's meeting in May 1986, the decision was made not to leave Washington, but to co-locate both departments on the grounds then occupied by DTM. A new research building would be built for both departments, and two existing structures—the main building and the cyclotron building—would be renovated. Planning for this co-location began immediately, and in May 1990, the Geophysical Laboratory personnel and much of their equipment, furniture, and "heirlooms" (many of which probably should have remained behind) were moved to the Broad Branch Road campus. We shared the new research building with DTM for almost a year while the main and cyclotron buildings were being renovated. Eventually, the administrative offices and library moved to the main building and the DTM geochemistry staff moved to the cyclotron building. Meanwhile, the old Geophysical Laboratory building on Upton Street was sold and is now a school of music.

In looking back, it is difficult to understand why life in the old Lab was so attractive. Much of the scientific equipment was very outdated. The electrical and water distribution systems were limited. (I remember spending most of one Christmas day with several others mopping up water after a pipe burst in the attic, probably because instruments were shut down and the water pressure was unusually high.) We had only four telephone lines to the outside world. (An old-fashioned chime system notified people of incoming calls.) As well, there was very little air circulation; cooling in the hot Washington summers relied on strategically located window air conditioners. For computing, we relied on a Digital Equipment Corp. VAX 11-780 that we shared with DTM. We entered the current computer age only reluctantly with the purchase of a few microcomputers. Nevertheless, I think people were happy then, and now that we have moved and corrected many of the "teething" problems with the new facility, are happy that the move took place.


▶ The Geophysical Laboratory was originally located in this building on Upton Street in northwest Washington, D.C.

Changes

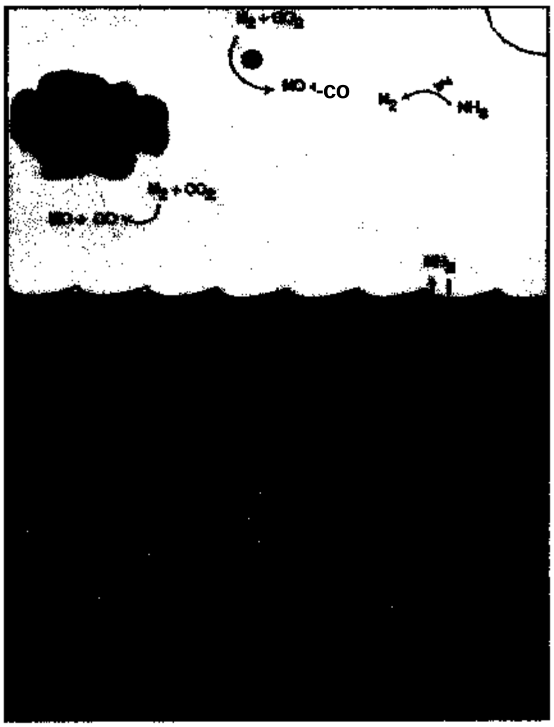
In the years since moving to the Broad Branch Road campus, many things have changed. Owing to a concerted effort by the staff and with financial support from president Singer, the trustees, and various federal and private funding agencies, we now have excellent and competitive scientific equipment and the means to keep it operating in good condition. We are connected to the world via the internet and, after some missteps, are developing extensive computer capabilities. These range from accommodation of complex theoretical codes on a Cray mini-supercomputer to microcomputer access for everyone in the department. One indicator of change is that computers now provide the graphics support that previously required two darkrooms. These rooms—considered essential when the new building was designed—have since been converted to spectroscopy laboratories. Another indicator of change, a more personal one, is that we are now receiving many of our best postdoctoral applications from other countries. We have postdocs and predocs from China, Japan, Russia, Germany, France, Switzerland, Turkey, and Poland, in addition to those from the United States.

Earth science itself is changing. Mining and petroleum extraction used to be major objectives of the earth science community in the United States. Now, mining has largely moved overseas, as have the major initiatives in petroleum exploration and production, some located in regions near or in the former Soviet Union. At the same time, various factors, including the end of the Cold War, have greatly reduced the urgency associated with assuring an adequate supply of mineral resources. Oil is abundant and prices are at a relative long-term

Members of the Geophysical Laboratory, First row, from left: G. Cody, D. Mao, R. Hazen, Y. Fei, P.E. Hare, C. Prewitt, H. Yoder, M. Fogel, D. Virgo, B. Mysen, R. Hemley, and J. Boyd. Second row: G. Zou, J. Shu, W. Xiao, V. Joe, S. Faulkner, A. Jayaraman, Y. Ma, P. Conrad, J. Brandes, D. George, S. Schmidt, M. Bacote, A. Antoszyk, M. Fantle, U. Wiechert, Y. Iizuka, P. Meeder, T. Filley, S. DeSantis, R. Filley, P. Esparza, and N. Boctor. Third row: W. Pike, R. Praseuth, B. Scott, E. Bloomfield, H. Hibbert, A. Berengaut, X. Noblin, M. Somayazulu, A. Goncharov, H. Yang, V. Struzhkin, and Y. Frieman. Fourth row: C. Bertka, D. Von Endt, M. Imlay, S. Gramsch, S. Coley, W. Jiao, S. Merkel, G. Saghi-Szabò, L. Patrick, R. Dingus, B. Collins, J. Straub, R. Scalco, C. Hadidiacos, H. Fricke, K. Wheeler, and J. Badro

low. Because of these trends and related perceived shifts in attitude of politicians and opinion setters, American university geoscience departments are emphasizing more societal-based programs, such as environmental science, hydrology, and hazard reduction. However, I believe there is still a need for research at the fundamental level that has always characterized the objectives of the Geophysical Laboratory. We are holding to that tradition, as we continue to pursue fundamental research in petrology, geochemistry, biogeochemistry, mineral physics, and, increasingly, materials science, physics, and chemistry.

At the same time, we are constantly on the lookout for new challenges. With DTM, for example, we recently became a part of the NASA-sponsored Astrobiology Institute, initiated at least partly because of excitement generated by suspected signs of former life in a Martian meteorite. Whether or not these meteorites do contain such evidence, the search for clues about the origin of life is a very exciting and important research direction. Even if we never really do learn how life began, there are already developments here and elsewhere that would not have taken place without the funding and encouragement of the Astrobiology Institute and other related initiatives. Bob Hazen, George **Cody,** Hatten Yoder, and Marilyn Fogel have demonstrated how fundamental geoscience backgrounds can be of considerable use in tackling problems that require a wide range of knowledge and techniques. One example of their work is the application of traditional inorganic hydrothermal synthesis techniques to the synthesis of organic compounds at moderate pressures and temperatures. As new and redirected resources become

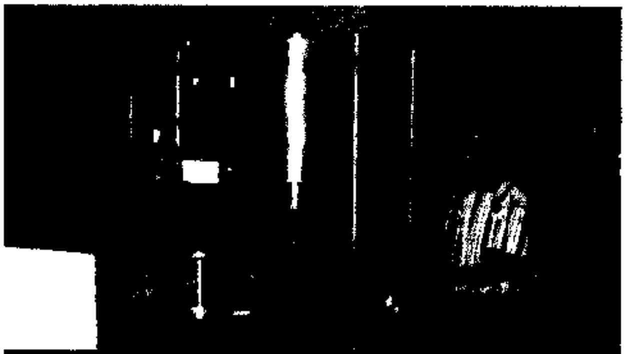


From a poster prepared by postdoctoral fellow Jay Brandes entitled "The Role of Geothermal Mineral Catalysis in Prebiotic Atmospheric and Oceanic Nitrogen Chemistry" available, they will undoubtedly result in many other new discoveries.

