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The Scanning Tunneling Microscope

A new kind of microscope reveals the structures of surfaces atom by atom. The instrument's versatility may extend to investigators in the fields of physics, chemistry and biology

by Gerd Binnig and Heinrich Rohrer

"The surface was invented by the devil," said the illustrious physicist Wolfgang Pauli. Pauli's frustration was based on the simple fact that the surface of a solid serves as the boundary between it and the outer world. Whereas an atom within a solid is surrounded by other atoms, an atom at a surface can interact only with other atoms on the surface, with atoms beyond the surface or with those immediately under it. The properties of the surface of a solid therefore differ radically from those of the interior. For instance, to minimize energy, surface atoms often arrange themselves differently from the other atoms in a solid. The resulting complexities of surface structures have long thwarted efforts to derive precise experimental and theoretical descriptions of them.

At the IBM Zurich Research Laboratory we have developed a device that makes it possible to characterize in a quantitative way such surface complexities: the scanning tunneling microscope. Our microscope enables one to "see" surfaces atom by atom. It can even resolve features that are only about a hundredth the size of an atom. Such a tool has important implications, for example, in the microelectronic industry. As the silicon chip, which is the key element in computer architecture, decreases in size its surface area increases sharply in relation to its volume. Therefore the surface becomes increasingly important in the chip's operation and in its interactions with other logic elements. The scanning tunneling microscope will probably contribute to the understanding of other physical, chemical and biological phenomena as well.

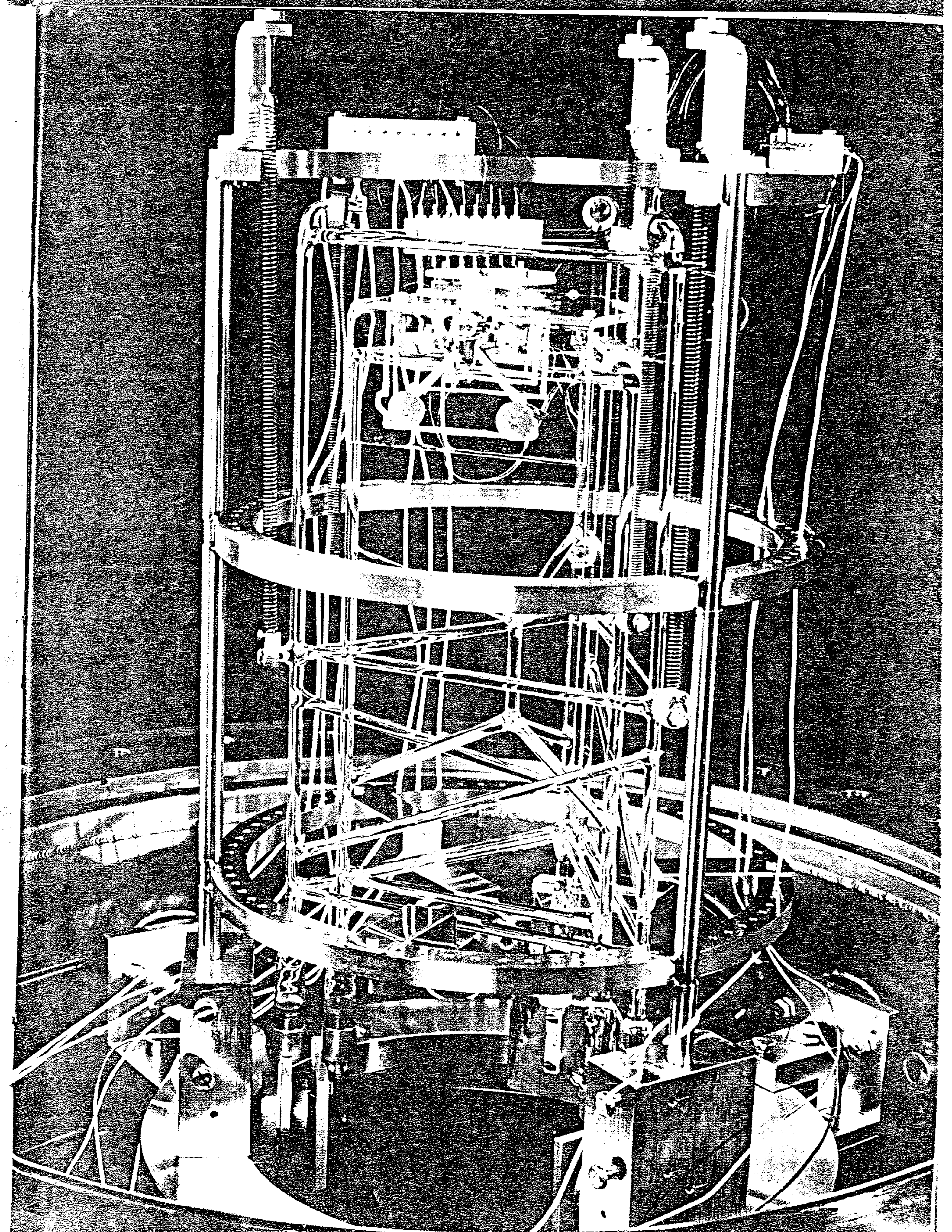
Scanning tunneling microscopy is the product of considerable evolution. Microscopy appears to have begun in the 15th century when simple magnifying glasses were made with which to observe insects. In the late 17th century Antony van Leeuwenhoek developed the optical microscope, which revealed the existence of single cells, pathogenic agents and bacteria. Although optical microscopy has developed into a sophisticated, versatile technique, a physical limit hampers it: the optical microscope cannot resolve atomic structures. The reason is that the average wavelength of visible light is about 2,000 times greater than the diameter of a typical atom, which is about three angstrom units. (One angstrom unit is one ten-billionth of a meter.) In other words, trying to probe atomic structures with visible light is like trying to find hairline cracks on a tennis court by bouncing tennis balls off its surface.

