

In touch with atoms

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Scanning tunneling microscopy appeared as a new method to deal with atoms, molecules, and nanometer-scale structures. It was the first of a growing family of local probes for imaging and measuring, which can serve at the same time as tools. Local probe methods have changed the way we perceive, think about, and treat atomic structures, and have brought about a new appreciation of mechanics. They play a central role for science and technology on the nanometer scale and will allow us to build systems of the same complexity as used by nature, which has built life on nanofunctionality. [S0034-6861(99)04402-5]

I. BACK TO THE FUTURE OF MECHANICS

Quantum mechanics has dramatically changed our perception of atoms, molecules, and condensed matter and established the central role of electronic states for electronic, chemical, and mechanical properties. Electronics, understood broadly as the motion of electrons and the deformation of their arrangements, has become the basis of our high-tech world, including “electronics,” computer science, and communications. Mechanics, on the other hand, understood as the motion of the mass of atomic cores and the deformation of their arrangements, played a lesser role, at best that of the guardian of the electron. Quantum mechanics has become, for many, synonymous with electronic states and electronics, whereas mechanics is considered the Stone Age. In this respect, the “mechanical” scanning tunneling microscope (STM) came as a surprise. The STM is a mechanically positioned, electrically sensitive kind of nanofinger for sensing, addressing, and handling individually selected atoms, molecules, and other tiny objects and for modifying condensed matter on an atomic scale (Sarid, 1991; Güntherodt and Wiesendanger, 1992; Chen, 1993; Stroscio and Kaiser, 1993; Hamers, Weaver, Weimer, and Weiss, 1996). And like with finger tips, it is the “touch” that makes the difference (see Fig. 1). Back to the future of mechanics: Nanomechanics, a new era.

The STM emerged as a response to an issue in technology. [For a historical review of STM see Binnig and Rohrer (1987a,1987b).] Inhomogeneities on the nanometer scale had become increasingly important as the miniaturization of electronic devices progressed. Condensed-matter physics, on the other hand, was occupied predominantly with periodic structures in solids and on surfaces and thus had developed very successfully momentum-space methods and concepts for the nanometer scale. Inspired by the specific problem of inhomogeneities in thin insulating layers — a central challenge to our colleagues working on the development of a computer based on Josephson tunnel junctions — and realizing the general scientific significance associated with it, we started to think in terms of local phenomena. Tunneling appeared a natural and promising

solution. This was the beginning of a new approach to the nanometer scale, the local-probe methods.

Local probes are small-sized objects, usually the very end of a sharp tip, whose interactions with a sample or a field can be sensed at selected positions. Proximity to or contact with the sample is required for good resolution. This is in principle an old concept, the medical doctor’s stethoscope being a well-known example. “Small sized” in this case means small compared to the wavelength of the sound to be heard and comparable to the distance from the sound source. The local-probe concept even appeared sporadically in the scientific literature in context with electromagnetic radiation (Synge, 1928,1932;

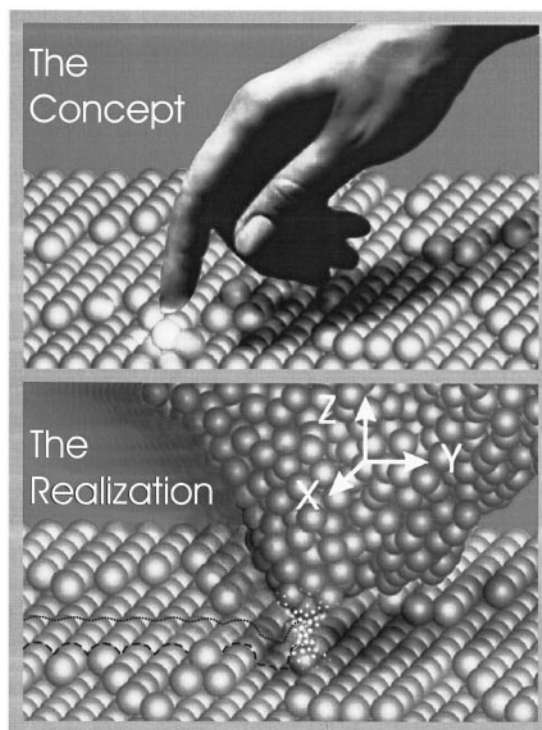


FIG. 1. Principle of a local probe: The gentle touch of a nanofinger. If the interaction between tip and sample decays sufficiently rapidly on the atomic scale, only the two atoms that are closest to each other are able to “feel” each other.