[illegible]

Before joining the Lab, I was a member of a National Research Council committee convened to review and eventually produce a report on the current state of research in mineral physics. The committee met several times, conducted a workshop for about 60 people at Airlie House in Virginia, and produced a report, "Physics and Chemistry of Earth Materials," widely known as the "PACEM" Report. The report recommended special attention and increased funding for several different areas in mineral physics, including synchrotron radiation for experiments, high-pressure science and technology, accelerator mass spectroscopy, and apparatus for rock deformation experiments. All of these eventually received substantial funding increases and are today significant components of geological research.

But just what is mineral physics? Mineral physics is a growing and important discipline in the earth sciences that concentrates on the physical and chemical properties of minerals. Its practitioners—a broad range of scientists—study how knowledge of these properties can contribute to the understanding of major geological phenomena. One of their major goals is to explore the crystal chemical constraints imposed by the high temperatures and high pressures within the Earth and to provide an overview of the dominant phases resulting from mixtures of the major elements (O, Si, Fe, and Mg) under these conditions. The pioneers, including Bernal, Goldschmidt, Bridgman, Birch, and Ringwood, made essential contributions to understanding how earth materials combine, dissociate, and transform as environmental conditions change. However, it has only been in the last 10 to 20 years, with the development of new instrumentation for x-ray diffraction and spectroscopy, particularly synchrotron sources, that we have had access to the experimental and theoretical tools that allow us to confirm or dispute the ideas of the pioneers and to make a priori predictions of what will happen when a particular mineral composition is subjected to specific conditions of temperature, pressure, or stress.



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Much current research at high pressure involves learning how the major elements form phases and how transitions take place in them as we simulate Earth's interior in laboratory apparatus or on computers. The phases of magnesiurn-iron silicates serve as model systems for studies of high-pressure structures, phase transitions, vibrational dynamics, and chemical bonding. In view of the wide-ranging importance of the high-pressure behavior of oxides, silicates, and sulfides, the literature on this subject is extensive and growing, but far from complete. Recent discoveries include new phases, electronic and magnetic transitions, contrasting results from hydrostatic or differential stress, insight into the role of hydrogen, and information about how specific phases respond to changing conditions. These studies have important implications for geology, planetary science, materials science, and fundamental physics.

Most of our mineral physicists are associated with the Center for High Pressure Research, a consortium funded by the National Science Foundation's Science and Technology Center Program and including the Geophysical Laboratory, State University of New York at Stony Brook, University of California at Davis, and University of California at San Diego. The center conducts research in both high-pressure science and technology and in using synchrotron-generated x-ray and infrared beams for a variety of experiments in diffraction and spectroscopy. We are now in our eighth year of operation, and we are scheduled to run for an additional three years, when the current grant will end. NSF policy states that, after 11 years, existing S&T Centers cannot continue to be funded to do the same kind of research they do at present. It is not clear, however, if this means that they will be terminated at the end of 11 years, or if other kinds of funding will be available. Whatever the outcome, the center has had an enormous influence on high-pressure science and technology all over the world. Our former postdocs occupy important positions in other research institutions and facilities, and produce excellent science in their own right.

Biogeochemistry

Biogeochemistry has been an important part of Geophysical Laboratory research for many years, and I believe it should be continued and even expanded in the future. It ties in well with NASA's new astrobiology program, to which GL/DTM personnel are major contributors, and it overlaps our program in geochemistry. The biogeochemistry effort was begun some 50 years ago when former GL director Phil Abelson crushed a handful of 25-million-year-old clam shells and proceeded to extract amino acids. Eventually, Abelson hired Tom Hoering and Ed Hare, who were later joined by Marilyn Fogel during Hatten Yoder's term as director. This trio, their postdocs and predocs, and collaborators from other institutions made major contributions to biogeochemistry over the years and laid a solid foundation for future research at the Geophysical Laboratory. When Tom Hoering retired, I hired George Cody, who is adding new dimensions to the research efforts, particularly in organic geochemistry and the macromolecular structure of bio- and geo-polymeric organics.


Ed Hare retired in October 1998

Of the original biogeochemistry trio, only one—Marilyn Fogel—remains. Ed Hare retired in October 1998. Last April, we held a conference, "Perspectives in Amino Acid and Protein Geochemistry," in honor of his retirement. Organized by Glenn Goodfriend, John Wehmiller, and Steve Macko, the conference was held at the American Geophysical Union building in downtown Washington. It was a great success and a fitting tribute to Ed's very significant scientific contributions. Ed worked on amino acid geochemistry through much of his career and influenced a large number of scientists in a variety of related disciplines. At the conference, he received an impressive "family tree" showing the connections between him, his immediate co-workers, and their postdoc and predoc "descendants." His friends also gave Ed and his wife, Patti, a gift of a raft trip down the Colorado River.

Petrology and Geochemistry

Petrology, or the study of rocks, is perhaps the most established part of research at the Geophysical Laboratory. While the techniques of petrology have evolved through the years, the goal remains the same—to understand how rocks on the Earth were formed and how they evolved with time. Geochemistry as a discipline is much broader than petrology in the sense that it involves the chemistry of virtually everything that exists on Earth, particularly if biogeochemistry is included.

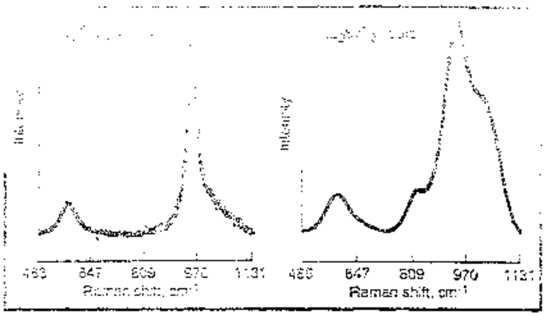
Our petrologists and geochemists pursue a broad range of topics, and often collaborate with scientists of other disciplines. There are such geographically-diverse, field-related projects as Neil Irvine's long-term study of the Skaergaard igneous complex in Greenland, Joe Boyd's work on the Kaapvaal craton in South Africa, and Doug Rumble's stable isotope analyses of high-pressure metamorphic rocks from China. Also included are application of contemporary analytical approaches, such as Bjorn Mysen's and John Prantz's high-temperature, high-pressure Raman spectroscopy of silicate melts and fluids, and Dave Virgo's analytical work on the hydrogen content of amphiboles.

Hatten Yoder, whose distinguished record in experimental petrology is recognized around the world, has become an essential contributor to the astrobiology effort through his experiments synthesizing organic compounds under hydrothermal conditions.