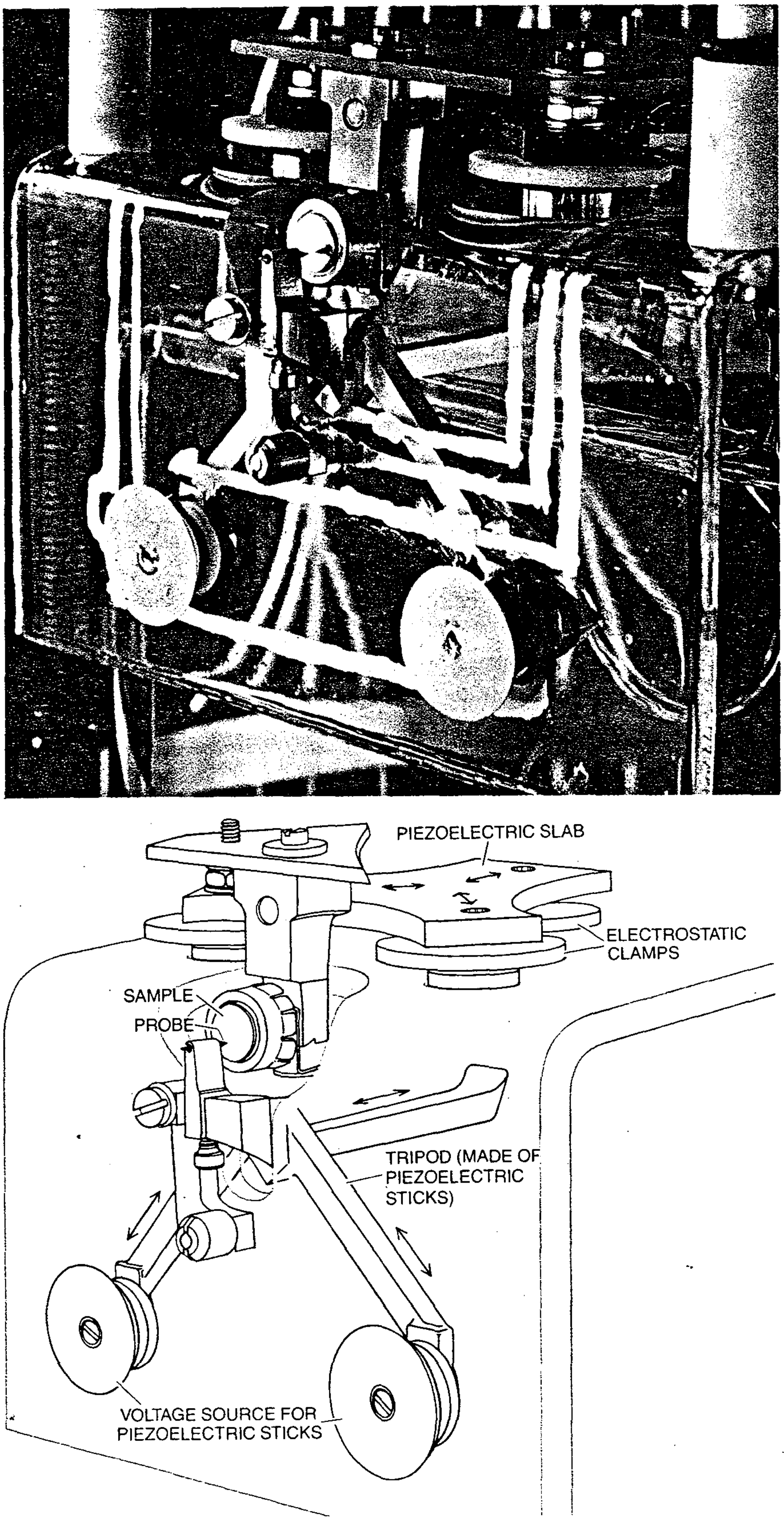
The first successful exploration of atomic structures grew out of a basic discovery of quantum mechanics. It is that light and other kinds of energy exhibit characteristics of both particles and waves. In 1927 Clinton J. Davisson and Lester H. Germer of the Bell Telephone Laboratories confirmed the wave nature of the electron. They also found that a high-energy electron has a shorter wavelength than a low-energy electron. An electron of sufficient energy exhibits a wavelength comparable to the diameter of an atom. This fact led to the invention of the electron microscope. With electron microscopy projections of atomic rows and even atomic orbitals in thin crystalline films have been observed.