O’Keefe, (1956); Ash and Nicolls, 1972), but met with little interest and was not pursued. Nanoprobes require atomically stable tips and high-precision nanodrives. The latter are based on mechanical deformations of springlike structures by given forces—piezoelectric, mechanical, electrostatic, or magnetic—to ensure continuous and reproducible displacements with precision down to the picometer level. They also require very good vibration isolation. Furthermore, the concept of contact—electrical or mechanical—blurs at the nanometer scale. In the case of electrical contact, no sharp boundaries exist because of the penetration of electronic wave functions into the potential barriers of finite height, giving rise to electron tunneling (Bardeen, 1961; Güntherodt and Wiesendanger, 1992; Chen, 1993; Stroscio and Kaiser, 1993). On the other hand, interference and quantum effects can lead to discontinuities like in quantum conduction (Imry and Landauer, 1998).

The resolution f of local-probe methods is given mainly by an effective probe size r , its distance from the object d , and the decay of the interaction. The latter can also be considered to create an effective aperture, e.g., by selecting a small feature of the overall geometry of the probe tip, which then corresponds to the effective probe. If the decay in the distance range of interest can be approximated by an exponential behavior, $\exp(-x/l)$, with an effective decay length l , a good approximation of the resolution is $f = A\sqrt{(r+d)l}$, where A is of order unity [e.g., $A \approx 3$ for a spherical STM tip of radius r and electronic s -wave functions (Tersoff and Hamann, 1983)]. Atomic resolution therefore requires probe size, proximity, and decay length, respectively, of atomic dimension.

In STM, the interaction can be described as the wave-function overlap of empty and filled states of a tip and sample, respectively, or vice versa, which leads to a tunnel current when a voltage is applied (Bardeen, 1961). The interaction and, thus the tunneling current, decay exponentially with increasing separation with a decay length l (nm) $\approx 0.1/\sqrt{\phi_{\text{eff}}}$ for free electrons, where ϕ_{eff} is the effective tunnel barrier. For electrons at the Fermi energy with momentum perpendicular to the tunnel barrier, ϕ_{eff} is the average of sample and tip work functions $\bar{\phi}$. For most tip and sample materials, $\bar{\phi}$ is 4 to 6 eV and thus $l \approx 0.05$ nm.

This short decay length ensures that the tunnel current is carried mainly by the frontmost atom of the tip, which thus represents a local probe of atomic dimensions as depicted in Fig. 1. For a tunnel current in the nanoampere to picoampere range, the distance has to be less than 1 nm. This leads in a natural way to atomic resolution, provided that tips and samples are mechanically and chemically stable. In other words, once tunneling was chosen, atomic resolution was inevitable. Fast fluctuations owing to thermal excitations such as phonons or the diffusion of atoms are largely averaged out. Therefore STM can be operated at elevated temperatures or in ambient or liquid environments with an acceptable signal-to-noise ratio.

The STM is an electronic-mechanical hybrid. The probe positioning is mechanics, whereas the interaction is sensed by the tunneling current, which is of quantum-mechanical origin. The most common imaging mode is the constant interaction or the “mechanical” mode in which a feedback loop adjusts the probe position with respect to the sample, say in the z direction, to a given tunneling current while scanning in the x - y direction over the surface. The x - y - z positions of the probe, i.e., the image, represent a contour of constant tunnel current or of whatever the tunnel current can be related to, e.g., in many cases a contour of constant local density of electronic states. On smooth surfaces, faster imaging can often be achieved by measuring the tunneling current while scanning on a given, smooth x - y - z contour, e.g., a plane parallel to an average surface portion, which is then called constant-height mode. For very weak interaction, i.e., for tunneling currents at or below 1 pA, the imaging speed is, however, limited by the current measuring bandwidth, not by the mechanical system response.