There exists such a continuum of interests among the fields described here, in fact, that categorizing people as belonging to a specific discipline, while convenient administratively, is misleading and obscures the connections that exist between people and their research. For example, a petrologist using Raman spectroscopy to investigate silicate melts and a geochemist using NMR spectroscopy for studies of coal can both be called mineral physicists. The important thing is that we do collaborate and make the best of all available talents and resources.

Other Institutions

One of the wonderful things about science is its international network, enabling scientists to maintain professional interactions with people all over the world. We communicate because of common interests. This is true for institutions as well as for individuals. I know, for example, of two other laboratories that share the interests and research objectives of the Geophysical Laboratory, and we maintain close ties with both. One is the Bayerisches Geoinstitut in Bayraith, Germany. This institute was organized in 1986 with funding primarily from the Bavarian government. Its first director was Friedrich Seifert, a GL staff member in the 1970s. The other institution with similarities to our own is the Institute for Study of Earth's Interior (ISEI) in Misasa, Japan. Its most recent director is Ikuo Kushiro, also a former GL staff member. Kushiro left Washington to become a professor and eventually a vice-president at the University of Tokyo before joining the ISEI. Although most of ISEI's support comes from the Japanese Ministry of Education, Monbusho, its research program is in many ways similar to that of a combined GL and DTM. Examples of collaboration include a joint ISEI/GL seminar ("Evolutionary Processes of Earth and Planetary Materials") during June 1996, coupled with tours of the Misasa facilities and a field trip to Hokkaido to visit recently active volcanoes and to view rocks derived from the upper mantle. In October 1997, scientists from ISEI, the Bayerisches Geoinstitut, and the Geophysical Laboratory, along with members of the Philippine Volcano Institute and a number of guests from several different countries, held a conference, "Materials Recycling Near Convergent Plate Boundaries," in the Philippines that also included field trips, this time to the Taal and Pinatubo volcanoes. The idea was to discuss common research interests and to exchange ideas about the future. These conferences were so successful that we've scheduled another for September 1999 in northern Italy. In addition to these periodic assemblies, there is constant interchange of personnel and research topics among the laboratories and frequent encounters at international meetings.



Raman spectra show the transformation from a crystal (left) to a liquid (right) of Na_2SiO_3 at the melting point of 1201°C. The spectra indicate that a change in molecular shape has occurred, from long SiO_4 chains to isolated SiO_4 tetrahedra that coexist with chains and sheets. It also demonstrates the close relationship between current investigations involving information from both petrology and mineral physics.

Doug Rumble adjusts the Lab's UV laser oxygen isotope microprobe, which he uses to analyze oxygen isotopes on the polished surfaces of minerals.

In a "clean lab" at the Institute for Study of the Earth's Interior, Misasa, Japan, (left to right) Victor Kress, Bjorn Mysen, Dave Virgo, and Joe Boyd (far right) listen as ISEI's Eizo Nakamura (second from right) describes his research.

Finances

Financial support for staff, postdoctoral, and predoctoral salaries, research expenses, equipment, and general operating expenses are always a concern of the director and the Carnegie administration. Before the 1970s, the Lab was largely run by income from the Carnegie endowment. During the 1970s, primarily because of the NASA Lunar Sample Program, a few federal research grants were obtained to cover personnel, equipment, and other research expenses. The fraction of expenses covered by grants began to grow substantially after I became director, especially after we were awarded the NSF Science and Technology Center grant for the Center for High Pressure Research. If equipment funds are included, about 50% of our total income today comes from sources external to the Carnegie Institution. This is not a comforting trend. It is important for the institution to address future funding requirements and resources and be ready to react positively if a crisis occurs.

The Future

What about the future? Where are we going from here? In recent years, a major departure from the traditional geoscience program at the Lab has been the increasing involvement of our personnel in areas more akin to materials science and physics than earth science. This is possible because of *GU$* substantial commitment to the frontiers of high-pressure research* and the growing interest in high-pressure phenomena among the materials science and physics communities. The Geophysical Laboratory is in a position to be a major player in this field, which is relatively small compared to many other parts of materials science and physics. With colleagues from Lawrence Livermore Laboratory and the University of Nevada at Las Vegas, David Mao and Russell Hemley are leading an effort to fund, design, build, and operate equipment devoted to high-pressure experiments at the Advanced Light Source (APS) synchrotron facility at Argonne National Laboratory. The equipment, called a "sector," consists of two x-ray beam ports and associated real estate. Although just in the preliminary planning stage, this initiative has a good chance of success and represents a substantial commitment of the institution, not only for material support but to a very specific direction for future research. The initial investment for construction is about $10 million, and will require additional, ongoing support for operation, maintenance, and new developments. This represents an exciting new departure for the Lab, but it also means that a significant fraction of our research will be taking place at a remote location, perhaps not much different from operating a telescope in a location removed from an astronomy department.

Research in other directions is very much open and will depend largely on decisions the new director makes in replacing retiring staff, on the continued search for financial support, and on the national and international trends that affect the scientific community. Clearly, there is great international interest in the inorganic/organic interface in geochemistry, and universities are seeking bright young graduates with related training. Petrologists are extending their reach from the Earth to solving problems in planetary science. We are learning more every day about how the solar system formed and it is likely that other similar systems will be identified and investigated in coming years. The fundamental research discussed above will always be applicable to new and exciting scientific challenges, and I believe the Geophysical Laboratory will continue to be one of the leading scientific establishments in the years to come.

— Charles T. Prewitt

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Yingwei Fei
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Marilyn L. Fogel
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Robert M. Hazen
Russell J. Hemley
T. Neil Irvine
Ho-kwang Mao
Bjørn O. Mysen
Charles T. Prewitt, *Director*
Douglas Rumble III
David Virgo
Hatten S. Yoder, Jr., *Director Emeritus*

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To February 28, 1996
To March 27, 1998

[illegible] 1997
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Jan[illegible] with the Smithsonian Institution and DTM
From December [illegible], 1997
To July 1, 1997
To August 31, 1997

From September [illegible], 1997
[illegible] 1997

From [illegible], 1998
[illegible] to Dec. 31, 1997; joint appointment with DTM
From [illegible] 1998
From [illegible] 1998
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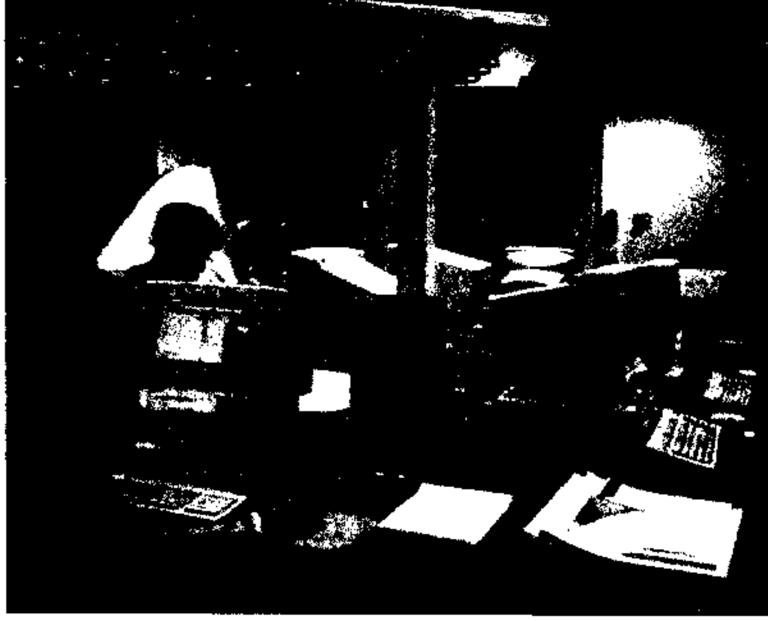

CARNEGIE SCIENCE FOR THE CITY: PREPARING FOR THE SECOND CENTURY

I[illegible] 1997, the Carnegie [illegible] its inhabitants [illegible] engineers, contractors, and [illegible]

Top: A view of the rotunda. New lighting was added to highlight the architectural features.