Since the electron microscope has such a high resolving power, why was it necessary to develop a new kind of microscope? Although electron microscopy has proved to be extremely successful in observing the bulk features of crystalline materials, it cannot resolve surface structures except under very special circumstances. A high-speed electron penetrates deep into matter and so reveals little of the surface structure. A slow-moving electron is easily deflected by the charges and the electric and magnetic fields of the sample. In the 1950's Edwin W. Müller made some progress when he invented the field-ion microscope, an instrument that is highly sensitive to surfaces. Unfortunately its range of applicability is narrow: a sample must sit on a fine needle tip that is only a few angstroms wide and the sample must be stable against the high electric fields characteristic of the technique.

The principle of operation of the scanning tunneling microscope makes it possible to avoid these difficulties. The main difference between the scanning tunneling microscope and all other microscopes is that it uses no free particles; consequently there is no need for lenses and special light or electron sources. Instead the bound electrons already existing in the sample under

SCANNING TUNNELING MICROSCOPE has two stages, suspended from springs, that nestle within a cylindrical stainless-steel frame. The innermost stage contains the microscope mechanism. To achieve high-resolution images of surface structures the microscope must be shielded from even such small vibrations as those caused by footsteps and sound. The copper plates (attached to the bottom of the stainless-steel frame) and the magnets (attached to the bottom of the inner and outer stages) damp vibrations. Any disturbance causes the copper plates to move up and down in the field generated by the magnets. The movement induces eddy currents in the plates. The interaction of the eddy currents with the magnetic field retards the motion of the plates and hence the motion of the stages. For work required in a vacuum a steel cover is placed over the outer frame of the microscope.





MICROSCOPE DEVICE contains a sample and a scanning needle. Piezoelectric materials, which expand or contract when voltage is applied to them, enable the device to resolve features that are only about a hundredth the size of an atom. A piezoelectric drive positions the sample on a horizontal metal plate. A piezoelectric tripod then sweeps the scanning needle over the surface of the sample, simultaneously achieving high stability and precision.

investigation serve as the exclusive source of radiation.

To understand this principle imagine that the electrons bound to the surface of the sample are analogous to the water of a lake locked in by the shore. Just as some of the lake water seeps into the surrounding land to form groundwater, so some of the electrons on the sample's surface leak out and form an electron cloud around the sample. According to classical physics, no electron cloud exists because reflection at the sharp boundaries of surfaces confines the particles. In quantum mechanics, however, each electron behaves like a wave: its position is "smeared out." This accounts for the existence of electrons beyond the surface of matter. The probability of finding an electron beyond the surface of a conductor falls rapidly, in fact exponentially, with distance from the surface. Since the electrons appear to be digging tunnels beyond the surface boundary, the effect is traditionally known as tunneling.

The first experimental verification of tunneling was made about a quarter of a century ago by Ivar Giaever of the General Electric Company. A thin, rigid insulating layer was used to separate two metal plates called electrodes. The gap between the electrodes was small enough to allow the electron clouds associated with the electrodes to overlap slightly. A potential difference between the electrodes, induced by applying voltage to them, causes electrons to flow from one electrode to the other through the overlapping clouds. The flow is analogous to the flow of groundwater between two adjacent lakes when one lake is higher than the other.

We built our scanning tunneling microscope by making a few basic changes in the standard tunneling configuration. First we replaced one of the electrodes with the sample we wanted to investigate. Then we replaced the other electrode with a sharp, needlelike probe. Finally we replaced the rigid insulating layer with a nonrigid insulator such as liquid, gas or vacuum so that we could scan the needle tip along the contours of the sample's surface.

