Although nanotechnology is currently receiving a lot of interest from academia, industry, and society in general, it must be recognized that at present the technology at nanoscale is almost nonexistent. Most of the work has been in the area of nanoscale science. The purpose of this workshop held on University of California, Berkeley, campus (4–5 August 2000) was to identify the key engineering issues that must be addressed, which when combined with nanoscience, will lead to nanotechnology. Five areas were identified: large-scale integration, energy conversion systems, biological sensing and processing, information storage and processing, and diagnostics and manipulation. This report describes the presentations and the discussions at this workshop.

LARGE SCALE INTEGRATION

One of the engineering challenges in nanotechnology is to integrate across the length scales. Optical lithography allows integration of macroscales down to about 100 nm, but it cannot be used for sub-100-nm fabrication. In addition, current processes allow for only 2-D or planar fabrication. It seems likely that integration across 1–100 nm must
require self-assembly processes. However, there are two requirements for this to be viable for engineering, namely: (1) it must be encoded such that nanoscale objects are spatially distributed in a rational manner; (2) it must interface with top-down lithography techniques (see Figure 1).

The session started with a keynote lecture by Dr. Fabian Pease (Stanford). He emphasized that in electronic microprocessors, the problem of going to nanoscale is not in making the devices but in the wiring of these devices. It is already apparent that the current generation of microprocessors is becoming more multilayered and the problems are in interconnecting the devices. In the future, when one approaches sub-100-nm features, three-dimensional integration will be the biggest challenge. An approach that might mitigate the resistance problem features true three-dimensional integration, in which the devices are formed in nanocrystals that can be formed in many layers, and so avoid the topological tyranny of today’s ULSI circuits, in which the active devices are constrained to one plane. Yet another approach, which mitigates the fabrication difficulty, might be to prefabricate a matrix of $x$-directed lines and $y$-directed conductors on adjacent levels (since forming periodic structures is relatively straightforward) and use a focused beam to form the required vertical contacts and make the necessary breaks.

In this regard, it is important to note that this is indeed true for biological processors (cells) which are not 2-D and the interconnects are in the form of molecules which switch on and off other molecules. Therefore, perhaps in the future, the processors will be truly 3-D, without metallic wire interconnects. Interconnects could be optical or molecular in nature.

Aksay (Princeton) provided a presentation about bio-inspired materials integration. What is of growing interest and enhanced ability in the utilization of nanotechnology is to control the structure of a wide range of material systems for applications ranging from biomaterials to electronics. Integrating multifunctionality into a material system at length scales starting at the nanometer level is the necessary requirement not only for miniaturization but also for developing new properties. Various approaches have been and are being developed to achieve this goal. A favored approach, akin to the synthesis

![Figure 1. Interfacing of top-down lithographic fabrication and bottom-up coded self-assembly.](image-url)
and processing methods of the biological world, is the self-assembly of organic/inorganic nanocomposites at temperatures < 100°C. The presentation focused on this approach to illustrate the utility of self-assembly in generating patterns at the 10 Å-to-1 μm length scale. The potential of this method through orientational epitaxy of adsorbed micelles on templates was illustrated. The organic amphiphiles self-assemble to form micellar nanodomains, which are then used to pattern an inorganic phase with nanoscale modulations. The ability to process inorganic/organic nanocomposites by these methods provides new technological opportunities for creating unusual composites. Since the ultimate goal is to introduce these nanostructured materials into larger systems, it is also necessary to modulate features at larger length scales. Field-assisted alignment is used to generate patterns at length scales larger than 1 μm. The utilization of such nanostructured “building blocks” for the construction of larger, viable composite materials can be accomplished through the lamination of thin films and patterning through microcontact printing and electrohydrodynamic (EHD) manipulation of fluids/suspensions.

Chakraborty (UC Berkeley) provided some theoretical insight into the statistical mechanics of pattern formation in self-assembly processes. He showed using thermodynamic arguments how biological cells in the immune system form synapses through self-organization of cell membrane components. Understanding the fundamentals of pattern formation is key to designing self-assembly processes and will lead to computer-aided design of future manufacturing processes.