Middle: Root Hall, with new seating, cleaned murals, and updated audiovisual equipment.

Bottom: CASE teachers using new computer facilities in the Cafritz Science Resource Center.

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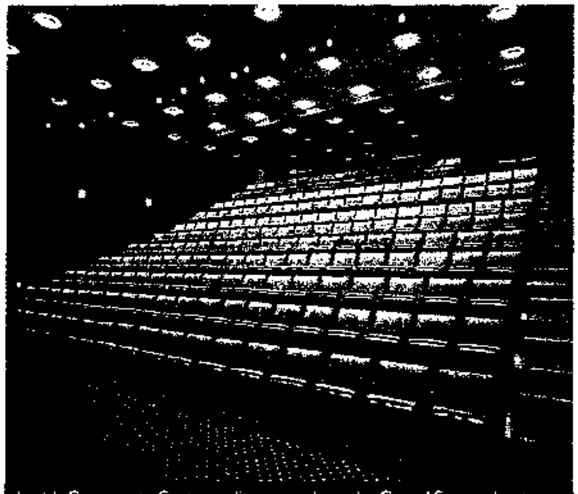
Jewish Community Center auditorium, where the Capital Science Lectures were held in the 1997-1998 season.

It Takes an Ocean: Submarine Volcanic Activity and Life in Our Solar System, by John R. Delaney (School of Oceanography, University of Washington), October 14, 1997

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Exploring the Giant Planets with the Hubble Space Telescope, by Heidi B. Hammel (Department of Earth, Atmospheric, and Planetary Sciences, MIT) January 20, 1998

Genetics of Breast Cancer: Families and Clues to New Therapies, by Mary-Claire King (Department of Medicine and Genetics, University of Washington), February 10, 1998

Probing the Depths of Geology, by Paul G. Silver (Department of Terrestrial Magnetism, Carnegie Institution), March 17, 1998

Barbara McClintock's Legacy: The Jokers in Genomes, by Maxine F. Singer (President, Carnegie Institution of Washington), April 14, 1998

Diamond Windows on a New Chemistry, by Russell J. Hemley (Geophysical Laboratory, Carnegie Institution), May 12, 1998

Publications of the President

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Maxine Singer

Financial Profile

Reader's Note: In this section, any discussion of spending levels or endowment amounts are on a cash or cash-equivalent basis. Therefore, the funding amounts presented do not reflect the impact of capitalization, depreciation, or other non-cash amounts.

The primary source of support for Carnegie Institution of Washington's activities is its endowment. This results in a fundamental independence in the conduct of the institution's scientific programs that is planned to continue into the future.

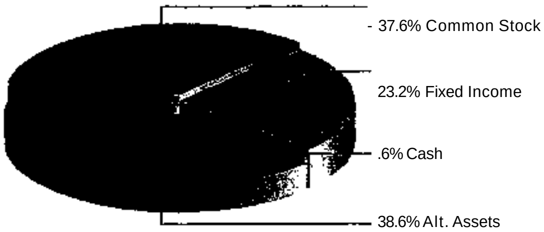
At June 30, 1998, the endowment was valued at approximately $423.3 million. Carnegie's endowment is allocated among a broad spectrum of asset classes. This includes fixed-income instruments (bonds), equities (stocks), arbitrage and distressed securities, real estate partnerships, private equity, an oil and gas partnership, and a hedge fund. The institution relies upon external managers and partnerships to conduct these investments and activities, and it employs a commercial bank to maintain custody.

For the fiscal year ended on June 30, 1998, Carnegie's endowment had a total return (net of management fees) of 16.3%. The annualized five-year return for the endowment was 13.7%.

The following chart shows the allocation of the institution's endowment among the asset classes it uses as of June 30, 1998:

	Target Allocation	Actual Allocation
Common Stock	40%	37.6%
Alternative Assets	35%	38.6%
Fixed Income	25%	23.2%
Cash	0%	0.6%

Actual Asset Allocation



Carnegie's objective is to maintain the long-term spending power of its endowment. The result is a budgeting methodology that provides for:

- averaging the total market value of the endowment for the three most recent fiscal years, and
- developing a budget that spends at a set percentage (spending rate) of this three-year market average.

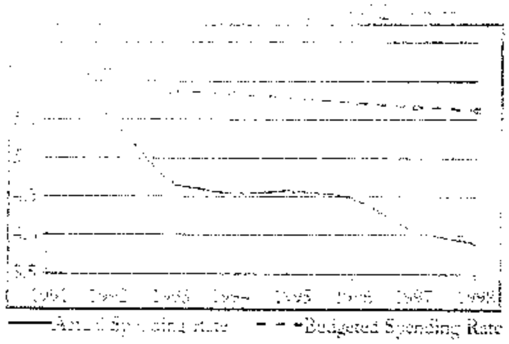
During the 1990s, this budgeted spending rate has been declining in a phased reduction, moving towards an informal goal of 4.5%. For the 1998-1999 fiscal year, the rate is budgeted at 5.5%. While Carnegie has been reducing this budgeted rate by between 5 and 10 basis points a year, there has also been continuing, significant growth in the size of the endowment. The result has been that, for the fiscal year ended in June 1998, the actual spending rate (the ratio of annual spending from the endowment to actual endowment value at the conclusion of the fiscal year in which the spending took place) declined to 3.87%.

The following table compares the planned versus the actual spending rates, as well as the market value of the endowment from 1991-1992 to the most recently concluded fiscal year, 1997-1998.

Endowment Spending Over Seven Years

(Dollars in Millions)

FY	91-92	92-93	93-94	94-95	95-96	96-97	97-98
Endowment Spending	$13.5	$12.5	$12.4	$13.9	$15.1	$15.5	$16.4
Actual Market Value at June 30	$246.6	$270.4	$275.5	$304.5	$338.0	$382.9	$423.3
% of Market Value	5.4[illegible]%	4.63%	4.51%	4.57%	4.48%	4.05%	3.87%
Planned Spending Rate in Budget	6.16%	5.86%	5.81%	5.76%	5.71%	5.66%	5.61%



Within Carnegie's endowment, there are a number of "Funds" that provide support either in a general way or in a targeted way, with a specific, defined purpose. The largest of these is the Andrew Carnegie Fund, begun with the original gift of $10 million. Mr. Carnegie later made additional gifts totaling another $12 million during his lifetime. This fund is now valued at $342 million.