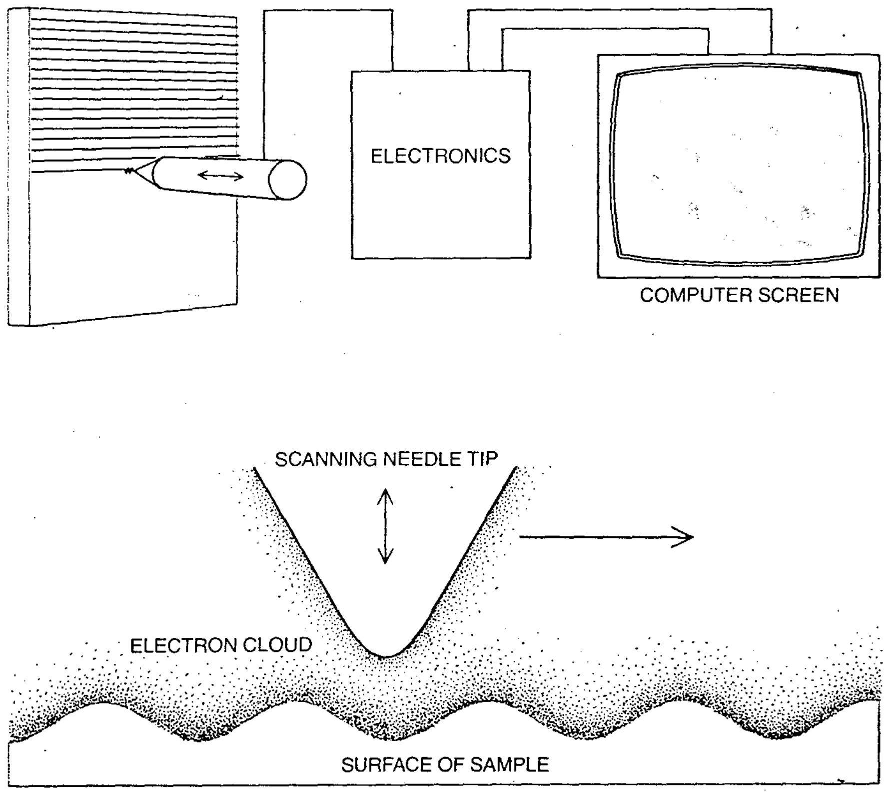
To scan the surface we push the tip toward the sample until the electron clouds of each gently touch. The application of a voltage between the tip and the sample causes electrons to flow through a narrow channel in the electron clouds. This flow is called the tunneling current. Since the density of an electron cloud falls exponentially with distance, the tunneling current is extremely sensitive to the distance between the tip and the surface. A change in the distance by an amount equal to the diameter of a single atom causes the tunneling current to change by a factor of as much as 1,000.

We exploit the sensitivity of the tunneling current to produce exquisitely precise measurements of the vertical positions of the atoms on the sample's surface. As the tip is swept across the surface a feedback mechanism senses the tunneling current and maintains the tip at a constant height above the surface atoms. In this way the tip follows the contours of the surface. The motion of the tip is read and processed by a computer and displayed on a screen or a plotter. By sweeping the tip through a pattern of parallel lines a three-dimensional image of the surface is obtained. A distance of 10 centimeters on the image represents a distance of 10 angstroms on the surface: a magnification of 100 million.

How is it possible to move the needle over a sample while maintaining a gap between the tip and the surface that is less than 10 angstroms and achieve a stability and precision that is better than .1 angstrom? First, the microscope must be shielded from vibrations such as those caused by sound in the air and by people walking around in a building. Second, the drives of the needle must be highly precise. Finally, the tip must be as sharp as the limits of rigidity and stability allow.

Two stages, or sections, suspended from springs, nestle within the stainless-steel cylindrical frame of the microscope and protect the tunneling gap from vibration. Both stages, triangular in cross section, are made of glass rods. The second stage slips into the first stage, from which it is suspended by three springs. The first stage in turn is suspended from the outer frame, also by three springs. The second stage carries the heart of the microscope: it contains both the sample and the scanning needle.

When the entire microscope sits in a vacuum, air resistance is minimal and the first and second stages could, if they were disturbed, bounce up and down almost indefinitely. To stop this motion we rely on the phenomenon of eddy-current damping. We let copper plates attached to the bottom of the first and second stages slide between magnets attached to the outer frame. As each plate slides up and down, the magnetic field causes the conducting electrons of the copper to move around, inducing a so-called eddy current. The reaction between the eddy current and the magnetic field retards the motion of the plate and thereby protects the microscope from even the smallest vibrations.



ELECTRON TUNNELING is the phenomenon that underlies the operation of the microscope. An electron cloud occupies the space between the surface of the sample and the needle tip (*bottom*). The cloud is a consequence of the indeterminacy of the electron's location (a result of its wavelike properties); because the electron is "smeared out," there is a probability that it can lie beyond the surface boundary of a conductor. The density of the electron cloud decreases exponentially with distance. A voltage-induced flow of electrons through the cloud is therefore extremely sensitive to the distance between the surface and the tip. As the tip is swept across the surface a feedback mechanism senses the flow (called the tunneling current) and holds constant the height of the tip above the surface atoms (*top*). In this manner the tip follows the contours of the surface. The motion of the tip is read and processed by a computer and displayed on a screen or a plotter. Sweeping the tip through a pattern of parallel lines yields a high-resolution, three-dimensional image of the surface.

Once the gross vibrations have been stopped the sample can be positioned. This is done with a specially developed drive that carries the sample across a horizontal metal plate on the second stage. The body of the drive consists of a slab of piezoelectric material that expands or contracts when voltage is applied. The drive has three metallic feet, arranged in triangular fashion, that are coated with a thin layer of insulating material. They can be clamped to the metal plate by establishing a voltage between them and the metal plate.

We move the drive in the following manner. Suppose, for instance, we clamp only one foot and apply a voltage to the piezoelectric body so that it contracts. The other two feet will move slightly. We then clamp those two feet, release the third foot and remove the applied voltage so that the body expands back to its original size. The drive has just moved one step. The step width can be varied between 100 and 1,000 angstroms. Since the drive can rotate about each of its feet, it can walk along the plate in any desired direction.

