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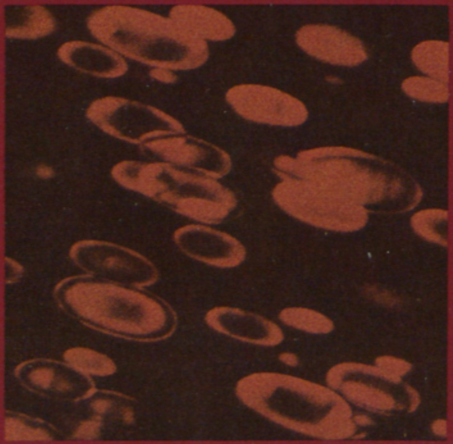

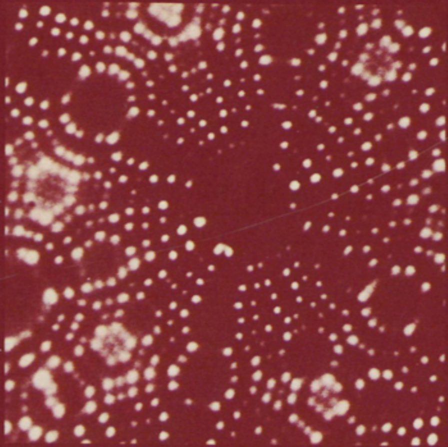

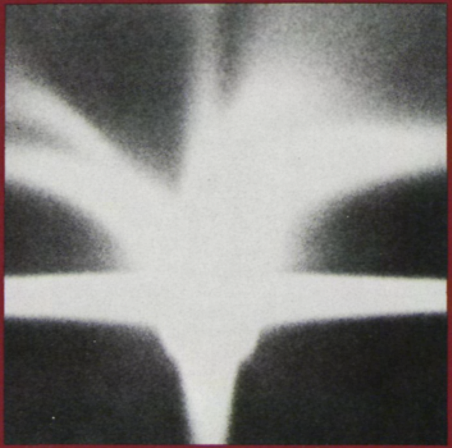

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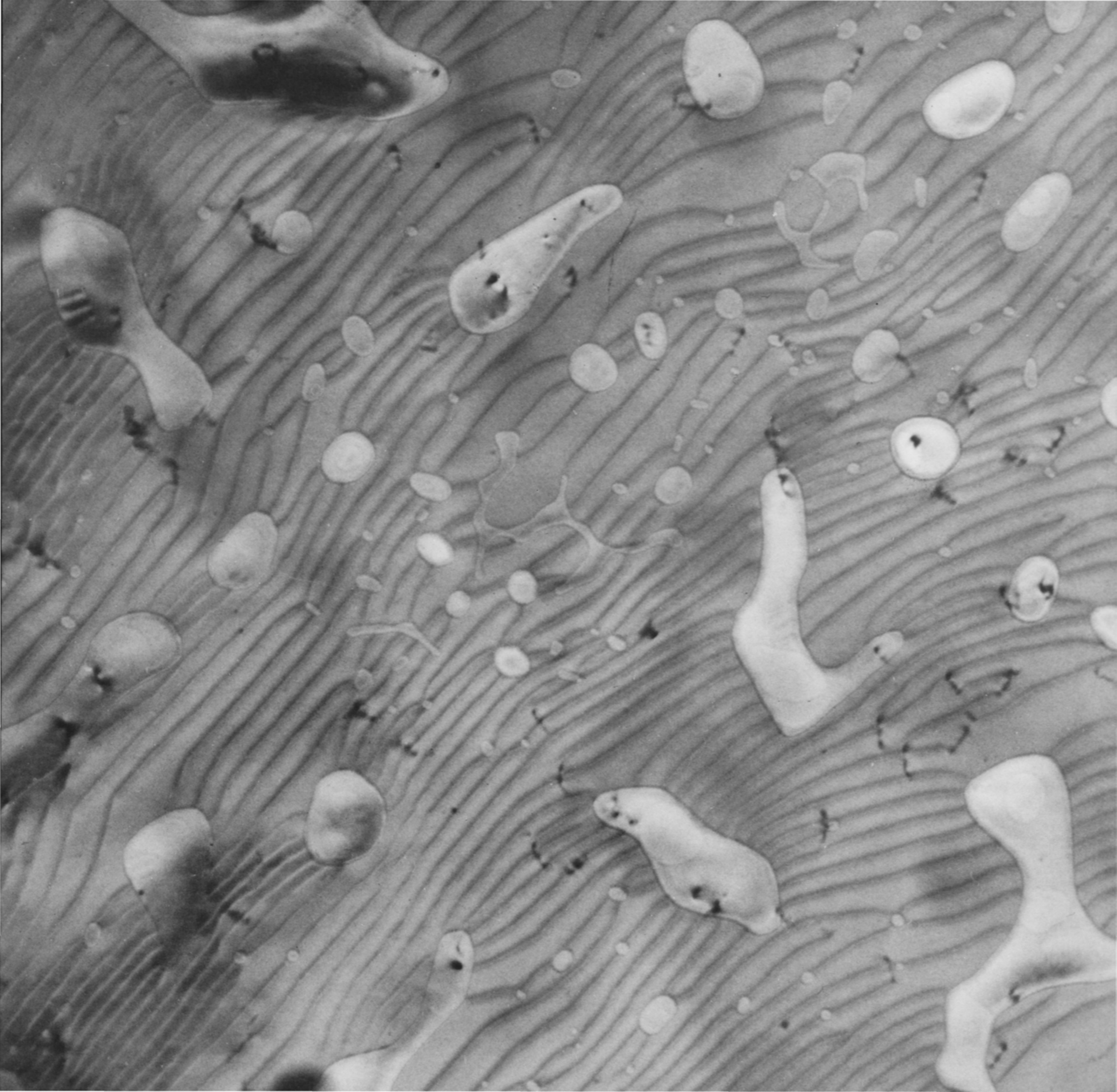
SEEING WITH ELECTRONS AND IONS



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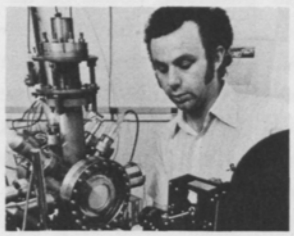

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Opposite: Grain boundary structure in gold, as revealed by an electron microscope. Outside cover illustrations: Top row, left to right: micrograph showing inclusions in a titanium-niobium alloy; grain boundaries in aluminum. Bottom row, left to right: field ion microscopic image of the surface of a tungsten specimen; part of an electron energy analysis spectrum of a diffraction pattern from an aluminum specimen.

THE CHEMICAL NATURE OF ATOMS

A New Subject for Electron Microscopy

by John Silcox

The widespread application of the electron microscope to the study of materials has arisen from the recognition that physical properties of technological importance often are controlled by the nature and arrangement of atoms in the material.

A major step forward, taken in the late 1950s, was the discovery that irregularities in the spatial arrangements of atoms could be studied easily in thin specimens. In particular, flaws in the crystal structure caused by maltreating the sample in various ways, such as subjecting it to fatigue or to irradiation by fast nuclear particles, could be detected and the effects of different treatments assessed. The article by Professor Stephen Sass elsewhere in this issue gives examples of the kind of work made possible by that discovery. As is not uncommon, a technical instrumental development made that step forward possible: improved electron gun characteristics permitted the irradiation of a relatively small part of the sample by an intense beam of electrons.

The information obtained by excellent modern instruments is still limited essentially to the spatial arrangements of atoms, however. The chemical nature of the atoms, for example, cannot be determined directly. Nevertheless, information of this type is carried by the electrons scattered by the specimen, and at the present time a number of instrumental developments have made it possible to begin extracting that information in a useful fashion. Some of this developmental work is being done at Cornell under the support of the Materials Science Center, and shows promise of providing a microanalytical technique of some value. I will outline some of the features of the instrumentation and the underlying interpretation strategy, and indicate some of the possible applications.

EXTRACTING CHEMICAL INFORMATION

To begin with, the chemical information is carried in the *inelastic* electron-scattering phenomena induced by the atoms of a material. Inelastic electron-scattering processes involve the transfer of energy to the specimen from the electrons, which then exhibit a wide range of energy distribution. To an ordinary electron lens, such electrons are a major nuisance, since the lens is not equipped to focus electrons of more than a small energy range. When the specimen introduces a wide energy span, the effect in a conventional microscope is a blurring of the image; there is a loss in resolution of the spatial image, which is determined predominantly by *elastic* scattering processes that involve no energy transfer.

The inelastic scattering of electrons can be used, however, to provide a different kind of information. If we note that the transfer of energy between specimen and electrons is determined closely by the electronic structure on a surprisingly localized scale, we realize that one ought to be able to extract information about the electronic structure and hence the chemical nature of the specimen.

THE DISTRIBUTION OF METALS IN AN ALLOY

The use of inelastic electron scattering is perhaps best explained in terms of a specific example—the study of inho-

Instrumentation consisting basically of an electron microscope and an electron spectrometer is used in an electron-energy analysis technique being developed at Cornell under the direction of Professor John Silcox (at left). Research Associate Roger Vincent (at top) is a member of the research group.

Figure 1

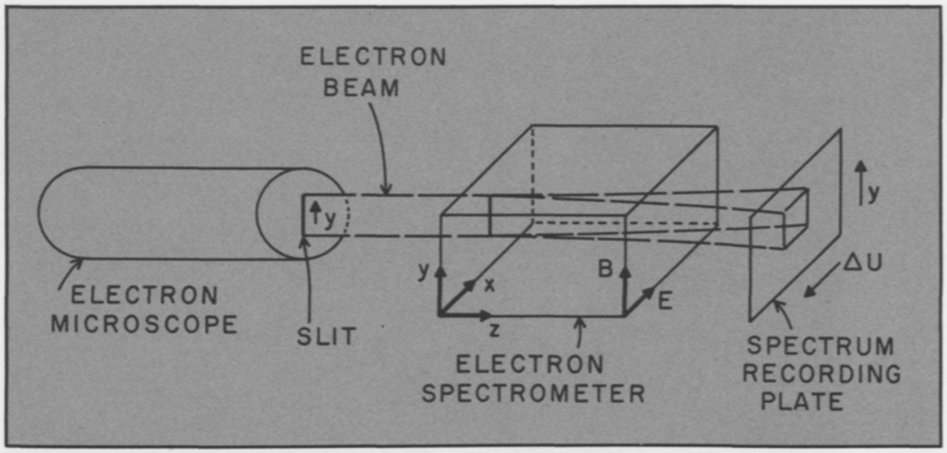


Figure 1. A schematic sketch of the combined electron microscope-electron spectrometer system.

mogeneity in metal alloys. This application was first demonstrated by a group in Cambridge, England, and now is being worked on here at Cornell.

Suppose we consider the conduction electrons in a metal specimen as a plasma in which the neutralizing positive ion charges remain stationary. Whenever a fluctuation occurs in the electron density, it is accompanied by a change in the local electric field, and as a result the electrons oscillate collectively with a plasma frequency expressed as $\omega_p = (4\pi ne^2/m)^{1/2}$, where m is the mass of the electrons and n the conduction gas density. This oscillation, known as the *plasmon,* has an associated energy $\hbar\omega_p$; a typical plasmon energy value for a simple metal is that of aluminum, for which $\hbar\omega_p = 15.3$ eV.

Suppose now that we consider an alloy such as aluminum with added copper or magnesium. In the simplest approximation, we can view the alloying element as changing the conduction electron density and therefore the plasmon energy. (In practice, of course, changes in other aspects of the electronic structure introduce complications with which we need not be concerned here.) The changes in plasmon energy are small; for example, the addition of 1% by weight of magnesium to aluminum causes a peak shift of only 0.055 eV. Nevertheless, such a shift can be measured. It should be possible, then, to study inhomogeneous alloys in which the concentration of the alloying metal varies from point to point by measuring local plasmon energy, relating this to the local concentration of the alloying metal, and thereby deducing an impurity distribution. Surprisingly, it appears possible to do this with a spatial resolution of better than 50 Å (five ten-millionths of a centimeter).

AN EXTENSION OF ELECTRON MICROSCOPY

What instrumentation do we need in order to make such measurements of impurity distribution? Essentially, we need an instrument that will measure electron energy losses—an electron spectrometer—used in combination with an electron microscope.

A schematic sketch of the combination instrument we have developed is shown in Figure 1. A slit cut at the bottom of the electron microscope allows electrons to pass from the microscope into and through the spectrometer, which disperses them according to velocity (and corresponding energy). The capability of taking electron micrographs is retained, and the electron micrographs may be compared with the electron-energy-loss spectra recorded at the exit of the spectrometer: those electrons that pass through the slit have contributed to image points along the line of the slit.

The plate at the exit of the spectrometer records the intensity of the electrons in terms of energy loss (ΔU) as a function of position in the image (y). A typical example of a spectrum obtained with an aluminum specimen is shown in Figure 2. In this case, the specimen was a film 1,000 Å thick, prepared by condensation of aluminum from the vapor phase.

Figure 2a shows an electron micrograph of a region containing a grain boundary identified by the fringes running from top to bottom. By placing the slit perpendicular to the boundary,

Figure 2. (a) A grain boundary, identified by the fringes and the change in contrast from one grain to the other, magnified 500,000 times. The specimen is of aluminum. (b) A corresponding energy-loss spectrum, taken with the slit perpendicular to the grain boundary at the same magnification. This spectrum shows plasmon losses at multiples of $\hbar\omega_p = 15.3$ eV. The micrograph and spectrum were recorded by Roger Vincent.

Figure 3. The energy-loss spectrum from an aluminum specimen containing a 2,500 Å particle of aluminum oxide at a magnification of 100,000. This was recorded by Roger Vincent.

as indicated in the figure, we obtain the energy-loss spectrum shown in Figure 2b. The spectrum is relatively simple: the predominant features are peaks in multiples of 15.3 eV, which reflect energy losses due to plasmon excitation. Note that the contrast detail observed at the boundary is also seen in the energy-loss spectrum.

If we were dealing with material different from aluminum in places, the energy-loss spectrum would be different and we could determine spatial changes in chemical composition. An example is shown in Figure 3, in which a particle of aluminum oxide 2,500 Å in diameter is identified within an aluminum matrix.

EXPERIMENTAL WORK AT CORNELL

The question of how well we can measure such characteristics as impurity gradients in aluminum alloys becomes a question of how quantitative an instrument can be made.

Several considerations prompted us at Cornell to make use of the crossed field analyzer (in which electric and

Figure 2

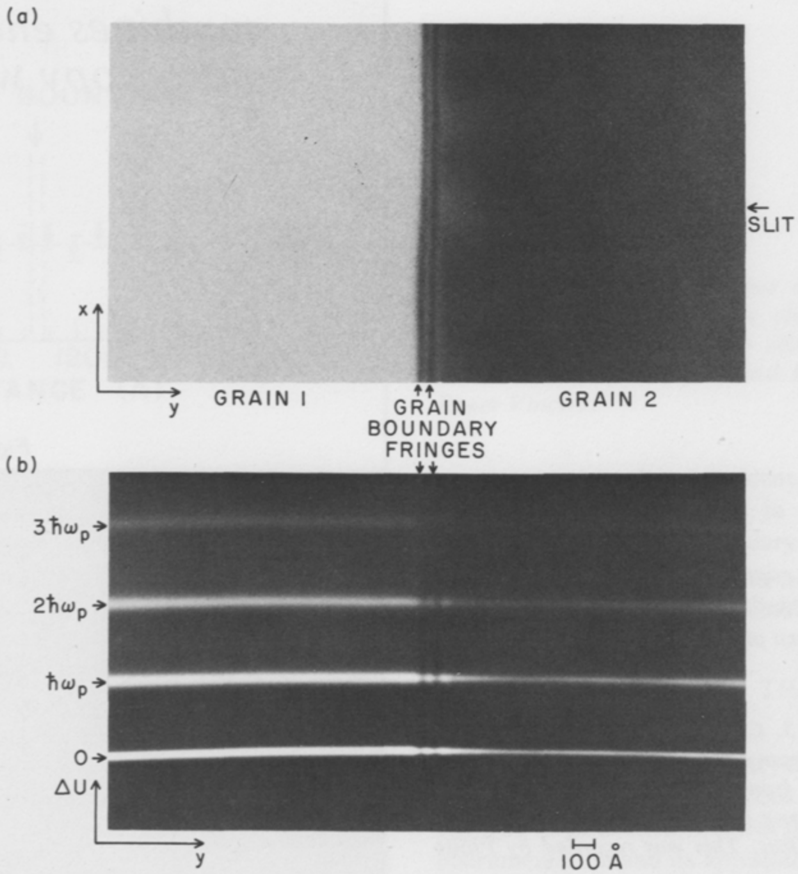
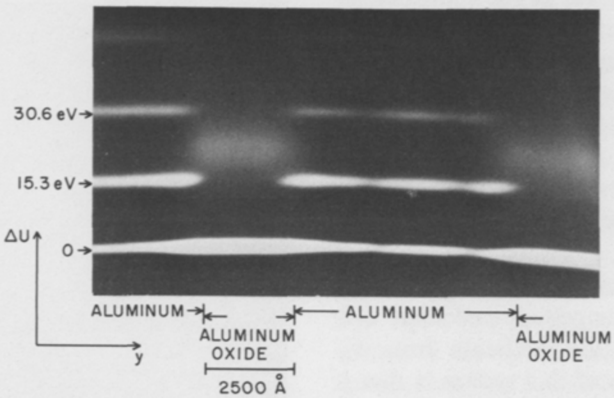


Figure 3



". . . this new instrumentation that combines energy analysis with electron microscopy will become a valuable new microanalytical tool."

Figure 4

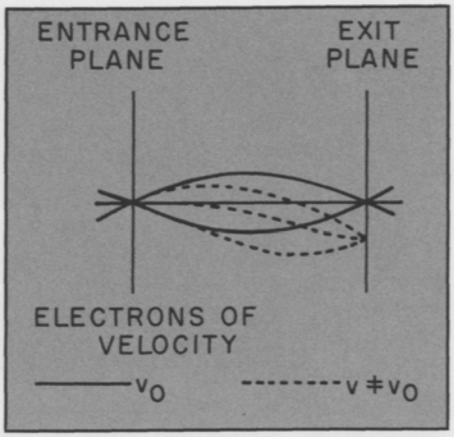


Figure 4. Electron paths through the analyzer. Note how the rays become focussed in the exit plane of the analyzer.