Market value of the Principal Funds Within Carnegie's Endowment

Andrew Carnegie	$341,997,603
Capital Campaign	26,690,920
Anonymous	10,468,951
Astronomy Funds	12,324,403
Mellon Matching	9,264,723
[illegible] Matching	6,687,585
Carnegie Futures	5,873,846
[illegible]	4,591,855
Golden	2,729,709
Bowen	2,178,869
Colburn	1,822,838
McClintock Fund	1,375,436
Special Instrumentation	963,320
Bush Bequest	859,329
Moseley Astronomy	725,269
Special Opportunities	635,279
Roberts	374,025
Lundmark	295,281
Starr Fellowship	671,693
Morgenroth	216,379
Hollaender	201,056
Bush	120,409
Moseley	131,034
Forbush	122,304
Green	85,589
Hale	81,415
Harkavy	76,746
Hearst Education Fund	[illegible]
Other	[illegible]
Total	**$431,802,740**

Independent Auditors' Report

To the Auditing Committee of the Carnegie Institution of Washington:

We have audited the accompanying statements of financial position of the Carnegie Institution of Washington (Carnegie) as of June 30, 1998 and 1997, and the related statements of activities and cash flows for the years then ended. These financial statements are the responsibility of the Institution's management. Our responsibility is to express an opinion on these financial statements based on our audits.

We conducted our audits in accordance with generally accepted auditing standards. Those standards require that we plan and perform the audit to obtain reasonable assurance about whether the financial statements are free of material misstatement. An audit includes examining, on a test basis, evidence supporting the amounts and disclosures in the financial statements. An audit also includes assessing the accounting principles used and significant estimates made by management, as well as evaluating the overall financial statement presentation. We believe that our audits provide a reasonable basis for our opinion.

In our opinion, the financial statements referred to above present fairly, in all material respects, the financial position of the Carnegie Institution of Washington as of June 30, 1998 and 1997, and its changes in net assets and its cash flows for the years then ended, in conformity with generally accepted accounting principles.

Our audits were made for the purpose of forming an opinion on the basic financial statements taken as a whole. The supplementary information included in [illegible] is presented for purposes of additional analysis and is not a required part of the basic financial statements. Such information has been subjected to the auditing procedures applied in the audit of the basic financial statements and, in our opinion, is fairly stated in all material respects in relation to the basic financial statements taken as a whole.

October 30, 1998

June 30, 1998 and 1997

Cash and cash equivalents	$ 147,343	2,759,057
Accrued investment income	665,437	477,140
Contributions receivable (note 2)	2,414,271	3,773,587
Accounts receivable and other assets	2,573,029	2,007,377
Bond proceeds held by trustee (note 6)	7,162,230	11,159,876
Investments (note 3)	431,802,740	380,747,708
Construction in progress (notes 4 and 5)	40,642,497	28,737,444
Property and equipment, net (note 4)	41,607,411	37,880,114
	$ 527,014,958	**467,542,303**

Liabilities and Net Assets

Accounts payable and accrued expenses	$ 2,409,330	2,068,094
Deferred revenue (note 5)	12,108,046	1,149,050
Broker payable (note 3)	2,171,665	0
Bonds payable (note 6)	34,806,460	34,769,596
Accrued postretirement benefits (note 7)	9,836,437	9,236,983
Total liabilities	61,331,938	47,223,723
Net assets (note 8):		
Unrestricted:		
Board designated:		
Invested in fixed assets, net	35,335,402	31,847,962
Designated for managed investments	369,733,863	331,472,827
Undesignated	10,489,238	6,728,893
	415,558,503	370,049,682
Temporarily restricted	14,172,427	15,586,090
Permanently restricted	35,952,090	34,682,808
Total net assets	465,683,020	420,318,580
Commitments and contingencies (notes 9, 10, and 11)		
Total liabilities and net assets	**$527,014,958**	**467,542,303**

Years ended June 30, 1998 and 1997

	Unrestricted	Temporarily restricted	Permanently restricted	Total	Unrestricted	Temporarily restricted	Permanently restricted	Total
Revenues and support								
Grants and contracts	$ 11,259,930	0	0	11,259.930	10,340,760	0	0	10,340,760
Contributions and gifts	709,030	3,894,584	1,144,309	5,747,923	740,031	6,058,154	2,220,044	9,018,229
Net gain (loss) on disposals of property	(90,224)	0	0	(90,224)	(60,694)	0	0	(60,694)
Other income	720,656	0	0	720,656	623,102	0	0	623,102
Net external revenue	12,599,392	3,894,584	1,144,309	17,638,285	11,643,199	6,058.154	2,220,044	19,921,397
Investment income (note 3)	54,982,546	4,016,507	124,973	59,124,026	53,009,i 13	3,387,347	II8,5O2	56,514,962
Net assets released from restrictions (note 8)	9,324,754	(9,324,754)	0	0	3,346,896	(3,346,896)	0	0
Total revenues, gains, and other support	76,906,692	(1,413,663)	1,269,282	76,762,311	67,999,208	6,098,605	2,338,546	76,436,359
Program and supporting services expenses:								
Terrestrial Magnetism	6,221,701	0	0	6,221,701	5,481,263	0	0	5,481,263
Observatories	5,799,559	0	0	5,799,559	5,595,168	0	0	5595,168
Geophysical Laboratory	6,283,859	0	0	6,283,859	5,648,244	0	0	5,648,244
Embryology	5,163,256	0	0	5,163,256	5,097,677	0	0	5,097,677
Plant Biology	4,562,436	0	0	4,562,436	4,450,109	0	0	4,450,109
Other Programs	1,050,946	0	0	1,050,946	943,838	0	0	943,838
Administrative and general expenses	2,316,114	0	0	Z3I6.H4	Z565.202	0	0	2565,202
Total expenses	31,397,871	0	0	31397,871	29,781501	0	0	29,78150f
Increase (decrease) in net assets	45308,821	(1,413,663)	1,269,282	45,364,440	38,217,707	6.098,605	2338546	46,654,858
Net assets at the beginning of the year	370,049,682	15586,090	34,682,808	420318580	331,831,975	9,487,485	3Z3H262	373,663,722
Net assets at the end of the year	$415,558503	14,172,427	35,95X090	465,683,020	370.049,682	15,586,090	34,682,808	4203f8,580

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Years ended June 30, 1998 and 1997

