NanoTechnology With Feynman Machines: Scanning Tunneling Engineering and Artificial Life

Dedicated to the original NanoTechnologist, Richard P. Feynman (11 May 1918—15 Feb 1988) and to a major pioneer of electronic NanoComputing, Forrest L. Carter (29 April 1930—20 Dec 1987)

In the year 2000, when they look back at this age, they will wonder why it was not until the year 1960 that anybody began seriously to move in this direction.

— Richard P. Feynman

It is difficult to suppress one's enthusiasm for the development of a viable molecular technological base when one recognizes the possible scientific, industrial and economic spin-off opportunities.

— Forrest L. Carter
1. INTRODUCTION

Artificial life involves the replication of the processes associated with natural life, but possibly in new media, or on new size scales, or with new organizing principles, etc. One intriguing set of possibilities for creating artificial life is based on Richard Feynman's suggestions in 1959 for ultraminiaturization and extension of our industrial manufacturing capabilities all the way down to the molecular level. Other early pioneers developed related concepts and further generalized them. We will describe several important technological developments along these lines later. Such technology is now termed nanotechnology (1 nanometer = 1 nm = 10^{-9} m). These approaches to artificial life involve operating directly at the molecular level.

There are many ways that nanotechnology can eventually be applied to the development of artificial life. The following two possibilities are selected to illustrate (1) the possibility of a fine grained continuum of structures spanning natural and artificial life, and (2) the scale invariance principle of artificial life applied to hybrid size scales and hybrid technology life forms. (1) We can start with a completely natural life form and gradually transform it (bootstrap it) into a totally artificial life form by using molecule-by-molecule replacement. (2) We can develop a hybrid living system that incorporates some nanotechnology for computing functions, some natural biology for material synthesis functions, and some microtechnology for artificial replication. We will return to these topics after reviewing the history and state-of-the-art of nanotechnology.

The term “nanotechnology” encompasses much of the subject matter of older terms such as “ultraminiaturization” and “molecular engineering.” A similar situation exists for “nanomachines” (“molecular machines”), “nanocomputers” (“molecular electronic devices,” “quantum computers,” “biochips”), “nanoreplicators” (“molecular replicators”), and so on. Franks’ excellent review paper on nanotechnology notes that the term “nanotechnology” was defined in 1974 by Taniguchi; Franks describes nanotechnology as,

...the technology where dimensions and tolerances in the range 0.1–100 nm (from the size of the atom to the wavelength of light) play a critical role... The field covered by nanotechnology is narrowed down to manipulation and machining within the defined dimensional range by technological means, as opposed to those used by the craftsman... Nanotechnology is an 'enabling' technology, in that it provides the basis for other technological developments, and it is also a 'horizontal' or 'cross-sectoral' technology, in that one technique may, with slight variations, be applicable in widely differing fields... Nanotechnology is seen to be of particular importance, and of immediate relevance, in areas such as materials science, mechanical engineering, optics and electronics.

[in this and all other quotes, emphasis is added.]
Taniguchi\textsuperscript{225} notes that "Nanotechnology' is the term used to classify the integrated manufacturing technologies and machine systems which provide ultra precision machining capability in the order of 1 nanometer...[It] might also be called 'extreme technology' because the theoretical limit of accuracy in machining of substances must be the size of an atom or molecule..." He examines the general trends in ultraprecision machining, which should continue on down into the \textit{substance synthesizing} domain, sometime around the year 2020. This trend is similar to that for very advanced lithography and corresponding experimental electronic integrated circuit devices. Taniguchi\textsuperscript{226} describes atomic bit machining as \textit{atom-by-atom processing} using energy beams. He discusses several types of atomic bit processing including separation, consolidation, deformation, cutting, polishing, and surface treatment—each of which would be useful for making experimental nanotools.

By extension, "picotechnology" (1 \textit{picometer} = 1 pm = 10^{-12} m) deals with the manipulation and modulation of individual atomic bonds and orbitals plus the special equipment where atomic or molecular measurements are made to sub-nanometer precision. There are already special cases where mechanical positioning and measurements of spacing between individual atoms has been pushed to a resolution of 1–10 picometers! The instrument with this phenomenal capability was

FIGURE 1 An early STM constructed with the author's coworkers. Photograph courtesy of Mark Voelker, Optical Sciences Center, University of Arizona, Tucson, Arizona.
invented early this decade; it is the scanning tunneling microscope—and it is also a fundamental tool for nanotechnology.

Scanning Tunneling Microscopes (STMs) can "image" atomic level (i.e., nanometer) structural, dynamic, and electronic properties of materials including metals, semiconductors, and biological molecules. In STMs, an electronic servo system driving a piezoceramic positioner controls highly localized, quantum mechanical, electron tunneling between ultrasharp electrode tips and chosen materials. Tip movement, which maintains constant tunneling current during surface scanning, translates to a surface map with atomic level resolution under optimal conditions. By holding constant different combinations of voltage, current, and tunneling distance, different types of information and material effects occur. Such versatility permits imaging and manipulation of molecules and molecular devices and endows STMs with nanoscale electromechanical interfacing and machining capabilities.

An early STM project initiated by the author and developed with the assistance of others at the University of Arizona (based on lots of useful information provided by Paul Hansma of the University of California at Santa Barbara) produced the STM shown in Figure 1. See Figures 2 and 3 for examples of STM images taken with more modern STMs.
FIGURE 3  (a) A STM image of graphite. Nanoscope II Parameters: Bias—14.0 mV; Setpoint—1.1 nA; Z—21.0 Å; X,Y—21.0 Å; and Samples—400/scan. Captured Tues., Aug. 25, 15:15:38, 1987. (b) A STM image of molybdenum disulfide; parameters and date included in photo. Both images were taken with a Digital Instruments Nanoscope II STM. Photographs courtesy of Virgil Elings, Digital Instruments, Santa Barbara, California.
The possibility and great value of molecular level machines was first noted by Nobel physicist Richard Feynman, who nearly 30 years ago proposed tools to construct nanoscale mechanisms and devices; such tools and mechanisms are *Feynman Machines*. Emergence of STMs and their applied hybrids should greatly facilitate implementation of a general purpose nanoscale manufacturing capability (*nanotechnology*) with major implications for the development and testing of molecular electronic devices and molecular photonic devices.

The application of STM technology to implement Feynman’s program was first described by Schneiker\(^{121}\) in order to: (1) refute claims that Feynman’s “top-down” approach to nanotechnology was not viable, (2) to provide an indication of the true scope of his ideas, and (3) to note previously unacknowledged contributions by other early nanotechnology pioneers. Since then, the relevance of Feynman’s early work (and that of others) has become much more widely recognized. Hansma and Tersoff\(^{108}\) note the possibilities of using STMs to realize Feynman’s nanotechnology vision. In their Nobel Prize lecture, Binnig and Rohrer\(^{18}\) note that the capabilities of STMs include the possibility “ultimately to handle atoms and to modify individual molecules, in short, to use the STM as a Feynman Machine.” Franks’ review of nanotechnology\(^{58}\) notes the tremendous potential of STM-derived tools for “scanning tunneling engineering.”

A “nanotechnology workstation,” suitable for scanning tunneling engineering, is proposed in Schneiker and Hameroff\(^{202}\). It is illustrated in Figure 7, and will be described later. Nanotechnology workstations and related instruments should greatly enhance the fabrication, testing, and realization of molecular devices and structures needed for artificial life and artificial evolution.

As anticipated by Feynman in 1959, nanotechnology is now becoming one of the most exciting areas of research and development. A brief history of nanotechnology is now in order.

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**A BRIEF HISTORY OF NANOTECHNOLOGY TO 1980**

Heinlein\(^{111}\) nearly invented the concept of nanotechnology in 1940 by suggesting a process for manipulating microscopic structures (see appendix). However, he completely overlooked the full implications of his idea and it had no impact on technological development. However, by the early 1960’s, several scientists had reinvented similar approaches to micromanipulation and miniaturization, but this time extending all the way down to the nanotechnology domain. Since then, nanotechnology has advanced substantially, although some related developments have sometimes been hidden by proprietary considerations and classification or hampered by lack of funding. Just as visions of future space faring technology include projections of
human travel across the galaxy, so too have visions of future nanotechnology possibilities greatly surpassed any reasonably probable near-to-medium-term technical development; these more speculative possibilities are summarized in the appendix.

FEYNMAN: ORIGINATOR OF NANOTECHNOLOGY

In his remarkably prescient 1959 talk “There’s Plenty of Room at the Bottom,” Feynman proposed using machine tools to make smaller machine tools, to be used in turn to make still smaller machine tools, and so on all the way down to the atomic level. Feynman prophetically concluded that this is “...a development which I think cannot be avoided.” Such nanomachine tools, nanomachines and nanodevices are termed Feynman Machines (FMs). FMs can ultimately be used to develop a wide range of submicron instrumentation and manufacturing tools, i.e., nanotechnology. Feynman’s suggested applications for these tools included producing vast quantities of ultrasmall computers and micro/nanorobots. A wide range of other nanotechnology applications have been anticipated.

Others, including Shoulders, realized the technological value of operating in this submicron nanoworld in the early 1960’s. In one of the earliest examples of an FM, Shoulders went beyond theory and in 1965 reported the actual operation of a micromanipulator able to position tiny items with 10 nm accuracy while under direct observation by field ion microscopy.