In view of its conceptual simplicity, the fact that no new theoretical insight and concepts nor new types of materials or components were required, and the prospect of a fundamentally new approach to the nanometer scale, it is remarkable that the STM—or local probes in general for the nanometer scale—was not invented much earlier. And when it was, it did not happen in one of the obvious communities. And after it was, it took several years and an atomically resolved, real-space image of the magical Si(111) 7×7 reconstruction (Binnig, Rohrer, Gerber, and Weibel, 1983) to overcome the reservations of a skeptical and sometimes rather conservative scientific community. There were certain exceptions, though.

II. COLORFUL TOUCH

The “touch” of a local probe with the nano-object is essentially given by the *type* of interaction, which addresses a distinct property, process, or function, by the *strength* of the interaction, which can make a tool out of the probe, and by the *medium*, such as liquid, ambient or vacuum, that provides the specific local “atmosphere,” the “nanosphere.” A colorful touch, indeed, with a rainbow of possibilities. However, to have a large variety of interactions at one’s disposal is one thing, to differentiate among them is another. Ideally, one would like to control the position of the probe and guide it over a specific, easily understandable contour, such as the object’s topography, by means of a control interaction and to work with other interactions, the working interactions, for addressing or changing the properties, processes, and functions of interest. Admittedly, the topography is a fuzzy concept on the nanometer scale but it nevertheless might be a useful one in many cases. But even if an appropriate control interaction can be found, one must still separate the working interactions because the measuring signal includes the effect of an entire class of interactions. In STM, the contribution of the elec-

tronic states to the tunneling current depends on their energy, momentum, symmetry, and density as well as on the tunneling barrier height and width and the tunneling process. Or the response of a force sensor is the composite action of different forces. Separating the interactions for imaging and working is the challenge and the art, the "touch," of working with local-probe methods.

Tunneling spectroscopy is the major technique to separate the contributions of the various electronic states and various tunneling processes to the tunneling current in order to associate specific image features with a characteristic surface property or process [see the chapters on spectroscopy in Güntherodt and Wiesendanger (1992), Chen (1993); Stroscio and Kaiser (1993)]. The tunneling current due to those electronic states that are homogeneous on the surface and reflect in many cases the total density of states is usually used as the control interaction. In this case, the contour traced can be regarded as the surface topography. At each measuring point on the topography, the electronic states of interest are extracted by the tunneling current in the appropriate voltage, i.e., energy window. This is done in practice with various techniques, [see Hamers, Weaver, Weimer, and Weiss (1996)]. There are many other ways to extract information from a local tunneling experiment. Ballistic electron-emission microscopy (BEEM) tests buried potential barriers; distance-current characteristics yield tunnel barrier heights and decay lengths of the electronic wave functions. Emitted photons owing to inelastic tunneling processes (Lambe and McCarthy, 1976; Gimzewski, 1995) are characteristic of local excitations such as surface plasmons, of local densities of states, of energy levels of adsorbed molecules, of electron-hole pair formation and recombination, and of spin polarization. Very powerful light emission from a Cu surface covered with polyaromatic molecules equipped with molecular spacers has recently been observed within an STM configuration (Gimzewski, 1998). The estimated conversion rate is as high as 30% or 10^8 photons/sec from a volume of several cubic nanometers, although inelastic-tunneling processes are otherwise lower than the elastic ones by four to six orders of magnitude.