Chou (Princeton) presented two new approaches for achieving large-scale integration of nanostructures and nanodevices. One is nanoimprint lithography (NIL), which patterns a resist by physical deformation of the resist shape using a mold, rather than by modification of the resist chemical structure using radiation as in conventional lithography. The fundamental difference in principle allows NIL to achieve sub-10-nm features over a large area (>4-in. diameter) in less a minute with low cost—a feat unattainable with other existing technology. The second approach is lithographically induced self-assembly (LISA), which uses a large pattern to guide the self-assembly of many much smaller structures, so that the location and orientation of each small pattern can be well controlled. Such control is essential to electrically connect each self-assembled structure. The two methods, used either individually or combined, offer powerful approach to large integration of nanostructures and devices. Finally, Quake (Caltech) provided methodologies for using soft lithography for fabricating fluidic devices. This is another example of a self-assembly process directed by lithography.

In addition to these techniques, it is important to note how biological system integrate across length scales. DNA and proteins make the self-assembly process highly encoded, and molecular building blocks (nucleotides and amino acids) are assembled one after the other in a particular designed pattern. The self-assembly process described in this session did not possess as much nanoscale encoding as biology does. Therefore, there is tremendous room for improvement, and it is likely that one will see use of biological molecules for the purpose of self-assembly. DNA-based self-assembly has already been reported by Mirkin (Northwestern U.) and Alivisatos (UC Berkeley, LBL) groups, as illustrated in Figure 2.

Such an approach is currently being used by Barhen and coworkers (ORNL) to locate gold nanoparticles precisely between lithographically patterned wires for the purpose of building nanoscale integrated circuits.
Dresselhaus and co-workers (MIT) have demonstrated that when thermoelectric materials are nanostructured, their figure of merit $ZT$ ($ZT = S^2 \sigma T / k$; $S =$ thermopower, $\sigma =$ electrical conductivity, $k =$ thermal conductivity) improves dramatically (see Figure 3). This provides the unique opportunity to synthesize thermoelectric energy con-

![Diagram of DNA-encoded nanoparticles](image)

**Figure 2.** Nanoparticles encoded by single-stranded DNA sequences ($J$ and $K$) can be assembled in a precise manner by introducing strands that are complementary ($J'K'$).

**Figure 3.** Thermoelectric figure of merit for 1-D and 2-D Bi nanostructures.
version devices with performance comparable to vapor- and gas-based refrigerators and engines.

Chen (UCLA) described the properties of photons, electrons, and phonons in materials in nature and how one can engineer the wave or particle properties in nanoscale to achieve the desired characteristics. As examples of wave property engineering, one can confine electrons inside quantum wells and photons inside photonic bandgap structures to quantize the energy states. The engineering material’s transport properties, such as the transmission coefficient and the group velocity, is particularly important for the design of novel devices. For example, the thermoelectric figure-of-merit for conversion of heat and electricity has not been much improved in the bulk materials in the last 30–40 years. However, optimization of the transmission properties in low-dimensional materials (quantum wells, wires, or dots) has recently shown substantial improvement. This is a good example of engineering of the bulk material properties using nanoscale modifications. Figure 4 shows that the thermal conductivity of Si/Ge short-period superlattice can be lower than that of amorphous Si material.

Shakouri (UCSC) described the miniaturization of optoelectronic devices (lasers, detectors, waveguides, switches). Even though photonic bandgap structures can make very small active and passive components, there are still orders-of-magnitude differences between what can be achieved optically (on the order of light wavelength) and electronically (on the order of nanometers). Another problem is sensitivity of typical optoelectronic devices to temperature variations. For example, laser wavelength and threshold current are strongly affected by temperature. Almost all commercial semiconductor lasers used for long-haul communication have active temperature stabilization using thermoelectric coolers. Making smaller devices makes the issue of overheating and heat sinking much more challenging. There are, however, novel means of cooling using thermionic emission current in heterostructures that can allow fabrication of very small refrigerators (Figure 5). One can also design novel opto-thermo-electronic devices with new functions and applications.

Figure 4. Thermal conductivity of SiGe superlattices.
Manson (Texas A&M) described Flagellar motor specifications (Table 1). *Escherichia coli* is a single-celled organism. It is equipped with a set of rotary motors only 45 nm in diameter. Each motor drives a long, thin, helical filament that extends several cell body lengths out to the external medium (Figure 6). The concentrated motion of several flagella enables a cell to swim. The speed is 20–30 μm/s, which is comparable to that of some fishes. A cell can move toward regions that it deems more favorable by measuring changes in the concentration of certain chemicals in the environment (mostly nutrients). This microorganism is a nanotechnologist’s dream: it includes rotary engines, particle counters, rate meters, and gearboxes. The rotary engine is estimated to be 100% efficient.