Feynman’s definitive source paper on nanotechnology is also reprinted (with Feynman’s permission) in Schneiker. It is worth quoting a few of the highlights from the original paper since it forms the basis of many later conceptual developments:

[Consider] the final questions as to whether, ultimately...we can arrange the atoms the way we want, the very atoms, all the way down...[When] we have some control of the arrangement of things on a small scale we will get an enormously greater range of possible properties that substances can have, and of different things that we can do...We can use, not just circuits, but some system involving the quantized energy levels, or the interactions of quantized spins, etc...Another thing we will notice is that, if we go down far enough, all our devices can be mass produced so that they are absolutely perfect copies of one another...[If] your machine is only 100 atoms high, you only have to have it correct to one-half of one per cent to make sure the other machine is exactly the same size—namely, 100 atoms high!...Ultimately, we can do chemical synthesis...Put the atoms down where the chemist says, and so you make the substance.

[A] point that is most important is that it would have an enormous number of technical applications...
A biological system can be exceedingly small... Consider the possibility that we too can make a thing very small, which does what we want—that we can manufacture an object that maneuvers at that level... So I want to build a billion tiny factories, models of each other, which are manufacturing simultaneously...

These possibilities for making and manipulating nanostructures are keys to artificial life. Krkumhansl and Pao\textsuperscript{140} presented an overview of microscience that was interspersed with germane references to Feynman's classic paper on nanotechnology. They noted [in 1979] that we have not [yet] quite achieved the possibility of fabricating structures at the molecular scale.

In later years, Feynman\textsuperscript{75} mentioned giving other talks on his ideas in this area; however, he was unable to locate his notes for them. He also indicated that he had originated his ideas in the early 1950's and that others had independently suggested similar top-down approaches for nanomanipulation in the late 1950's and early 1960's. Freeman Dyson\textsuperscript{59} mentioned that Tommy Gold also "was talking about nanotechnology as early as Feynman. But I have nothing in writing." Another one of the people that Feynman alluded to was probably our next remarkable pioneer, K. R. Shoulders.

**SHOULDERS: NANOTECHNOLOGY EXPERIMENTALIST**

Shoulders' early work (1960–1965) paralleled Feynman's in several important respects. However, Shoulders expended considerable effort in pioneering experimental work. Although he thought about nanoscale structures, he generally limited the scope of his writing to scales he thought he personally could accomplish in the lab. Shoulders\textsuperscript{207} rejected the use of biological building blocks, even though biological "processes do work, and they can do so in a garbage can without supervision." He saw them as too limited environmentally and too difficult to control with available technology; instead, he sought to directly produce much simpler, more powerful, and much more rugged nanostructure arrays, at video frequencies rates, which in turn could ultimately aid in their own replication. These early efforts may be viewed as an early approach to a nonbiological proto-life system suitable for vacuum environments.

For robotic artificial life forms, superabundant computing power is one means to manage the complex organizational functions of the sensing, analysis, construction and manipulation tasks required for the replication and evolution of increasingly advanced systems. Both Shoulders and Feynman saw the possibilities and importance of building immensely more powerful computing machines and robots that would rival the human brain in numbers of parts and complexity. These would be important for advanced robotic replicators and for controlling nanomanipulators. Shoulders\textsuperscript{206} states: "We want to build electronic data processing systems that have the complexity of human neural networks but are capable of operating with
electronic speed.” Feynman also thought that the “possibilities of computers are very interesting … if they had millions of times as many elements…” Shoulders elaborates:

We propose … a component based upon the quantum-mechanical tunneling of electrons into the vacuum … The transit time for electrons would be about $10^{-13}$ sec …

Ultimately, we would use a vacuum-tunnel effect cathode array for our electron source. The emission from discrete areas would be controlled by local grids … Thus we have components made by electronic micromachining responsible for the building of new systems by the same method. In the end, self-reproduction would be a distinct possibility without the use of a lens system, because all copies would be made on a one-to-one size basis.

As foreseen by Morrison, this technology clearly had potential for an artificial life form. Shoulders maps out an integrated circuit technology based on field-emission vacuum-tunnel-effect devices using this technology and adds:

Our over-all component size is constrained by the [electron beam] construction techniques [currently available at the time] to be within the limits of one-tenth of a μm and two μm … The lower limit is set by the resolution of the machining process. A single metal and a single dielectric … seem to be the only materials needed … The geometry is extremely simple … Electrostatic relays, electromechanical filters, light generators and detectors, all of similar scale and simplicity are proposed for I/O channels and memory.

Note that since the resolution of electron beam technology has improved by one to two orders of magnitude, many of Shoulders’ proposals could now be scaled down to the 1–10 nm range. Indeed, Feynman suggested using the end of a conical STM tip to make experimental nanoscale triode structures. Since then, Fink has developed a technique to make monoatomic STM tips in which the last three atomic layers in the tip form an atomically perfect pyramidal structure. Thus, the key part for experimenting with absolutely minimum scale (and perhaps maximum performance) nanotechnological vacuum diodes and triodes now exists (Figure 8). Fink has recently made field-emission measurements on the exceptionally narrow and intense electron beams from single atoms on monoatomic tips; those results and the analysis of Garcia et al. indicate that it may be the key to the “micromicroscope” (a greatly improved scanning electron microscope which Feynman wanted developed as part of his nanotechnology program.

Shoulder’s proposed electrostatic relays could also incorporate wear-free, non-contacting, subnanometer, vacuum-tunneling gaps, incorporating just a few atoms in the limiting case. These could also be used for electrostatic nano-actuators and mechanical power sources. Shoulders later reports testing of prototype devices and structures.
Another innovative concept that might eventually bear on artificial life and nanotechnology is outlined in Shoulders, including the discussion of plasma machines:

This is the most fantastic tale. I will discuss how to make an intelligent organization without any [mechanical] parts at all... I am primarily interested in man- or machine-made plasmas organized so as to constitute intelligent machines... This... leads potentiality to great structural richness, provided that we can organize the process to the critical level of complexity, which perhaps separates man from other animals, beyond which the machine can assist itself at organizing at a rate greater than the rate provided by more limited man... So, the question is—how do we get started and take advantage of all of these potentialities?... In the simplest case, the machine should be an iterative array of components that are isolated from each other, but have the ability to intercommunicate via sinusoid electron paths. The components must be able to launch, adsorb, receive and steer electrons or groups of electrons. Such an organization would allow the creation of order within the machine at the dictate of other organized areas. This newly-made order could be propagated physically through the machine and then be destroyed if found wanting. The components could then be used again for higher levels of organization. This arena concept (using fundamental elements at fixed or movable loci but having flexible connectivity and a reversible change of state without leaving a residue) would greatly modify most present concepts of machine organization... We will claim that field-emission devices could be used to fabricate a "wireless" machine using any interesting organization... and that a complete machine could be built on this principle.

Shoulders describes some experiments in electrodynamic particle confinement and notes that "it will be a long time to the product phase of this kind of machine." He later adds,

By learning the laws of organization through fixed structures we may eventually be able to organize plasma structures to the point that they provide enough inherent stability to become their own container. The number of interactions possible in a plasma system and the speed and energy density of these interactions make it highly desirable to seek a way of organizing them.

Finally the connection with nanotechnology:

Nothing would be more desirable to me, as a researcher on intelligent structure organization than to dispense with the need for tediously carving microscopic shapes by taking advantage of the almost infinite elasticity and plasticity of plasma structures by organizing our machines in the large and
then squeezing the structures down to size by changing the confinement parameters.

Shoulders\textsuperscript{210} indicated that he is still interested in self-organizing systems that could increase their complexity in order to evolve into artificially intelligent, self-conscious entities.

In discussing the brain's computing abilities, Feynman\textsuperscript{72} also considered computing from a mechanical perspective: "But our mechanical computers are too big; the elements in this box are microscopic. I want to make some that are submicroscopic." Shoulders\textsuperscript{208} considered a similar electro-mechanical alternative: "...we may reconsider a mechanical electrostatic relay..." Although (electro)mechanical nanocomputers are an interesting idea, both Shoulders and Feynman noted that when it came to speed, ...the real promise of nanocomputing lay in utilizing quantum mechanical effects.

Feynman\textsuperscript{72,76} suggested quantum effects might be used for computing and Carter\textsuperscript{22} has proposed a chemical structure that would use quantum mechanical, electron tunneling effects for implementing a computer logic element. These and several other tantalizing possibilities are discussed later.

\textbf{ETTINGER, WHITE, DARWIN, DONALDSON: MEDICAL NANOTECHNOLOGY}

Ettinger\textsuperscript{63,64} suggested using nanotechnology for life extension and artificial evolution, and "nanominiaturization" of robots was later suggested by Ettinger\textsuperscript{69} White,\textsuperscript{239} Darwin,\textsuperscript{38} and Donaldson\textsuperscript{48,49} envisioned the use of genetic engineering and other possibilities for making nanorobots that could function as cell repair machines. These possibilities are discussed in the appendix.

\textbf{VON HIPPEL, VON FOESTER, ZINGSHEIM, ELLIS, FULLER: MOLECULAR ENGINEERING}

Forrest\textsuperscript{85} notes, in connection with Von Hippel, that "...nanotechnology... will evolve from the integration of such diverse disciplines as genetic engineering, biophysics, robotics, artificial intelligence, computer-aided design and manufacture (CAD/CAM), biology, chemistry, physics, computer science, materials science, and many others. The concept of integrating these technologies is not new. Arthur von Hippel foresaw it at least as early as 1963, and others probably even before that."

Von Hippel\textsuperscript{236} noted the fantastic possibilities that better materials technology holds for the world if only current science and engineering limitations could be conquered: "Suddenly all this is changing. 'Molecular science'...has made a more powerful approach possible: 'molecular engineering,' the building of materials and devices to order."
Von Foester\textsuperscript{235} commented that von Hippel's anticipation of "engineering of molecules according to specification" may "also show us some novel manifestations of life." Von Foester derived some mathematical constraints for the molecules needed for such a "molecular bionics" modeled on chemical modifications to a particular macromolecular structure called a \textit{macromolecular sequence computer}.