STM was followed by the scanning near-field optical microscope (SNOM) [Pohl, Denk, and Lanz, 1984] and the atomic force microscope (AFM) (Binnig, Gerber, and Quate, 1986; Sarid, 1991) with all its different force derivatives. In the SNOM a photon current is a measure of the interaction. Although it extended the resolution of optical microscopy far beyond the diffraction limit and offers the power of optical spectroscopy, it did not arouse widespread attention. The atomic-resolution capability of STM appeared to be a serious handicap for SNOM, just like the STM once had to overcome the bias for established surface-science methods. Fortunately, this has changed and SNOM has found its champions and proper place.

A major extension of local-probe methods was brought about by the invention of the AFM. It allows nanometer-resolution, in special cases even atomic-

resolution, imaging of conducting and nonconducting objects and local force detection below the picoNewton level. The various forces that are mainly used for imaging are repulsive interatomic, electrostatic, magnetic, van der Waals (all of electronic origin), and lateral (friction) forces (Mate, McClelland, Erlandson, and Chiang, 1987; Güntherodt and Wiesendanger, 1992; Chen, 1993; Stroscio and Kaiser, 1993; see also Hamers, Weaver, Weimer, and Weiss, 1996). The AFM also uses a sharp tip as local probe, but, unlike STM where the tunnel current is a measure of the interaction, a force between tip and sample is detected via the deformation of a spring, generally the bending of a cantilever beam carrying the tip at one end. In the static mode, the excursion of the beam determines the force, in the dynamic mode it is the amplitude and frequency responses of the oscillating cantilever, e.g., a shift of resonance frequency or damping, that are measured and can be used to control the lever position. The force interaction is first transformed into mechanics before being measured. The AFM, therefore, is of an even more mechanical nature than the STM. Today, a large number of deflection sensors yield subangstrom sensitivity; some are electrical and integrated into the lever, others are external. For sensitivity, the beam has to be soft, for vibration protection and to achieve an acceptable imaging speed, its eigenfrequency has to be high. Both requirements can be satisfied by miniaturization in all dimensions because both compliance and resonant frequency increase linearly with decreasing dimension. Microfabricated cantilevers with resonance frequencies above 1 MHz and spring constants below 1 N/m are in use today. Designs are flexible for applications requiring either higher frequencies or lower spring constants.

Shortly after the introduction of the AFM, atomic periodicities—easily confused with atomically resolved structures—were observed. It took a few years, however, before true atomic resolution could be achieved (Ohnesorge and Binnig, 1993). Repulsive forces of the order of only 10^{-10} N between the frontmost atom of the tip and the closest sample atom can deform even a hard sample and tip such that they adapt their shapes to each other. The resolution then is no longer given by the frontmost atom of the tip but rather by its overall radius of curvature. For sharp tips there are nevertheless only a small number of tip atoms in contact with the sample, and periodicities are not completely averaged out. This then simulates atomic resolution, however, with defects either smeared out or not visible at all.

Most scientists operate the AFM in air. In contrast to STM, atomic resolution in air is hardly possible with an AFM. There will be always some humidity present, and therefore the tip and sample will be covered with a water film. As a result, capillary forces will drive the tip with a relatively strong force against the sample. In principle this force can be counterbalanced by pulling the lever away from the sample and prebending it this way. Unfortunately the capillary forces and the maximum tolerable loading forces differ by so many orders of magnitude that a counterbalancing is spoiled by tiny variations