When the drive has carried the sample to the wanted tunneling position, we begin scanning the surface of the sample. We use a rigid tripod made of three piezoelectric sticks to move the tip of the scanning needle. When we apply a voltage to expand or contract one of the sticks, the other two bend slightly. Consequently the tip moves in a straight line over distances as great as 10,000 angstroms. Furthermore, this motion is quite sensitive to the magnitude of the applied voltage: a voltage on the order of .1 volt results in a motion of 1.0 angstrom. The precision of the tripod's drive is so good that at present only vibration limits the vertical resolution of the sample's surface. This resolution at present is in the range of approximately a few hundredths of an angstrom.

The lateral resolution of the surface is limited by the sharpness of the tip. In this instance nature has been kind to the vacuum tunneler. It is relatively easy to make a sharp tip that yields a lateral resolution of about six to 12 angstroms: one simply grinds the end of a needle, which is usually made of tungsten.

To achieve a lateral resolution of two angstroms, however, the needle must have a single atom sitting securely on top of its tip. Such an atom usually comes from the sample itself. It is dislodged by high electric fields that are caused by applying a voltage difference of from two to 10 volts between the sample and the tip. Since luck plays a large role in the final stage, we are trying to sharpen the tip by bombarding it with a high-energy beam of ions. This causes the atoms on the surface to sputter away in a highly controlled manner.

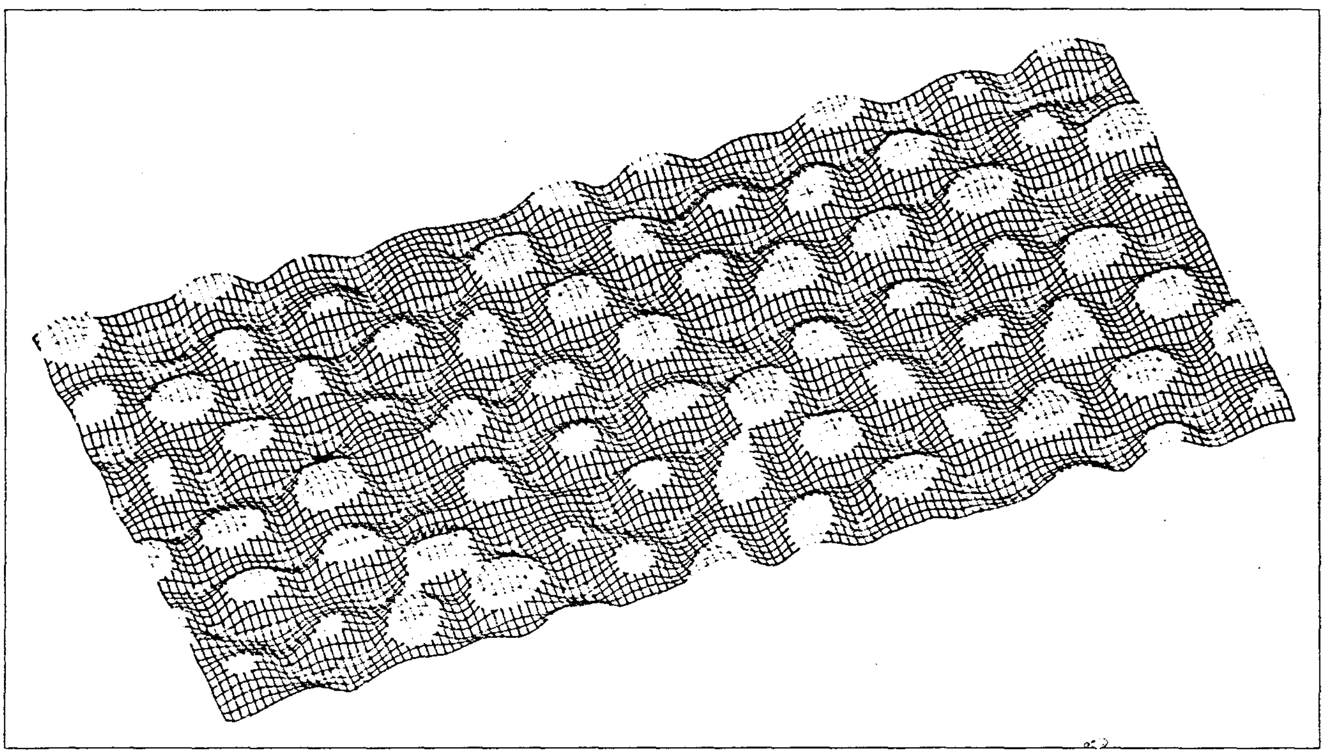
In addition to delineating the atomic topography of a surface, the scanning tunneling microscope reveals atomic composition. The tunneling current depends both on the tunnel distance and the electronic structure of the surface and on the fact that each atomic element has an electronic structure uniquely its own.

The ability of the microscope to resolve both topography and electronic structure will make it useful to investigators in physics, chemistry and biology. We first pursued the simplest case: the topographic structures of single crystals characterized by a homogeneous surface structure. Crystals consist of identical atomic layers built one on top of another. While results from scattering experiments indicate that the top layer is different from and more complex than the others, the precise structure of this layer was hard to determine.