Bachand described another kind of nanoscale biological motor: the enzyme ATP synthase (ATPase). The motor F₁-ATPase is about 1 μm tall and 150 nm in diameter.

**Figure 5.** Measured cooling on $50 \times 50$ μm² $p$-SiGe/Si cooler at various substrate (heat sink) temperatures.
Table 1. Flagellar motor specification (approximate)

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>45 nm</td>
</tr>
<tr>
<td>Speed</td>
<td>6,000–60,000 rpm</td>
</tr>
<tr>
<td>Power output</td>
<td>$10^{-9}$ hp</td>
</tr>
<tr>
<td>Power output per unit weight</td>
<td>10 hp per pound</td>
</tr>
<tr>
<td>Power source</td>
<td>Proton current ($\text{H}^+$, $\text{Na}^+$)</td>
</tr>
<tr>
<td>Cylinders (torque-generating parts)</td>
<td>8</td>
</tr>
<tr>
<td>Number of different kinds of parts</td>
<td>30</td>
</tr>
<tr>
<td>Gears</td>
<td>Forward and reverse</td>
</tr>
</tbody>
</table>

(see Figure 7). The gamma subunit of the F1 portion rotates at up to 17 rps, and it can generate 100 pN nm of work. The propeller is made of nickel wire. It is 450 nm long and 150 nm in diameter. The motor and the propeller are assembled on a substrate with nanofabricated pillars (Figure 7). Rotation of the pillar in 2.5 h was observed. The apparent failure mechanism was propeller detachment. The efficiency of the motor was estimated to be 50–80%. The long-term goal of this project is to create integrated nanomechanical devices actuated by biomolecular motors, design mechanisms to specifically control motor functionality using chemical signals, and finally to design a system to continuously supply fuel to biomolecular motors. The fuel delivery was investigated using different methods. Bacteriohodopsin (BR) or carotene-porphyrin-naphthoquinone (CPQ) was used to establish the electrochemical gradient and synthesize ATP. Implementation of a light-driven ATP production system was also investigated.

Figure 6. Schematic diagram of a flagellar motor.
Nanotechnology challenges in energy conversion systems include the following.

Thermal issues in nanoscale devices may be a problem.
Optical devices do not scale down as easily as electronic devices (limited by light wavelength).
Waste heat recovery can benefit from nanoengineering of material properties.
Biological systems are efficient for energy conversion: Can they provide power for nanodevices? This will solve the problem of energy delivery to nanometer scale devices.
Biological nanosystems are typically inside liquids and need membranes. This is not compatible with traditional semiconductor devices operation.

Figure 8. Nanoscale conversion between different forms of energy.

BIOLOGICAL SENSING AND PROCESSING

The session on Biological Sensing and Processing focused primarily on sensing methodologies and how nanotechnology could benefit from both new ways of processing
as well as how it could influence creation of novel processing technologies. One of the key points that arose during this session was that a lot of traditional areas of interface science are actually nanotechnology based, that manipulations on the macroscale can influence nanotechnology properties, and that the converse is also true, that nanoscale manipulations using macroscopic tools can lead to very interesting new materials and interfaces that rely on biology for its components and inspiration. The primary message for going forward from this session was that the U.S. Department of Energy (DOE) needs to continue to support efforts and in addition develop modeling tools to determine the potential effects of nanoscale manipulations, because it is impossible to observe many of these changes directly at this point. It was also determined that the other reason modeling of systems for biological processing is needed is because it will be a long time before one can predict the effect of nanoscale manipulations from first principles as for VSLI.

The other key points that came out of the session were as follows:

There is a need to create tools to do diagnostics in the nano regime.
Integrated systems need to be developed based on nanotechnology or that are inspired by manipulations on the nanoscale that integrate with lab-on-a-chip-type devices.
There is a need to create nanoengineered interfaces between macro devices to enable the integration of biological and nonbiological systems. In this way one can take advantage of the enormous biological capability by co-opting the biological systems in a short time frame—i.e., direct interfacing with cells and tissues.
Lastly, at some point one needs to consider the idea that continually striving to shrink existing biological and medical analysis systems will run into incompatibilities at smaller size regimes that cannot be overcome or will be Rube Golberg-like in nature in the smaller regime. The community needs to develop methods of engineering totally new devices and concepts based on nanotechnology properties despite the long time frame for accruing concrete results.