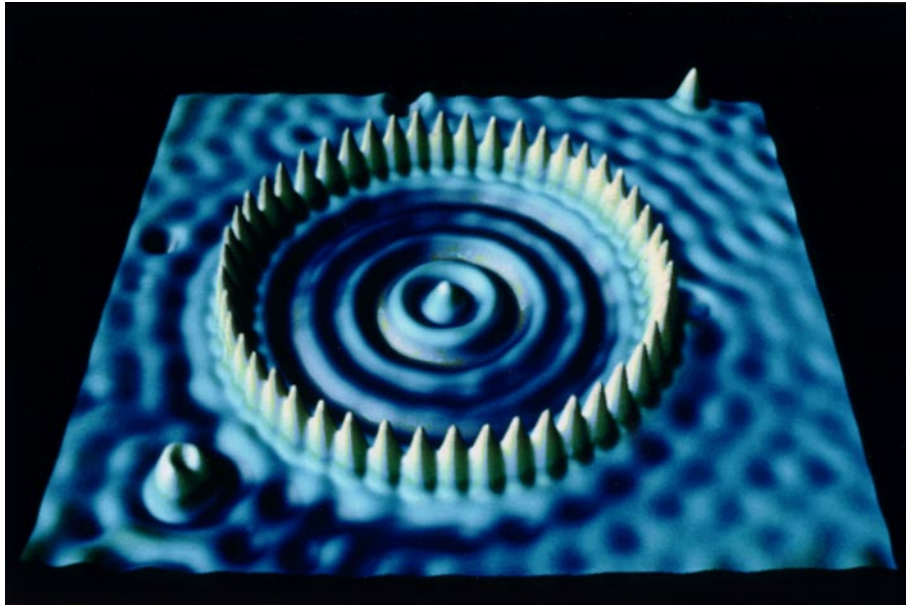


FIG. 2. (Color) STM image of a quantum corral for electrons built with 48 iron atoms on copper. The same tip is used to position the iron atoms into a 12.4-nm-diameter ring and to image them and the wave-structure interior caused by the confined surface-state copper electrons. Courtesy D. Eigler, IBM Research Center, Almaden, CA.

in these forces during the scan. Operating the cantilever in vacuum solves the problem. Operating it in water or an aqueous solution also solves this problem and another one: van der Waals forces do not decay as rapidly as tunneling currents and therefore a background attraction of the tip (and not just its very front) is present. In liquids, e.g., aqueous solution, this background attraction can be counterbalanced completely by the van der Waals forces that act on the solution by pulling it into the gap between tip and sample (Garcia and Binh, 1992).

Of prime interest in AFM are the topography, the type of contact, and the local mechanical properties. The dynamic mode is used to address local elastic constants, whereas force-distance curves in and out of contact provide information about contact, intermolecular forces, and binding. Adding a known Coulomb force allows one to separate Coulomb, van der Waals, and magnetic forces. These methods have their counterparts in spectroscopy in STM.

Following the scanning near-field optical microscope and the AFM, a profusion of local-probe techniques using various interactions appeared, each geared to solve a specific class of problems in a given environment. They include Maxwell stress microscopy, ion conductance microscopy, scanning electrochemical microscopy, higher-harmonics generation of microwaves and optical photons, and many others, and more are still appearing. Their adaptability to different types of interactions and working environments is one of the greatest assets of local-probe methods.

Another one is the ease of making a nanometer-scale tool out of a probe (see Fig. 2). Probe or tool is a matter of the strength of the interaction and of the local sensitivity to it. Changing the distance between probe and object by a fraction of a nanometer can change the in-

teraction strength by several orders of magnitude. Alternatively, applying a few volts can result in electric fields of the order of intramolecular fields, which are sufficient to break individual chemical bonds or to initiate a local chemical reaction. A wide variety of local manipulation and modification possibilities are in use, ranging from gentle atom and molecule displacements to their individually selected removal and deposition, to local chemical changes, to brute-force nanometer-sized scratching and chiseling (Güntherodt and Wiesendanger, 1992; Chen, 1993; Stroscio and Kaiser, 1993; Hamers, Weaver, Weimer, and Weiss, 1996).

III. CHANGE AND CHALLENGE

Since the advent of local-probe methods, atoms, molecules, and other nanometer-sized objects are no longer “untouchables.” They forsook their anonymity as indistinguishable members of a statistical ensemble and became individuals. We have established a casual relationship with them, and quite generally with the nanometer scale. Casual, however, does not mean easy. They are fragile individuals, whose properties and functions depend strongly on their context and which are usually quite different from those in the isolated state. Interfacing them to the nanoscopic, microscopic, and macroscopic worlds in a controlled way is one of the central challenges of nanotechnology. Imaging them or communicating with them is the easiest of these tasks, although not always trivial. Besides the effects of immobilization, even weak-electric-contact probes like STM tips are not strictly noninvasive because of the forces present at tunneling distances, in particular when weak contrast or weak electric signals require extreme proximity. Adhesive and electrostatic forces, both from applied voltage