Figure 5

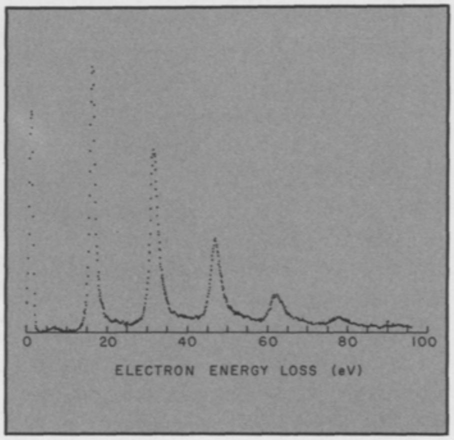


Figure 5. Computer controlled and processed scan of the energy losses from 0 to 100 eV from an aluminum specimen. The plot shows the intensity as a function of energy loss. This was recorded by Philip Batson.

magnetic fields are at right angles) invented by Wien seventy-five years ago. Given the geometry indicated in Figure 1, an electron traveling with a velocity v_0 along the z axis will be undeflected if $v_0 = -E/B$, since under these conditions the Lorentz force on the electron is zero: $F = -e[\underline{E} + (\underline{v} \times \underline{B})] = 0$. On the other hand, electrons with velocities slightly different from v_0 will be deflected with a magnitude and sense corresponding to the deviation from v_0. One advantage of this system is that it has a straight-through optical path. A second advantage is that the point of maximum dispersion corresponds also to the focussing condition; that is, rays at the point of entrance into the analyzer will be brought to focus in the exit plane. Figure 4 illustrates the ray paths through the analyzer.

We were able to improve the efficiency of the instrument by mounting the analyzer on a high-voltage electrode tied to the accelerating electrode in the electron gun. This enables us to slow the electrons down to an energy U_0, typically in the range of 100 to 500 eV. The electric and magnetic fields then become low and the required stability is easily obtained. We were able, therefore, to achieve relatively high electron transmission for a given energy resolution.

Once this high transmission rate had been achieved, we proceeded to implement on-line computer control of the whole microscope–analyzer system; this computerization has just been accomplished, along with the introduction of appropriate scanning and detection systems. All indications so far are that the instrumentation yields results that

Figure 6

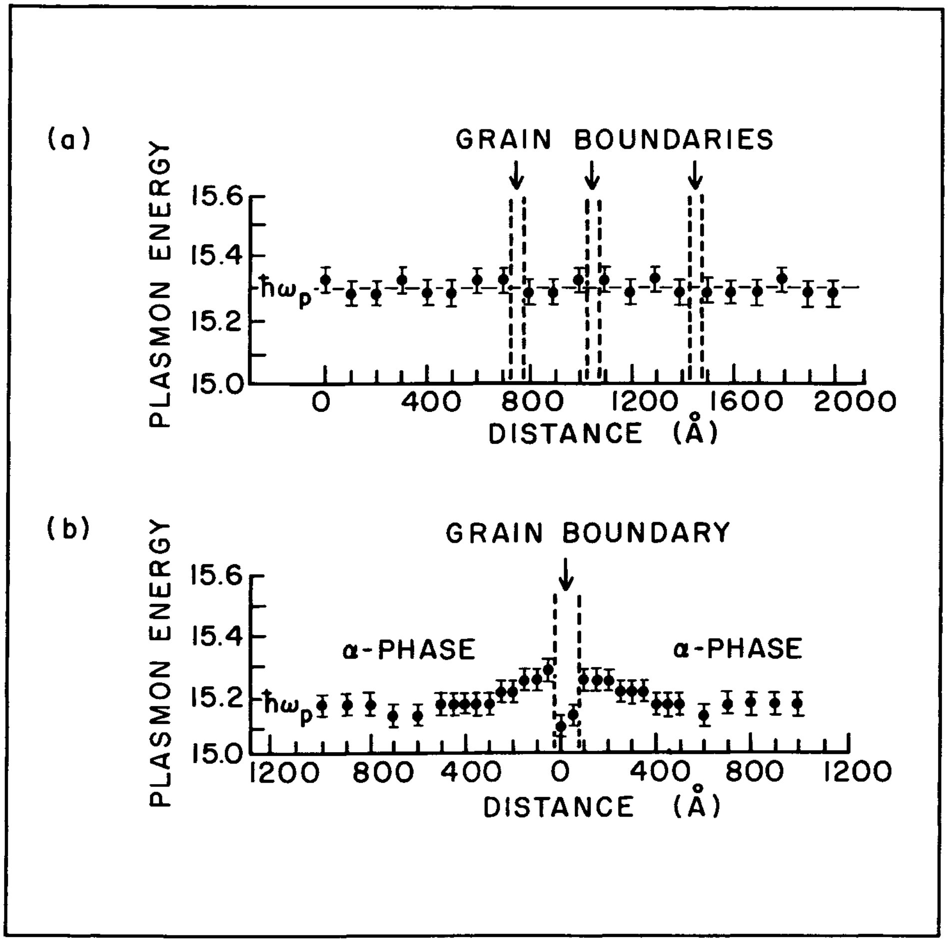


Figure 6. Plasmon loss values close to grain boundaries in (a) pure aluminum and (b) an aluminum-copper alloy. The data were determined by Prakash Rao and Roger Vincent.

are accurate and reproducible enough for the kind of analysis desired. Figure 5 illustrates data recorded in this fashion.

Before the computerization of the instrument had been accomplished, researchers in the Department of Materials Science and Engineering—Prakash Rao, a research associate, and Professor Paul S. Ho—had proceeded with the determination of impurity gradients by a more laborious method. They were interested in impurity gradients near grain boundaries in aluminum-copper alloys, and they determined these from photographs of spectra taken in my laboratory by Roger Vincent, a research associate. The procedure they used involves taking microdensitometer traces of the spectra to determine peak positions. Figure 6 shows the changes in plasmon energy that were measured in regions close to grain boundaries in pure aluminum and also in an alloy specimen of aluminum containing 5.65% by weight of copper. With the pure aluminum specimen, no change is seen, but in the alloy, changes over a 400 Å scale are evident. These changes imply a decrease in copper concentration as the boundary is approached and a sharp increase in copper concentration within about 50 Å of the boundary.

MEASUREMENTS AND THEIR INTERPRETATION

The successful development of a research program such as the one we are engaged in at Cornell requires not only instrumentation and its application, but also an understanding of the phenomena on which the microanalysis is based. Some of our work is devoted to that end.

An example is our use of the combined electron microscope and electron spectrometer in experiments designed to elucidate energy-loss processes. If the combined system is considered from the point of view of the spectrometer, the electron microscope can be regarded as a sophisticated and sensitive five lens electron optical bench placed ahead of the spectrometer. According to this view, the function of the electron microscope is to control the entrance

opment of better electron optics. The ability to obtain higher transmitted intensity and correspondingly faster observations may be expected to lead to kinetic studies or to improved energy resolution. The measurement of losses associated with the generation of x rays is beginning and it appears likely that these loss processes too will be susceptible to study and exploitation.

Our expectation is that this new instrumentation that combines energy analysis with electron microscopy will become a valuable new microanalytical tool.

slit and angular parameters that govern the trajectories of electrons entering the spectrometer. One application of this concept is the use of the electron microscope in the determination of energy losses as a function of scattering angle. We found that when we made measurements at scattering angles very close to the incident electron beam, a relatively high angular resolution of 10^{-5} radians could be achieved; normally, electron spectrometers are not capable of an angular resolution better than 3×10^{-4} to 5×10^{-4} radians. Moreover, this scattering angle regime turned out to be an interesting one for the kinds of energies with which we are concerned.

For example, low-angle scattering is effective in studies of energy-loss processes at surfaces. At the interface between two media, such as aluminum and vacuum or aluminum and aluminum oxide, electrons can lose energy to surface plasmons, which are plasma oscillations localized at the surface. The value of the energy loss as a function of the scattering angle of the incident electron changes quite markedly at small angles, and in a characteristic fashion. The form of the function also changes at oblique incidence, and again in a characteristic fashion. Observations of this nature serve both to confirm the underlying theory and to identify such losses in more complex materials.

We have also identified energy losses in semiconductors that occur as a result of the excitation of Cerenkov radiation by 75-keV electrons passing through the specimen. The angular distribution of the scattered electrons can be related to the energy-dependent dielectric constant of the material. These experiments are another example of observations that would not be possible without the combined instrumental system, and that serve to reinforce our confidence in our interpretation of the loss processes.

The pace of the development of instrumentation in this area is such that it seems safe to predict greatly expanded capabilities in the near future. We can anticipate the addition of some of the improved electron guns of recent years to these systems, and the devel-

John Silcox, who is internationally known in the field of electron microscopy and diffraction, is professor of applied physics and director of the School of Applied and Engineering Physics at Cornell. He has been a member of the faculty since 1961.

Professor Silcox was born and educated in England. He received the B.Sc. degree in physics from Bristol University in 1957 and the Ph.D., also in physics, from Cambridge University in 1961. During his sabbatic leave from Cornell in 1967-68 he conducted research at Cambridge and with the Faculté des Sciences d'Orsay, France, as a Guggenheim fellow.

His research activities have been concerned with many aspects of solid state physics in addition to the microscopy of electron scattering. He has made significant contributions in transmission microscopy, and has done experimental work in such areas as superconductivity, ferromagnetism, and imperfections in crystals.

Professor Silcox is a member of the Physical Society in Great Britain and in America; the Electron Microscopy Society of America; the Metallurgical Society of the American Institute of Mining, Metallurgical and Petroleum Engineers; and the (British) Institute of Physics.

ELECTRON MICROSCOPY IN THE STUDY OF MATERIALS

by Stephen L. Sass

A major goal of materials science is to relate the structure of materials to their physical properties. An understanding of how such characteristics as crystal structure and crystal imperfections affect the behavior of materials is essential to the development of ways to improve them for specific technological applications.

An instrument for the examination of microstructure is therefore an important and basic tool for the materials scientist. One such tool is the electron microscope, which has been brought to a high level of effectiveness and widely applied in the materials field over the past fifteen years.

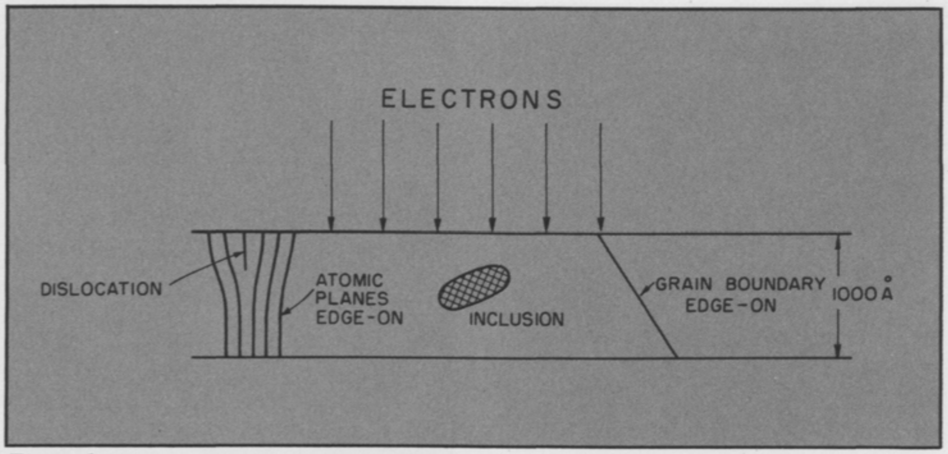


Figure 1

OPERATION OF THE ELECTRON MICROSCOPE

A microscope functions by gathering information in the form of radiation scattered by an object and utilizing that information to form a highly magnified, detailed image of the object. The greater the amount of radiation that is scattered and can be utilized, the closer the resemblance between image and object, and hence the better the resolution—the ability to distinguish closely spaced features—of the microscope. Also, the shorter the wavelength of the scattered radiation, the better the resolution. Since the wavelength of 100,000-volt electrons ($\lambda = 0.037$ Å)* is much shorter than that of light ($\lambda = \sim 5500$ Å), an electron microscope has much better resolution than an optical microscope, and so is becoming a more and more popular instrument in materials research.

** 1 Å = 0.00000001 centimeter. Atoms in crystals are 2 to 3 Å apart.*

The principle of the electron microscope is quite analogous to that of an optical microscope. The major difference besides the use of electrons instead of light is that magnetic lenses are used in place of glass lenses. Electrons produced by heating a tungsten filament are accelerated by an applied potential of, typically, 100,000 to 200,000 volts, and impinge on a thin crystal specimen (see Figure 1). Electrons transmitted through the specimen then pass through three magnetic lenses and are focussed to form an image on a phosphor screen.

Imperfections in crystalline solids are revealed in micrographs taken with a 200-kV electron microscope in the Materials Science Center laboratory in Bard Hall. Figure 2 shows a grain boundary parallel to the thin crystal surface in gold. The dislocations appear as a grid of black lines. (Micrograph courtesy of Professor Robert W. Balluffi and Tilman Schober.) Figure 3 illustrates a fine grain structure in aluminum. Here the grain boundaries are inclined to the thin crystal surface and appear as a fringe pattern. (Micrograph courtesy of Professor Paul S. Ho and Lucien Glowinski.) Figure 4 shows inclusions present in a titanium-niobium alloy. Such inclusions contribute to the high strength of this alloy. (Micrograph courtesy of Arthur T. Balcerzak.) Fine dislocation lines as well as fringe patterns resulting from the overlapping of several crystals are seen in Figure 5, a micrograph of a multi-layer polyethylene single crystal. (Courtesy of Edwin L. Thomas.)