Zingsheim\textsuperscript{252,253} was interested in molecular engineering using nanometer surface microstructures. He noted that "The aim of molecular engineering ... is the design and construction of man made complex supramolecular systems from building blocks of molecular dimension." He further noted that it concerns the "development of molecular components and assembly tools allowing manipulations at molecular dimensions."

In a paper on microteleoperators, Ellis\textsuperscript{60} reports:

Electrically operated micromanipulators add automatic high-speed movement to normal manual control ... In addition to their use in biological investigations, piezoelectric micromanipulators may find important new uses in the development of semiconductor devices and microcircuits. For example, semiconductor junctions could be formed by microetching and electroplating with microelectrodes. Complex circuit paths could be formed by etching through a conducting layer deposited on an insulating substrate ... With these techniques, complex circuits of unprecedentedly small size could be fabricated automatically.

Its interesting to note that these very same functions could be performed at or near the ultimate limits of miniaturization using STMs. These discussions of control methods, linkages, dynamics, etc., for teleoperated microtools still have relevance to Feynman Machines.

Buckminster ("Doing More With Less") Fuller proposed a nanoarchitecture having an interesting recursive or fractal structure (Fuller and Applewhite\textsuperscript{89}). Its macro level structure is simply a tensegrity mast, which is a rigid structure constructed from an ingenious configuration of interconnected tension (cable) and compression (strut) members, with the unique feature that the struts are isolated from each other. In one version of the macro-tensegrity mast, each individual solid strut and cable may be replaced by a miniaturized version of the macro-tensegrity mast. And then each one of the miniature solid struts may itself be replaced by a still smaller subminiature tensegrity mast. And so on recursively, down to the atomic level. The end result is an extremely light, mostly empty, yet rigid structure. This same idea may be applied a large variety of other structures.
CHANGEUX AND KUHN: MOLECULAR MACHINES AND DEVICES

The feasibility of artificial molecular machines is implied by the view that biology is based on molecular machines. Changeux notes that,

The analogy between a living organism and a machine holds true to a remarkable extent at all levels at which it is investigated ... An organism can be compared to an automatic factory ...

[The] cell is a mechanical microcosm: a mechanical machine in which the various structures are interdependent and controlled by feedback systems quite similar to that of the systems devised by engineers who specialize in control theory ...

Regulating the production lines are control circuits that themselves require very little energy ... The elementary machines of the cellular factory are the biological catalysts known as enzymes ... Built into [their] structure, as into a computer, is the capacity to recognize and integrate various signals.

Langmuir-Blodgett films are one molecule thick films that are made by spreading fatty acid molecules across an air-water interface. These films may have other molecules inserted into them, and a simple dipping process may be used to stack up such film into multilayer structures. Kuhn describes his pioneering work (starting in the 1960's) in applying Langmuir-Blodgett films to molecular scale devices:

The construction of an artificial system acting as a complex machinery with cooperating components of molecular dimensions is a great challenge. First attempts in the early 1960's to approach this aim were governed by the idea that the Langmuir-Blodgett technique ... might be suitably modified and could then offer a way to arrange appropriate functional molecules of different species in an adequate fixed structure where the molecules could cooperate in a complex and purpose-oriented manner. Many different techniques to reach that goal have been developed and are summarized: methods to control monolayer formation and transfer and to study monolayer absorption, reflection and fluorescence spectra; special techniques to check the architecture of monolayer organizates by combining energy and electron transfer; synthesis of sterically interlocking and functionally cooperating molecules ...

[It] should be mentioned that the search for the basic mechanisms in the origin of life can be strongly stimulated by studying possibilities of the formation of artificial machineries of molecular size and that quite unorthodox views are obtained from such studies. Conversely, the study of these mechanisms should indicate new ways of obtaining artificial devices of molecular size ...
The synthesis of molecules for use as components in designed assemblies to be used as tools of molecular size should be a challenging new field.

Kuhn\textsuperscript{142} adds, “To our knowledge, the first demonstration of arranging molecules by means of an electron beam using a STEM (not STM) was realized in Kuhn’s group by H. P. Zingsheim.”\textsuperscript{252} Nature provides us with a wealth of prototypical molecular machines; some basic mechanisms of some of these machines are examined by Mitchell\textsuperscript{167} and McClure.\textsuperscript{162}

**LAING: ARTIFICIAL NANOREPLICATORS**

In a series of papers with direct relevance to artificial life, Laing\textsuperscript{144–148} wrote about artificial replicators. In particular, his 1974 and 1975 papers are motivated by considerations of artificial molecular replicating machines, constrained to be “biologically reasonable” (including future biological possibilities and, hence by implication, artificial life). These papers have direct relevance to artificial nanoreplicators and microreplicators. While Von Neumann\textsuperscript{237} formulated a general theory of replicating automata in abstract form, Laing has considered some important design possibilities for molecular realizations of such automata. One form of these nanoreplicators described by Laing\textsuperscript{145} utilized molecular (data) tapes (based on the idea of universal Turing machines) to implement replicators (based on Von Neumann’s generalization of self-replicating Universal Turing machines). He then showed three ways that such molecular machines might replicate themselves. His exploration of “artificial organisms” was “a vehicle for the exploration of broad biological possibilities.”

Laing’s\textsuperscript{146} studies of kinematic replicators results in a new self-inspecting design that leads to the interesting conclusion that “contrary to von Neumann’s surmise, a priori description is not essential to the nondegenerative machine self-reproductive processes.” Among other interesting features, this new replicator design has interesting self-repairing capabilities as well.

**ROTHSTEIN, AVIRAM, RATTNER, CONRAD, CARTER, LIEBERMAN: MOLECULAR NANOCOMPUTING**

Scientists extrapolating the development of electronic devices in the 1950’s and 1960’s noted that the next century should see the development of electronic devices the size of individual molecules and much faster than neurons. Rothstein\textsuperscript{194} examined some fundamental limits on chemical information storage systems. In 1974, Aviram and Ratner\textsuperscript{4} presented one of the earliest specific proposals for a molecular electronic device, in this case a molecular rectifier. Conrad\textsuperscript{20,21} has studied information processing in molecular systems, molecular automata, and molecular computing in general. Forrest Carter\textsuperscript{20,21} of the Naval Research Laboratory started
searching for means to assemble entire computers from molecular devices. Lieberman examined some of the possibilities for “molecular computers,” including their phenomenal memory capacities, noting that while on a modern computer there are about $10^{10}$ simple memory elements, that on the other hand, “on an excellent machine of the distant future... there might be $10^{20}$ elements.”

**YOUNG, WARD, SCIRE, TEAGUE: PROTO-STM**

The STM was very nearly invented 10 years earlier, but success was prevented by equipment vibrations and other problems. Young, Ward and Scire reported metal-vacuum-metal tunneling experiments and described a machine they had developed for these experiments at the National Bureau of Standards:

A noncontacting instrument for measuring the microtopography of metallic surfaces has been developed to the point where the feasibility of constructing a prototype instrument has been demonstrated...In the MVM mode, the instrument is capable of performing noncontacting measurement of the position of a surface to within about 3 Å. The instrument can be used in certain scientific experiments to study the density of single and multiple atoms steps on single crystal surfaces, absorption of gases, and processes involving electronic excitations at the surfaces.

And, as in most current STMs, piezo scanning systems were used in their system. They were so very close to constructing a full STM—just before their funding was cut in 1972 (Gadsuk!)

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**THE SECOND ERA OF NANOTECHNOLOGY: DIRECT NANOMANIPULATION TOOLS**

The period from 1980 onwards is the second era of nanotechnology. It is characterized by the development of tools for direct molecular and atomic scale “imaging” and manipulation, including “scanning tunneling engineering” (Franks) and “atomic bit machining.”
THE SCANNING TUNNELING MICROSCOPE

One extremely desirable nanotechnology tool has been missing: a nondestructive, relatively inexpensive and easy-to-use nanometer resolution imaging capability—hence the value of STMs. The STM was invented at the IBM Zürich Research Labs\textsuperscript{11,12} in 1981. Binnig and Rohrer\textsuperscript{12} describe how the STM originated from their attempts to study thin oxide layers on semiconductors in late 1978.

The STM (Figure 4(a)) scans an ultrasharp conducting tip, using tungsten, for example, over a conducting or semiconducting surface. When the tip is within a few angstroms of the surface (Figure 4(b)), a small voltage applied between the two gives rise to a tunneling current of electrons, which depends exponentially on the tip-to-substrate separation (about an order of magnitude per angstrom). A servo system uses a feedback control that keeps the tip-to-substrate separation constant by modulating the voltage across a piezoelectric positioning system. As the tip is scanned across the surface, variations in this voltage, when plotted, correspond to surface topography. Depending on the substrate, typical tunneling currents and voltages are on the order of tenths of nano-amperes and hundreds of millivolts, respectively. Binnig and Smith\textsuperscript{17} have recently developed a simpler, more compact piezoelectric scanner mechanism consisting of a single tube (Figure 4(c)) which should prove useful for multi-tip operations.

An added advantage is that STMs can function over wide ranges of temperature and pressure, and in liquid as well as gas environments. With STM-derived technology, the capabilities for building FMs can now be much more easily realized, for they reduce the originally proposed "building down" sequence to just one step, while providing an extremely useful feedback mode. Needless to say, Feynman was delighted when I first informed him about STMs and their capabilities.