The best-known surface structure is the diamond-shaped unit cell of silicon. Since each of the four edges of the cell measures seven atomic spacings, the cell is referred to as the 7-by-7. Each 7-by-7 contains 12 bumps that have not been visualized before. Each bump apparently corresponds to a single atom. The arrangement of the surface atoms is, although aesthetically pleasing, quite complex. This is in contrast to the relatively simple structure of any bulk layer found in silicon. Its unit cell, 49 times smaller in area than the 7-by-7, contains only two atoms. Another great difference between the two kinds of layers is that the surface layer is much rougher than any bulk layer. Although the surface pattern is now known and a vast amount of information about it has been gained from other experiments, the reason this and not a different structure forms is not yet understood.

Another crystal whose surface structure is now better understood is the gold crystal. We found that when we cut the crystal in a direction parallel to its atomic layers, the resulting face is smooth. A cut in a direction diagonal to the atomic layers results in a rougher face. Just as one learns from studying the earth's crust how it was formed millions of years ago, so we have learned from studying these surfaces how they took shape. Current theories reveal that the diagonally cut surface assumes its jagged nature because such a configuration has a lower energy and is consequently stabler than a smooth configuration.

A more exotic branch of physics, the study of superconductivity, has also benefited from the application of scanning tunneling microscopy. A superconducting material is characterized by its complete lack of electrical resistance. The use of superconductors to make cables that are free from power losses could save enormous amounts of energy. The colliding-beam acceler-



SURFACE OF SILICON as disclosed by the scanning tunneling microscope consists of a pattern of diamond-shaped unit cells. Each cell measures 27 angstrom units (one angstrom unit is one ten-billionth of a meter) on a side. The cell is called the 7-by-7 because each side measures seven atomic units. Each 7-by-7 contains 12 bumps that are arranged in two groups of six. The bumps, which have never before been resolved, apparently correspond to the surfaces of individual atoms. They stand as much as 1.3 angstroms above the rest of the surface. The image was formed by applying a voltage so that electrons flowed from the needle tip to the surface.

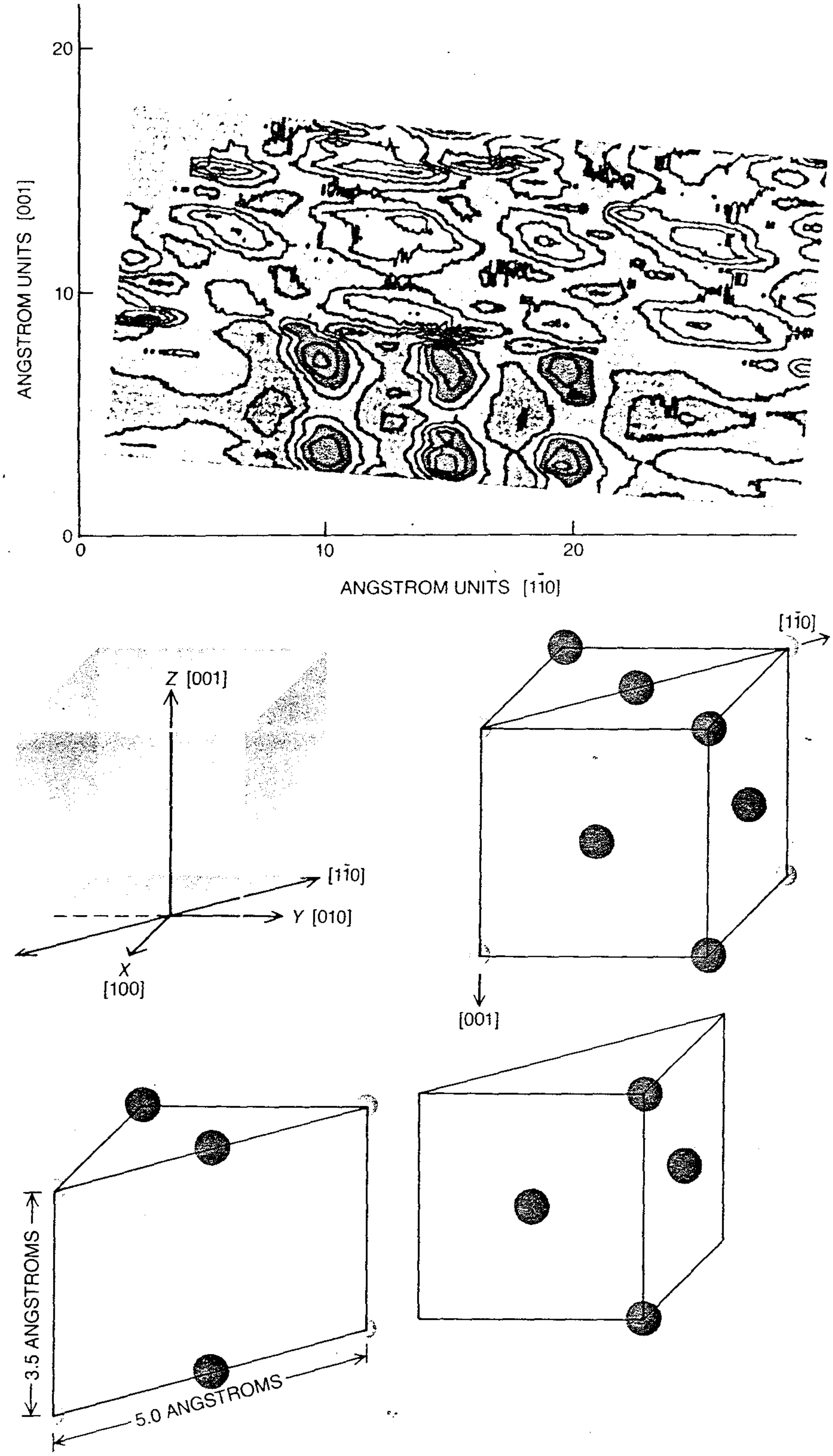
ator at Fermilab uses superconducting magnets to achieve high magnetic fields while saving energy. There is a catch, however. Superconductivity is only known to occur in some conductors that have been chilled below a critical temperature, typically a few degrees above absolute zero (−273 degrees Celsius).