Figure 4

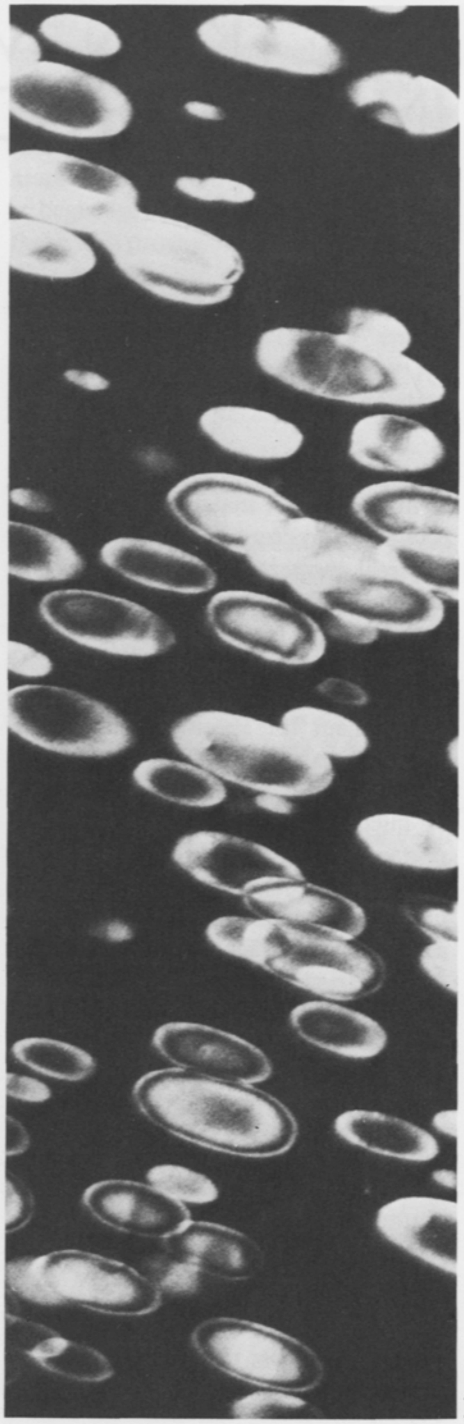


Figure 2

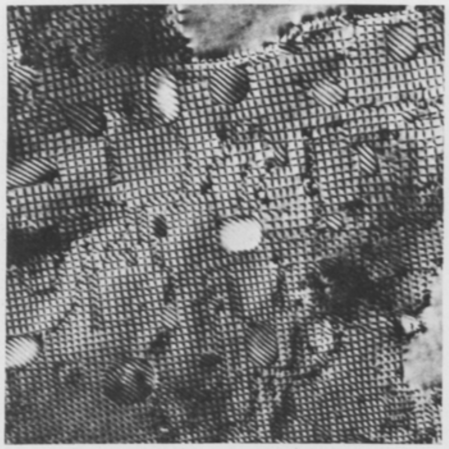


Figure 5

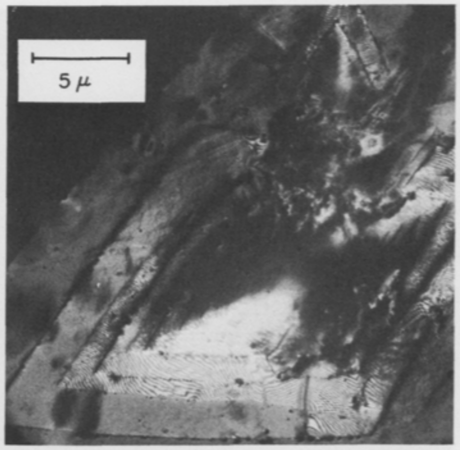
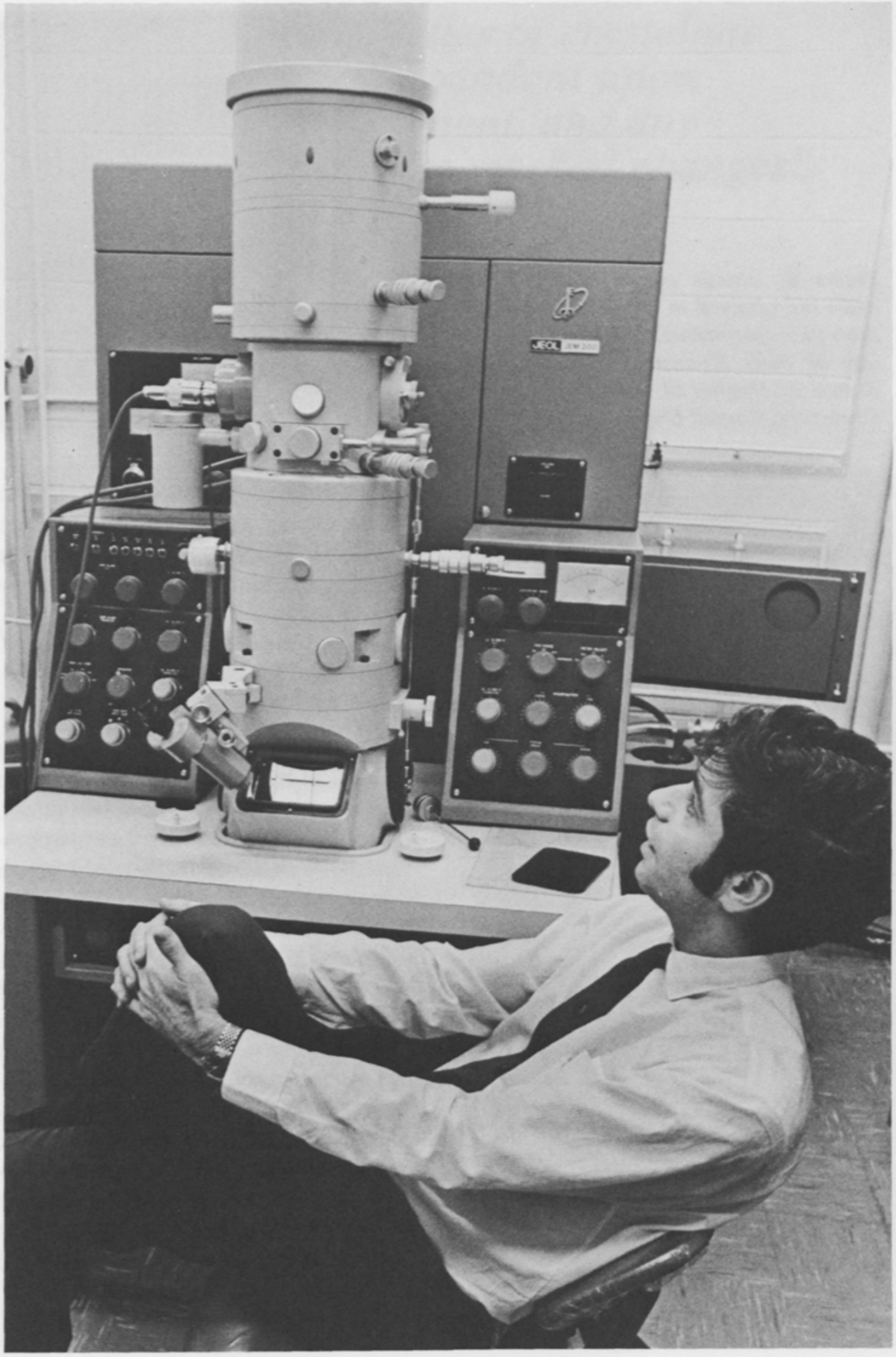


Figure 3



A JEM 200-kV electron microscope is among the instruments available to researchers in the Bard Hall laboratory supervised by Professor Sass, shown here.

A permanent record may be obtained by letting the image fall onto a photographic plate.

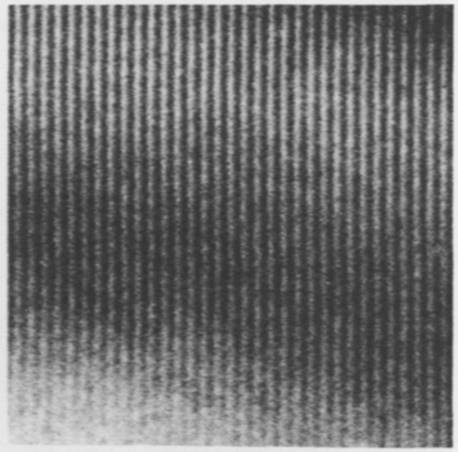
This article will discuss just a few of the many research projects carried out in the electron microscope laboratory located in Bard Hall, the facility of the Department of Materials Science and Engineering.

SEEING IMPERFECTIONS IN CRYSTALLINE SOLIDS

Most problems in materials science have to do with crystalline solids, which can be thought of as being built up by a periodic stacking of planes of atoms. The physical properties of crystalline materials are strongly dependent upon this periodic arrangement, and any imperfection produces marked changes in various properties.

Figure 1 illustrates several types of imperfections that can be present. A *dislocation* is a line imperfection which results when an atomic plane terminates within the crystal. A *grain boundary* marks the interface of two crystals which have the same atomic structure but different orientations in space. An

Figure 6. *Atomic planes spaced 14 Å apart are resolved in a crystal of magnesium fluorogermanate. (Micrograph courtesy of Peter Kunzmann and Professor Robert E. Hughes of the Department of Chemistry, Cornell University.)*



inclusion results from the formation of a new small crystal, with a different atomic structure, within the old crystal.

Obviously, there is a great deal of strain in the vicinity of a dislocation. It is, in fact, often a source of weakness in the crystal, since the dislocation line moves easily under an applied stress.

Quite often a grain boundary is made up of an array of dislocations, such as shown in Figure 2, a micrograph of a specimen of gold. This micrograph illustrates a special case in which the grain boundary plane is parallel to the thin crystal surface. A more typical example is illustrated in Figure 3, in which the grain boundaries in an aluminum specimen are inclined with respect to the surface of the thin crystal and give rise to fringe patterns. Also visible are isolated dislocation lines which show up as sharp dark lines within the many small grains.

Not all imperfections are sources of weakness in materials; inclusions can have a very beneficial effect on macroscopic properties. For example, the great strength of titanium alloys, which are important in the aircraft industry because of their high strength-to-weight ratio, depends on the formation of hard inclusions which impede the motion of dislocation lines through the crystal. A typical microstructure of a titanium-niobium alloy (Figure 4) shows the presence of the ellipsoidal inclusions which contribute so much to the strength of this material.

The field of materials science includes the study of polymers as well as of metals, and much current research is directed toward an understanding of the factors that affect the mechanical properties of polymers such as polyethylene and nylon. An example of what can be observed by electron microscopy of polymers is shown in Figure 5. Visible in the multi-layered polyethylene crystal are very fine dislocation lines, as well as complex fringe patterns resulting from the overlapping of several crystals. It is suspected that in polymers, as in metals, dislocations are an important source of weakness.

The electron microscope can also be used to resolve the atomic planes within crystals. The fringe pattern in Figure 6, a micrograph of magnesium fluorogermanate, represents the atom planes, which are spaced 14 Å apart. This micrographic technique is often useful in determining the atomic structure of solids.

THE MATERIALS SCIENCE CENTER AT CORNELL

All of the research discussed in this article has been conducted in the Bard Hall electron microscope laboratory, one of two such facilities that are operated by Cornell through its Materials Science Center. The goal of these laboratories is to make available to researchers in many fields the most modern equipment, which would be much too expensive for any individual scientist to purchase. Equally important for the performance of sophisticated experiments is the presence in these laboratories of experienced personnel who are knowledgeable in advanced techniques and microscope maintenance and are available for consultation with inexperienced as well as experienced microscope users.

"The physical properties of crystalline solids are strongly dependent upon this periodic arrangement, and any imperfection produces marked changes"

Stephen L. Sass, assistant professor of materials science and engineering, is director of the Bard Hall electron microscope facility of Cornell's Materials Science Center. His own research interests center on the application of electron microscopy and diffraction to the study of phase transformations in solids, hydrogen in metals, and polymer crystals.

Professor Sass received his undergraduate education at the City College of New York, earning the B.Ch.E. degree in 1961. From 1961 to 1966 he attended Northwestern University, which awarded him the Ph.D. degree in materials science. He spent sixteen months as a Fulbright scholar at the Technische Hogeschool in Delft, The Netherlands, before joining the Cornell faculty in 1967.

He is a member of the American Institute of Metallurgical Engineers, the American Society for Metals, the Electron Microscopy Society of America, and the American Crystallographic Association. He is on the Board of Review of Metallurgical Transactions, *and a member of several technical committees.*

HIGH-RESOLUTION MICROSCOPY OF BIOMACROMOLECULES

Present Limitations and Future Possibilities

by Benjamin M. Siegel

Within the past decade, engineering development has brought the capability of the electron microscope to a level of reliability and performance that has enabled research workers who number in the thousands to use the instrument as a basic research tool for delineating the ultrastructure of biological systems and the defect structure of materials.

In the hands of a skilled worker, the routine instrumental resolution is at the 5 Å level. At this level, information on biomolecular configuration is limited by characteristics of the specimen itself: the artifacts introduced by dehydration during preparation; a low level of contrast in the image, resulting in a low signal-to-noise ratio; and perhaps most importantly, radiation damage introduced by the electron beam and by the conditions under which biological materials are examined in presently available commercial instruments.

A few research groups are attempting to extend the resolution limit of the electron microscope down to a level at which single atoms could be resolved and the molecular configuration of biomacromolecules could be discerned at atomic dimensions. Significant advances have been made in the last two years, and it is now possible to image single heavy atoms bonded to organic molecules. Using a commercial electron microscope tuned to the highest level of performance, my associates and I have succeeded, as have workers in a handful of other laboratories, in obtaining convincing images of single atoms with atomic number greater than about 80 (mercury, tungsten, thorium, and uranium, for example).

Even at their best, however, the optical characteristics of the electron lenses available to us are very poor compared to the optics available for light microscopes. The large gain in resolving power of the electron microscope over the light microscope is realized because accelerated electrons have extremely short effective wavelengths: $\lambda = 0.037$ Å for electrons accelerated to 100 kV as compared to $\lambda = \sim 5{,}000$ Å for green light. Most of this advantage is lost, though, because the electron lenses have large aberrations and the critical one, spherical aberration, cannot be corrected by conventional methods. In practice, the objective lens is stopped down to an extremely small numerical aperture, equivalent to an acceptance angle of 1×10^{-2} radians, giving a net resolution limit of 3 Å for electron microscopes now available. Under these conditions, the transfer function of the instrument is strongly dependent on the focus of the objective lens, a condition that is made dramatically evident in phase contrast imaging.

COMPENSATING FOR DEFECTS IN THE IMAGING

Considerable effort is being made to enhance the information that can be extracted from an electron microscope image. For example, devices can be introduced into the objective lens to modify or correct oscillating phase shifts. The strong phase shift of the electron wave caused by spherical aberration of the lens can be partially compensated by defocussing to produce a phase shift in the opposite sense, but since the angular dependence is different for each of these phase shifts, only a limited improvement in the transfer function of the lens can be achieved.

". . . it is a reasonable expectation that the actual configuration of the carbon atoms . . . could be delineated."

We have introduced an additional controllable phase shift by mounting an extremely fine wire (0.25 microns in diameter) across the back focal plane of the objective lens. This wire takes on an equilibrium positive charge set by the balance between the intensity of the incident electrons and the amount of secondary scattering. With this "phase plate," the transfer function of the objective lens can be extended down to lower spatial frequencies; phase-contrast images can be obtained with maximum contrast of detail at spatial dimensions from 10 to 40 Å, a range particularly important for observing biomolecular configurations.

Another type of aperture we have used is a half plane in the back focal plane. By also allowing that part of the electron beam that was unscattered to pass the aperture, we obtain a reference wave and can achieve an effect that is the equivalent of single sideband holography. Instead of having oscillating bright and dark phase contrast, the image shows lateral shifts that are also functions of the spherical aberration and defocus. The introduction of these lateral shifts can be compensated by the use of a coherent optical image reconstruction system that introduces exactly the same shifts in the opposite sense.

COMPUTER PROCESSING OF THE IMAGE

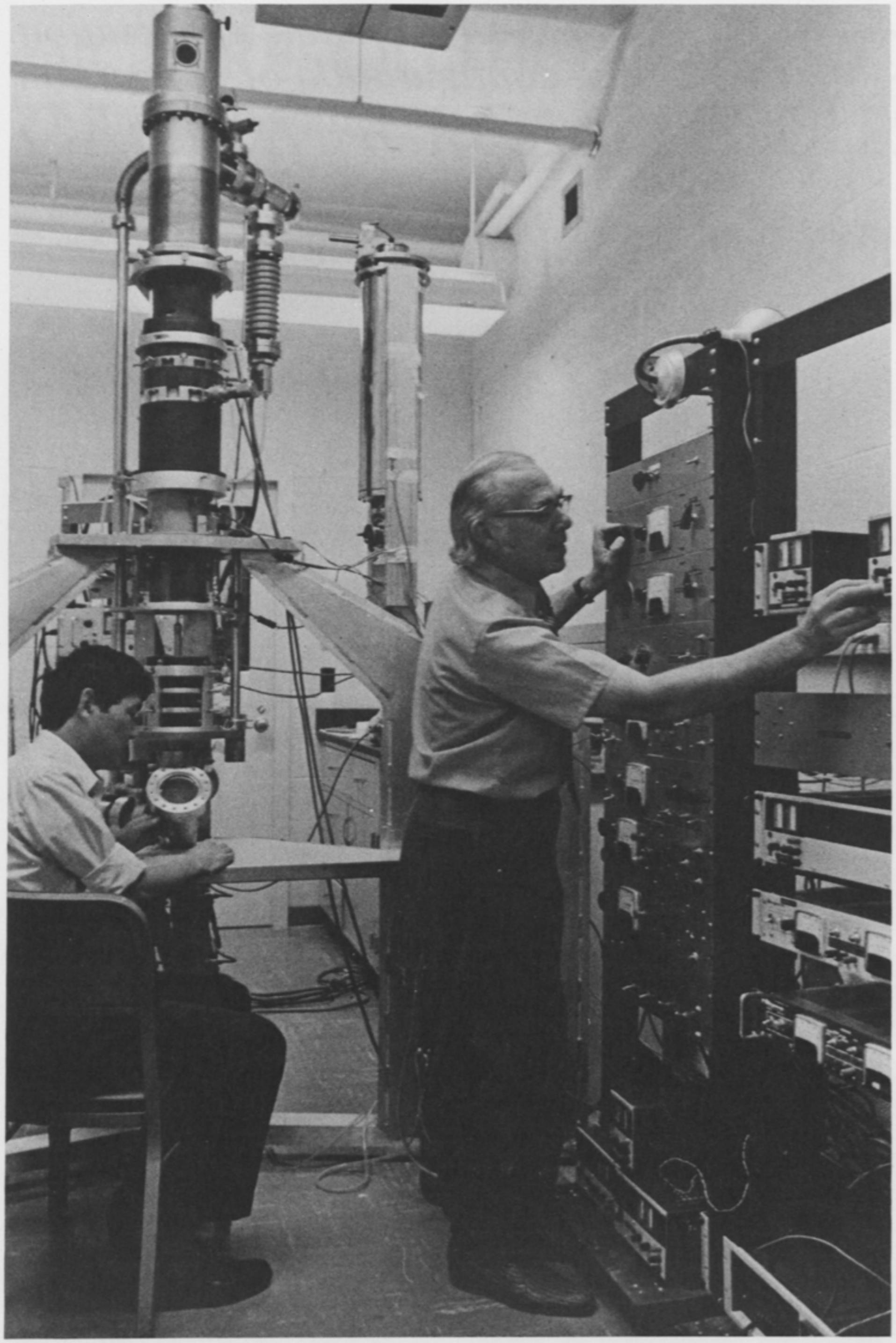
But the most powerful means of "correcting" the defects of the transfer function, and also extracting the maximum information, is by computer processing of the image.

The first step in the procedure is to obtain the image in digital format. The image-digitizing system we have assembled consists of a minicomputer with the necessary peripherals: a scanning densitometer that digitizes any image on photographic film, random access discs for intermediate buffers, and a tape transport on which the digitized image can be stored for subsequent use with the full image-processing programs on the large computer. The final processed image can be displayed or a copy can be made on photographic film.

A computer program that is of particular interest and is being used here is one that enables us to discriminate between heavy and light atoms. We use a set of phase contrast electron micrographs that represent a focal series of a biomolecular specimen containing heavy atoms. First we obtain, by a least squares fit, the instrumental transfer function for the in-focus image. Then, from the observed contrast relations, we obtain the complex scattering wave, which has a different dependence on atomic number, Z, in its real and imaginary parts. The imaginary part of the scattered wave has a $Z^{4/3}$ dependence, and by extracting it in the image processing, we can display images in which the heavy atoms stand out in high contrast to the low-atomic-number atoms that make up the noisy substrate and the organic part of the molecule. This processing thus provides a method by which we are able to observe specific heavy-atom labeling or substitution in biomolecular objects.

THE EXPERIMENTAL INSTRUMENT AT CORNELL

The present limitations on the observation of biomolecular structure by electron microscopy are set by factors



Left: Professor Siegel (standing) adjusts controls for the experimental electron microscope under development in his laboratory. The complete instrument is designed to include an ultrahigh vacuum column, a field emission source, and a superconducting objective lens.
Opposite: A coherent optical system for analog image processing is used by members of Professor Siegel's research group. This is the equipment used in the single sideband holograph method described in the article. The Fourier transform of the object is obtained in the back focal plane of the first lens and a properly constructed grating introduces the necessary correction to give the reconstructed image.

beyond the resolving power of the instrument. Radiation damage appears to be one of the most serious considerations, and yet the transmission electron microscopes that are presently available require observation of the specimen under environmental conditions adverse to the minimization and study of such damage. These conditions include contamination in the vacuum surrounding the specimen, uncontrolled temperature, and insufficiently controlled beam irradiation.

We have constructed an experimental electron microscope that was designed to eliminate or at least minimize these adverse conditions and enable us to make a systematic investigation of radiation damage under controlled conditions. With this instrument we hope to be able to provide the optimum conditions for the examination of biological material.

