The Future Impact of Molecular Nanotechnology on Textile Technology and on the Textile Industry

David R. Forrest[1]

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[1] ~~Business address: Research Specialist, Allegheny Ludlum Steel, Technical Center, Alabama & Pacific Aves., Brackenridge, PA 15014-1597. Voice: 412-226-6434, FAX: 412-226-6452, Internet: DRForrest@aol.com~~

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Introduction

Molecular nanotechnology is an emerging, interdisciplinary field combining principles of molecular chemistry and physics with the engineering principles of mechanical design, structural analysis, computer science, electrical engineering, and systems engineering. Molecular manufacturing is a method conceived for the processing and rearrangement of atoms to fabricate custom products. It would rely on the use of a large number of molecular electro-mechanical subsystems working in parallel and using commonly available chemicals. Built to atomic specification, the products would exhibit order-of-magnitude improvements in strength, toughness, speed, and efficiency, and be of high quality and low cost. In **Part 1: Technical Issues**, I provide an overview of molecular nanotechnology and explore ways in which molecular manufacturing could be applied to improve textile products. In **Part 2: Economic and Social Policy Issues**, I review the origins of the field, the current state-of-the-art, forces affecting its development and progress, and the implications of its eventual emergence as the dominant manufacturing technique of the 21st century.

Part 1: Technical Issues

In this section I provide basic definitions of relevant terms, and draw what I hope are useful distinctions between molecular nanotechnology and similar areas of study. A brief discussion of biological examples of molecular machines leads to a general discussion on the design of molecular devices. Recent designs are described in some detail; in aggregate they represent a set of devices that could build objects to complex atomic specifications. With this capability, one product will be materials 10-100 times stronger and tougher than we have today on a commercial basis. Molecular nanotechnology will also enable a very fine-grained integration of computers and sensors with materials.

Definition of Terms

Molecular nanotechnology is defined as:

> *Thorough, three-dimensional structural control of materials and devices at the molecular level; the products and processes of molecular manufacturing.*

It is useful to clarify the definition of the technology by drawing distinctions between it and some related fields. Molecular nanotechnology is distinguished from solution chemistry by the manner in which the chemical reactions will occur: instead of the statistical process of molecules bumping together in random orientations and directions in solution until a reaction occurs, discrete molecules are brought together in individually controlled orientations and trajectories to cause a reaction to occur at a specific site. Furthermore, this is performed under programmable control.

In biological systems ribosomes build proteins by "grabbing" onto tRNA molecules and transferring their amino acids to a growing polypeptide chain, under the programming specified by mRNA from its DNA template (Figures 1 and 2). Unlike biological systems, molecular manufacturing systems:

(1) could transport raw materials and intermediate products more rapidly and accurately with conveyor belts and robotic arms (Figures 3 and 4),

(2) would control *all* trajectories and orientations of *all* devices in the system, not just the relative orientations at points where reactions occur (ribosomes, tRNA, mRNA, amino acids, and DNA are suspended freely in the cell environment and rely on random collisions and diffusion for the transport of raw materials and products),

(3) would make heavy use of positional assembly (such as a blind robot thrusting a pin into the expected location of a hole) as opposed to matching assembly (a tRNA molecule bumping around a ribosome until it fits into the slot with the matching pattern of hills and valleys and positive and negative charges on it surface), and

(4) would, like auto factories and textile mills, lack the ability to independently evolve (a mutation in a molecular nanomachine would simply render it inoperable).

Microtechnology is also quite different: nanolithography is the patterning and selective etching of bulk material (usually silicon) to create devices with features as small as a few nanometers at their narrowest point. Micromachines such as electrostatic motors and steam engines have been fashioned in this way and we refer to this as a "top-down" manufacturing approach. These devices are inherently limited by the defects present in the original bulk material. Molecular manufacturing, by contrast, is "bottom-up"—building structures by piecing together (defect-free) atoms and molecules.

The term *assembler breakthrough* refers to the point in time when assembler technology is sufficiently advanced for the systems to make copies of themselves.