The basic modes of operation of an STM, described in Hansma and Tersoff\textsuperscript{109} can be summarized as in Table 1. Here \(i, v, \) and \(h\) are the tunneling current, the voltage across the gap, and the gap size. Mode I is used to measure the topography of the surface of a metal or semiconductor and is the slowest mode since the electro-mechanical servo system must follow the shape of the surface during the scanning operation. The scanning speed here is determined by the response of the servo system. Modes II and III are faster since the tip maintains only a constant average height above the surface. The scanning speed in these modes is determined by the response of the preamplifier only. Mode IV measures the joint density of states which, for a small tip, is a measure of the local density of states of the substrate. For this mode, one dithers the tip-to-substrate bias voltage with a small ac signal and monitors \(i/v\). One can actually do spatially resolved tunneling spectroscopy using this mode.
TABLE 1 STM operating modes

<table>
<thead>
<tr>
<th>Mode Number</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
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<tr>
<td>Quantity held constant</td>
<td>i, v</td>
<td>h, v</td>
<td>h, i</td>
<td>h, i, v</td>
</tr>
<tr>
<td>Quantity measured</td>
<td>h</td>
<td>i</td>
<td>v</td>
<td>i/v</td>
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</table>

1 i, v, h are tunneling current, voltage and height respectively.

Binnig and Rohrer\textsuperscript{15} note that the STM is,

\ldots even energy selective (only electrons lying within the energy window Fermi energy ± applied voltage contribute to the tunneling) and spin selective (this in the case of a polarized tip). Thus, STM is not simply a surface structural method, but also, say, a surface chemical method with the same atomic resolution, which at present reaches 0.05 Å and 2 Å laterally \ldots Electron energies and electric fields on the surface lie in the mV and 10\textsuperscript{4} V/cm range, respectively, (typical values used at present, but, in principle, there are no difficulties going to considerably lower energies and fields and, if desired, also to higher ones) \ldots Preliminary experiments on DNA on carbon look very promising \ldots

There is, of course, an abundance of further applications of STM in science and technology \ldots Just imagine, for instance, what could be done with a highly focussed beam (say with a diameter of 10 Å and upwards) of low-energy electrons (meV and upwards).

McCord and Pease,\textsuperscript{163} who had done previous studies of fine electron beams generated by other techniques, followed up on this last suggestion. Fink\textsuperscript{78} reports beams of 10 μ amps with his mono-atomic STM tips when operated in field emission mode. This is an enormous current density for one atom. Fink\textsuperscript{79} has recently reported some other remarkable characteristics of his tips. If such tips could be mass produced, then the devices studied by Shoulders at last might be tested on the atomic scale, with potential performance exceeding that of most proposed molecular electronic devices.

STM\hspace{1pt}S are emerging as remarkably versatile tools. They have been operated in air, water, ionic solution, oil, and high vacuum.\textsuperscript{51,166} Their scanning speed may be pushed into the real-time imaging domain.\textsuperscript{19} They may be used for high-resolution potentiometry and as atomic level force transducers.\textsuperscript{172} Nanolithography
FIGURE 4  (a) Schematic of STM x-y-z piezo scanner, (b) substrate-to-tip tunneling, (c) single piezo-tube scanner, and (d) nanomilling/nanolithography.
with STMs has also been pursued.\textsuperscript{109} STMs can be used to map out surface work functions and image charge-density waves. Reviews of these and other state-of-the-art applications are given in Binnig and Rohrer\textsuperscript{19} and Golovchenko\textsuperscript{99}; Morita et al.\textsuperscript{169} have used an STM for electrochemical studies.

Techniques to make very sharp STM tips are described by Dietrich, Lanz and Moore.\textsuperscript{46} A transmission electron microscopy study of STM tips sharpened by electrochemical etching followed by argon ion milling is reported in Biegelsen et al.\textsuperscript{10} By virtue of removing residual contamination left from chemical etching, "Ion milling is a simple, reproducible technique to achieve high yield for STM operation." McCord and Pease\textsuperscript{165} have used STM tips as micromechanical tool bits for machining away 20-nm-thick strips of an insulating film without damage to either the substrate or the tips. (As might be expected, the process also generates submicroscopic corkscrew shavings.)

**NANOOPTICAL MICROSCOPY**

STM tips may be used to make subwavelength-dimension apertures.\textsuperscript{13,14} Such apertures, in combination with STMs to position them extremely close to an object to be viewed, may be used in Scanning Near-Field Optical Microscopes (SNOMs). Durig, Pohl and Rohwer\textsuperscript{54,55} describe these remarkable instruments which can provide images with 20-nm resolution! Other optical techniques that provide subwavelength imaging capabilities are the De Brabander et al.\textsuperscript{39} approach and the Allen\textsuperscript{2} approach; both involve some form of “video-enhanced contrast optical microscopy.”

**ATOMIC FORCE MICROSCOPES**

An outgrowth of the STM, the atomic force microscope (AFM) is another very high-resolution, mechanically scanned microscope that uses nanoscale tip-to-substrate atomic forces rather than tunneling currents to “image” surface topography. Unlike STMs, AFMs can image insulators. The AFM was invented by Binnig, Quate and Gerber,\textsuperscript{17} who reported that:

The scanning tunneling microscope is proposed as a method to measure forces as small as \(10^{-18}\) newtons. As one application to this concept, we introduce a new type of microscope capable of investigating surfaces of insulators on an atomic scale. The atomic force microscope is a combination of the principles of the scanning tunneling microscope and the stylus profilometer. It incorporates a probe that does not damage the surface. Our preliminary results in air demonstrate a lateral resolution of 30 Å and a vertical resolution of less than 1 Å . . .

We are concerned in this paper with the measurement of ultra small
forces on particles as small as single atoms. We propose to do this by monitoring the elastic deformation of various types of springs with the STM.

As with the STM, the AFM has undergone a rapid series of technical improvements. Atomic resolution images of graphite have been achieved by Binnig et al.\textsuperscript{18} using an STM constructed using a silicon micromechanical lever as the deflection element. Atomic force profiling utilizing contact forces has been demonstrated by Yang, Miller and Bryant.\textsuperscript{247} Atomic forces can also be measured directly with an STM using a mechanical technique developed by Tang, Bokor and Storz.\textsuperscript{223} Marti et al.\textsuperscript{161} have imaged an organic monolayer using an AFM and Marti, Drake and Hansma have achieved atomic resolution images of liquid covered surfaces with and AFM. Gould et al.\textsuperscript{101} have even used an AFM to image amino acid crystals with subnanometer resolution.

The STM, AFM, and SNOM, as newly invented instruments, are expected to revolutionize our basic knowledge of atomic forces and atomic structure. In the past few years STMs have demonstrated that they can "image" single atoms at room temperature in either air or water, probe the forces acting between atoms and measure the density of states of molecular structures. Becker, Golovchenko and

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{image.png}
\caption{A STM image of an organic molecule pinned to a graphite substrate by the same STM. Photograph courtesy of John Foster, IBM Almaden Research Center, San Jose, California.}
\end{figure}
Swartzentruber\textsuperscript{5} reported using an STM to deposit a single atom on a surface! The achievement of the atomic placement capability suggested by Feynman and illustrated in Figure 10 seems feasible in the not-to-distant future. STM-related technology should enable researchers to harmlessly image and manipulate molecules, proteins, genes, viruses, bacteria, semiconductors, metals, dielectric nanoparticles.

Many additional papers on STMs and AFMs may be found in Feenstra.\textsuperscript{67}

Now let's see some real STM images of atoms and molecules. Figure 2 shows a STM image of sulphur adatoms on an Mo(111) substrate at atmospheric pressure; it was made at Lawrence Livermore National Laboratory.\textsuperscript{159} Figure 3 shows STM images of graphite and molybdenum disulfide at atmospheric pressure; it was made at Digital Instruments, using a commercially available STM. Note how individual atoms are clearly visible in these scans.

Figures 5 and 6 provide a dramatic demonstration of actual molecular manipulation using STMs at IBM's Almaden Research Center. Figure 6 shows a STM image of an organic molecule that was pinned to the surface of graphite using a voltage pulse to the STM tip. The image frame is 27 Å x 27 Å. Figure 6 shows a STM image of an organic molecule that was first pinned to the surface of graphite using a voltage pulse to the STM tip, and then subjected to a second voltage pulse.
The small size of the remaining fragment (about 4 Å) indicates that the molecule was probably cleaved by the second pulse. The image frame is 11 Å × 11 Å. This fascinating work was reported in Foster, Frommer, and Arnett. Their work also holds great potential for computer memories. Quate recently received a patent for the application of STMs to data storage.

FIGURE 7 NanoTechnology WorkStation: (a) overall view of (simplified) system, (b) graphic displays, (c) multi-tip analysis of a microtubule, and (d) STM-induced/detected molecular conformation change.
NANOTECHNOLOGY WORKSTATIONS

One tool that would be useful is a "nanotechnology workstation," proposed in Schneiker and Hameroff. The nanotechnology workstation concept combines multiple STMs, optical microscopes plus illumination and detector fiber optic waveguides (Figure 7(a) and (b)). Some of the possibilities for using such multi-tip STM capability are shown in Figures 7(c) and (d). There are many more applications for the nanotechnology workstation described below; these are also very important since they can lead to better understanding of the relevant chemistry and physics of nanoscale systems, and thus ultimately for artificial life. For convenience, both STMs used as FMs and STM-derived FMs will be denoted STM/FMs below.

The positioning systems for STMs are accurate to fractions of an Å and can be easily adapted to a wide variety of STM/FMs. For our purposes, the STM can be viewed as an ultraminiature robot fingers that can both "see" and be used to directly and precisely manipulate nanostructures along the lines suggested by Feynman.