	1998	1997
Cash flows from operating activities:		
Increase in net assets	$ 45,364,440	46,654,858
Adjustments to reconcile increase in net assets to net cash provided by operating activities:		
Depreciation	2,488,284	2,458,035
Net gains on investments	(47,591,512)	(45,740,779)
Loss (gain) on disposal of property	90,224	60,694
Amortization of bond issuance costs and discount	36,865	36,865
Contribution of stock	(1,425,784)	(1,499,164)
(Increase) decrease in assets:		
Receivables	793,664	(939,112)
Accrued investment income	(169,530)	368,324
Increase (decrease) in liabilities:		
Accounts payable and accrued expenses	341,236	(451,265)
Deferred revenues	10,958,996	(98,279)
Accrued postretirement benefits	599,454	576,112
Contributions and investment income restricted for long-term investment	(2,716,782)	(5,233,565)
Net cash provided by (used for) operating activities	8,769,555	(3,807,276)
Cash flows from investing activities:		
Draws from bond proceeds held by trustee	3,997,646	3,872,682
Acquisition of property and equipment	(6,305,806)	(2,116,260)
Construction of telescope, facilities, and equipment	(11,905,053)	(5,324,147)
Investments purchased, net of change in broker payable of ($2,171,665) and ($23,752,995) in 1998 and 1997, respectively	(427,075,366)	(436,911,531)
Proceeds from investments sold or matured	427,190,728	441,715,012
Net cash (used for) provided by investing activities	(14,098,051)	1,235,756
Cash flows from financing activities – proceeds from contributions and investment income restricted for		
Investment in endowment	1,269,282	2,497,544
Investment in property and equipment	1,447,500	2,736,021
Net cash provided by financing activities	2,716,782	5,233,565
Net increase (decrease) in cash and cash equivalents	(2,611,714)	2,662,045
Cash and cash equivalents at the beginning of the year	2,759,057	97,012
Cash and cash equivalents at the end of the year	**$ 147,343**	**2,759,057**
Supplementary cash flow information		
Cash paid for interest	**$ 1,564,792**	**1,621,971**

June 30, 1998 and 1997

Organization and Summary of Significant Accounting Policies

Organization

The Carnegie Institution of Washington (Carnegie) conducts advanced research and training in the sciences. It carries out its scientific work in five research centers located throughout the United States and at an observatory in Chile. The centers are the Departments of Embryology, Plant Biology, and Terrestrial Magnetism, the Geophysical Laboratory, and the Observatories (astronomy). Carnegie's external income is mainly from gifts and federal grants and contracts. In addition, income from investments represents approximately 75 percent of Carnegie's total revenues.

Basis of Accounting and Presentation

The financial statements are prepared on the accrual basis of accounting. Expenses are separately reported for major programs and administrative and general expenses. Revenues are classified according to the existence or absence of donor-imposed restrictions. Also, satisfaction of donor-imposed restrictions are reported as releases of restrictions in the statements of activities.

investments and Cash Equivalents

Carnegie's debt and equity investments are reported at their fair values. Carnegie also reports investments in partnerships at fair value as determined and reported by the general partners. All changes in fair value are recognized in the statements of activities. Carnegie considers all highly liquid debt instruments purchased with remaining maturities of 90 days or less to be cash equivalents. Money market and other highly liquid instruments held by investment managers are reported as investments.

Income Taxes

Carnegie is exempt from federal income tax under Section 501(c)(3) of the Internal Revenue Code (the Code). Accordingly, no provision for income taxes is reflected in the accompanying financial statements. Carnegie is also an educational institution within the meaning of Section 170(b)(l)(A)(ii) of the Code. The Internal Revenue Service has classified Carnegie as other than a private foundation, as defined in Section 509(a) of the Code.

Fair Value of Financial Instruments

Financial instruments of Carnegie include cash equivalents, receivable, investments, bond proceeds held by trustee, accounts and broker payables, and bonds payable. The fair value of investments in debt and equity securities is based on quoted market prices. The fair value of investments in limited partnerships is based on information provided by the general partners.

The fair value of Series A bonds payable is based on quoted market prices. The fair value of Series B bonds payable is estimated to be the carrying value, since these bonds bear adjustable market rates.

The fair values of cash equivalents, receivable, and accounts and broker payable approximate their carrying values based on their short maturities.

Use of Estimates

The preparation of financial statements in conformity with generally accepted accounting principles requires management to make estimates and assumptions that affect the reported amounts of assets and liabilities and disclosure of contingent assets and liabilities at the date of the financial statements. They also affect the reported amounts of revenues and expenses during the reporting period. Actual results could differ from those estimates.

Property and Equipment

Carnegie capitalizes expenditures for land, buildings and leasehold improvements, telescopes, scientific and administrative equipment, and projects in progress. Routine replacement, maintenance, and repairs are charged to expense.

Depreciation is computed on a straight-line basis over the following estimated useful lives:

Buildings and telescopes	50 years
Leasehold improvements	lesser of 25 years or the remaining term of the lease
Scientific and administrative equipment	5 years

Contributions

Contributions are classified based on the existence of donor-imposed restrictions. Contributions and net assets are classified as follows:

Unrestricted - includes all contributions received without donor-imposed restrictions on use or time.

Temporarily restricted - includes contributions with donor-imposed restrictions as to purpose of gift or time period expended.

Permanently restricted - generally includes endowment gifts in which donors stipulated that the corpus be invested in perpetuity. Only the investment income generated from endowments may be spent. Certain endowments require that a portion of the investment income be reinvested in perpetuity.

Gifts of long-lived assets, such as buildings or equipment, are considered unrestricted when placed in service. Cash gifts restricted for investment in long-lived assets are released from restriction when the asset is acquired or as costs are incurred for constructed assets.

Grants

Carnegie records revenues on grants from federal agencies only to the extent that reimbursable expenses are incurred. Accordingly, funds received in excess of reimbursable expenses are recorded as deferred revenue, and expenses in excess of reimbursements are recorded as accounts receivable. Reimbursement of indirect costs is based upon provisional rates which are subject to subsequent audit by Carnegie's federal cognizant agency, the National Science Foundation.

Certain prior year amounts were reclassified to conform to the current year presentation.

(2) Contributions Receivable

Contributions receivable are summarized as follows at June 30, 1998:

Unconditional promises expected to be collected in years ended June 30

1999	$ 2,041,690
2000	144,690
2001	102,000
2002	27,000
2003	27,000
2004 and later	71,891
	$ 2,414,271

(3) Investments

At June 30, 1998 and 1997, investments at fair value consisted of the following:

	1998	1997
Time deposits and money market funds	$ 20,253,740	18,488,606
Debt mutal funds	55,886,196	65,150,721
Debt securities	40,071,660	24,122,834
Real Estate Partnerships	51,744,690	39,657,484
Equity Securities	155,190.157	144,759,793
Limited partnerships	108,656297	88,568,270
	$431,802,740	380,747,708

Investment income for the years ended June 30, 1998 and 1997, consisted of the following:

	1998	1997
Interest and dividends	$ 13,092,269	11,744,238
Net realized gains	28,100,705	26527,556
Net unrealized gains	19,490.807	19,2[illegible]3.223
Less - investment management expenses	(1,55[illegible]75[illegible])	(970,055)
	$ 59,124,025	56,514,962

Carnegie purchased and sold certain investment securities on dates prior to June 30,1998. These trades were settled subsequent to June 30,1998, and are reflected in the investment balances reported at year end. The net obligation for these unsettled trades is reported as broker payable in the accompanying statements of financial position.

The fair value for approximately $33 million of Carnegie's $160 million of real estate and limited partnership investments has been estimated by the general partners in the absence of readily ascertainable market values. However, the estimated fair values may differ from the values that would have been used had a ready market existed.