Our experimental electron microscope is equipped with an ultrahigh vacuum column that should reduce contamination to an absolute minimum. This feature reduces the possibility of damage to the specimen by collisions

with ions, and therefore also facilitates the assessment of how much damage is caused by the high electron flux that is required in order to obtain significant amounts of information in the image. Another feature is a special liquid-helium cryostat to contain the specimen and the superconducting objective lens. This cryostat provides both temperature control and cryopumping, and affords maximum resolution and stability. The instrument also incorporates a field-emission illuminating system of flexible design that produces an irradiation source variable over a wide range of electron flux and capable of illuminating only the very small area of the specimen being imaged.

NEED FOR IMPROVED SPECIMEN PREPARATION

These enhanced instrumental and image-analyzing capabilities must be accompanied by significant improvement in present specimen and substrate preparative techniques if they are to be utilized adequately. Except for the imaging of single heavy atoms, there has been no report yet of methods for observing details of biomolecular structure below the 7 to 10 Å range. The weak scattering from these molecules requires methods for contrast enhancement that seem to limit the resolution to approximately 10 Å. Other factors that contribute to this present limitation in resolution and contrast are the radiation damage and contamination already discussed. And a severe limiting factor in the present state of the art is the "noise" from the substrate on which the macromolecule is supported.

logical specimens. We must consider the relatively small scattering cross sections of the atomic species C, O, and N that make up biomacromolecules. The atomic scattering factors of these atoms set limits on the maximum signal-to-noise ratios (and therefore the maximum information) that can be obtained in imaging these molecules even with optimum phase contrast or dark field.

In order to illustrate the ultimate performance that could be obtained in electron transmission microscopy of biological specimens, we prepared some simulated images with the aid of computer calculations. We calculated phase contrast images of single atoms, taking into consideration both the transfer function at optimum phase contrast and the atomic scattering amplitude and phase. Then, from our computer data, we simulated photographic images of arrays of atoms as they would project in the object plane. An example with biomolecular interest is shown in Figure 2. Simulated here are images of two bases—guanine and cytosine labelled with methyl bromide—as they would appear if our superconducting objective lens could be utilized at its theoretical resolving power. The molecules are aligned in the most favorable orientation, and noise, or signal from a supporting substrate, is assumed to be negligible.

These "ideal" images represent the information that we could expect to obtain by direct visual impression at the very limits of present instrumentation. What we would be seeing is the primary structure of a planar molecular configuration, in this case the bases of a polynucleotide. It is a reasonable expectation that with an instrument perfected to the point that it could produce

REDUCING THE BACKGROUND NOISE

Thin evaporated carbon films are now considered the best available substrates, but they produce a random noisy background that often has as much contrast as the unstained biomacromolecule. The best hope of removing this random noise from the image would appear to be the use of thin stable crystalline graphite films as substrates, for the periodic image they produce could be subtracted in the image, either by filtering in an optical image reconstruction system or through digital computer processing of the image.

To obtain the type of crystalline substrate required, we have developed a method of growing thin graphite single-crystal films. First, single-crystal films of nickel are grown epitaxially on mica with the (111) face parallel to the surface. After the nickel films have been annealed, graphite films 20 to 30 Å thick are grown on the nickel by catalytic disproportionation of carbon monoxide at 500°C. The graphite films are continuous but consist of individual crystallites, each typically a micron across, aligned with their basal planes parallel to the surface.

An electron diffraction pattern from a typical graphite film is shown in Figure 1. The pattern shows that the observed part of the specimen is a good single crystal. Since it is the equivalent of the Fourier transform, this pattern illustrates how easy it should be to filter out the contribution from this type of substrate in the "Fourier transform plane."

ULTIMATE LIMITS OF RESOLUTION AND CONTRAST

Assuming that we have a satisfactory periodic substrate on which biomolecular dispersions can be supported, and that the substrate structure is completely erased from the image, and assuming also that other limitations such as contamination and radiation damage do not interfere, what factors still remain to limit the information that can be obtained? The transfer function of the electron microscope sets a limit, of course, and in addition there are limitations imposed by the nature of the bio-

Figure 1

Figure 1. The electron diffraction pattern of a graphite film.

Figure 2. These simulated images represent the ultimate resolution that can be expected with the electron microscope today. The images of guanine and cytosine labeled with methyl bromide were obtained from computer calculations of the phase contrast images from single atoms. The corresponding structural formulas are shown below as an aid to identification of the imaged atoms.

Figure 3. A dark field micrograph of SV40 DNA molecules.

Figure 4. An electron micrograph showing fibrin polymerization, the initial stage of blood clot formation.

Figure 2

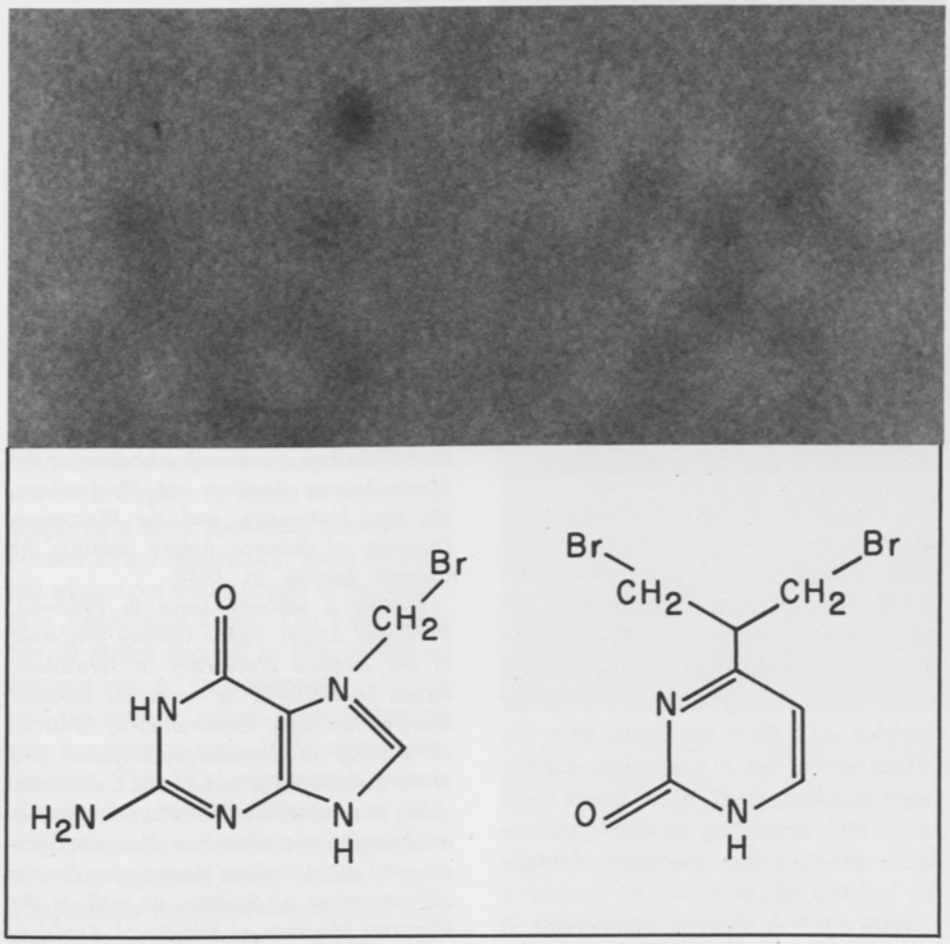


Figure 3

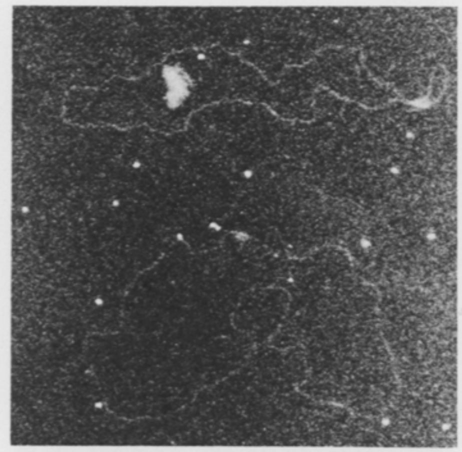
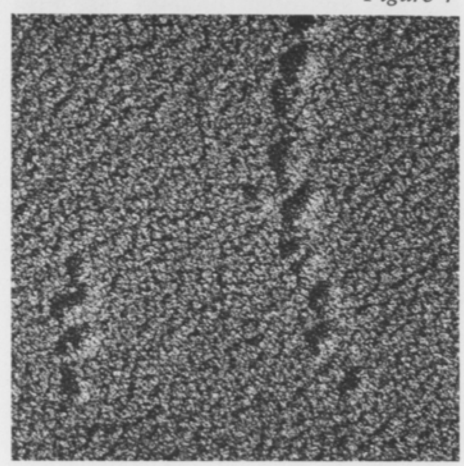


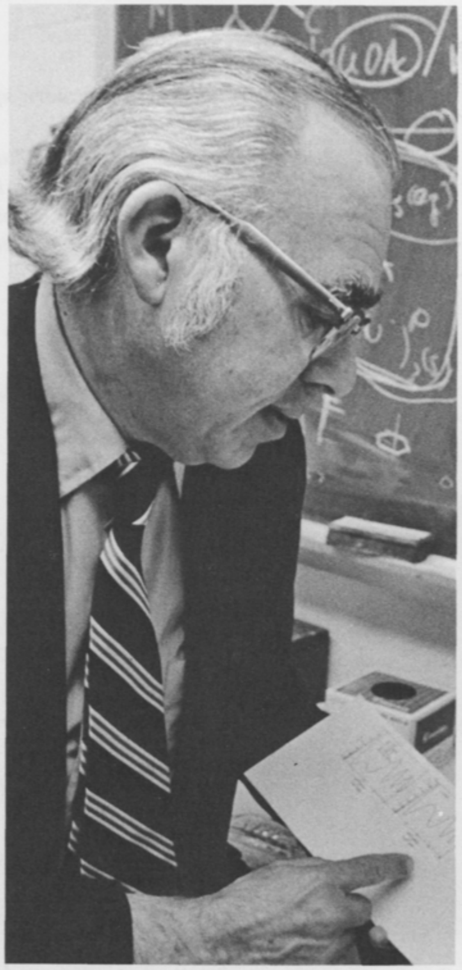
Figure 4



images of the quality of these simulated ones, it would be possible to determine the base sequence of short sections of single strands of polynucleotides. Biochemical labeling with heavy atoms would still be required, certainly to distinguish adenine from guanine and cytosine from uracil.

But with these possibilities, we are extrapolating to the very limits of our expectations. It is undoubtedly more realistic to talk of observing secondary or tertiary structure of the nucleic acids (see Figure 3), or the substructure of enzymes and other proteins (see Figure 4). The bindings and interactions of such proteins and the location of active sites might be detected if the site were labeled with a substrate molecule containing atoms of high atomic number.

If we are to consider the possibility of obtaining atomic resolution of biomolecular configurations in which molecules 10 to 20 Å thick are imaged with overlapping atoms in projection, much more stringent conditions will be required in the imaging process. Radiation damage produced by the interaction of the irradiating electrons with the biomolecule will undoubtedly be a factor setting a limit on the allowable incident electron dose. Theoretical considerations, and more recently some experimental observations, indicate that it will be necessary to go to megavolt energies. At 5 MeV we should have the advantages of 0.5 Å resolution, require fewer incident electrons to image each atom, and, according to recent indications, produce less radiation damage per incident electron.



With a 0.5 Å electron microscope, it is a reasonable expectation that the actual configuration of the carbon atoms in a macromolecule could be delineated. But pursuits at this level of resolution are the work of the next decade.

Benjamin M. Siegel, professor of applied physics, has been working at Cornell in the area of electron microscopy since 1949. Widely recognized as an authority in this field, he is currently president-elect of the Electron Microscopy Society of America.

His major research interests at the present time center on the development of an advanced experimental electron microscope and the application of high-resolution electron microscopy to the observation of biogenic macromolecules, including nucleic acids and enzymes. He has published extensively in this field and participated in a number of special conferences here and abroad.

Professor Siegel received his undergraduate and graduate education at the Massachusetts Institute of Technology, earning the B.S. degree in physical chemistry in 1938 and the Ph.D., also in physical chemistry, in 1940. He spent a year at the California Institute of Technology and then served as a research associate at the Massachusetts Institute of Technology, Harvard University, and the Weizmann Institute of Science before joining the Cornell faculty in 1949.

During a sabbatic leave in 1962–63, Professor Siegel was a visiting professor at the Hebrew University in Jerusalem, Israel. In 1970–71 he spent his sabbatic leave at the MRC Laboratory of Molecular Biology in Cambridge, England, and at the Salk Institute in LaJolla, California.

He is a member of the Physical Society of America, the American Vacuum Society, and the American Association for the Advancement of Science, as well as the Electron Microscopy Society of America.

SEEING WITH IONS

High-Resolution Magnification Without Lenses

by David N. Seidman

The field ion microscope is a remarkably simple instrument that enables one to look at individual atoms on the surface of a metal. It is able to reveal, in the most direct manner that is presently available, the internal structure of a metal. This unique microscope is being used in a number of projects, such as studies of point defects in irradiated or quenched metals, that are being carried out at Cornell in the Department of Materials Science and Engineering.

An example of what can be seen with the field ion microscope (FIM) is shown in Figure 1, which is the micrograph of a gold specimen recently recorded in my laboratory. Each individual white spot corresponds to the image of a single gold atom. The total number of atoms imaged in this particular micrograph is approximately 10,000, and the area in which these atoms reside is approximately 10^{-11} square centimeters. This FIM micrograph reflects directly the internal symmetry of gold, which has the crystalline configuration of a face-centered cubic lattice. Figure 2 represents the three-dimensional configuration of this type of lattice.

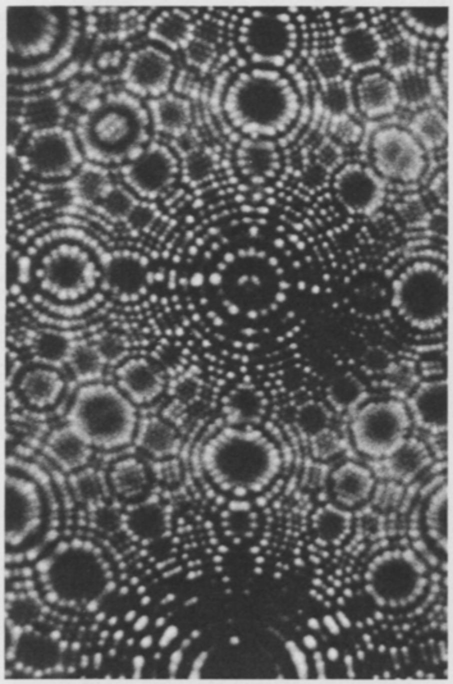


Figure 1. A field ion micrograph of a gold specimen imaged at 28°K with the use of neon as the imaging gas. Each white spot represents a single gold atom. This micrograph was taken by Robert S. Averback, a research associate.

THE SYMMETRY REVEALED IN A MICROGRAPH

An understanding of how the symmetry of the FIM micrograph of gold relates to that of the unit cell structure may be gained from a simple visual experiment.

Mentally rotate the cube in Figure 2 around the z axis by 90°, and note that the unit cell in this new position is indistinguishable from the unit cell in its original position. Repeat this 90° rotation three times, and after each rotation note that the unit cell appears the same as it did before. Now carry out the same operation around the x and y axes and observe that the same rotational symmetry exists around these axes also. The technical term for an axis with this kind of symmetry is a *four-fold rotation* axis.

The FIM micrograph of gold also has a four-fold rotation axis. To see this, rotate Figure 1 about the normal to the plane of the paper and note that each 90° rotation brings the micrograph into perfect coincidence with its former appearance. A more detailed examination of the FIM micrograph

Figure 2 (below). A unit cell of the face-centered cubic lattice of gold. Individual atoms are indicated by spheres (not drawn to scale).

Figure 3 (right). A simplified schematic of a field ion microscope.

Figure 2

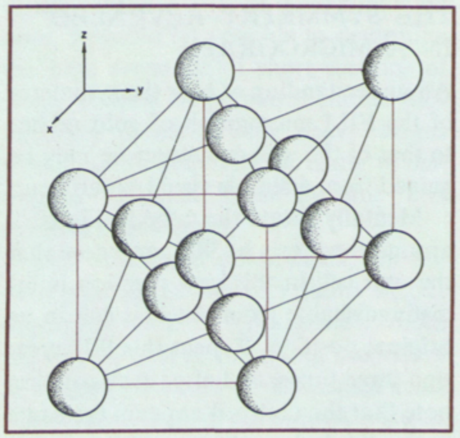
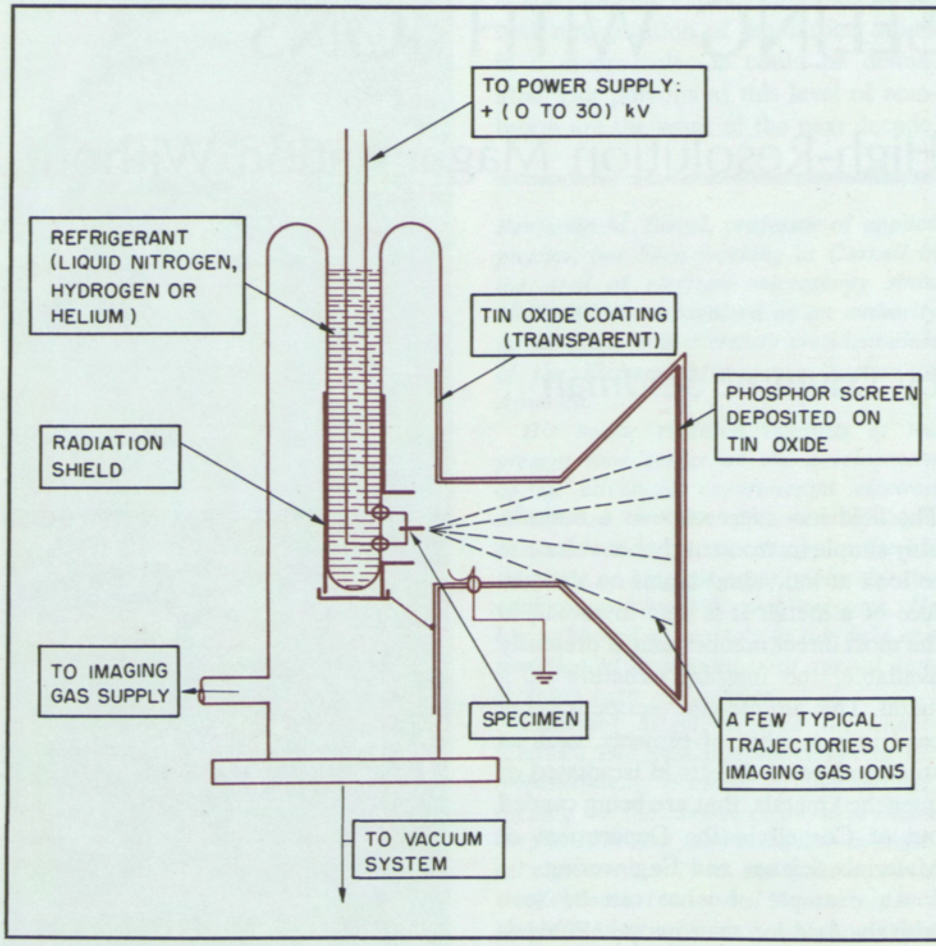


Figure 3



reveals that it possesses exactly the same symmetry elements as the unit cell of the face-centered cubic lattice shown in Figure 2.