There are many possibilities for STM modifications and associated functions. Some possibilities are: (1) tip shape modifications—including scalpel, chisel, cylindrical, and other configurations—for scanning, scribing, etching, milling, and polishing operations or for electrical interfaces, electrochemical synthesis or machining; (2) structures attached to tips—including enzymes, synthetic catalysts, shape selective crown ethers, transducer molecules, etc.—for molecular recognition with species selective (and perhaps electrostatic or electromagnet assisted) pick, place, join, and cleave operations, or nano-environmental sensing; (3) multi-tip configurations—in parallel, radial, etc., configurations—for use as ultraminiature tweezers, jigs, and arcs or interface electrodes, or to generate rapidly rotating electric fields; and (4) tip materials modification—including insulating, semiconducting (silicon, ion implanted diamond), ferroelectric or ferromagnetic—for electrostatic, electromagnetic, magnetic, kHz-GHz acoustic (longitudinal, transverse, or torsional) and THz optical modulation in mono- or multi-polar configurations.

In addition to the above modifications, the STM/FMs or their tips could be augmented with a wide variety of sensors and transducers; the atomic force microscope of Binnig, Quate and Gerber is an excellent example of the many possibilities here. The augmentation of STM/FMs with fiber optic interferometers (or comparable techniques) could provide extremely accurate real-time calibration of absolute and relative STM/FM tip positioning, thus overcoming the problems of electrical noise, creep, aging and hysteresis inherent in present STM piezo-positioning systems. The technique given in Dietrich, Lanz and Moore for making tips with uniform tip-to-base conical profiles, augmented by the techniques of Fink for making perfect monoatomic tips, would be useful for STM/FMs using closely spaced multiple tips.

Using properly configured feedback control instrumentation, STM/FMs can operate as machine tools with effectively perfect lead screws and bearings, although of course their components include neither of these items. Augmented STM/FMs
also can be used as sub-atomic resolution proximity detectors and coordinate measuring machines (on conducting surfaces) to monitor nearly perfect, superaccurate nanomachining operations (limited by the graininess of atoms and other materials science considerations). Many useful macroscopic mechanical structures and mechanisms may thus be duplicated at the submicron level, and many of these mechanisms may require no lubrication due to force/area scaling and very rapid heat dissipation. For even smaller mechanisms, a switch to Feynman’s mechanical chemistry approach would be needed to build up molecular devices in a series of joining and trimming operations.

Over 6 million chemical structures have been cataloged to date. Rather than mechanically build up structures atom by atom, it is likely that some of these existing chemicals would be used as elementary building blocks in a series of joining (Vander Waals, ionic, and covalent bonding) and trimming (bond cleavage) operations, using electrical and mechanical operations.

As an example of one of the building blocks available, Yamamoto reports on molecular gears and Iwamura has prepared a system that forms a chain of beveled molecular gears. For simple molecular gears, the rotation rate is thought to approach 10^9/sec. Yamamoto describes compounds that “exist in conformations which are regarded as static meshed gears with a two-toothed and a three-toothed wheels and that some of them behave as dynamic gears…” In addition, Iwamura reports that, “Recently we have prepared a doubly connected bevel gear system. [Transfer] of information from one end of the molecule to the other end could take place in large molecules via cooperativity of the torsional motions of the chain.”

STM/FMs may execute many complex mechanical motions for driving such nanomechanisms. For instance, various three-dimensional tip motions (single straight lines, circles, spirals, helices, etc.) can be made at speeds presently limited mainly by mechanical resonances in the driving system of current STMs—another motivation for miniaturizing them considerably. Thus it would be possible, for example, to directly drive a molecular-scale mechanical positioning device and other nanomechanical mechanisms. Fluorescence techniques might be used to determine when an artificial receptor molecule attached to an STM tip has acquired or released a specific host molecule.

The capabilities of STM/FMs have been heretofore nonexistent; therefore, applications may abound in the near future as scientists in many disciplines become aware of this versatile and inexpensive technology. Certain techniques developed for electron microscopy might be adapted and used for STMs: (1) Furuya et al. have used metal cluster labels with their scanning transmission microscope to implement a nanoscale distance measurement technique. (2) Panitz has developed techniques for preparing and characterizing immunologically active, field emitter tips. His goal is to develop a single molecule detection capability.
NANOMILLING AND NANOLITHOGRAPHY

Dietrich, Lanz and Moore\textsuperscript{46} describe how to use argon ion milling to produce very uniform STM points with a \textit{sharpness of 2 nm and better}. A similar etch process can also produce knife edges. These have potential use as electrodes and nanotools as well.

McCord and Pease\textsuperscript{163} have analyzed the STM's capabilities for generating intense electron beams and their application. They observe that the

...scanning tunneling microscope is a recent demonstration of an extreme case of this principle [of field emission]; the probe comes to within about 1 nm of the target and the resulting vacuum tunneling occurs over a distance of the same order. The potential difference between target and source is usually less than 1 V. In this paper we describe some preliminary calculations of an intermediate configuration in which the potential difference and the source-to-target distance are both increased. The resulting probe should be energetic enough for certain writing mechanisms and hence, might have application in microlithography or microstorage...

We have the possibility of heating materials on a much finer lateral scale than had been previously thought possible...

Another striking departure from the limits on beams formed by focusing optics is that the minimum beam radius should reduce in value as the electron energy is reduced. This conclusion, although surprising, is consistent with the very fine (< 1 nm) probes obtained experimentally in the scanning tunneling microscope.

Ringen\textsuperscript{190} demonstrates that a nanometer pattern can be fabricated using an STM and concludes that the STM could yield a new tool for nanolithography. Further demonstrations of nanolithography are reported by McCord and Pease.\textsuperscript{164,166}

NANOSTRUCTURE AND NANOPATTERN FORMATION

Structure and pattern formation are fundamental processes needed for artificial life. This section describes a few of the (non-STM) techniques that are available for forming nanostructures and nanopatterns.

Although Langmuir-Blodgett films have been major workhorses of molecular electronics research, especially due the work of Hans Kuhn\textsuperscript{141} and his associates, researchers are also branching out into other systems. Netzer, Isocvici and Jacob\textsuperscript{175} describe one such alternative:
Monolayer formation by adsorption offers certain important advantages as compared with the Langmuir-Blodgett method; adsorption is a spontaneous process leading to thermodynamically equilibrated film structures, there is no mechanical manipulation of the films, water is not indispensable for monolayer formation, monolayer composition and structure are usually dependent on the chemical nature and microscopic organization of the solid surface, covalent binding to the substrate and intralayer polymerization may take place simultaneously with the monolayer formation process, there are no restrictions regarding the macroscopic shape and size of the substrate... Our present results demonstrate that a molecular spontaneous organization process combined with a suitable chemical triggering procedure may result into a controllable route to the synthesis of an artificial super molecular organize.

Williams and Giordano\textsuperscript{241} have “fabricated Au wires as small as 80 Å in diameter using a technique involving etched nuclear tracks in mica.” Sacharoff, Westervelt and Bevk\textsuperscript{195} have “...produced single ultrathin Pt wires with diameters as small as 80 angstroms...” They “have also produced Pt yarn containing over 1.5 million individual Pt wires...”

Craighead\textsuperscript{34} notes, “An analytical electron microscope has been used to fabricate a variety of ultrasmall structures and to test the size limits on some basic concepts of high-resolution, electron-beam lithography... Devices and structures have been made so small that the width of these structures was only tens of atoms.”

Salisbury et al.\textsuperscript{196} reports “that holes and lines of about 3-nm width may be cut directly in calcium fluoride by electron-beam lithography technique which has been designated sub-nanometer cutting and ruling by an intense beam of electrons (SCRIBE), in which no chemical development stage is required... It is clearly possible to machine external shapes on a nanometer scale.”

Fischer and Zingsheim\textsuperscript{81} have developed submicron optical pattern transfer processes that use visible light for replicating submicron structures. Fischer and Zingsheim\textsuperscript{77} further note that the resolution of contact imaging with light is limited by the distance between object and image and not by wavelength... when the bleaching of a dye is inhibited by energy transfer to a metal in close proximity.

Garber et al.\textsuperscript{89} note that,

Certain insoluble copolymers form characteristic liquid crystalline structures at water/copolymer interfaces. The formation of these structures... correlates with biological activities as immunological adjuvants... These casts appeared highly accurate... resolved to less than 10 nm. This technique seems ideal for accurate replication of surfaces formed by nonmiscible liquids and should prove helpful in studies of other materials in aqueous suspension.
Ehrlich\textsuperscript{62} notes that, “The behavior of individual atoms on solids has long been of interest for understanding the physical and chemical properties of surfaces. Now, through the use of the field ion microscope, it is possible to directly image single atoms on metal surfaces and to examine their properties quantitatively.”

Koma, Sunouchi and Miyajima\textsuperscript{137} describe a process in which epitaxial growth proceeds with Van der Waals forces, called Van der Waals epitaxy, which “seems to be one of the most hopeful techniques used to prepare a good quality of heterostructure with atomic order thickness... The present technique has opened a new way to prepare many kinds of heterostructures consisting of metal, semiconductor or insulator films with any thickness from subnanometer by using various transition metal dichalogenide materials.”

Deckman et al.\textsuperscript{40–43} have developed a number of nanoscale structuring techniques. One technique involved using a regular monolayer lattice of natural molecules as a lithographic pattern mask. Variations on this technique involve using reactive ion etching, chemical etching, and the use of amorphous semiconductor superlattice substrates. Accurately controllable slot widths may be fabricated in the 10 Å to 500 Å range. Douglas and Clark\textsuperscript{50} describe a related technique for nanometer molecular lithography.