The latter four workshop results need to be addressed in engineering research at the DOE from the standpoint of integration with existing technologies and to prioritize the integration of the modeling into all four points. The presentation by CFD Research Corporation pointed to a number of applications of multiphysics computational design and analysis tools for the interrogation of biophysical/biochemical nanoscale phenomena that govern the functionality of biomicrofluidic devices. Ideas for computational techniques for coupling nanoscale processes with microscale phenomena was also discussed. Sample results from numerical studies involving competitive multiprotein absorption, DNA hybridization, electrokinetic manipulation of cells and biomolecules, etc., was presented and overlapped all of the points made in the other presentations (Figure 9). The modeling presentation also allowed the conceptualization of the other presentations and discussion in terms of engineered solutions versus empirical-based solutions or focused efforts from a materials standpoint.

DNA analysis, one of the primary early applications of nanoengineering, was elegantly described in a presentation given by Nanogen, where active microelectronic arrays are being developed for applications in DNA diagnostics and pharmacogenomic research (Figure 10). These active microelectronic devices combine the best attributes of both DNA array and “lab-on-a-chip” technologies. These microarray devices are able to cre-
Figure 9. Electrokinetic transport of DNA molecules in a microchannel.

ate reconfigurable electric field transport geometries on the array surface, which allows charged reagent and analyte molecules (DNA, RNA, oligonucleotide probes, amplicons antibodies, proteins, enzymes), nanostructures, cells, and even semiconductor structures to be moved to or from any of the microscopic test sites on the device surface. Applications include cancer diagnostics, genetic/forensic identification, infectious disease diagnostics, and combinatorial drug discovery. For micro/nanofabrication applications, Nanogen believes that the same microelectronic array devices can be used for combinatorial selection processes to create higher-order mechanisms and for the directed self-assembly of molecular, nanoscale, and microscale components into more complex structures. Electric field-assisted self-assembly using active microelectronic arrays is being developed as a “pick-and-place heterogeneous integration” process for fabrication of two- and three-dimensional devices and structures within defined perimeters of larger silicon or semiconductor structures. This technology has the inherent hierarchical logic of allowing one to control the organization, assembly, and communication of structures and components from the molecular scale → to nanoscale → to microscale systems, in which modeling tools will play a key role.

The presentation by Sandia focused on their well-known “lab-on-a-chip” devices in which microfabrication and nanomaterials are combined to develop the next generation of high-throughput analytical tools. Microfluidic systems allow one to miniaturize conventional biochemical analysis approaches such as one- and two-dimensional chemical separations. Integrating nanomaterials with microfluidic systems opens the door to completely new ways to sort, recognize, and detect molecules. The presentation focused on self-assembly as a key tool both for the development of the nanomaterials and for the operation of these new nanodevices.

Clemson presented work on using self-assembled monolayers (SAMs) surface modification to control the intrinsic and geometric properties of surfaces in contact with biological systems. The use of surface modification techniques allows the tailoring of the interface between biological/nonbiological materials at nanoscale dimensions independent of the bulk composition of the nonbiological material that mimics extracellular
Figure 10. Depiction of Nanogen DNA microarray system based on electrical field-assisted DNA transport.
matrix composition. The ability to control the surface composition of the in-vitro system as well as controlling other variables, such as growth media and cell preparation, all play important roles in creating a defined system for creating cellular devices.

Geometric control of the surface composition by SAM photolithography was used to create in-vitro circuits of mammalian neurons. SAMs alone were shown to differentially effect neuronal adhesion and control a key developmental parameter during development of the polarity of neurite outgrowth (Figure 11).

These cellular systems can be used in studies concerned with a more fundamental understanding of cellular development as well as creating sensors using living neurons as the sensor element and transducer. The key technical hurdle being the engineering of the interface to allow cellular placement and communication to nonbiological devices. The continuing development of this technology was discussed, as well as the implications and applications for (1) biosensor fabrication, (2) neuronal circuit design, and (3) biological computation.

This work was contrasted with the work presented by Berkeley, where a new class of devices was discussed focusing on integration of Nano probes in Polymer Opto Electro Mechanical Systems (NanoPOEMS) for bionanotechnology. NanoPOEMS can be used for biological analysis and imaging to characterize and control molecular behavior in nonfluidic environments. This simple strategy could lead to development of advanced nanofluidic circuits with specific electrically modulated surface properties. The hybridization of biocompatible polymer micromachining technology, nanophotonics, active nanolens, and single-photon avalanche-diodes would enable critical capabilities of NanoPOEMS for total bioanalysis. For example, the NanoPOEMS can be used for the detection of single-molecule probes, DNA hybridization, subcellular organelles, or neurotransmitters for determining exposure to chemical and biological warfare agents. Compact NanoPOEMS enable the detection capability for single-probe molecules, which will greatly affect future bioassay analysis.