(4) Property and Equipment

At June 30,1998 and 1997, property and equipment placed in service consisted of the following:

	1998	S997
Buildings and improvements	$ 38,904,093	34,660,342
Scientific equipment	15,917,470	14,736,201
Telescopes	7,910,825	7,910,825
Administrative equipment	2,334,975	2,3 (6,444
Land	787,896	787,896
Art	34,067	34,067
	65,889,326	60,445,775
Less accumulated depredation	24,281,915	22,565,66!
	$41,607,411	37,880,114

At June 30,1998 and 1997, construction in progress consisted of the following:

	Iff 8	Iff 7
Telescope	$ 38.447,209	26,924,587
Buildings	U 47,369	1523337
Scientific equipment	1,047,919	289,520
	$40,642,497	28,737,444

At June 30,1998 and 1997, approximately $44 million and $34 million, respectively, of construction in progress and other property, net of accumulated depreciation, was located in Las Campanas, Chile. During 1998 and 1997, Carnegie capitalized net interest costs of approximately $1,169,000 and $1,154,000, respectively, as construction in progress.

(5) Magellan Consortiym

During the year ended June 30, 1998, Carnegie entered into an agreement (Magellan Agreement) with four universities establishing a consortium to build and operate the Magellan telescopes. The two Magellan telescopes are currently under construction on Manqui Peak, Las Campanas in Chile. The total construction costs of the two telescopes are expected to be approximately *$72* million and will be recorded as assets by Carnegie. Title to the Magellan facilities is held by Carnegie. As of June 30,1998, construction in progress of $37,892,570 related to the Magellan project.

The university members of the consortium, by contribution to the construction and operating costs of Magellan, acquire rights of access and oversight as described in the Magellan Agreement. Total contributions by the university members for construction are expected to be $36 million, 50% of the total expected costs and these monies are being used by Carnegie to finance part of the Magellan Telescopes' construction costs. As of June 30,1998, the university members had contributed $12,146,100 which is included in deferred revenue in the accompanying statement of financial position. The deferred revenue will be recognized ratably as income over the estimated useful lives of the telescopes.

(6) Bonds Payable

On November 1,1993, Carnegie issued S17.5 million each of secured Series A and Series B California Educational Facilities Authority Revenue tax-exempt bonds. Bond proceeds axe used to finance the Magellan telescope project and the renovation of the facilities of the Observatories at Pasadena. The balances outstanding at June 30, 1998 and 1997, on the Series A issue totaled $17,380,068 and $17,357,224, respectively, and on the Series B issue totaled $17,426,392 and $17,412,372, respectively. The balances outstanding are net of unamortized bond issue costs and bond discount. Bond proceeds held by the trustee and unexpended at June 30, 1998 and 1997, totaled $7,162,230 and $11,159,876, respectively.

Series A bonds bear interest at 5.6 percent payable in arrears semiannually on each April 1 and October 1 and upon maturity on October 1,2023. Series B bonds bear interest at variable money market rates in effect from time to time, up to a maximum of 12 percent over the applicable money market rate period of between one and 270 days and have a stated maturity of October 1, 2023. At the end of each money market rate period, Series B bondholders are required to offer the bonds for repurchase at the applicable money market rate. If repurchased, the Series B bonds would be resold at the current applicable money market rate and for a new rate period.

Carnegie is not required to repay the Series A and B bonds until the October 1, 2023, maturity date, and Carnegie has the intent and the ability to effect the purchase and resale of the Series B bonds through a tender agent; therefore all bonds payable are classified as long term. Sinking fund redemptions begin in 2019 in installments for both series. The fair value of Series A bonds payable at June 30,1998 and 1997, based on quoted market prices is estimated at $18,600,000 and $18,300,000, respectively. The fair value of Series B bonds payable at June 30, 1998 and 1997, is estimated to approximate carrying value as the mandatory tender dates on which the bonds are repriced are generally within three months of year end.

(7) Employee Benefit Plans

Retirement Plan

Carnegie has a noncontributory, defined contribution, money-purchase retirement plan in which all United States personnel are eligible to participate. After one year's participation, an individual's benefits are fully vested. The Plan has been funded through individually owned annuities issued by Teachers' Insurance and Annuity Association (TIAA) and College Retirement Equities Fund (CREF). There are no unfunded past service costs. Total contributions made by Carnegie totaled approximately $1,850,990 and $1,783,000 for the years ended June 30,1998 and 1997, respectively.

***Postretirement** Benefits Plan*

Carnegie provides postretirement medical benefits to all employees who retire after age 55 and have at least ten years of service. Cash payments made by Carnegie for these benefits totaled approximately $341,000 and $374,000 for the years ended June 30, 1998 and 1997, respectively.

The expense for postretirement benefits in 1998 and 1997 under the provisions of SFAS No. 106 was approximately $627,000 and $950,000, respectively. The 1998 postretirement benefits expense was approximately $286,000 more than the cash expense of $341,000, and the 1997 postretirement benefits expense was approximately $576,000 more than the cash expense of $374,000. The postretirement benefits expense was allocated among program and supporting services expenses in the statements of activities.

The following items are the components of the net postretirement benefit cost for the years ended June 30,1998 and 1997:

	iffS	1997
Service cost - benefits earned during the year	$ 237.CXX5	3 i 4,000
Interest cost on projected benefit obligation	502,000	636,000
Amortization of gain	(112,000)	-
Accrued postretiremen! benefit cost	$627,000	950,000

The following table sets forth the funded status of the postretirement medical benefits plan as of June 30,1998 and 1997:

Actuarial present value of the accumulated postretirement benefit obligation for		
Inactive participants	$ 4,180,000	4,618,000
Fully eligible active participants	1,651,000	2,012,000
Other active participants	2,210,000	2,647,000
Accumulated postretirement benefit obligation for services rendered to date	8,041,000	9,277,000
Unrecognized net gain (loss)	1,795,000	(40,000)
Accrued postretirement benefit cost	**$9,836,000**	**9,237,000**

The decrease in accrued postretirement benefit cost and the increase in the unrecognized net gain are a result of changes in the number of employees covered by the Plan.

The present value of the benefit obligation as of June 30,1998, was determined using an assumed health care cost trend rate of 9.4 percent and an assumed discount rate of 6.75 percent. The present value of the benefit obligation as of June 30,1997 vas determined using an assumed health care cost rend rate of 10 percent and an assumed discount rate of 7.5 percent. Carnegie's policy is to fund postretirement benefits as claims and administrative fees are paid.

For measurement purposes, a 9.4 percent annual rate of increase in the per capita cost of covered health care benefits was assumed for 1998; the rate was assumed to decrease gradually to 5.5 percent in 13 years and remain at that level thereafter. The health care cost trend rate assumption has a significant effect on the amounts reported. An increase of 1.0 percent in the health care cost trend rate used would have resulted in a $1,209,000 increase in the present value of the accumulated benefit obligation at June 30,1998, and a $133,000 increase in the aggregate of service and interest cost components of net periodic postretirement benefit cost for the year ended June 30,1998.