Control of electric currents and fields, magnetic fields, highly localized temperature gradients, etc., to modulate local surface growth processes are an alternative to atom-by-atom placement for nanoconstruction. The use of ultrastrong magnetic fields to grow higher quality crystal substrates for integrated electronic circuits is a macroscale analogy of such possibilities.

Howard et al.\textsuperscript{116} show how advances in microfabrication technology are greatly advancing scientific instrumentation; Feynman Machines obviously have enormous scientific potential in this context. There are many synergistic possibilities. Just as STMs have been combined with SEMs (Gerber et al.\textsuperscript{55}), they might later be combined with FEMs (Ehrlich\textsuperscript{62}) or TEMs. The Japanese Research and Development Corporation is organizing a “NanoMechanism” research project in view of the scientific and engineering possibilities of NT.

**NANOCOMPUTERS: MOLECULAR ELECTRONICS AND QUANTUM COMPUTING**

Carter\textsuperscript{22} organized the First International Workshop on Molecular Electronic Devices, held at the Naval Research Laboratories on March 23–24, 1981. He notes:

Simple extrapolation suggests that in approximately two decades electronic switches will be the size of large molecules. It takes little imagination to recognize that the practical realization of this possibility will produce a
revolution in the areas of computation, technology, science, medicine, warfare, and lifestyle that will be more significant than any which occurred in the last fifty years.

Yates\textsuperscript{248} organized another conference on chemical computing. Carter\textsuperscript{25,26} organized two more conferences on molecular electronic devices. Conrad\textsuperscript{32} presents several interesting and innovative possibilities for molecular computing, based on studies spanning nearly two decades.

Carter\textsuperscript{23} describes three molecular fabrication techniques: (1) modular chemistry: a potentially very powerful generalized Merrifield approach [which works by precisely controlled, sequential addition of specific, individual molecular groups onto a collection of growing molecular chains], (2) molecular epitaxial superstructuring and modulated structuring, and (3) Langmuir-Blodgett film structuring. “The point of view adopted here is that of building structures up from the molecular level rather than imposing structure from the outside.” Additional techniques are proposed in Carter.\textsuperscript{24} Robinson and Seeman\textsuperscript{192} present a more recent proposal for constructing molecular-scale computer memories using self-assembling nucleic acid junctions.

The ability to use multi-tip STM/FMs for mechanical chemistry and as electrical interfaces might solve two formidable problems in the development of molecular electronic devices as envisioned by Carter\textsuperscript{23}: (1) the synthesis of prototype devices, and (2) making individual, reliable, electrical connections to them for testing.

STM/FMs could be used for more conventional ultraprecise circuit or component trimming and repair operations. The extremely accurate positioning systems of STM/FMs can be exploited for minimal-scale wirebonding systems. Even though STM/FMs may not ultimately be used to mass produce such devices, they could be used to construct prototypes, help characterize test devices, and be used to optimize them. STM tip-induced sputtering\textsuperscript{13,14} might be used to etch or mill ultrafine conductors for such devices.

Efficiently interfacing these and other such devices to the outside world in a manner that can effectively utilize their potential computing bandwidth presents some interesting problems in clocking, input/output, etc. The very-high-frequency “optical electronics” technology suggested by Javan\textsuperscript{128,129} may find application here, and in other nanoapplications as well. Using micro- and nano-antennas coupled to laser radiation, it is possible to generate intense, localized, high frequency electric fields (modulated by the laser beam’s intensity, phase, and polarization) which could control and power swarms of STM/FM constructed nanoscale devices.

During a recent talk on his quantum computing ideas, Feynman briefly speculated on a simple possibility for making nanocomputer components: use a STM tip to make tiny holes in very thin metal sheets, thus forming grids for tunneling “nano-vacuum tubes,” perhaps around 3 to 10 nm in size.\textsuperscript{75} Even more compact and potentially faster experimental configurations using several ultrasharp STM tips were mentioned in further speculations by Feynman.\textsuperscript{73,75} Unfortunately, no one
FIGURE 8 A schematic drawing illustrating the concept of a "nano-vacuum tube." This is the near-minimum-scale case of the submicron triodes proposed by Shoulders, but using an STM tip as suggested by Feynman. A perfect monoatomic STM tip, similar to one later invented by Fink, is shown here.

has followed up on his ideas with either calculations or experiments. Analogous, but much larger (down to 100 nm scale) devices with calculated, subpicosecond-range, switching speeds have been proposed by Shoulders. Although he considered even smaller, faster devices, limitations of electron beam micromachining technology at that time prevented further size reduction.

Computing in general and quantum computing in particular was Feynman’s "Holy Grail" of nanotechnology; when I told him about STMs, his first thoughts about it involved computing devices. Computing components each consisting of a few atoms might use quantized energy levels or quantum-mechanical spin effects. Feynman analyzes quantum computing and concludes that, “At any rate, it seems
that the laws of physics present no barrier to reducing the size of computers until bits are the size of atoms, and quantum behavior holds dominant sway. If such devices could be designed and assembled, they could be *10,000 times faster* than conventional transistors.

FIGURE 9  Modulation of tunnel gaps. The tunneling atom or group may be physically translated or rotated (by direct mechanical positioning, molecular conformation changes, electrostatic forces, etc.) or their orbitals may be otherwise modified (via interactions involving photons, solitons, electromagnetic fields, etc.).
The development of quantum computing holds fascinating possibilities for artificial life based on automata. Albert\textsuperscript{1} states: “An automaton whose states are solutions of quantum-mechanical equations of motion is described, and the capacities of such an automaton to ‘measure’ and to ‘know’ and to ‘predict’ certain physical properties of the world are considered.” He notes that its self-description “has no precedent and no analogue among classical automata.”

Further developments in the field of systems-theoretic controllability of quantum-mechanical systems may provide some of the missing links needed to implement quantum-mechanical computers, and comparable sensors and effectors.\textsuperscript{119,176} Erber and Puttermann\textsuperscript{61} examine the implications of the quantum theory of single atoms for algorithmic complexity theory and chaotic functions. Other researchers are studying a surprising new class of computation that directly depends on the nonclassical operating modes that quantum computers could potentially implement\textsuperscript{157,158}; they could be formally/computationally more powerful than universal Turing Machines. See also Conrad and Rossler,\textsuperscript{32} Beinoff,\textsuperscript{6} Bennett et al.\textsuperscript{8} and Deutsch\textsuperscript{44,45} for related topics of interest. Bennett\textsuperscript{7} discusses changes required in programming techniques for quantum computing.

Using STMs and AFMs for holding single atoms or molecules would be very interesting for quantum computing studies, and for developing modulated tunnel effect devices, as illustrated in Figure 9. The substrates shown can be replaced by more sophisticated molecular structures. Tunnel gaps will be an essential part of some types of nanodevices. A very large class of nanoswitches and nanosensors may ultimately be based on this simple principle.\textsuperscript{203,204} This same principle may also be applied on a slightly larger size scale at higher voltages by using field emission rather than tunneling.

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**ARTIFICIAL LIFE-RELATED APPLICATIONS**

Nondestructive STM interactions with biological material have immense potential, assuming certain technical obstacles are overcome.

Several groups have succeeded in imaging biomaterials in air such as protein-coated DNA and virus structures. The tunneling is thought to occur from tip onto biomolecular surface followed by low-resistance electron transport to the conducting substrate.\textsuperscript{231} Simultaneous optical microscopy, as can occur with the nanotech workstation, may help this situation since photons have been shown to lower tunneling barriers, thus an appropriate choice of optical microscopy wavelengths may facilitate STM imaging by permitting non-damaging tunneling currents. Immunofluorescence techniques may be utilized to identify specific biomolecular targets. The STM probes may also be made (immuno)fluorescent to enhance their visibility.
FIGURE 10 A-B (a) A micro-STM formed on a silicon substrate. Thousands of these structures may be placed on a single silicon chip. The side and top views of a fine Z-axis STM drive are shown. Microlithography techniques are used to etch a cantilever beam that is deflected by the voltage across two electrodes E-1 and E-2. The tip at the end of the cantilever, non-STMs, and other microactuators may be fabricated on a single chip for parallel operation. (b) Tunnel junctions with vacuum regions, liquid or molecular devices (filler), M-1, M-2, or mechanical junctions with modulation (due to external force/strain, pressure, thermal expansion/contraction, etc.).
An alternative approach is to utilize an atomic force microscope (AFM) mode of operation for the nanotechnology workstation. In this case, a cantilever arrangement is adapted to, and mounted on, the STM which trails along just above the surface, or is held steady to observe mechanical dynamics of the material (i.e., protein conformational change). The movement of the cantilever is monitored by the STM, so that mapping and dynamics might be observed without direct tunneling through the biomaterial.

FIGURE 10  C-D  (c) formation of near-field optical nano-apertures. L: light; D: detector; TS-1,TS-2: transparent substrates; TR: transparent rod; X: direction of movement until light detected; CS: conducting substrate; and T: STM tip. (d) molecular movement and construction with an STM. There are a wide range of STM tip motions that may be employed for pick and place operations. Multiple tips may be used where needed.
Biomaterials should be studied in a stable aqueous environment. Temperature, pH, ionic concentrations, availability of high-energy phosphate groups and numerous other parameters need to be closely regulated. Paul Hansma’s studies at the University of California, Santa Barbara, have demonstrated that STM imaging can occur at ionic liquid-solid interfaces. By insulating STM probes to very near their tips, significant leakage of current to the ionic aqueous environment is apparently avoided.215

Potential applications of STM (and the nanotech workstation in particular) to biology and medicine—and hence artificial life—are abundant. The possibility of studying dynamic structural changes (via alterations in the AFM mode), detection of propagating phonons or solitons (using the multiple STM configurations, one tip can perturb and another detect perturbation at a second position on a macromolecule or polymer), spectroscopic analysis (i.e., DNA base-pair reading), and real-time imaging (via high-speed scanning) on living structures can expand the horizons of experimental biosciences. Further, a capability for nanoscale manipulation of biomaterials and organelles offers a host of imaginative possibilities. The most advanced operations require the development of atomically sharp, near perfectly conical STM tips; this objective is probably within reach of present-day nanomachining technology.