The final talk discussed the use of a nanoscale device—a microcantilever. It has become apparent that microcantilevers have enormous potential in biological sensing. Several different types of mechanical responses due to molecular absorption can be used in detection. Of particular interest are mass loading, which changes the resonance frequency of the cantilever, and surface stress variation, which causes cantilever deflection. Deflection due to changes in stress can be readily detected if the absorption is con-

![Figure 11. Surface manipulation to central process outgrowth and polarity in developing neuronal systems.](image-url)
Figure 12. Depiction of cantilever assembly and detection system.

fined to one side. ORNL has demonstrated that microcantilevers can detect analytes with sensitivity in the parts-per-trillion range. Physisorbed and chemisorbed species can be separated using simultaneous detection of resonance frequency and cantilever bending (Figure 12). Results and application for mechanical detection of DNA single-nucleotide polymorphism, multiple mismatch localization, and hybridization kinetics were presented and are just a small part of the research ongoing in this truly nanosensor device.

As illustrated above, the biological sensing and processing area is one of the most promising for technology applications for nanoengineering and in most cases is a reaffirmation of research ongoing in the engineering section on basic energy sciences at the DOE. It also points to the overlap of the micro and nano regimes—and even the macro area—in systems developed through nanoengineering and points to the need to develop tools and methodology that will allow researchers and application engineers to go easily from one regime to the other to understand the implication of work in any one area.

**NANOSCALE INFORMATION STORAGE AND PROCESSING**

The session on nanoscale information storage and processing featured five talks (by B. Toomarian, J. Barhen, K. Likharev, J. Mamin, and D. Bogy) which presented a thin but representative slice of a broad area of advanced research in the field of information storage and processing in systems with nanoscale components. Without trying to reproduce the valuable material presented in these talks, we will draft the main conclusions which we believe may be drawn from the presentations.

1. **Current Technology Scaling**

Several existing technologies (with certain modifications) may be extended well into the nanoscale region. The examples include:

Magnetic storage systems where a single pixel size may be scaled down to about $30 \times 1,000 \text{ nm}^2$—providing storage density up to 100 gigabits/in.$^2$ (Figure 13)—in just a few years (J. Mamin and D. Bogy)
Ballistic SOI MOSFETs whose channel length may be scaled down to 6–8 nm, without major performance sacrifice (K. Likharev). Semiconductor flash memories which, with relatively minor modification, may be turned into fast, nonvolatile random access memories (“NOVORAM”) with a bit cell size scalable down to ~10 x 10 nm^2—see Figure 14 (K. Likharev).

This is why several alternative device and system proposals, including single-electron transistors for logic devices and memories, as well as the ESTOR (Figure 15) and MILLPEDE (Figure 16) concepts for data storage, may face an uphill battle for their practical introduction. More generally, the development of novel concepts should be carried out with due respect to the prospects of the continuing, evolutionary progress of “conventional” technologies.

2. New Concepts

Because of the tough competition, successful introduction of novel nanoscale electronic devices will probably require a system approach, with simultaneous change of the whole operation paradigm. Examples of such new paradigms, presented at the session, included:

A quantum-dot-array version of the so-called quantum cellular automata (QCA), which apparently may overcome some intrinsic problems of this concept and simultaneously provide some degree of fault-tolerance—see Figure 17 (B. Toomarian). Neuromorphic networks based on quantum-dot arrays with phonon-assisted tunneling (J. Barhen), and
Figure 14. Scaling of semiconductor nonvolatile random access memory.

Figure 15. Scanning a probe containing a single electron transistor on the tip can be used for read.
“MILLIPEDE” Concept

AFM-based Storage System:
High Data Density But Low Data Rate
Highly Parallel Operation

Figure 16. Array of microcantilevers used to detect deformations on surface by thermal means and use for data storage.