and contact potential, can lead to reversible local deformations, in many cases even to irreversible displacements. The latter, undesirable in imaging, has become the basis for atom manipulation (Crommie, Lutz, and Eigler, 1993). The measuring process on the nanoscale is somewhere between an intricate quantum-mechanical one and a straightforward macroscopic one. Generally speaking, the smaller the object or the higher the required resolution, the more delicate the measuring process; and the stronger the required interactions, e.g., for controlling a function or process, the more demanding their control.

The real-space, nano- to atomic-scale resolution of local probes changed our way of thinking and working in many areas and created new ones with distinct properties and behavior on the nanometer scale such as nanotribology, nanoelectrochemistry, and nanomechanics.

In surface science, most of the more complex surface structures and reconstructions could be resolved by STM, often together with other surface-science techniques, and are understood reasonably well. The real-space imaging capability proved to be crucial to unravel the structure of the enlarged unit cell of reconstructions [for an example of the richness of reconstructions see Xue, Hashizume, and Sakurai (1997)]. This is even more so for the study of more local phenomena such as surface structures coexisting on short length scales, nucleation and growth phenomena, heterogeneous catalysis, phase transitions, and surface chemistry. Changes always occur and propagate locally. Still awaited is a general nanoscopic chemical-analysis method.

In electrochemistry, local probes brought in a new era by advancing *in situ* resolution from at best that of optical microscopy for observation and macroscopic for processes to the atomic and nanometer scale, respectively [for a review, see Siegenthaler (1998)]. The significance of working in a liquid environment, however, extends far beyond electrochemistry. The liquid-solid interface is, in our opinion, the interface of the future, at least on equal footing with the solid-vacuum interface of classical surface science. Liquids provide a very adaptive environment for protection, process control, and modification of surfaces, they carry ionic charges and atomic and molecular species, and they remove many of the “traffic restrictions” typical for a two-dimensional solid surface.

Ambient environment and liquids are also a key for *in situ* and *in vivo* local-probe methods for macromolecules and biomaterial (Drake *et al.*, 1989). STM and AFM imaging have made good progress, both in problem areas not accessible to other methods as well as complementary to electron microscope imaging (Engel and Gaub, 1997; and references therein) Fig. 3; breakthroughs such as decoding DNA still lie ahead.

In the technology domain, local-probe imaging and measurements in vacuum, at ambient and in liquids, have begun to be applied routinely in the surface analytical sector, where instrumentation is predominantly of the AFM type. The long-range perspective of local probes in general, however, is their use as local sensors, flexible and adaptable tools, and in massive parallel op-