THE FIM: A MICROSCOPE WITHOUT LENSES

The field ion microscope is most correctly described as a point-projection microscope. Its most surprising feature is that it contains no lenses! In this respect, the FIM is quite unlike the conventional and special electron microscopes that are discussed by Professors Sass, Siegel, and Silcox in this issue: those instruments all employ rather sophisticated systems of magnetic lenses. In the case of the FIM, the specimen itself serves as both the imaged object and as a "lens."

Basically, the FIM consists of a vacuum system capable of maintaining a background pressure of 10^{-8} Torr or less, a cryostat or cold finger to maintain the temperature of a specimen in the range between 4.2 and 300°K, a phosphor screen to image the individual atoms, a source of high voltage which can be varied between zero and approximately 30,000 volts, and finally a means of backfilling the instrument with an imaging gas. An FIM specimen is, typically, a wire about 0.01 centimeters in diameter. Before it is inserted into the FIM, it is etched or electropolished to a very fine point that has a radius of curvature of only 50 to 100 Angstrom units.

A simplified schematic drawing of an FIM, containing all the essential components, is shown in Figure 3. The basic operating procedure consists of

Figure 4

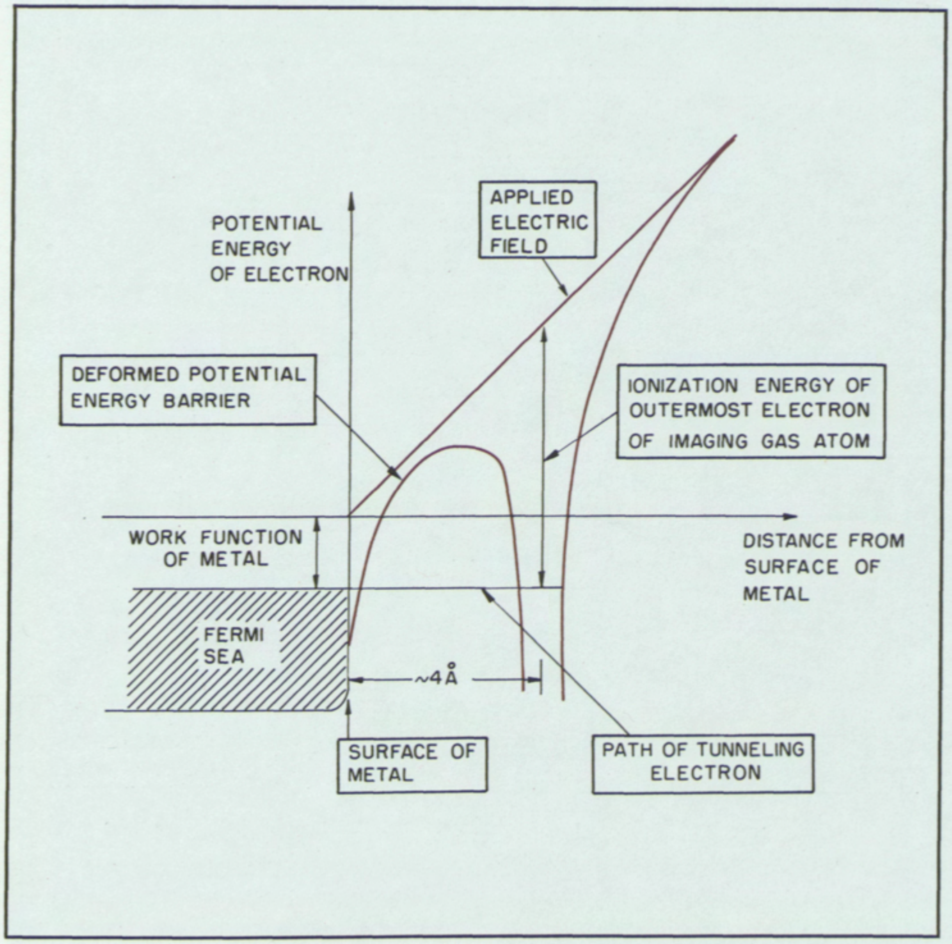


Figure 4. A potential energy versus distance diagram illustrating the process of field ionization of an imaging gas atom in a field ion microscope. In the presence of a very high electric field, atoms of the imaging gas become ionized near the surface of the metal specimen. The electric field deforms the electron potential energy barrier so that the outermost electron of an imaging gas atom can tunnel into an unfilled energy state near the top of the Fermi Sea of electrons within the metal. This leaves the gas ion free to accelerate toward the phosphor screen.

first obtaining a background pressure of 10^{-8} Torr, next cooling the specimen, by means of liquid helium, to a temperature between 10 and 70°K, and then backfilling the microscope with an imaging gas, typically helium or neon, to a pressure of 10^{-4} Torr.

THE PROCESS OF FIELD IONIZATION

With the aid of a high-voltage supply, the specimen can be placed at a positive potential with respect to the phosphor screen, which has been deposited on top of a conductive coating of tin oxide. Since the specimen has a very small radius of curvature, one can easily generate a local electric field as large as 500 million volts per centimeter with the application of only a few thousand volts to the tip. The high local electric field that can be generated by this simple technique is basic to the operation of an FIM.

In the high local electric field of 450 to 500 million volts per centimeter near the FIM specimen, helium atoms will be ionized by means of a mechanism known as *tunneling*. This tunneling mechanism is illustrated schematically in Figure 4. In the presence of the very high electric field, the outermost electron of an atom of the imaging gas can tunnel through the deformed electron potential energy barrier along the indicated path in a time of less than 10^{-9} seconds. The positively charged helium ion which is created by this process is then accelerated along an electric field line to the phosphor screen, where its energy is converted into visible light.

The process of ionization of an atom by a tunneling mechanism is a quantum mechanical effect which was first predicted theoretically by J. Robert Oppenheimer in 1928; however, the effect was not observed experimentally until 1951, when Erwin W. Mueller invented the FIM. The term currently used in the literature to describe the above process is *field ionization*.

Figure 5 is a schematic diagram illustrating the field ionization of a helium atom above the surface of an FIM tip. A helium atom is ionized in the high local electric field above each atom, after the atom has accommo-

Figure 5

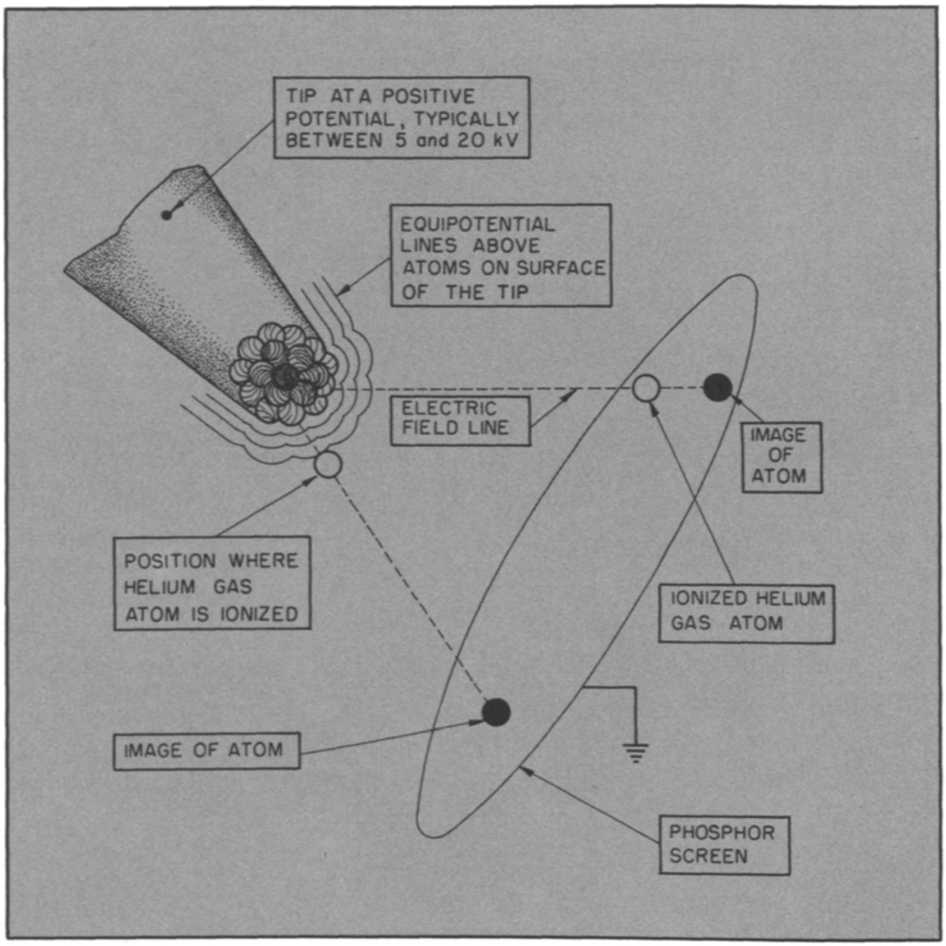


Figure 5. A highly schematic diagram of a helium gas atom being ionized in the high local electric field above the site of an atom on the surface of a tip—which is the specimen under examination—in the field ion microscope. After the helium atom is ionized, it travels along an electric field line until it reaches the grounded phosphor screen. What is "seen" is an image, produced by helium ions, that corresponds to the atomic pattern of atoms on the surface of the specimen.

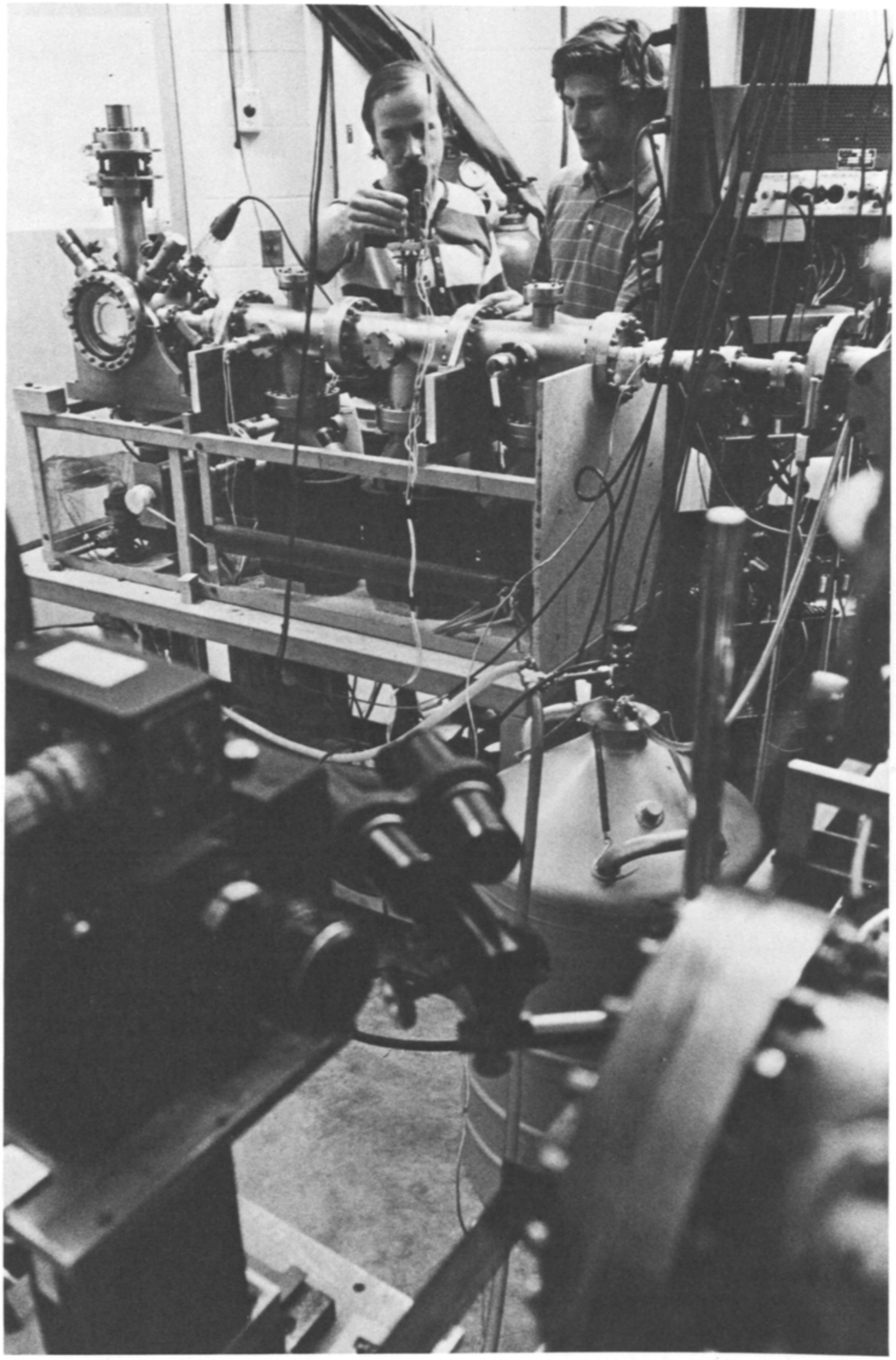
dated thermally to the temperature of the FIM specimen. Thus, what one "sees" in an FIM micrograph is a direct reflection of the local electric field distribution above the atoms on the surface of a sharply pointed tip. The fact that the tip is cooled to a low temperature is an essential aspect of the excellent atomic resolution achieved. Each helium atom reaches almost the same temperature as the tip prior to its being ionized, so that the component of velocity of the ion perpendicular to an electric field line is very small. The smallness of this normal velocity component implies that the pencils of ions which are generated above two neighboring atoms do not interfere with one another during their flight to the phosphor screen.

THE PROCESS OF FIELD EVAPORATION

The FIM has another highly useful capability that permits the "dissection," atom by atom, of the metal specimen under observation. This is a process called *field evaporation,* the controlled sublimation of the specimen under the influence of the electric field. If the imaging voltage on the specimen is increased to a certain level, the atoms on the surface begin to evaporate, even though the specimen is as cold as 4.2°K. The exact value of the electric field at which field evaporation commences is a function of the particular metal being examined. For example, the evaporation field is approximately 570 million volts per centimeter for tungsten, 250 million for titanium, and 350 million for gold. Since the ionization field of the imaging gas is independent of the metal being studied, one must use a gas with an ionization field that is less than or equal to that of the metal under examination. Hence the micrograph of gold shown in Figure 1 was obtained with the use of neon as the imaging gas: a neon atom requires a field of approximately 350 million volts per centimeter in order for it to be field ionized.

An example of the field evaporation process is illustrated in Figure 6. In this case we applied voltage pulses to a tungsten specimen in such a way that

Working with the field ion microscope are research associates Kenneth Wilson (at left) and Robert Averback (at right). Directly in front of them is the flight tube which connects the heavy-metal-ion accelerator (not visible) and the microscope. The window through which the image is viewed can be seen in the upper left-hand corner of the picture. This instrument is used to study interstitials and vacancies produced in metals as a result of irradiation by heavy-metal ions—research that is relevant to the problem of radiation damage in nuclear reactor housings.



the evaporation was performed in a highly controlled manner. The pulses were a few microseconds in duration, and at an applied voltage of 2 or 3 kilovolts. As seen in the figure, the atoms in the small plane are evaporating at the rate of approximately one atom per frame of ciné film, allowing us to look at the internal structure of the specimen on an extremely fine scale. In my laboratory, we have developed methods which allow the recording and analysis of as many as 500,000 frames of ciné film for a single investigation.

THE STUDY OF VACANCIES IN METAL LATTICES

Since point defects have a marked effect on the macroscopic properties of metals, the microscopic study of various kinds of defects is an important aspect of materials science. The properties of vacant lattice sites, for example, are crucial to our understanding of such phenomena as diffusion, sintering, high-temperature creep, and the formation of voids in metals subject to fluxes of fast neutrons in a breeder reactor.

Figure 6

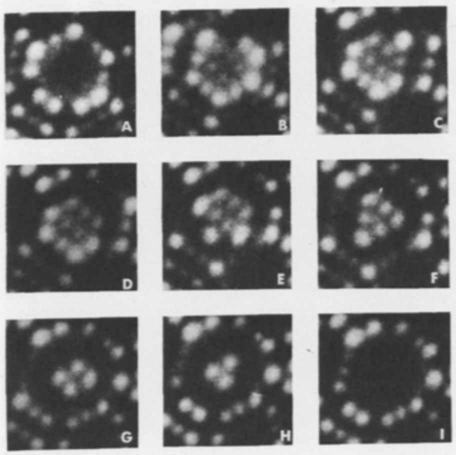


Figure 6. The pulse-dissection sequence of a high-index plane of a tungsten specimen. The atom-by-atom dissection is shown in frames A through I. Note that in frame F six atoms are on the plane, in frame G only four atoms remain on the plane, and finally in frame I all the atoms in this plane have been field evaporated. These micrographs were taken in Professor Seidman's laboratory by Kenneth L. Wilson during the course of Ph.D. thesis research.