QCA Architectures

Fault Tolerant QCA Majority Gates

Majority Gate based on an irregular array of QCA with precise alignment
A Majority Gate based on an irregular array of QCA with imprecise alignment

Figure 17. Array of quantum dots that can be used for computations using quantum cellular automata.
Self-adaptive neuromorphic networks based on single-electron self-routing switching arrays (Figure 18), which may open a way to the replication of the natural evolution of the cerebral cortex at a much faster time scale (K. Likharev).

It is interesting (and probably not incidental) that all three concepts involve the use of quasi-uniform, two-dimensional arrays of small conducting islands (quantum dots). These arrays may help to provide the redundancy and fault tolerance which are so vital for practical nanoscale systems.

3. Quantum and Molecular Information Processing

The quantum degrees of freedom of a nanostructure can be exploited for computations. Theoretical understanding of quantum computations are well established and have been shown to be extremely powerful. However, it has been difficult to establish physical manifestations of qubits. There are various possibilities, ranging from isolated atoms in a lattice, to arrays of quantum dots or other quantum devices that allow entanglement. There is much work to be done to establish a method for quantum computations that can be practically realized. The benefits of quantum computations are, however, enormous. They can drastically change the way computations can be done, and problems that are too complex to solve by electronic processors could be handled by quantum computers.

Starting with the pioneering work of Adleman in 1994, molecular computations using DNA have been well established. It has been shown that computation problems that require massively parallel searches (satisfiability problems—SAT) can be efficiently solved by molecular computers using DNA and its modifying enzymes. In addition, the energy required to solve such computations is insignificant compared to electronic processors. However, practical realizations of molecular computers have not been achieved. That is primarily because of the lack of programmability and the cumbersome molecular operations that one must perform to achieve the computations. In addition, since many of the steps require amplification of DNA, error propagation could be a problem.
Hence, fault-tolerant algorithms need to be developed. Regardless of its drawbacks, practical molecular computers can enable rapid information processing for certain classes of computational problems.

**NANOSCALE DIAGNOSIS AND MANIPULATION**

One of the critical challenges in nanoscale science and engineering is the ability to observe and manipulate objects and phenomena in the length scale regime of 1–100 nm. Scanning probe microscopes (SPMs) form a whole class of instruments that have revolutionized the way this is achieved. Although they were originally developed to obtain topographical images of solid surfaces, they have now found wide applications. Although the last two decades have seen tremendous progress in this field, many critical challenges still remain.

A group from IBM-Almaden (Mamin, Rugar) and Stanford (Kenny) presented a promising approach for chemical identification—magnetic resonance force microscopy (MRFM)—shown schematically in Figure 19. The technique relies on creating a high magnetic field gradient from a magnetized tip such that a thin slice of spins fall in resonance with an externally applied rf field. The presence of the field gradient also creates a force interaction between the tip and the sample, which can be detected by modulating the rf field at the resonant frequency of the cantilever. One of the major challenges of this technique is the following. The magnetic resonance force from a single electron in a 2 G/Å field gradient is $10^{17}$ N-rms, whereas that from a single nuclear spin (proton) in the same gradient is $10^{20}$ N-rms. Currently available AFM cantilever probes, however, have a force resolution of $10^{12}$ N-rms. Hence, to achieve single-atom chemical identification, one has to really push the limits of force resolution. Tom Kenny’s group at Stanford has developed novel AFM probes (see Figure 20) which have noise densities in the range of $10^{18}$ N/√Hz at room temperature. To achieve these force resolutions one requires not only novel engineering of microfabrication but also a fundamental understanding of dissipation mechanisms and noise sources. Much work still remains to achieve atomic-scale chemical identification, but MRFM seems very promising indeed. In addition to chemical identification, it also allows one to obtain 3-D imaging of thin slices of the sample medium where the slice location is controlled by the external rf frequency. Finally, MRFM can potentially provide the readout for spin-based quantum computers, offering the opportunity to bring quantum computing into reality.

![Figure 19. Schematic diagram showing principle of magnetic resonance force imaging.](image-url)
While there are many techniques to study electronic or dielectric properties of materials at nanometer scales (tunneling, capacitance, electrostatic force, spreading resistance, etc.), there are very few approaches to measure thermal or thermoelectric properties at that scale. This is particularly important for energy conversion applications, where nanostructured materials exhibit higher thermoelectric performance. In addition, since heat flows in all materials and in all directions, thermal microscopy offers the opportunity to observe objects below the surface by measuring the resistance to heat transport. Majumdar (UC Berkeley) presented the latest developments in scanning thermal microscopy (SThM). Figure 21 shows batch-fabricated probes that contain a temperature at the tip. Some of the more advanced probes contain more than two sensors, such that heat flux can be measured. Such probes have been used to obtain thermal images of electrically heated carbon nanotubes (see Figure 21). What lies in the future is to develop a scanning $ZT$ microscope which would measure the local thermal ($k$), thermoelectric ($S$) and electrical ($\sigma$) properties of a sample and there by obtain the local thermoelectric figure of merit, $ZT = S^2\sigma T / k$. Although the spatial resolution is in the range of 10–20 nm, quantitative measurement of the properties remains a challenge.