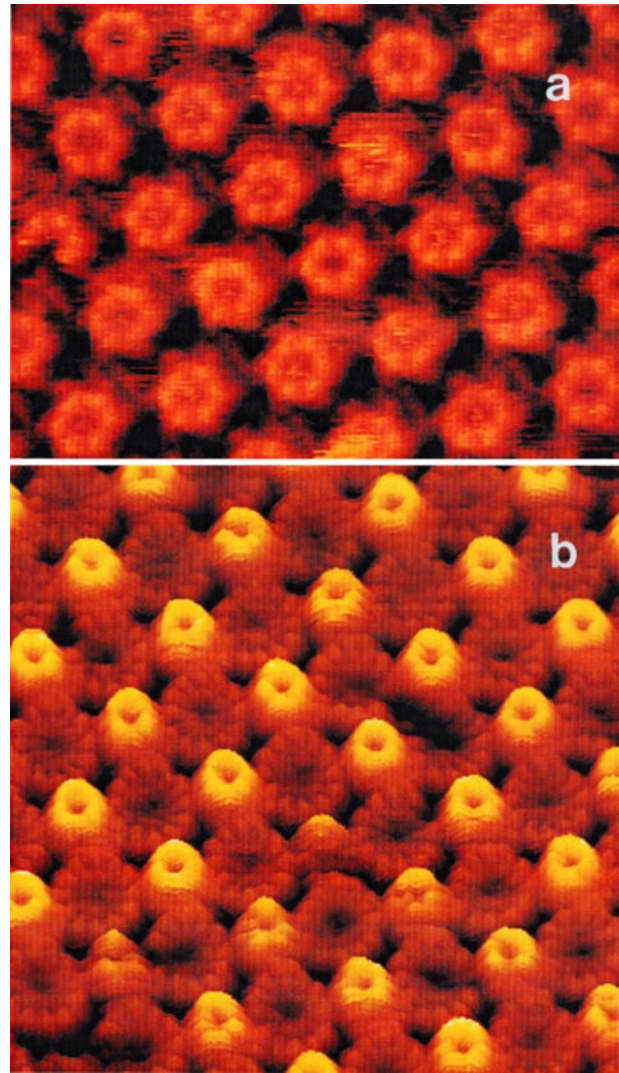


FIG. 3. (Color) (a) The cytoplasmic surface of the hexagonally packed intermediate (HPI) layer is an essential part of the cell envelope of *Deinococcus radiodurans*. It is supposed to have a protective function and to act as a molecular sieve. The pores seen in the protruding cores are probably the channels of this sieve, and as shown by AFM for the first time, the channels exhibit two conformations that change dynamically. The unit cell size is 18 nm, and the brightness range corresponds to 3 nm (Müller, Baumeister, and Engel (1996)). (b) Two-dimensional crystals of bacteriophage F 29 head-tail connectors recorded with the AFM in buffer solution. The connectors are packed in up-and-down originations, exposing their narrow ends that connect to the tail and their wide ends that connect to the head. The 12-fold symmetry and vorticity of this complex is clearly demonstrated by this topograph. The unit cell size is 16.5 nm, whereas the brightness range corresponds to 4 nm (Müller *et al.*, (1997)). Courtesy A. Engel, Univ. Basel.

erating devices. Cantilever probes have a special status. Besides their great force and strain sensitivity, they are fast, yielding, and robust. They ensure soft contact in the microNewton to the nanoNewton range. They are, therefore, especially suited for cantilever array applications where fine control of each individual cantilever might be too cumbersome, impractical, or infeasible.

Even though the individual local experiments in a specific application might still require μsec to milliseconds, massive parallel operation of cantilevers in batch-fabricated arrays opens new possibilities. Lithography applications (Minne *et al.*, 1998; Wilder *et al.*, 1998) take advantage of very fast “chemics” on the nanometer scale, as diffusion times scale with the square of linear dimension.

An illustrative example of an array application with mechanics is the “Millipede,” a mechanical-electronic pocket-sized terabit storage device (Binnig, Rohrer, and Vettiger, 1997; Lutwyche *et al.*, 1998). It consists essentially of a two-dimensional array of smart AFM cantilever beams with integrated read, write, and actuation capabilities, which are addressed and controlled via a multiplex scheme. With feasible bit-space requirements of $30 \times 30 \text{ nm}^2$, e.g., indentations in a polymer storage medium, a million cantilevers serve one terabit on $3 \times 3 \text{ cm}^2$. At realistic read and write speeds of 10 to 1000 kbit/sec, the data-transfer rate is limited by the multiplex speed rather than by mechanics. The architecture of the Millipede solves two basic issues in miniaturization to the nanometer scale, namely the effective-space requirement and the deterioration of signal strength. The degree of miniaturization is determined by the active part and the periphery, which is necessary to build a functional element. The periphery often becomes the space-limiting requirement for nanometer-scale active parts. In the Millipede, the periphery, i.e., the smart cantilever, is of the same size as the megabit it addresses. The effective miniaturization is, therefore, given by the bit size. Secondly the read/write signal can be prepared during the multiplex cycle. In spite of the enormous data-transfer rate, the signal deterioration due to both decreasing bit size and increasing read/write speed is greatly reduced. Most exciting, however, is the prospect of new approaches for combining data storage and *in situ* processing.