MICROTECHNOLOGY: A BRIDGE TO NANOTECHNOLOGY

Yates’ conference248 on chemical computing contains several discussions of the enormous technical difficulties facing developers of molecular computing systems. Additionally, Haddon205 points out that the prospects for “conventional” technology present a much stronger and rapidly advancing challenge than is usually assumed:

It is claimed that advances in lithography will soon allow feature sizes of [10 nm]...[It] is even claimed that 3-dimensional systems with stacked elements can be constructed—all by extension of conventional chip manufacturing techniques. It is therefore important to realize that the silicon semiconductor industry presents a moving target and has yet to achieve its full promise.

This paper goes on to describe the many difficult tasks and problems that must be solved in order to build a working molecular electronic or a biochip computer. These problems suggest that the most viable paths to general nanotechnology may simply result from pushing rather conventional technology toward its ultimate limits. For instance, many advances in nanometer semiconductor structure electronics are proceeding rapidly.246 There is another reason why much future nanotechnology (and artificial life) might be partly semiconductor based: the semiconductor processing technology developed for integrated circuits is also being adapted for making silicon microstructures, including a wide variety of sensors
and effectors. Additional work on silicon micromechanics has been done by Csepregi and Kaminsky. Fan, Tai and Miller have extended this technology to make micro-pin joints, microgears, microsprings and microcranks. Gabriel, Mehragany and Trimmer describe additional micromechanical components. A recent conference held on the subject of microrobotics and teleoperators was dominated by papers on silicon microstructures; the possibility and desirability of developing silicon microrobots, teleoperators and replicators was suggested previously in Schneiker. The same scaling advances toward the nanoscale cited by Haddon above for silicon integrated circuits will also apply to these systems. Indeed, this technology can be used to mass produce micro-STM's and micro-AFM's (Figure 10). See Howard, Jackel and Skocpol for recent work on semiconductor nanostructure fabrication.

MICRO VON NEUMANN MACHINES FOR NANOGENESIS

As anticipated by Shoulders, the concept of replication can be extended into the artificial nanoworld. In contrast to earlier proposals that would require major advances in the chemistry of molecular structures, his proposal required mainly micro- or nano-milling and electroforming: this is a tremendously important (i.e., practical) technological simplification. The replication concept may be applied to the full range of potential nanotechnology applications we mentioned earlier in connection with the work of Feynman, Shoulders, von Hippel, Ettinger, Ellis and Laing.

The first forms of artificial life involving nanotechnology seem most likely to be based on distributed micro-systems augmented with nano-tools rather than nanoreplicators. Constructing artificial (nonbiological) nanoreplicators is probably a much more difficult task than developing constructing microreplicators for these reasons: (1) potentially greater design difficulty, (2) debugging difficulty due to complexity coupled with analytical equipment/inspection limitations, (3) reliability or repeatability requirements, 4) materials handling limitations involving transfer, purity/contamination, stability and waste by-products of fabrication, packaging or testing, and (5) inability to simply bootstrap with parts made by silicon micromachining using the mass production, pattern-making capabilities from the integrated circuit industry.

Since microreplicators can be designed to make micro Feynman Machines, they can make nanotools and parts. So even without nanoreplicators, you can still effectively replicate arbitrary quantities of specific nanotools or nanoparts. As new nanotechnological devices are developed with top-down micro Feynman Machines, they can be replicated without nanoreplicators, i.e., nanoreplicators are totally unnecessary for the unlimited mass production desired for the widespread application of an evolving nanotechnology industrial base. (Invoking the scale-invariance property for artificial life, we see immediately that even if we desire replication, there is no reason whatsoever to require nanoreplication.) Indeed, with appropriate forms
of self-assembly, or techniques suggested by Carter\textsuperscript{23} and others, one may even dispense with replicators altogether. Likewise, with the hierarchical manufacturing processes envisioned by Feynman for generating huge numbers of computing elements, especially if based on another very-high-volume mass production technology (such as very-large-scale integrated circuit fabrication technology), the ultimate productivity possible would be so large as to also render replicators superfluous. Thus, the development of general nanotechnology does not hinge on the prior development of nanoreplicators.

Dyson\textsuperscript{56} suggested that for practical reasons, early replicators may initially be a \textit{symbiotic} combination of natural life and artificial automata, located in space:

It will probably contain a small colony of microscopic plants which are able to utilize efficiently the feeble sunlight... It will also contain a self-reproducing automaton... One of the functions of the automaton will be to build a green-house out of local materials for its colony of plants. One of the functions of the plants will be to supply construction materials and fuel to the automaton... Also the machine may be able to take care of the problem of maintenance by mixing biological and mechanical techniques.

The design of real-world nontrivial replicators is a very complex and difficult task. Von Neumann made many simplifying assumptions for his famous proof and noted that he may have avoided the most difficult part of the problem. It is important to simplify the problem. This can be done by: reducing the number of types of materials/parts needed, reducing the number of scale-dependent factors (path lengths for material/signal transport, replicator population), reducing the needed part tolerances and wear, increasing reliability (to eliminate/reduce repair), and design for automation (to reduce assembly complexity). It is also important to keep the numerous possibilities for simple hybrids in mind, for example, combining sets of 1–3 enzymes with 1–3 molecular electronic devices and 1–3 (silicon) nanostructures in a living cell. Other possibilities might start with the nonliving artificial cells developed by Chang\textsuperscript{27} or the vesicle systems of Fendler.\textsuperscript{71}

Dyson's\textsuperscript{58} study of life's origins suggests that: (1) deferring the development of nanoreplicators, and (2) not requiring atomically perfect replication, may actually speed up the development of artificial life incorporating nanotechnology. Dyson believes that "replication and error-tolerance are naturally antagonistic principles" and that \textit{precise} molecular replication was a secondary development of early life, preceded by the process of cellular reproduction by division "into two cells with approximately equal shares of their cellular constituents." He "considers the primal characteristics of life to be \textit{homeostasis} rather than replication,...the error-tolerance of the whole rather than the precision of the parts." In 1950, Crand\textsuperscript{35} described some principles for the assembly of larger parts from smaller parts which could automatically generate many biological forms. He noted that if, at each level in the hierarchical assembly process, imperfect units were cast aside, then complex structures could be generated without requiring high accuracy at any step. In
the 1970's, a process which increased the selectivity of enzymes involved in genetic translation, termed kinetic proofreading, was proposed and discovered. Some or all of these principles may be applied to the development of artificial life.

One of the advantages of the STM/FM approach is that it is also applicable to larger structures, just on this side of the “optical ledge,” where visible feedback is readily obtained. This makes it very valuable for interfacing—a key consideration for the efficient development, deployment and application of nanotechnology—and microreplicators. Interfacing is necessary to build on the enormous technical base of microtechnology and to capitalize on intermediate hybrid technology. This intermediate range of possibilities, at the borderline between microreplication and nanoreplication seems a desirable extrapolation of earlier work cited in Schneiker. This certainly seems like the approach that would be the most feasible for first generation replicators; moreover, the preliminary development work could be initiated immediately.

Microreplicators have the advantage of being more easily able to use conventional casting, forging, milling, cutting, etching, joining, and molding operations. While these operations can be scaled to atomic dimensions, nano-phenomena such as surface diffusion, Van der Waals forces, etc., will make design, implementation, and debugging operations much more difficult for non-trivial systems.

Replicator, micromachine, and nanomachine component design might be greatly simplified using the mechanical analogues of the Mead-Conway VLSI electronics design rule method. This is another reason to not push all linear dimensions to their smallest limit for early nanotools.

The recent, dramatic increase in the maximum superconducting transition temperature to above the boiling point of liquid nitrogen (77° K) may soon make the development of superconducting microreplicators easier than other alternatives—especially if the transition temperature is raised to room temperature. Schneiker lists and discusses the design and operational advantages of such systems, which follow from the great ease and efficiency with which magnetic fields may be generated, maintained, altered, repelled, and sensed.

CONCLUSION

We are living in a truly remarkable era where the old nanotechnology dream of atomically precise mechanical manipulation of matter has finally been achieved in some very special and very limited cases. The possible synergies between various emerging nanotechnologies to build on these and the many other developments described above hold enormous potentials for still further acceleration of nanotechnology research and development. Looking back at the last 30 year's worth of nanotechnology developments, we can see that a staggeringly enormous amount of work...
still needs to be done to turn even Feynman’s and Shoulder’s delightfully straightforward nanotechnology visions into an everyday reality, let alone the Promethean visions of Ettinger and Feinberg. In the mean time, advancing the development of nanotechnology using Feynman machines and scanning tunneling engineering with the aim of developing Artificial Life is a superb scientific quest of human understanding and advancement.

POSTSCRIPT—STM/FM COMPETITION

At the end of his classic paper, Feynman offered two prizes, one for writing a page of a book with the linear scale reduced by 1/25,000 and the other for constructing an operating electric motor with dimensions 1/64 inch cubed). Both prizes have been awarded. His goal: to provide an economic incentive to get people interested in doing actual lab work in this field. For the same reason, Schneiker and Hameroff have offered a series of $1,000 prizes for building a particularly useful type of Feynman Machine: miniaturized STMs. In addition, we want to eventually set up another annual memorial “Feynman Prize” for the most significant yearly achievements in nanotechnology—which will bring us ever closer to the sublime possibilities of artificial life. As Feynman urged,

... have some fun! Let's have a competition between laboratories.