Besides magnetic resonance and thermal microscopy, another area that offer the prospects of chemical identification and/or subsurface imaging is near-field optical. Whereas most researchers in near-field optics have used metal-coated tapered fibers with subwavelength apertures, Goodson, Kino, and Quate (Stanford) have developed batch-fabricated solid-immersion lenses (see Figure 22). Using these probes, they have been able to obtain subwavelength resolution. The main issue with near-field optics is to be able to batch-fabricate probes and yet achieve resolutions in the 10-nm range.

While most of the research using SPM focuses on imaging and diagnostics, they can also be used for manipulation. Requicha and co-workers (USC) are using the AFM as a nanorobot to pick up nanostructures from a surface and relocate them elsewhere. This is shown in Figure 23, which demonstrates this concept using 15-nm particles. It is possible to automate and program the AFM for the purpose of assembling nanosstructures. While this is a sequential process and therefore time consuming, it does offer the promising prospects of assembling objects that cannot be brought together by chemical or thermodynamic self-assembly. In that respect, it is much more flexible. One can also envision the combination of imaging and manipulation to form an intelligent nano-assembling machine. However, AFMs at present are limited. Increasing AFM speed remains as one of the major challenges.
Figure 21. SEM images of batch-fabricated thermal microscopy probes with one and two sensors. Topographical and thermal images of electrically heated multiwall carbon nanotube.

Figure 22. SEM images of batch-fabricated cantilevers with silicon solid-immersion lenses as tips for near-field optical microscopy.
There are several ways of increasing AFM speed. One is to make ultrashort AFM cantilevers such that their resonant frequency can be increased to the range of 500 kHz (currently they are 40–50 kHz) while maintaining their stiffness less than 1 N/m. This is being currently pursued in the Hansma lab (UC Santa Barbara), which have been able to achieve real-time imaging. Another approach is to make multiple cantilever probes on one chip that are controlled independently. One needs to have a nonoptical cantilever detection technique, such as piezoresistive detection and piezoelectric actuation. Quate’s (Stanford) group is pioneering this approach and have been able to image large objects by parallel AFM. West (Thermomicroscopes) presented an approach to perform multiprobe AFM which would allow higher functionality to nanoscale imaging. However, much engineering research needs to be done for high-speed and large-area nanoscale imaging.

Serry (Digital Instruments) presented other applications of AFM to measure spreading resistance at nanometer scale which can be used to image electrical conductance of grains and other nanostructures. In addition, he also discussed the possibility of using quantum fluctuation Casimir forces for data storage and imaging. Lindsay discussed the peculiarities of nanoscale contacts to molecules.

Finally, Pui (U Minnesota) presented a talk on high-throughput injection biomaterials into cells. This is particularly useful for gene transfection. The high-throughput feature of this technique renders it very useful for large-scale genetic engineering.

In summary, there were many novel presentations related to nanoscale diagnostics and manipulation. The grand challenges that remain and that must be emphasized are

1. Three-dimensional imaging with nanometer-scale resolution in solid and fluid environments
2. Chemical identification of nanoscale objects
3. High-speed, large-area, and time-resolved imaging
4. Multifunctional diagnostics

WORKSHOP ORGANIZERS

Arun Majumdar, Department of Mechanical Engineering, University of California, Berkeley
Paul Alivisatos, Department of Chemistry, University of California, Berkeley
WORKSHOP PROGRAM

Friday, August 4
1:00–2:30 Registration (3110 Etcheverry Hall)
2:30–3:00 Opening Reception
3:00–3:30 Opening Remarks by Chang-Lin Tien, University of California, Berkeley
3:30–4:15 Tools for Nanotechnology: Calvin Quate, Stanford University
4:15–4:30 Discussions
4:30–5:15 Epitaxial Semiconductor Nanostructures: Harnessing Nature’s Way: Anupam Madhukar, University of Southern California
5:15–5:30 Discussions
5:45–6:30 Cash Bar (Faculty Club)
6:30– Dinner Banquet (Faculty Club)