The prime activity in local-probe methods focused initially on super-resolution and the understanding of imaging, manipulation, and modification processes. Interest is now expanding to high-sensitivity measuring processes, which often require a tradeoff between resolution and sensitivity/precision, to local-probe systems, and generally to include more complexity in local probes and systems of them such as the cantilever arrays mentioned above. Combining spin-resonance techniques with magnetic force microscopy introduces the possibility of unprecedentedly high-resolution spin-resonance imaging (Sidles, 1991; Rugar *et al.*, 1994). Often, however, imaging merely serves to determine the appropriate position for the experiment or is not used at all. Studies performed predominantly in STM configurations include electron transfer through individual molecules and other nano-objects, frequency mixing using nonlinear tunnel characteristics, multiprobe systems for correlation and local resistivity measurements, and quantum transport through and mechanical properties of metallic nanoconstrictions—the latter in an AFM configuration with conducting tip. Functionalized cantilever-type force

sensors are used to detect forces in the piconewton to femtonewton range as well as ultrasmall strains produced on the beam itself. Examples are molecular recognition via the binding behavior between two selected molecules, one of which is attached to the tip, measurement of reaction heat in the femtojoule to picojoule range on a functionalized bimorph (a double-layer lever of silicon and aluminium with very different thermal expansion) cantilever, or detection of dilution in the (10^{-18} mol) range due to the strain induced by adsorbed molecules. Smallness comes to bear in three ways: picometer deflection detection brings the extreme sensitivity, and the small dimensions of the cantilever yield short response times and allow nearly noninvasive local sensing. There are still many other uses of cantilevers, e.g., the water meniscus which can form at ambient conditions between tip and surface and which is undesirable in imaging, can serve atomol chemistry in modification processes (Garcia, Calleja, and Perez-Murano, 1998), or the nonlinear coupling of cantilevers can be used for mechanical processing. It is amazing how much can be done and how much potential lies in a primitive cantilever, when it is small enough and properly functionalized.

Local probes play a crucial role in our understanding of how to create an interface to molecular and biofunctional units and, quite generally, they pave the way to building problem-specific nanosystems. In many cases, they might not be the final word, but act merely as a midwife for new experimental approaches and novel technological devices.

IV. NATURE'S WAY

Problem-specific nanosystems allow us to work on the same scale as nature does. Nature has built life on nanofunctionality, the ultimate purpose of nanotechnology. Sensing, processing, actuation, and growth take place on the nanometer scale and are joined in intricate ways to macroscopic properties, processes, and functions.

Nature uses mechanics abundantly and generally does not even separate it from electronics. Nanomechanics has many attractive features: energies required to produce the deformations useful for sensing and actuation are in the thermal energy (kT) range, strains obtained from bending scale with thickness, mechanical eigenfrequencies reach megahertz to gigahertz values and can be adapted to the problem, e.g., low attempt frequencies for transitions, and diffusion times come down to μsec to picoseconds. Nature's nanomechanics rests predominantly on deformation and on the transport of atoms, molecules, small entities, and ionic charges, in contrast to translation and rotation in macromechanics. Simple deformations on the nanometer scale can be synthesized to create complex macromotions. Finally, the small energies required for local activation, sensing, and processing can be provided by distributed chemical-energy reservoirs.

“Distributed” seems to be Nature's general approach to solving so many tasks much more elegantly, efficiently, and successfully than we can do or even attempt

to do with present-day macroinstrumentation, central processing, and computation. The nanometer-scale elements allow all kinds of densely interwoven, distributed storage, programming and processing; software is built into the hardware. The same should become true for lifting disciplinary boundaries. The nanoscale is the bifurcation point where materials develop their properties and the science and engineering disciplines their particularities in thinking, working, and terminology. Coming down from the macro and micro scales, the nanometer scale should become the merging point. This then could also be the starting point for the human bottom-up approach to functionality—Nature's way.

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