Figure 7. A unit cell of a face-centered cubic lattice containing a monovacancy, which is simply a missing atom. Compare this figure with Figure 2.

Figure 8. A unit cell of a face-centered cubic lattice containing a nearest-neighbor divacancy. Compare this figure with Figures 2 and 7.

Figure 7

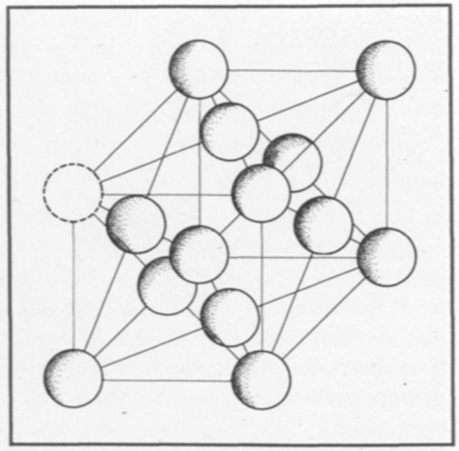
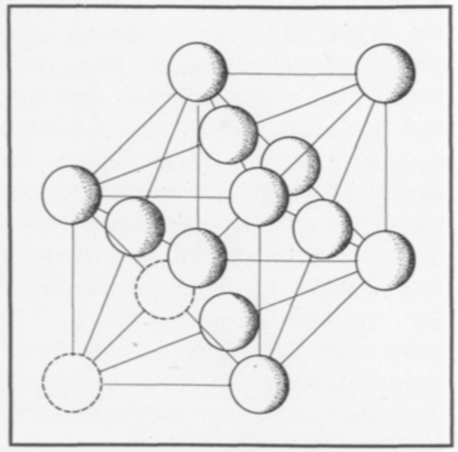


Figure 8



The simplest point defect in a metal is a vacancy. A vacant lattice site in a metal crystal is called a *monovacancy;* Figure 7 shows a schematic diagram of a monovacancy in a face-centered cubic lattice. When two nearest-neighbor sites on a face-centered lattice are vacant, the defect is called a *divacancy* (see Figure 8). At the melting point of most face-centered cubic metals, the equilibrium concentration of vacancies with respect to the atoms present in the crystalline structure is between 10^{-3} and 10^{-4}. This means that only one in a thousand to one in ten thousand atomic sites are vacant in a metal at such an elevated temperature.

PULSE DISSECTION REVEALS VACANCIES

A sequence showing pulse dissection of a high-index crystallographic plane containing a monovacancy in a quenched platinum specimen is shown in Figure 9. The specimen had first been quenched at the rate of approximately 12,000°C per second from 1,700°C in order to "freeze in" the vacancies, which are in thermal equilibrium at this temperature. Frames 4 to 9, which are representative of the approximately fifty frames of film recorded in this interval, show the plane that contained the monovacancy. This monovacancy was detected during the course of a recently completed Cornell study of the properties of vacancy defects in platinum. The purpose of this investigtaion, which was supervised by myself and Professor Robert W. Balluffi, was to study the fundamental properties of monovacancies and divacancies.

THE ASSESSMENT OF RADIATION DAMAGE

The irradiation of a metal with high-energy electrons, protons, neutrons, or heavy-metal ions produces certain lattice defects called *Frenkel pairs,* which are distributed in a manner characteristic of the bombarding particles. Since these defects cause profound changes in the physical properties of the metal, their study is important in such fields as the development of the cladding materials employed in nuclear reactors.

A Frenkel pair consists of a vacant lattice site and an *interstitial atom,* which is a lattice atom that has been displaced from its normal position into one of the interstices of the crystal. In the case of a face-centered cubic lattice, there are six possible geometric configurations of an interstitial. The configuration with the lowest total energy, and therefore the most stable, is thought by some investigators to have the geometry shown in Figure 10, although this is still a matter of considerable controversy. An interstitial atom with this configuration is referred to as a *split or dumbbell interstitial.*

For the past five years, we have been studying the basic properties of interstitial atoms using the FIM in combination with a heavy-metal-ion accelerator. The use of this equipment enables us to simulate neutron reactor damage under rather simple laboratory conditions. The radiation damage caused by one 60-keV tungsten ion, for example, is as great as that produced by a single fast neutron in a breeder reactor.

An example of an interstitial atom produced in tungsten (a metal with a body-centered cubic lattice configuration) that had been irradiated with 30-keV tungsten ions is shown in Figure 11. This interstitial atom was detected during the course of a warming experiment. In this experiment, the specimen was irradiated *in situ* at 10°K in the combination heavy-metal-ion accelerator and FIM, and then warmed at a rate of approximately 2°K per minute from this temperature to 100°K. During the warming experiment, the surface was continuously photographed at a rate of approximately one frame of 35-millimeter ciné film per second. The interstitial in Figure 11 appears as an extra bright spot on a terrace between two ledges of atoms on the surface of the tip. This contrast effect is produced when the interstitial atom diffuses from inside the specimen tip to the surface. This type of experiment allows us to determine the *diffusivity* (a measure of the root mean square distance an interstitial can move in a given time at a given temperature) of this point defect.

The diffusivity of an interstitial is crucial to explaining in detail why voids form in metals that have been subjected to very high neutron doses in a

Figure 9

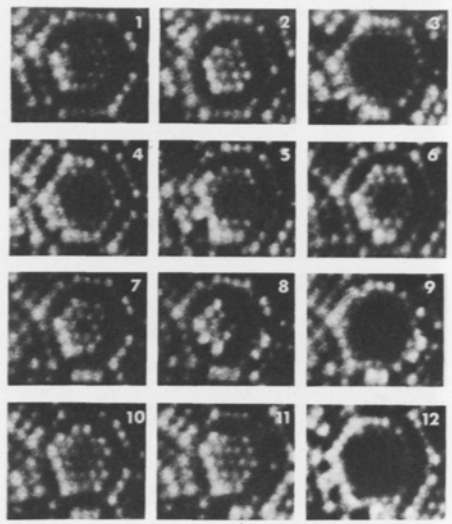


Figure 9. A monovacancy in a quenched platinum specimen revealed by the pulse dissection of three successive planes. The dissection of the plane directly above the monovacancy, the plane containing the monovacancy, and the plane directly below the monovacancy are shown in frames 1 to 3, 4 to 9, and 10 to 12, respectively. These micrographs were taken by Arnold S. Berger, a research associate working with Professors Seidman and Balluffi.

Figure 10

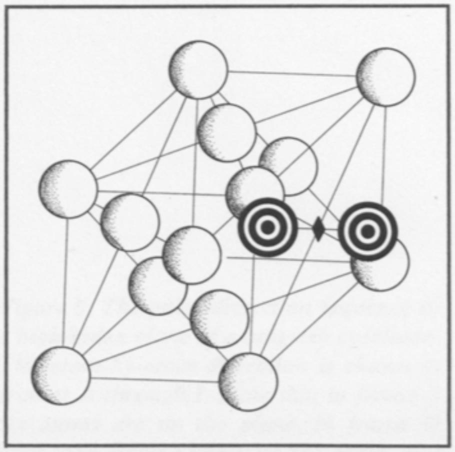


Figure 10. A split or dumbbell interstitial in a unit cell of a face-centered cubic lattice. This is the most probable geometric configuration of a type of lattice defect that is caused by high-energy irradiation of metal, such as occurs in nuclear reactors. The two black-and-white spheres represent the interstitial configuration, and the diamond indicates the center of mass of this configuration. The atom diameters are not drawn to scale. Compare this figure with Figure 2.

Figure 11

B

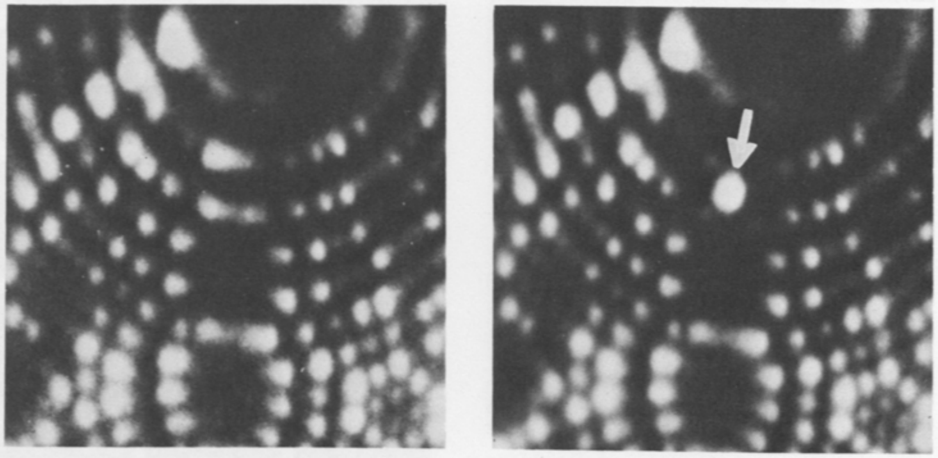


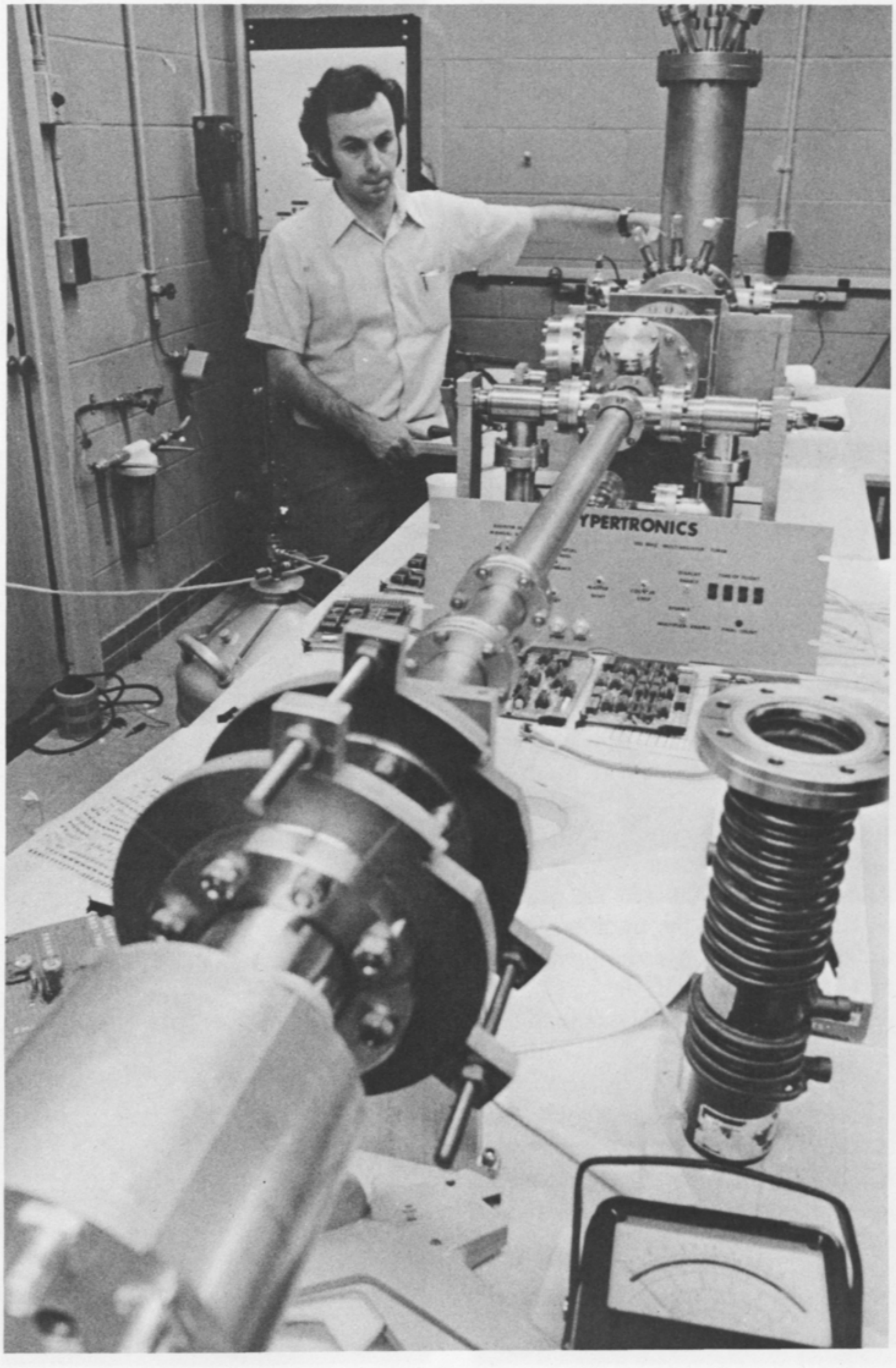
Figure 11. The appearance of an interstitial at the surface of a tungsten specimen as a result of heavy-metal-ion bombardment. The specimen was irradiated at 10°K with 30,000-volt tungsten ions and then warmed slowly to 100°K while the surface was photographed continuously at the rate of one frame per second. The interstitial, indicated by the arrow in frame B, appeared at 51.4°K. It is actually just beneath the surface. This micrograph was recorded by Kenneth L. Wilson during the course of Ph.D. thesis research under the direction of Professor Seidman.

Opposite: An atom probe field ion microscope is used in field evaporation experiments directed by Professor Seidman. Single atoms, sublimated one by one from a metal specimen by application of short high-voltage pulses, travel down the long flight tube to a detector, which is located inside the housing visible in the foreground. Film records of a field evaporation sequence are shown in Figure 6.

fast-breeder reactor. Since the formation of voids in the cladding metals employed in breeder reactors limits the cycling time of these reactors, a knowledge of the fundamental properties of interstitials plays a rather important role in understanding and controlling a practical engineering problem. It is interesting to note that scientists had been studying the properties of interstitials in metals long before the void problem in breeder reactors had been discovered; once the effect was observed, it could be readily interpreted in terms of existing knowledge.

In this brief article I have presented a qualitative picture of how a field ion microscope works and have given a taste of some of the problems currently being studied at Cornell by this technique.

The FIM provides us with quantitative information about the properties of point defects that is not obtainable, at present, by any other technique. With the recent invention of the atom-probe field ion microscope by Mueller, it is now possible to measure the charge-to-mass ratio of a single preselected atom on the surface of a FIM specimen. We have recently constructed such an instrument here at Cornell, and in the near future we will be using this instrument to study the interaction of point defects with impurity atoms. The use of the field ion microscope has made possible a deeper understanding of point defects in metals, and the additional possibility of studying directly interactions between point defects and impurity atoms makes this field of study a very exciting one for the future.



David N. Seidman, associate professor of materials science and engineering, is spending the current academic year in Israel, conducting research on point defects in metals at Tel-Aviv University and at the Technicon-Israel Institute of Technology in Haifa. He is on sabbatic leave from Cornell, and has a Guggenheim fellowship.

Professor Seidman has been at the Cornell College of Engineering since 1964, when he began work as a postdoctoral research associate with Professor Robert W. Balluffi. In 1966 he was appointed to the faculty as assistant professor of materials science and engineering, and has been an associate professor for the past two years. He spent a previous leave from Cornell, in the fall term of 1969-70, at the Technicon-Israel Institute of Technology.

His research interests include the study of lattice defects and radiation damage in metals, and his work in field ion microscopy is centered in those areas. In 1967 he was awarded the Robert Lansing Hardy Gold Medal of the American Institute of Mining, Metallurgical and Petroleum Engineers (AIME) for his "exceptional promise as a metallurgist under thirty years of age."

Professor Seidman holds three degrees in metallurgy: the B.S. and M.S. degrees from New York University, awarded in 1960 and 1962, respectively, and the Ph.D. from the University of Illinois, awarded in 1964. He is a member of the American Physical Society and AIME.

REGISTER

For the sixth time in its history, the Cornell College of Engineering will welcome a new dean when Edmund T. Cranch succeeds Andrew Schultz, Jr., in December. Dean Schultz, who last spring announced his decision to resign from the top administrative position, will be returning to the College as professor of operations research after a sabbatic leave. An article about him is contributed by Associate Dean John F. McManus.

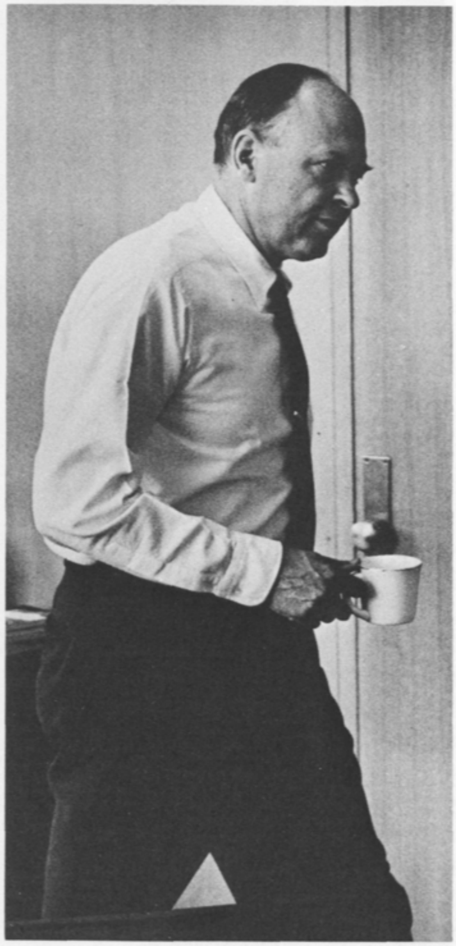
An autobiographical sketch of Dean Cranch is given here; an interview with him, in which he discusses his views on engineering and engineering education, will be reported in the Winter 1973 issue of the Quarterly.