ACKNOWLEDGMENTS

APPENDIX—SOME LONG-TERM NANOTECHNOLOGY POSSIBILITIES

The following possibilities involve nanotechnology and were all first anticipated over two decades ago. Picking up and moving individual atoms and molecules, building miniature teleoperators that operate on neurons, unlimited life span and reversal of ageing using robot-directed, molecular-level repair, boundless wealth, defenses against virtually all diseases and virtually unlimited in situ evolution, super compact personal computer databases that could easily store the Library of Congress, etc. Let's take a closer look at the historical context of these proposals.

In the prehistory of nanotechnology, the late science fiction author Robert Heinlein\textsuperscript{111} envisioned the extensive use of life-size teleoperator hands, called "waldoes," complete with sensory feedback for full, remote-controlled telepresence. His hero, A.K.A. Waldo, used a series of these mechanical teleoperated hands, for building and operating a series of ever smaller sets of such mechanical hands. The smallest mechanical hands, "hardly an eighth of an inch across," were equipped with micro-surgical instruments and stereo "scanners." The smallest set of hands were used to "manipulate living nerve tissue, [to examine] its performance in situ" and for nerve surgery.

Feynman\textsuperscript{72} reports that a friend, Albert R. Hibbs, suggests that you could put a "mechanical surgeon inside the blood vessel..." Other small machines might be permanently incorporated inside the body..." Such machines could be very small, for as Feynman explicitly stressed in presenting the context of his ideas, "there is plenty of room at the bottom" for miniaturization. Feynman urged us to consider the possibility, in connection with biological cells, "...that we can manufacture an object that maneuvers at that level!" Ultimately, as Ettinger\textsuperscript{64} originally suggested, cellular-level or even molecular-level repair might be developed for life extension. Ettinger forecast that "...surgeon machines, working twenty four hours a day for decades or even centuries, will tenderly restore the frozen brains, cell by cell, or even molecule by molecule in critical areas..."

In 1962 and 1964, Ettinger\textsuperscript{53,64} argued that continued scientific progress would logically one day make it possible to repair and reanimate properly frozen humans. Feinberg\textsuperscript{68} also supported Ettinger's conclusions. Ettinger\textsuperscript{64,65} cited prior references suggesting some possibilities for molecular-scale technology and suggested some other interesting possibilities.

In 1968, Taylor\textsuperscript{227} in examining the anticipated progress in biology, also concluded that death was not necessary. He cited the possibilities for genetic engineering and even genetic surgery: "The microsurgery of DNA may possibly be achieved by physical methods: fine beams of radiation (probably laser light or pulsed X-rays) may be used to slice through the DNA molecule at desired points..." He also cited predictions that bacteria would soon be programmed, and that, in combination with related developments, "such work opens up practical prospects at which the
imagination boggles." He further notes that many scientists consider the creation of life feasible. Indeed, in 1965, the *synthesis of life was publicly proposed as a national goal* by the president of the American Chemical Society, Professor Charles Price. He pointed out that many new types of life might be made, not "mere imitations" of biology as we know it.

In 1967, Asimov\textsuperscript{9} suggested the future possibility of "factories...where the working machinery consists of submicroscopic nucleic acids" and that a "repertoire of hundreds or thousands of complex enzymes" could be used to "bring about chemical reactions more conveniently than any methods now used" and also for "helping to construct life."

In 1970, Jeon et al.\textsuperscript{130} carried out "the reassembly of *Amoeba proteus* from its major components: namely nucleus, cytoplasm, and cell membrane," taken from three different cells.

In 1970, Vol'kenshtein\textsuperscript{234} noted that "the creation of a nonmacromolecular system which would act as a model for a living organism is definitely possible" but could not arise by itself, and that the macromolecularity of present organisms is not essential, but due to their evolutionary origins. "Consequently, the cybernetic nonmacromolecular machine, which simulates life, could have been and can be created on earth only by man. Then it could perfect itself without limits."

Nemes\textsuperscript{174} discussion of self-reproducing machines includes the description of how to construct "an automatic lathe able to reproduce itself," a concept developed before Von Neumann's work on replication. The same principle could be applied to Feynman's\textsuperscript{79} suggested nano-lathes.

In 1972, Danielli\textsuperscript{37} described an array of possibilities for generating new life forms via "life-synthesis" and genetic engineering. He also noted that "macromolecular engineering" might enable the development of very powerful and compact macromolecular computer systems. In his Nobel lecture, Lehn\textsuperscript{150} summarizes the wide range of advances in supramolecular design and engineering that have occurred since then and which "open perspectives toward the realization of molecular photonic, electronic, and ionic devices that would perform highly selective recognition, reaction, and transfer operations for signal and information processing at the molecular level."

In 1974, Halacy\textsuperscript{106} noted "some rather inglorious ways" to use "the miracle of artificial life," including potential capabilities for *growing* diverse items ranging from *computers to airplanes*. Halacy also noted that "Leonard Engel wrote in 1962 that 'cold-war-minded scientists have in fact urged a crash program to guarantee a U.S. first' in creating living matter in the laboratory."

In 1974, Morowitz\textsuperscript{170} suggested cooling cells to cryogenic temperatures in order to analyze and determine their structure. Artificial cells would likewise be constructed at such temperatures and then set in motion by thawing. He further reported that microsurgery experiments on amoebas "have been most dramatic. Cell
fractions from four different animals can be injected into the eviscerated ghost of a fifth amoeba, and a living functioning organism results."

In 1974, Ettinger\textsuperscript{65} proposed genetic engineering for making nanorobots: "Genetic engineering's most sensational impact will concern the modification of humans; but it will have other uses as well. Some of the 'robots' that will serve us will need to be nanominiaturized..." Ettinger\textsuperscript{65} also cites the earlier ideas of White\textsuperscript{239} for programmable, i.e., effectively computerized, cell repair machines:

It has been proposed that appropriate genetic information be introduced by means of artificially constructed virus particles into a congenitally defective cell for remedy; similar means may be used for the more general case of repair. Progress has been made in many relevant areas. The repair program must use means such as protein synthesis and metabolic pathways to diagnose and repair any damage...[Information] can be preserved by specifying that the repair program incorporate appropriate RNA tapes into itself...

In 1977, Darwin\textsuperscript{38} further develops several notable advances on the theme of tissue repair and cellular repair machines. In 1978, Donaldson\textsuperscript{48} presents an updated case for the viability of molecular level repair.

In addition to proposing nanorobotics, Ettinger also suggests a form of hybrid artificial life via the modification of existing organisms:

If we can design sufficiently complex behavior patterns into microscopically small organisms, there are obvious and endless possibilities, some of the most important in the medical area. Perhaps we can carry guardian and scavenger organisms in the blood, superior to the leukocytes and other agents of our human heritage, that will efficiently hunt down and clean out a wide variety of hostile or damaging invaders.

Ettinger also cited even earlier suggestions of future molecular computing, (i.e., nanocomputing) technology.

Ettinger notes the possibilities of artificial human evolution: "...in principle a machine can be made to do anything that is physically possible; and if we envision the human brain coupled to a machine or complex of machines—so that the machines are extensions of the person—then, with only modest reservations to be noted later, we can do anything, which means we can be anything."

In 1981, Donaldson\textsuperscript{48} elaborated on his earlier discussion on how cryonically suspended human beings could be repaired, which he had discussed earlier in Donaldson.\textsuperscript{48} He extended the earlier concepts of Ettinger and White, concluding that with such hybrid technology as "micro-miniature biological-mechanical machines the size of viruses" and related technology, "it seems unlikely that (to repair a single cell) there would be any difficulty at all in principle to carrying out any imaginable repair." He calculated that about ten programmable cell-repair
machines could be introduced into a cell to be repaired without causing too much mechanical disruption. He noted some other interesting possibilities for repair if for some reason more machinery was required than could be introduced into a given cell.

In 1985, Feinberg\textsuperscript{70} described several possible approaches to nanoengineering and some related applications.

In 1986, Drexler\textsuperscript{53} expands on Drexler\textsuperscript{52} and contains a discussion of some potential developments, applications, and implications of nanotechnology; however, references to the real originators of many of the ideas that he discusses are not given.

Thompson\textsuperscript{230} reports on optically pumped X-ray lasers at Lawrence Livermore National Laboratory, which could become tremendously valuable for studying natural life in addition to helping "debug" first attempts at artificial life based on nanotechnology.

The laser's wavelength is now around 10 nanometers. The experimenters would like to get down to 3 or 4 nanometers. At 10 nanometers scientists could do surface studies of nonliving materials, as well as holograms of living cell surfaces, but they are limited mainly to surfaces. Between 3 and 4 nanometers, imagery can go inside the cell. Water will transmit the X-rays—"Most of these things are swimming in water," Matthews reminds us—and images of both carbonaceous and calciferous structures in cells could be made. "With enough resolution you could even see the chains of carbon in the DNA," he says.

Even better resolution might be obtained with a gamma-ray laser (see Collins et al.\textsuperscript{29}.

One of the most prolific sources of very speculative and yet often plausible nanotechnology schemes used to appear at the end of the Ariadne column of the New Scientist magazine. It used to detail the latest exploits of the extraordinarily creative Daedalus, which frequently involved molecular mechanisms. In recent months, columns on the ingenious Daedalus have been sighted in the journal Nature. Unfortunately, lack of space precludes summarizing his numerous and extensive contributions.

As for the very long-term future of life, we will close on a positive note by citing Dyson's\textsuperscript{57} conclusion that if the universe is open, life may continue forever. May you do the same.
REFERENCES