(8) Net Assets

At June 30, 1998 and 1997, temporarily restricted net assets were available to support the following donor-restricted purposes:

	1998	1997
Specific research programs	$ 9,278,140	8,225,980
Equipment acquisition and construction	4,894,287	7,360,1 10
	$14,172,427	**15,586,090**

At June 30,1998 and 1997, permanently restricted net assets consisted of permanent endowments, the income from which is available to support the following donor-restricted purposes:

	1998	1997
Specific research programs	$ 12,747,371	11,478,089
Equipment acquisition and construction	1,204,719	1,204,719
General support (Carnegie endowment)	**$22,000,000**	22,000,000
	$35,952,090	**34,682,808**

During 1998 and 1997, Carnegie met donor-imposed requirements on certain gifts and, therefore, released temporarily restricted net assets as follows:

Specific research programs	$3,979,778	2,364,853
Equipment acquisition and construction	5,344,976	982,043
	$9,324,754	**3,346,896**

{9} Federal Grants and Contracts

Costs charged to the federal government under cost-reimbursement grants and contracts are subject to government audit. Therefore, all such costs are subject to adjustment. Management believes that adjustments, if any, would not have a significant effect on the financial statements.

(10) Commitments

In 1997, Carnegie entered into a contract with the University of Arizona for the construction of the primary mirror and support system for the second telescope in the Magellan project. The amount of the contract is approximately $9,700,000 of which approximately $7,000,000 had not been incurred at June 30,1998. Carnegie had previously entered into an agreement with the University of Arizona for the primary mirror and support system for the first telescope and had outstanding commitments of approximately $700,000 at June 30, 1998. Carnegie also has other contracts relating to the construction of Magellan with outstanding commitments totalling approximately $6,000,000.

Carnegie has outstanding commitments to invest approximately $3.8 million in limited partnerships.

Carnegie leases a portion of the land it owns in Las Campanas, Chile to other organizations. These organizations have built and operate telescopes on the land. Most of the lease arrangements are not specific and some are at no-cost to the other organizations. One of the lease arrangements is noncancelable and has annual future rents of $120,000 through fiscal year 2001. For the no-cost leases, the value of the leases could not be determined and is not considered significant, and, accordingly, contributions have not been recorded in the financial statements.

Carnegie also leases a portion of one of its laboratories to another organization for an indefinite term. Rents to be received under the agreement are approximately $183,000 annually, adjusted for CPI increases.

Carnegie leases land and buildings. The monetary terms of the leases are considerably below fair value, however, these terms were developed considering other non-monetary transactions between Carnegie and the lessors. The substance of the transactions indicates arms-length terms between Carnegie and the lessors. The monetary value of the leases could not be determined, and has not been recorded in the financial statements.

Years ended June 30, 1998 and 1997

	1998			1997		
	Carnegie funds	**Federal and private grants**	**Total expenses**	**Carnegie funds**	**Federal and private grants**	**Total expenses**
Personnel costs:						
Salaries	$10,341,061	2,852,217	13,193,278	9,763,705	2,972,498	12,736,203
Fringe benefits and payroll taxes	3,512,361	773,285	4,285,646	3,616,358	800,952	4,417,310
Total personnel costs	13,853,422	3,625,502	17,478,924	13,380,063	3,773,450	17,153,513
Fellowship grants and awards	1,325,949	888,367	2,214,316	1,360,445	647,853	2,008,298
Depreciation	2,474,898	0	2,474,898	2,458,035	0	2,458,035
General expenses:						
Educational and research supplies	866,150	1,000,382	1,866,532	798,925	1,060,501	1,859,426
Building maintenance and operation	1,512,049	33,229	1,545,278	1,744,184	387,676	2,131,860
Travel and meetings	634,442	530,816	1,165,258	560,818	509,570	1,070,388
Publications	38,197	84,898	123,095	32,348	79,656	112,004
Shop	57,282	0	57,282	46,262	0	46,262
Telephone	175,120	12,613	187,733	176,209	385	176,594
Books and subscriptions	226,358	9,328	235,686	231,418	6,278	237,696
Administrative and general	647,577	161,494	809,071	515,693	51,277	566,970
Printing and copying	91,256	2,546	93,802	216,664	5.239	221,903
Shipping and postage	110,560	65,522	176,082	108,851	39,494	148,345
insurance, taxes and professional fees	663,824	138,847	802,671	919,764	116,960	1,036,724
Equipment	0	1,914,681	1,914,681	13,673	816,397	830,070
Fund-raising expense	321,420	0	321,420	338,380	0	338,380
Total general expenses	5,344,235	3,954,356	9,298,591	5,703,189	3,073,433	8,776,622
Indirect costs - grants	(2,791,705)	2,791,705	0	(2,846,024)	2,846,024	0
Capitalized scientific equipment and construction projects funded by Federal and private grants	(68,858)	0	(68,858)	(614,967)	0	(614,967)
	$20,137,941	S1,259,930	31,397,871	19,440,741	10,340,760	29,781,501

[redacted]

Schedules of Expenses

Schedule 1

Years ended June 30, 1998 and 1997

	1998			1991		
	Carnegie funds	**Federal and private grants**	**Total expenses**	**Carnegie funds**	**Federal and private grants**	**Total expenses**
Personnel costs:						
Salaries	$10,341,061	2,852.217	13,193,278	9,763,705	2,972,498	12,736,203
Fringe benefits and payroll taxes	3,512,361	773,285	4,285,646	3,616.358	800,952	4,417,310
Total personnel costs	13,853,422	3,625,502	17,478,924	13,380,063	3,773,450	17,153,513
Fellowship grants and awards	1,325,949	888,367	2,214,316	1,360,445	647,853	2,008,298
Depredation	2,474,898	0	2,474,898	2,458,035	0	2,458,035
General expenses:						
Educational and research supplies	866,150	1,000,382	1,866,532	798,925	1,060,501	1,859,426
Building maintenance and operation	1,512,049	33,229	1,545,278	1,744,184	387,676	2,131,860
Travel and meetings	634,442	530,816	1,165,258	560,818	509,570	1.070,388
Publications	38,197	84,898	123,095	32,348	79,656	112,004
Shop	57,282	0	57,282	46,262	0	46,262
Telephone	175,120	12.613	187,733	176,209	385	176,594
Books and subscriptions	226,358	9,328	235,686	231,418	6,278	237,696
Administrative and general	647,577	161,494	809,071	515,693	51,277	566,970
Printing and copying	91,256	2.546	93,802	216,664	5.239	221,903
Shipping and postage	110,560	65,522	176,082	108,851	39,494	148,345
Insurance, taxes and professbnal fees	663,824	138,847	802,671	919,764	116,960	1,036,724
Equipment	0	1,914,68!	1.914,681	13,673	816,397	830,070
Fund-raising expense	321,420	0	321,420	338,380	0	338,380
Total general expenses	5,344,235	3,954,356	9,298,591	5.703,1**39**	3,073,433	**8,776,622**
Indirect costs - grants	**(2791,705)**	2,791,705	0	(2,846,024)	2,846,024	0
Capitalized scientific equipment and construction projects funded by Federal and private grants	**(68,858)**	0	(68,858)	(614,967)	0	(614,967)
	$20,137,941	11,259,930	31,397,871	**19,440,741**	**10,340760**	**29781,50!**

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"I give, and bequeath the sum of $______ (or % of my residuary estate) to the Carnegie Institution of Washington, 1530 P Street, N.W., Washington, DC 20005-1910."

For additional information, please call Susanne Garvey, Director of External Affairs, at 202.939.1128, or write:

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