Another organizational change noted in the Register *is the merger of several College units to form the Sibley School of Mechanical and Aerospace Engineering, with Edwin L. Resler as director.*

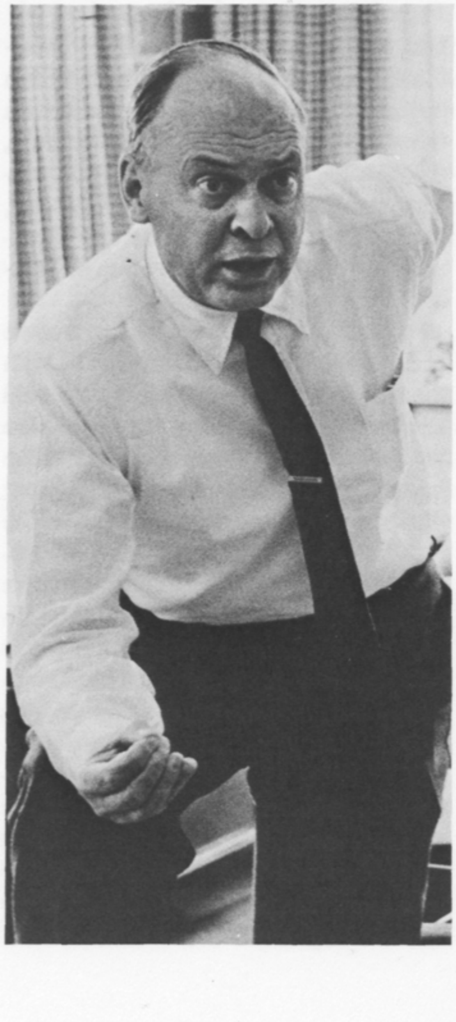
Also covered in the Register *is the appointment of aerospace engineering professor A. Richard Seebass as associate dean. John M. Bird, who was recently named professor of geological sciences, is introduced along with other new members of the faculty. Finally, the designation of Bruno A. Boley as dean of the Technological Institute of Northwestern University is noted.*

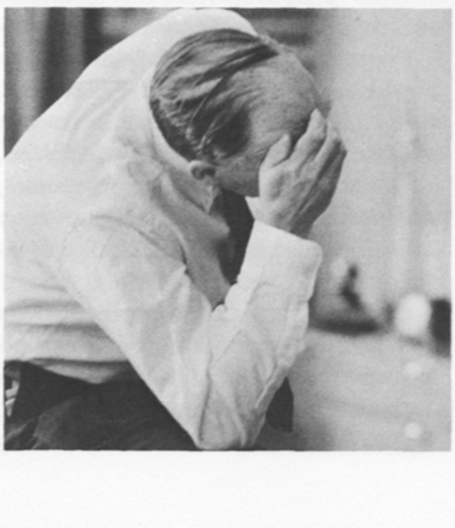
■ An interesting aspect of the deanship of engineering at Cornell is that it has, over the history of the College, infused "new blood" into the lineage so as to both preserve the unique characteristics that brought Cornell fame in engineering from its earliest years, and inject new ideas and even irritants to shake up complacency and prevent stagnation. Andrew Schultz, Jr., dean since 1963 and soon to complete his tenure in this position, has encompassed both aspects of this assignment. A Cornellian since 1932 as student, professor, and administrator, he entered the deanship with sensitivity to the traditions of the College, but with a determination not to be shackled in shaping its present and future role in technology and society.

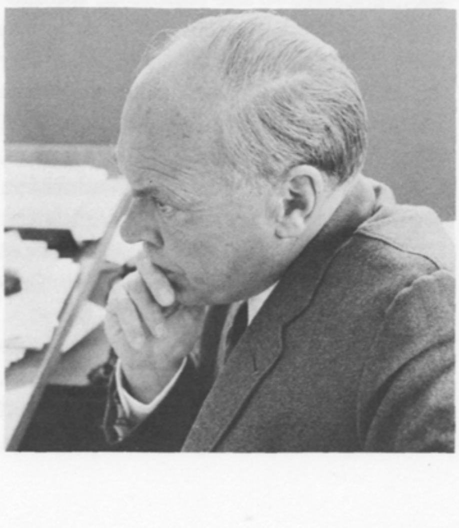
His years as dean have spanned an era of great change in technology and in the educational programs upon which it is built. Dean Schultz has been an articulate prognosticator of such change; he has also been a doer. He has instituted novel curricular programs and pedagogical experimentation; he has stimulated the extension of research



Andrew Schultz, Jr., who has resigned as dean effective in December, is shown in the picture at left with former deans Dale R. Corson (left), now president of Cornell, and Solomon Cady Hollister (center), professor of civil engineering, emeritus. The occasion was last October's centennial Engineering Convocation. Other photographs of Dean Schultz, taken in his Carpenter Hall office over the nine years of his tenure, present an informal pictorial study of the fifth dean of the College of Engineering.







"Flexibility is perhaps the keynote of his administration"

into new areas and encouraged interdisciplinary research efforts both within engineering and in combination with other divisions of the University; and, through his work on a number of professional and governmental agencies, he has influenced the goals and directions of engineering education nationally.

"Flexibility" is perhaps the keynote of his administration; it pertains to both the organizational and educational structure of the College as they have developed during his tenure. And there has been a great deal of development during those years. Schultz has had the rather awesome responsibility of recommending the appointment of more than half of the current faculty of almost two hundred, and in so doing has had a major role in shaping the character of Cornell engineering for a long time to come. His concern in the process of selection and development of faculty has been to seek out and encourage the kind of intellectual capability that will enable a faculty member to "leave his thesis behind" and seek out new areas to explore.

The long-standing controversy of research versus teaching has continued locally and nationally during the decade of Schultz's tenure. He has maintained that faculty research is not detrimental to teaching, but, indeed, essential for keeping it alive and exciting. During the Schultz years, the annual dollar value of sponsored research has almost trebled, the range and sophistication of the research effort has greatly increased, and there has been a steady growth in the quantity and quality of graduate and postdoctoral work. A significant fact, attesting to the stature of the faculty, is that the research growth has been sustained during the past few years in the face of serious cutbacks in funds available to sponsoring agencies. As a supplement to sponsored research, Schultz has used a Ford Foundation grant to encourage research initiation by young faculty members and to assist experienced professors to move into new research fields.

Dean Schultz has been equally vigorous in his support of improvement in teaching methods, student advising, and in fact the whole student experience. He is fond of saying that engineering education has created the new technology, but does not know how to use it for its own purposes. In response, he has encouraged the faculty to experiment with new teaching techniques and devices, including audiovisual carrels, self-paced learning, and student-response systems, with the intent of improving both the effectiveness and the efficiency of the teaching operation.

A related goal is increased flexibility in the curriculum. During the tenure of Dean Schultz, the College has taken a number of steps to relax the rigidity of traditional engineering curricula without compromising the disciplined structure essential to professional education. One intent has been to enable faculty and students to explore new specialties, perhaps new combinations of studies, without committing the College to a formalized curriculum for each emerging specialty.

Changes in both the organization and content of programs at all levels have been extensive. The underclass Basic Studies program was revised, "mini courses" were instituted to bring freshmen into contact with faculty members from many departments and to introduce them to a variety of engineering fields, an expanded advising and counseling service was set up, and a program for minority-group students was established and supported with special counseling services and financial aid personnel. The dean's emphasis on new approaches stimulated a receptivity by the faculty toward flexibility and educational exploration. And it resulted in the development of a professional master of engineering program with orientation toward engineering design and project work, in parallel with the long-established M.S. and Ph.D. programs oriented toward research.

The efforts of Dean Schultz in developing the M.Eng. program reflect his strong advocacy of a practical relationship between engineering education and the "real world." An effective input from industry into the M.Eng. project work has been achieved, and a continuing education program and a consortium arrangement with a group of industries have been developed. Before "relevance" joined "viability" in the special jargon of education, Schultz was urging that engineering research not only continue to seek out new avenues of investigation and new pieces of knowledge, but that it be directed also toward an attack on the massive technological problems ahead, particularly those with complex sociological implications. Most areas of the College have initiated research projects and educational programs—some cooperatively with other divisions of the University—with such objectives.

This commentary has not become the usual catalog of a man's work in terms of dates and places, of assignments and affiliations, of achievement and recognition. The personal data sheet for Dean Schultz would have a full listing under these categories, but here is sufficient to say that in his professional life he has enriched his career as an engineering educator and administrator with a broad range of service as a member of governmental, industrial, and educational boards and commissions; as a consultant and adviser; and as a military officer.

Does this recital of some of the progress of engineering at Cornell during his deanship portray or even sketch the personality and character of Andrew Schultz? Probably not. Perhaps within it is the suggestion of a man to whom descriptive terms such as dynamic, forceful, competitive, and leader may be applied. Perhaps there is the suggestion of a man impatient with the status quo for its own sake but sensitive to the heritage of an institution and a profession. Perhaps the qualities of educational philosopher and spokesman appear in the review of the objectives of the educational developments accomplished during his tenure, though his writings and his work with educational agencies may reveal this more directly.

It is no surprise that, as the expression has it, "he is no stranger to conflict," for no man introduces change of this magnitude without controversy, and Schultz expounds and advances his ideas with conviction. But Andrew Schultz assumed the deanship during a period of turbulence in engineering education and national controversy over the role and direction of technology in society. It was a time during which his "can do" attitude, his persuasive energy, and his positive positions helped to shape distinctive programs and directions.

Over the years, Cornell engineering has had the singular good fortune to have the right man at the right time for leadership of the College. Andrew Schultz has fitted this pattern well.

—JOHN F. MCMANUS

John F. McManus, contributor of the article on Dean Schultz, writes from the perspective of long association with the College and three of its deans. He has been a member of the College of Engineering administrative staff since 1948, first as an executive assistant, then as assistant dean beginning in 1956, and since 1970 as associate dean with responsibilities for budgetary and personnel matters. He is a 1936 civil engineering graduate of Cornell and serves as 1936 class secretary. He is also secretary of the Engineering College Council, an advisory board.

Edmund T. Cranch

■ When Edmund T. Cranch becomes dean of engineering in December, the College will acquire the leadership of a man with extensive experience in engineering education at Cornell, in University affairs, in research and professional activities, and in national and international concerns involving technology.

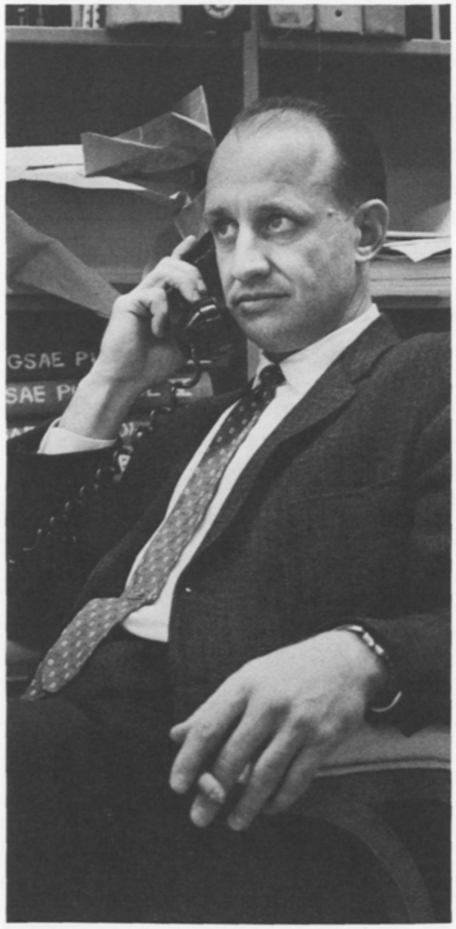
Dean Cranch first came to Cornell in 1943 as a student in the World War II naval training program. He had already completed two years of study at the Newark College of Engineering, and in 1945 he received both the B.M.E. degree (with distinction) from Cornell and a commission as a naval ensign. After active duty as engineering officer on a light cruiser and a year at the Bell Telephone Laboratories, he returned to Cornell to study for a Ph.D. in mechanics, mathematics, and physics, granted in 1951. He was appointed assistant professor of mechanics that year, and has been on the College faculty ever since. His service has included terms as head of the Department of Engineering Mechanics and Materials and as chairman of the Department of Theoretical and Applied Mechanics. He became associate dean of the College in 1967, with special responsibility in the area of graduate study and research.

He has been a member of the University Board of Trustees since 1970, when he was elected as a faculty representative. For the past year, while he was theoretically on sabbatic leave, he has served as chairman of the President's Advisory Committee on Long Range Financial Planning, which has just issued an extensive report expected to have an important bearing on the shaping of Cornell education for some years to come. And until very recently, he has been serving as director of Cornell's Program on Policies for Science and Technology in Developing Nations.

Throughout his career at Cornell, Dean Cranch has maintained an active teaching and research program. He is a professor of theoretical and applied mechanics, and has been a member also of the applied physics and mechanical engineering faculties, the Center for Applied Mathematics, and the Materials Science Center. His research interests include the dynamics of shells and wave propagation in solids, and he has published extensively in these and related fields. He is an author of the text, *Engineering Mathematics,* which is used in sophomore engineering mathematics courses. He has been active also as a consultant for industrial and research organizations.

During previous sabbatic leaves, Dean Cranch held National Science Foundation fellowships at Stanford University (1958-59) and at the Federal Institute of Technology in Zürich, Switzerland (1964-65).

He is a member of the American Society of Mechanical Engineers, the American Society for Testing and Materials, the Society for Experimental Stress Analysis, the American Society for Engineering Education, Sigma Xi, and Tau Beta Pi.



Edwin L. Resler, Jr.

■ Although it has changed names many times over the years, there has been a Sibley engineering college or school at Cornell for more than a century. This year a merger of faculties has created the Sibley School of Mechanical and Aerospace Engineering.

The new school combines the Sibley School of Mechanical Engineering, which included the Department of Mechanical Systems and Design and the Department of Thermal Engineering, and the Graduate School of Aerospace Engineering. Director of the new school is Edwin L. Resler, Jr., the Joseph Newton Pew Jr. Professor in Engineering, who has been director of the aerospace school. Albert R. George, associate professor of aerospace engineering, is assistant director.

The new alignment will make it possible for Cornell to respond more effectively to major problems of national concern, according to Professor Resler. These include the use and production of energy, the development of laser technology, and problems associated with transportation needs. These and related areas of activity are common to members of both the mechanical and aerospace faculties, Professor Resler said, and since there will be no departments within the new school, the coordination of activities in particular areas will be facilitated. "The merger will broaden the scope of both schools and enable us to do things that were not possible or were more difficult in the past," he said. "We think it will result in a better balance among advanced research study, professional graduate programs, and undergraduate education."

Involved in the merger are eighteen mechanical engineering and eight aerospace engineering professors, and sixty mechanical engineering and thirty aerospace engineering graduate students. There are currently 110 undergraduate mechanical engineering students in the upperclass years.

The name of Sibley was first used at Cornell for the Sibley College of the Mechanic Arts, named in honor of Hiram Sibley, an early benefactor. The name was altered from time to time to reflect changing areas of instruction and educational units. The Graduate School of Aerospace Engineering had its beginnings in 1946.

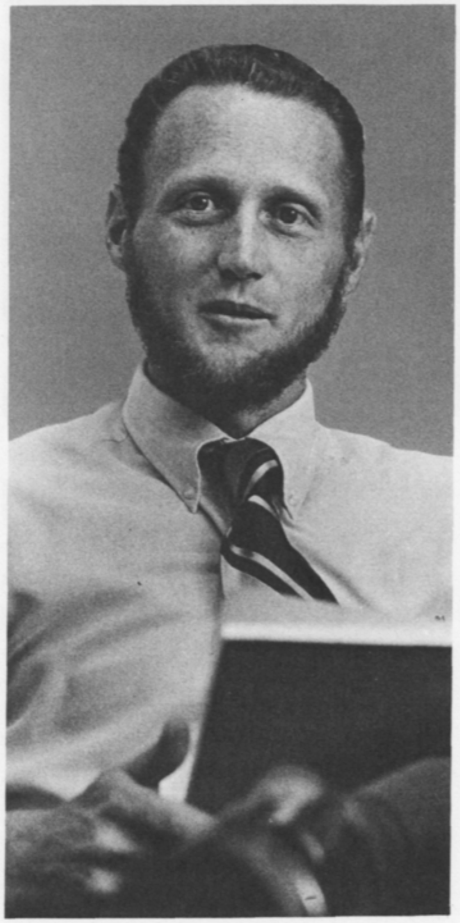
■ *A. Richard Seebass,* associate professor of aerospace engineering, has been named associate dean of the College of Engineering with major responsibility in the area of faculty research programs. He had served as acting associate dean since January.

Dean Seebass, a specialist in aerodynamics and in particular the phenomenon of sonic boom, has served on numerous national research and study panels concerned with problems in this area. Among these are the National Academy of Sciences Committee on SST-Sonic Boom.

In 1967–68 he spent a year at the National Aeronautics and Space Administration (NASA) headquarters, developing and revising research programs in fluid mechanics. He has served as consultant to the Department of Transportation Office of Noise Abatement, the Institute for Defense Analyses, and the General Applied Science Laboratories. In 1970 he spent a sabbatic leave as a faculty associate of the Boeing Scientific Research Laboratories.

Dean Seebass was graduated magna cum laude from Princeton University in 1958 with the degree of bachelor of science in engineering. In 1961 he was awarded the degree of master of science in engineering by Princeton, and in 1962 the doctor of philosophy degree in aerospace engineering by Cornell. He joined the Cornell faculty after completing his graduate studies.

A. Richard Seebass



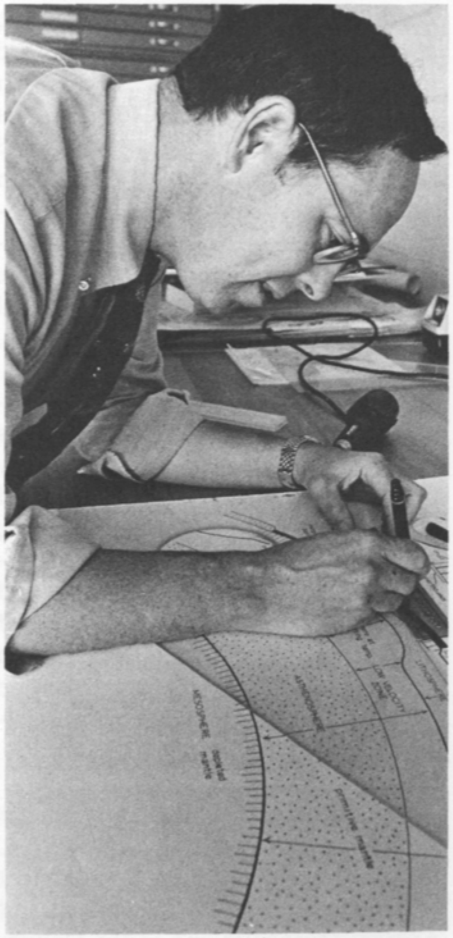
During his tenure at Cornell, Dean Seebass has served as graduate field representative for aerospace engineering and on a number of University and College committees. He has been a member of the Faculty Council and the administrative board of the Cornell Council. In 1968–69 he served as acting director of the Center for Applied Mathematics.