Synthesis of exact structures would be performed in an environment where no unwanted side reactions could occur and with no contaminants present. The term *machine-phase* has been coined to draw a distinction between this type of environment and solid-, liquid-, and gas-phase systems [1]:

- A machine-phase system is one in which all atoms follow controlled trajectories (within a range determined in part by thermal excitation).
- Machine-phase chemistry describes the chemical behavior of machine-phase systems, in which all potentially reactive moieties follow controlled trajectories.
- Machine-phase conditions can be described as eutactic: Characterized by precise molecular order, like that of a perfect crystal, the interior of a protein molecule, or a machine-phase system; contrasted to the disorder of bulk materials, solution environments, or biological structures on a cellular scale.

Designing Molecular Machines and Devices

The ribosome example shows that specialized molecular mechanical devices work in biological systems. But this system is of little use in the envisioned implementation of molecular nanotechnology. We still need to show how a more general kind of assembler could be used to make different kinds of structures with a wider range of capabilities. One can start by noting that it is more difficult to design mechanical systems with the irregular shapes characteristic of many proteins, and what we would like instead are things that look more like simple, conventional mechanical parts that we can use to build more complex subsystems like robot arms and conveyor transports. As shown in Table 1, biological systems are not devoid of structures with these more traditional mechanical shapes and functionalities.

Table 1. A comparison of macroscale and biomolecular components and functions (from reference [2]).

Device	Function	Molecular example (s)
Struts, beams, casings	Transmit force, hold positions	Microtubules, cellulose
Cables	Transmit tension	Collagen
Fasteners, glue	Connect parts	Intermolecular forces
Solenoids, actuators	Move things	Conformation-changing proteins, actin/myosin
Motors	Turn shafts	Flagellar motor
Drive shafts	Transmit torque	Bacterial flagella
Bearings	Support moving parts	Sigma bonds
Containers	Hold fluids	Vesicles
Pumps	Move fluids	Flagella, membrane proteins
Conveyor belts	Move components	RNA moved by fixed ribosome (partial analogue)
Clamps	Hold workpieces	Enzymatic binding sites
Tools	Modify workpieces	Metallic complexes, functional groups
Production lines	Construct devices	Enzyme systems, ribosomes
Numerical control systems	Store and read programs	Genetic system

As a result of these similarities, some biological forms do look and act more like robots than what we normally think of as living organisms. An often-cited example is the T4 phage (Figure 5), which is a virus that infects bacteria cells. The ends of the tail fibers selectively stick to the surface of the bacterial cell wall. When the tail fibers bend and the end plate contacts the cell wall, the plate distorts from a hexagonal to a star shape—inducing a martensitic transformation in the tail sheath [3]. The outside of the sheath contracts and its rigid core bores through the cell wall, injecting DNA from the head into the bacterium. The new genetic information reprograms the cellular machinery to make more copies of the virus. Eventually the cell becomes so full of virus copies that it bursts apart, freeing them to go out and infect more cells.

Since the publication of *Nanosystems* in 1992 [1] there is now a small library of designs of molecular mechanical parts which can be employed to create an assembler system with general capabilities for the mechanosynthesis of a wide range of materials and devices. The balance of this section first reviews computational tools for the design of molecular mechanical systems, then describes some of the designs and results of the performance calculations.

Calculating Geometries and Forces in Nanomechanical Devices. Because of the long computational times associated with the use of molecular orbital methods to approximate the Born-Oppenheimer approximation to the Schrödinger equation, a popular approach to the analysis of molecular structures is to use molecular mechanics. In molecular mechanics methods, the atoms in a molecule can be thought of as bound by mutually independent springs, restoring natural values of bond lengths and angles [4]. The functions and empirical parameters used to compute the potential energy surface of a molecule are chosen to closely approximate experimentally measured geometries, energies, and vibrational frequencies. Bond stretching, angle-bending, and torsion are generally well predicted: for hydrocarbons, typical errors are about 0.1% for bond lengths, 0.6° for bond angles, and energies are accurate to within a few times 10^{-21} J.