Saturday, August 5
7:30–8:15 Continental Breakfast (3117B Etcheverry Hall)
8:15–8:45 Large Scale Integration of Nanostructures: Fabian Pease, Stanford University
8:45–9:00 Discussion
9:00–10:30 SESSION ON LARGE-SCALE INTEGRATION (Session Chair: Steve Chou)
Speakers (15 minutes each):
 Integrated Nanostructured Materials: Ilhan Aksay, Princeton University
 Statistical Mechanics of Pattern Formation in Biological Systems: Arup Chakraborty, UC Berkeley
 Large-Scale Integration of Nanodevices by Nanoimprint Lithography and Lithographically-Induced Self-Assembly: Steve Chou, Princeton University
 Open Forum
10:30–10:45 Coffee Break
10:45–12:30 SESSION ON NANOSCALE DIAGNOSIS AND MANIPULATION (Session Chair: Arun Majumdar)
Speakers (10 minutes each):
 Technologies and Applications for Suspended Nanostructures: Tom Kenny, Stanford
 Making Electrical Contacts to Molecules: Stuart Lindsay, ASU
 Multifunctional SPMs and Sub-surface Imaging: Arun Majumdar, UC Berkeley
 Magnetic Resonance Force Microscopy: Progress and Lessons: John Mamin, IBM
 A Novel Approach for Introducing Bio-materials into Cells: David Pui, University of Minnesota
Nanorobotics: Aristides Requicha, University of Southern California

Zero-Point Vacuum Forces and Their Potential Use in Nanometer-Size Devices: F. Michael Serry, Digital Instruments

A Multiple Probe System with Independent Probe Control: Paul West, Thermomicroscopes

Open Forum

SESSION ON ENERGY CONVERSION SYSTEMS (Session Chair: Ali Shakouri)

Speakers (12 minutes each):

Engineering Nanostructures for Energy Transport and Conversion: Gang Chen, UCLA

Infrared Microscopy Using a Micromachined Solid Immersion Lens: Ken Goodson, Stanford University

Energy Conversion and Heating in Nanoscale Optoelectronic Devices: Ali Shakouri, UC Santa Cruz

Flagellar Motors: Michael Manson, Texas A&M Univ.

A Photonic-Biomolecular Motor System for Powering Nano-electro-mechanical Devices: Carlo Montemagno, Cornell Univ.

Open Forum

12:30–2:00 Lunch

SESSION ON BIOSENSING AND PROCESSING (Session Chair: Jay Hickman)

Speakers (12 minutes each):

Directed Growth of Neuron and Their Applications as Sensors: Jay Hickman, Clemson Univ.

Nano-POEMS Luke Lee, UC Berkeley

Computational Analysis of Nanoscale Phenomena in Biomicrofluidic Devices: Vinod Makhijani, CFD Research Corp.

Nanomaterials for Biomolecular Analysis: Alan Burns, Sandia National Laboratory

Microcantilever Biosensors: Thomas Thundat, Oak Ridge National Laboratory

Open Forum

SESSION ON NANOSCALE INFORMATION STORAGE/PROCESSING (Session Chair: Konstantin Likharev)

Speakers (12 minutes each):

Fault Tolerant Architecture for Quantum Dot Cellular Automata: Benny Toomarian, NASA-JPL

Neuromorphic Quantum Dot Arrays for Computations: Jacob Barhen, Oak Ridge National Lab.

Handling Digital Information on Nanoscale: Prospects and Problems: Konstantin Likharev, SUNY—Stony Brook

Data Storage Based on the Atomic Force Microscope: John Mamin, IBM Almaden Research Lab.
Nanoengineering Needs in Conventional Data Storage Systems:
David Bogy, UC Berkeley

Friction and Fatigue at the Nanoscale: R. Budakian and Seth Putterman, UCLA

Open Forum
3:30–4:00 Coffee Break
4:00–4:30 Microelectronic Array Devices for DNA Diagnostic, Pharmacogenomic, Combinatorial Selection and Nanofabrication Applications: Michael Heller, Nanogen

4:30–4:45 Discussion
4:45–6:00 Session Chair Reports (15 minutes by each chair)
6:00–6:30 Closing Remarks by Paul Alivisatos, UC Berkeley