A group of Stanford University investigators led by Calvin F. Quate has developed a scanning tunneling microscope that operates effectively at low temperatures. The workers first used their microscope to map the electronic structure of the surfaces of several conductors at room temperature. Then they chilled the conductors below the critical temperature of each and recorded the changes in electronic structure. The group can now document the growth of regions of superconductivity on surfaces.

The scanning tunneling microscope has also led to new understanding of certain chemical interactions. Our group has now observed on an atomic scale the adsorption of oxygen by nickel [*see illustration at right*]. Our finding confirms the results from earlier scattering experiments: The spacing of the oxygen atoms bound to the nickel surface varies according to direction. In particular, oxygen atoms that lie in one specific direction, designated [001], are separated by one lattice spacing, or the distance between two adjacent nickel atoms in that direction. Oxygen atoms that lie in another direction, designated [1$\bar{1}$0], are separated by two or five lattice spacings but never by one, three or four. We suspect that some kind of screening effect between the electric charges of the nickel and oxygen atoms is responsible for the anomaly, but more investigation is needed to determine the actual details of the physical interaction.

All the applications we have so far discussed have hinged on the ability of the microscope to detect structures whose dimensions are measured in mere fractions of an angstrom. Such high resolution is not always necessary. Even where the resolution of the scanning tunneling microscope is no better than some tens of angstroms, we expect on the basis of previous results that it will yield novel information and stimulate significant progress. In particular the possibility of operating the scanning tunneling microscope in air at ordinary pressure will in many applications more than compensate for any loss in resolution.

One such application is found in the study of friction. In order to minimize friction energy losses, investigators are



OXYGEN ADSORBED ON NICKEL (*top*) is observed on an atomic scale. The oxygen atoms (*color*) are 3.5 angstroms apart in one direction, designated [001], and 5.0 angstroms apart in the other, [1$\bar{1}$0]. The face-centered cubic model of the nickel crystal (*bottom*) suggests the reason. The geometry of the model dictates that if the lattice spacing between two adjacent nickel atoms in the [001] direction is 3.5 angstroms, the spacing in the [1$\bar{1}$0] direction must be 2.5 angstroms. The electronic repulsion between two oxygen atoms is too great, however, to allow them to rest stably at lattice points separated by a mere 2.5 angstroms. Therefore oxygen atoms lying along the [1$\bar{1}$0] direction must be separated by at least two lattice spacings, which corresponds to the observed 5.0-angstrom distance. Separations of five lattice spacings are sometimes seen, but never separations of three or four. Additional investigation may yet disclose the underlying reasons for the anomaly.

interested in learning more about the structure and causes of surface roughness of industrial materials. Recent studies suggest that the scanning tunneling microscope is ideally suited to the required work.