He is now serving the College as chairman of the Liaison Committee for the sophomore courses in engineering mathematics and as a member of the Core Curriculum Committee. In recent months he has worked on the Educational Goals and Priorities Subcommittee of the President's Advisory Committee on Long Range Financial Planning.

Dean Seebass is an editor, with thermal engineering professor Sidney Leibovich, of *Nonlinear Waves,* to be published by the Cornell University Press, and of *Sonic Boom Research,* published by NASA in 1967. He has published extensively in professional journals on his research in the fields of fluid mechanics, aerodynamics, and magnetohydrodynamics.

He is an associate fellow of the American Institute of Aeronautics and Astronautics and a member of the American Association for the Advancement of Science, the Society for Industrial and Applied Mathematics, Sigma Xi, and Tau Beta Pi.

John M. Bird



■ The appointment of *John M. Bird,* an internationally known specialist in plate tectonics, as professor of geological sciences is a part of the University's long-range plan to develop a strong center for teaching and research in the geological sciences at Cornell.

Professor Bird, who was formerly professor of geology and chairman of the Department of Geological Sciences at the State University of New York (SUNY) at Albany, is best known for his work in interpreting the evolution of mountain belts and geologic history of the northern Appalachian region in terms of the new theory of plate tectonics. As a modern theorist with interest and experience in field geology, he is felt to augment and complement the Cornell department's development as a center for study and research in the area of plate tectonics. Other recent senior faculty appointees, Jack E. Oliver, the chairman, and Bryan L. Isacks, are specialists in plate tectonics from the aspect of seismology and geophysics.

Professor Bird received his undergraduate degree with a major in geology from Union College in 1955. He took his graduate work at Rensselaer Polytechnic Institute, earning the M.S. in geology in 1959 and the Ph.D. in 1962. He joined the geology faculty at SUNY as an instructor during his last year in graduate school, and progressed to become chairman of the department in 1969 and a full professor in 1971. For the past several years he has also served as senior research associate at the Lamont-Doherty Geological Observatory of Columbia University.

His experience in field geology began during his undergraduate years, when he held a summer job as a mine geologist's assistant with the Sunshine Mining Company in Idaho. Later he served as a geologic consultant with the P. C. Mining Company in Wyoming and with James R. Dunn Associates in New York, and as a geologist for a geological survey conducted by the New York State Museum and Science Service. He has done field work in many areas, including eastern New York State, Quebec, Newfoundland, the Polish and Czechoslovakian Carpathians, the Swiss and Austrian Alps, and the Apennines of Italy.

In 1968 Professor Bird visited the Polish Academy of Sciences as an exchange visiting scientist under the auspices of the National Academy of Science. Last year he lectured at various North American universities as a distinguished visiting scientist of the American Geological Institute.

Especially noted among his published works are several papers, with John F. Dewey of SUNY, on the application of plate tectonic theory to the Appalachians, particularly of the geographical area of eastern New York State.

Professor Bird is a fellow of the Geological Society of America and the Geological Association of Canada, and a member of the American Geophysical Union, the American Association for the Advancement of Science, and Sigma Xi. He is currently serving as chairman of the Appalachian Working Group of the United States Geodynamics Project. He is an associate editor of the *Journal of Geophysical Research* and a critical reader for several other professional journals.

■ Among new faculty members of the College is *Patrick P. Bergmans,* assistant professor of electrical engineering. A native of Belgium, he attended the State University of Ghent, which granted him the B.E.E. degree in electrical engineering in 1968 and the B.Eng. Physics degree in 1969. He was awarded the Ph.D. in electrical engineering by Stanford University this past June. Professor Bergmans is a specialist in the areas of information theory, computer systems, and linear systems theory. He has had summer work experience with a Belgian firm engaged in nuclear reactor development and in electronic data-processing techniques. His theoretical research work has been in information and communication theory.

■ Returning to his undergraduate and graduate university as a visiting professor in the Department of Operations Research this year is *Saul Blumenthal,* a specialist in statistics who is a professor in the Department of Industrial Engineering and Operations Research at New York University. He received the B.M.E. degree from Cornell in 1958 and the Ph.D. in 1962.

■ *Perino M. Dearing, Jr.*, a specialist in location theory, joined the Department of Operations Research this fall as an assistant professor, after completing his work for the Ph.D degree from the University of Florida. He also holds B.S. and M.A. degrees in mathematics from the University of North Carolina, and an M.E. from Florida in operations research. He has had experience in the teaching of college mathematics and as a mathematician for the Air Force.

■ *Lutgard C. De Jonghe,* a specialist in ceramic materials, is a new assistant professor of materials science and engineering. A native of Belgium, he studied at the Higher Technical Institute for his B.S. degree, granted in 1961. He received the M.S. degree in metallurgy in 1968 from Delaware University, and the Ph.D. in materials science in 1970 from the University of California at Berkeley. During 1961-65, Professor De Jonghe was employed as a scientist at the Nuclear Research Center in Belgium, and from 1970 until he came to Cornell, he was a postdoctoral fellow in applied physics at Harvard University.

■ New on the faculty of the School of Civil and Environmental Engineering is *J. Neil Kay,* an assistant professor whose speciality is soil mechanics. A native of Australia, Professor Kay received his undergraduate education at the University of New South Wales, earning the B.E. degree in mining engineering in 1957. He was awarded M.S. and Ph.D. degrees in civil engineering in 1969 and 1971, respectively, at Northwestern University. He has had ten years' experience in field work, first in Australia as an engineer and project manager in building construction, and later in Hawaii as a project manager in soil mechanics and foundation engineering and as a design engineer in subdivision development. Last year he served as an assistant professor of civil engineering at San Diego State College.

■ *Pamidipula Kotiveeriah,* a 1972 Cornell Ph.D. in electrical engineering, has joined the electrical engineering faculty as an instructor this year. He received his undergraduate education in India, his native country, earning the B.E. degree at Andhra University in 1959 and the B.Eng. at the Indian Institute of Science in 1961. He was awarded an M.E.E. degree from Stevens Institute of Technology in 1968. He is a specialist in systems and network theory.

■ An associate professor new to the College of Engineering is *Simon A. Levin,* who holds a joint appointment in the Department of Theoretical and Applied Mechanics and in the University's Section of Ecology and Systemics of the Division of Biological Sciences. He first came to Cornell in 1965 as an assistant professor in the College of Arts and Sciences, and last year was promoted to associate professor of applied mathematics. His main area of interest is the application of mathematics to various fields, including ecological and evolutionary studies, artificial intelligence, and mechanics. Professor Levin holds the B.A. degree from Johns Hopkins University (1961) and the Ph.D. in mathematics from the University of Maryland (1964).

■ *Aaron Lewis,* assistant professor of biophysics in the School of Applied and Engineering Physics, recently completed a two-year period at Cornell as an NIH postdoctoral fellow, working on the spectroscopy of biopolymers. His major research interest is in the area of laser Raman scattering from molecules of biological interest. Professor Lewis graduated from the University of Missouri in 1966 with a B.S. degree in chemistry and mathematics, and earned the Ph.D. in molecular spectroscopy at Case Western Reserve University in 1970. Before coming to Cornell, he did postdoctoral research in quantum mechanics at Case Western Reserve.

■ A Cornell Ph.D. and former postdoctoral research associate who has been appointed assistant professor of applied physics is *Richard V. E. Lovelace,* a specialist in plasma physics and radio astronomy. He received his B.S. degree in physics in 1964 from Washington University, and then came to Cornell for his graduate work in theoretical physics. As an NSF graduate fellow, he did his postdoctoral research in the Cornell Laboratory of Plasma Studies, working on a thermonuclear fusion reactor project. Professor Lovelace has had summer work experience with the MacDonnell Aircraft Corporation and has spent time in research at the National Astronomy and Ionosphere Center in Arecibo, Puerto Rico, at the Institute of Theoretical Astronomy in Cambridge, England, and at the Lawrence Radiation Laboratory, Livermore.

■ New to the Department of Thermal Engineering this year is Assistant Professor *William J. McLean,* who recently completed doctoral research in combustion and air pollution at the University of California at Berkeley. He received all three of his degrees in mechanical engineering from Berkeley: the B.S. in 1963, the M.S. in 1965, and the Ph.D. in 1971. During his graduate years, he was an Air Pollution Special Fellow under the sponsorship of the Environmental Protection Agency, and in 1971 he was awarded a NASA postdoctoral associateship. Prior to his doctoral studies, he had several years' experience as a development engineer with the Aerojet General Corporation. He spent the past year as a research scientist at Lockheed Research Laboratory, investigating environmental effects of supersonic transport aircraft.

■ An instructor this year in the Division of Basic Studies is *George D. Meixel, Jr.,* who is completing his Cornell Ph.D. in plasma physics. He received his B.S. degree from Cornell in 1967 and spent one year in graduate study at Princeton University before returning to Cornell for his Ph.D. work. He has served as a teaching assistant in the Department of Theoretical and Applied Mechanics and as a graduate research assistant in the Laboratory of Plasma Studies.

■ *Charles G. Moore III,* assistant professor in the Department of Computer Science, is a specialist in systems design and operating systems. He received the B.A. degree in mathematics from Dartmouth College in 1965, and the M.A. and Ph.D. in computer and communications sciences from the University of Michigan in 1967 and 1971, respectively. Before coming to Cornell, he spent some months at the University of Bologna, Italy, as a consultant in queueing network simulation, and at the University of Grenoble, France, as a researcher in the use of virtual machines.

■ *Vincent O. S. Olunloyo,* a Cornell-educated engineer from Nigeria, has joined the faculty as an acting assistant professor in the Department of Theoretical and Applied Mechanics and the Division of Basic Studies. His Cornell degrees are the B.S. in mechanical engineering and the Ph.D. in fluid mechanics, awarded in 1967 and 1972, respectively. Last year Professor Olunloyo served as a postdoctoral associate in theoretical and applied mechanics, and as a tutor in the undergraduate minority-student program. He has had summer work experience as an environmental systems engineer with the International Business Machines Corporation.

■ *Clifford S. Orloff,* who studied at Cornell for both B.S. and Ph.D. degrees, has joined the faculty this fall as an assistant professor in the Division of Basic Studies and the Department of Environmental Engineering. After receiving his undergraduate degree in industrial engineering and operations research in 1968, Professor Orloff studied at the Massachusetts Institute of Technology, and in 1970 was granted the M.S. degree in civil engineering systems, with specialization in computer applications. His Ph.D. dissertation, completed last summer, concerns vehicle routing and scheduling algorithms.

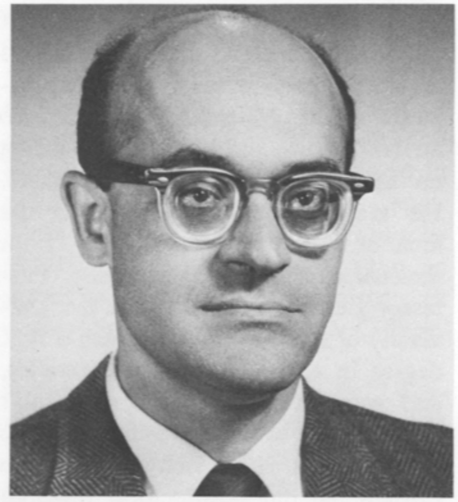
■ Under a joint appointment by the Department of Economics in the College of Arts and Sciences and the

School of Civil and Environmental Engineering, *Richard E. Schuler* has joined the faculty as an assistant professor in the area of environmental economics. His degrees are in engineering (the B.E. degree in electrical engineering from Yale University in 1959), business administration (the M.B.A. from Lehigh University in 1969), and economics (the Ph.D. from Brown University in 1972). Before completing his graduate studies, he accrued ten years' experience in application engineering and in marketing and public relations with the Pennsylvania Power and Light Company, and as an energy economist with the Battelle Memorial Institute.

■ New to the operations research faculty this year is Assistant Professor *Dennis G. Severance,* a specialist in management information systems. After receiving the B.S. degree in mathematatice from the Polytechnic Institute of Brooklyn in 1965 and the M.S. in mathematics from the University of Michigan in 1966, he spent two years developing information systems at the Pentagon. In 1969 he returned to Michigan to continue graduate study in the area of computer and communications systems, earning the M.S. degree in 1970 and the Ph.D. in 1972. Professor Severance's experience in the field of operations research includes developmental work in information systems at the General Motors Proving Grounds, analysis for the United States Army Management Systems Support Agency, and systems programming for the Bell Telephone Laboratories.

■ The application of mathematics to ecological problems is a major research interest of *Christine Shoemaker,* who joined the School of Civil and Environmental Engineering faculty this fall as an assistant professor. Last year, as a research associate at Cornell, she worked in the Department of Entomology and the Center for Environmental Quality Management on a joint project on ecology and systems analysis in pest control problems. She is continuing her work on this project along with her new teaching responsibilities. Professor Shoemaker holds two degrees in mathematics: the B.A., awarded by the University of California at Davis in 1966, and the Ph.D., awarded by the University of Southern California in 1971.

■ *Shoichi Yoshikawa* is working in the Laboratory of Plasma Studies this year as the Mary Shepherd B. Upson Visiting Professor of Engineering. A senior research physicist in plasma physics at Princeton University, he received his B.S. degree in physics from the University of Tokyo in 1958 and his M.S. and Ph.D. degrees in nuclear engineering from the Massachusetts Institute of Technology in 1960 and 1961.



■ *Bruno A. Boley,* chairman of the Department of Theoretical and Applied Mechanics since 1968, will become dean of the Technological Institute of Northwestern University in January. He will replace Walter S. Owen, who also went to the Northwestern deanship from Cornell and is now vice president for science and research there.

Boley, who holds the Joseph P. Ripley Professorship in Engineering at Cornell, previously served as professor of civil engineering at Columbia University. He has taught also at Ohio State University and at the Polytechnic Institute of Brooklyn, where he earned his graduate degrees. He received his undergraduate education at City College of New York.

He is the author of numerous technical papers and of three books on temperatures and materials, and is currently serving on the editorial boards of six professional journals. He is a member of the American Society of Mechanical Engineers and the International Union of Theoretical and Applied Mechanics.

FACULTY PUBLICATIONS

The following publications and conference papers by faculty members and graduate students of the Cornell College of Engineering were published or presented during February, March, and April 1972. Earlier publications inadvertently omitted from previous listings are included here with the date in parentheses. The names of Cornell personnel are in italics.

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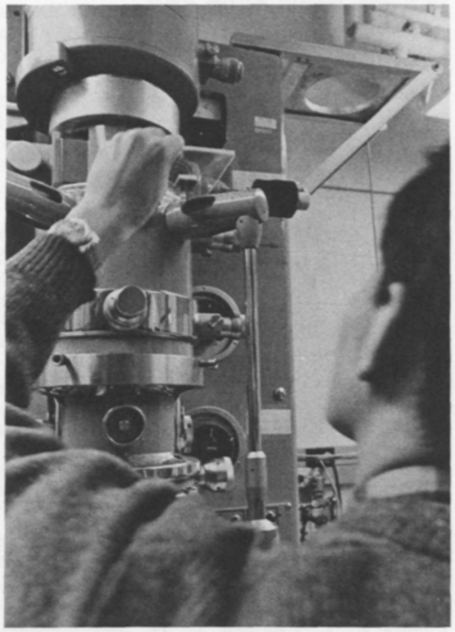
Seeing With Electrons and Ions



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The articles on high-resolution microscopy in this issue of the *Quarterly* discuss some of the highly scientific work that forms a part of the research program at the College of Engineering. The projects described here have a double thrust: they are contributing fundamental knowledge and providing highly sophisticated new tools and techniques for basic research and at the same time they are contributing to the solution of specific problems in applied science.

John Silcox and his group, for example, are using the electron microscope in conjunction with an electron spectrometer to obtain new information by analyzing the energy distribution of scattered electrons. As physicists, Silcox and his associates are interested in the fundamental physics of electron scattering; as engineers, they are interested in developing the instrumentation and techniques needed to solve practical problems.

Benjamin M. Siegel and his associates, who are conducting research in the more established field of transmission electron microscopy, are working toward direct observation of the primary structure of biologically important macromolecules. Here again, while the work involves basic physics, extensive innovation in electron optical instrumentation is required, and the results have great import in applied science.

Stephen L. Sass, another *Quarterly* contributor, describes some of the ways in which Cornell professors and their groups are using transmission electron microscopy for research in materials science and engineering. Among professors who are directing research in this area are Robert W. Balluffi, Boris W. Batterman, Che-Yu Li, Paul S. Ho, Dieter G. Ast, and Edward J. Kramer; the subjects being studied include defects in metals, polymer structure, and electrical properties of amorphous materials. Transmission electron microscopists in other College departments include George G. Cocks of Chemical Engineering, who has been studying polymers and, most recently, the structure of yeast-cell plasmalemma by a freeze-etching technique; and Miriam Salpeter of Applied Physics, whose interests are in biological studies, especially cytology.

Field ion microscopy, discussed here by David N. Seidman, provides another approach to high-resolution microscopic study. Seidman describes its applications to the study of metal surfaces. Field electron microscopy, using high resolution energy analysis in the study of chemical reactions and electron structure of solid surfaces, is being carried out by Thor Rhodin of Applied Physics.

"Seeing with electrons and ions," one facet of a varied program in research at the College, serves to illustrate that a hallmark of modern "engineering" research is the productive combination of "pure" and "applied" science.

—THE EDITOR