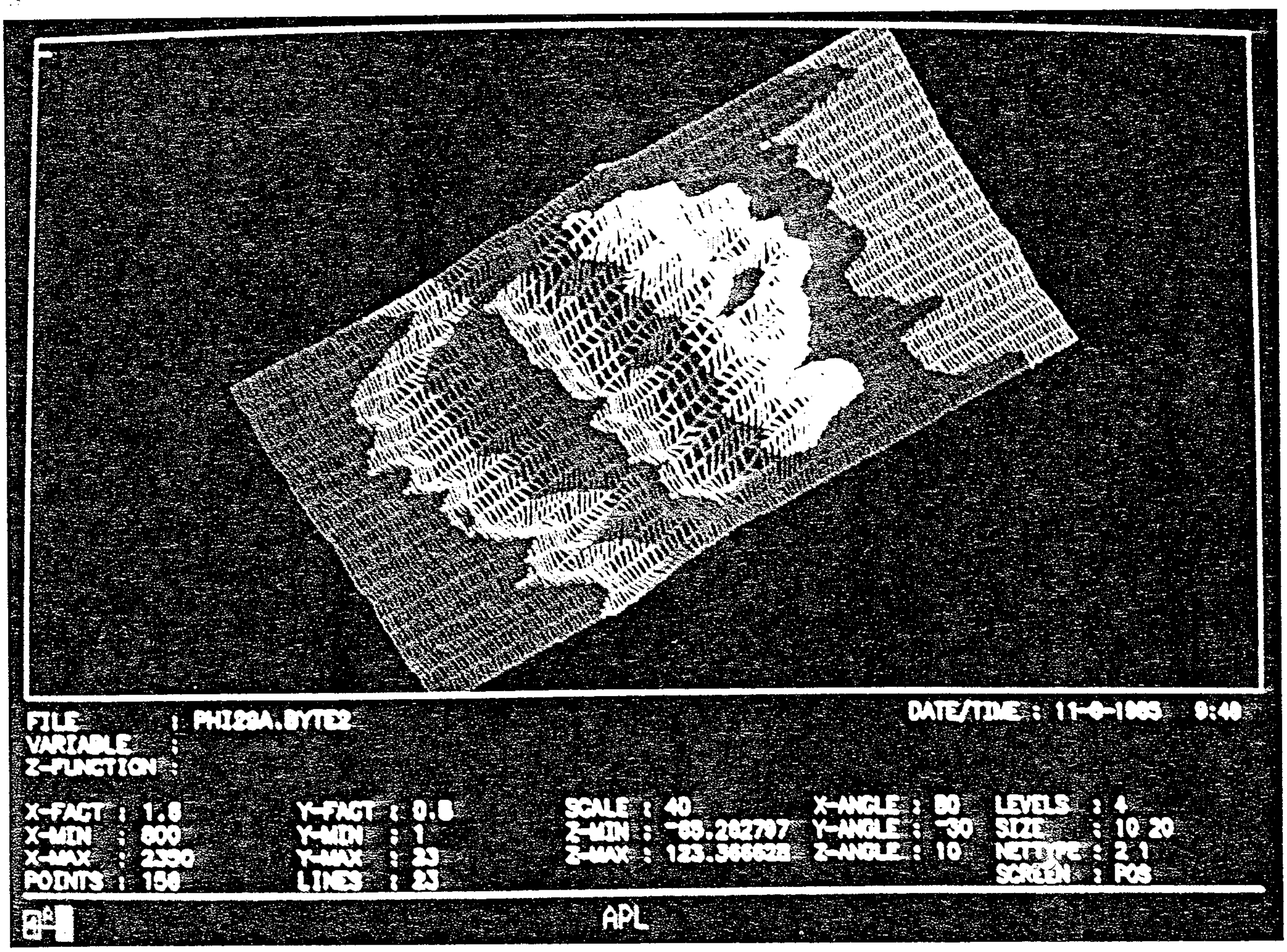
Our microscope has also demonstrated its usefulness in biology, even though at present it can achieve lateral resolutions of only 10 angstroms. In this case the relatively poor resolving power of the microscope is more than compensated for by its ability to provide a direct and nondestructive method of viewing biological samples.

Other microscopes in some sense partially destroy the samples on which they have been focused. In standard electron microscopy, for instance, samples must be coated with a thin layer of metal and, because they must be studied in a vacuum, they dry out. Since water molecules are an important part of biological substances, this might change the samples in an undesirable—and uncontrollable—way. In the scanning tunneling microscope water can even be used as the insulating layer between the sample and the probing needle. (Water is a relatively poor conductor unless it contains ions such as those formed when sodium chloride dissolves in it.) Exploiting the sensitivity of the scanning tunneling microscope, we have, with the help of E. Courtens of the IBM Zurich Research Laboratory and H. Gross and J. Sogo of the Swiss Federal Institute of Technology, scanned the surface of the nucleic acid DNA. We observed a series of zigzags corresponding to its helical structure.

In a collaborative effort with Arturo Baró, Nicolas Garcia and Rodolfo Miranda of the Autonomous University of Madrid and José L. Carascosa of IBM Spain, we found that the head of the virus known as phi 29 measures $400 \times 300 \times 200$ angstroms. The structure of the connection between the head and the tail of the virus, called the collar, which appears to play a significant role in the process of infection, has been unraveled; the results agree with those obtained by means of image-processed electron micrographs.

Apart from imaging, the probe tip will also be useful for testing electronic circuits. As components continue to shrink, the probes that test them must also be continuously miniaturized. The tip then serves as both a local voltage probe and a current source.

In all the foregoing applications it is vital that the imaging process not destroy or even alter the object. But the scanning tunneling microscope also offers promise as a tool for spurring specific chemical processes. One of the unique features of the microscope is its highly focused low-energy electron beam, or tunnel current. The energies of the beam lie within the range of those of most chemical processes. Therefore by tuning the beam to specific energies workers can cause particular reactions to occur. This mode of operation and the other capabilities of the instrument appear to open an entire new gamut of investigative possibilities.



COLLAR OF VIRUS PHI 29 connects the head of the virus to its tail. Raw, unprocessed electron micrographs such as this one have aided in unraveling the structure of the collar, an understanding of which is critical in controlling the spread of some viral infections.