Much of the design work described in the following sections was performed by Eric Drexler using the MM2 model developed by Norman Allinger and coworkers [5] All of it is taken from *Nanosystems* [1], and is provided without further citation. The MM2 model does have some shortcomings, principally its inaccurate prediction of vibrational frequencies. It turns out that MM2 predicts lower stiffnesses (which affect vibrational frequencies) for structures than the more accurate MM3 model, which means that the MM2 designs are (generally) conservative. The non-bonded interactions are also less accurate in MM2 which resulted in harder interactions between surfaces. In the case of molecular bearings and other non-bonded interactions, the calculated stiffnesses were too high—although increasing the loads could compensate for that. The MM3 surfaces were also smoother than calculated with MM2, making the computed drag of bearing surfaces again conservative. Thus, performance calculations of the designs shown should be regarded as conservative; smoother, stiffer structures can be expected in practice.

Readers are referred to chapter 3 of *Nanosystems* for a detailed discussion of the applicability of the molecular mechanics approach to the design of nanomechanical systems.

Components and Systems. The next step in making a case for replicating assemblers with a general capability for the mechanosynthesis of a wide range of structures is to show some examples of parts which could be used to make these assemblers. Note that these parts cannot be synthesized with today's technology (especially in environments common to solution chemistry, where they would be unstable), but could be made readily in the eutactic environment assumed for machine phase chemistry.

Carbon is the principal element in these designs, which are referred to as *diamondoid* structures. There are important advantages to this choice:

- high strength and stiffness
- low atomic mobility
- low density
- high abundance and relatively low cost of hydrocarbon feedstocks
- ease of analysis using existing molecular mechanics software which has been designed for organic molecules.

Structural components such as tubes, rods, strained shells, and brackets have been designed. They can serve as stiff, passive members of housings and frameworks to constrain moving parts, or they can serve as moving parts themselves. Substitution of atoms such as O, N, and Si for C results in enormous numbers of possible stable conformations for different desired shapes. Analysis of a series of rod structures (shown in Figure 6) showed that the linear moduli of the rods ranged from 1/2 to more than 3/4 of the bulk-diamond modulus.

Moving parts have also been either designed or outlined to some reasonable degree; these include sleeve bearings, nuts and screws, rods in sleeves, constant force springs, axle bearings, spur gears, helical gears, rack-and-pinion gears, roller bearings, bevel gears, worm gears, belt-and-roller systems, cams, planetary gear systems, dampers, detents, clutches, and ratchets. For example, an analysis of molecular sleeve bearings has shown that energy barriers to rotation can be so small as to be virtually frictionless. Figure 7a shows a schematic of a sleeve bearing with m outer and n inner atoms of the sliding surfaces. Calculation of the barrier heights for different values of m and n showed that when m and n are greater than 25, the energy barriers are negligible compared to kT_{300} even when the bearing is heavily loaded perpendicular to the axis (values for the resulting offsets are shown in Figure 7b).

A similar analysis for molecular gears showed that energy barriers to gear tooth slippage are large (>500 maJ) with moderate numbers of teeth (more than 20), while energy barriers to corotation are small (<0.01 maJ). These gears are highly efficient at transmitting power. For a gear system operating at a shear force of 1nN, phonon scattering and thermoelastic drag losses account for only three thousandths of a percent of the transmitted power. Gears can even be integrated with bearings by proper choice of surface atoms to tune the interfaces to either catch (for the gear teeth) or slide (for the bearing surface), as shown in Figure 8.

Planetary gears can be used to convert shaft power from one angular frequency to another in a stiff colinear mechanism. The particular gear system shown in Figure 9 was designed to atomic detail by Eric Drexler and Ralph Merkle at Xerox Palo Alto Research Center; energy minimization was performed using the Polygraf molecular modeling software (Molecular Simulations, Inc., Burlington, MA).

Subsystems of intermediate complexities have been either designed or outlined with supporting calculations. These include:

- Mechanical measurement devices
- Stiff, high gear ratio mechanisms such as harmonic drives and toroidal worm drives

- Seals and pumps for fluid transport
- Vacuum systems to remove contaminants
- Cooling systems with fractal plumbing
- Electromechanical transducers and actuators
- Electrostatic nanomotors

Only the latter two are addressed in this paper due to space constraints.

A common question about molecular systems relates to how it will be possible to communicate with them. One solution is to use electrical inputs to effect mechanical motion in an output rod. (Mechanical signals can be readily employed by mechanical nanocomputers, discussed in the following section.) As we now use scanning tunneling microscopes with metal wires thinned to atomically sharp tips to image atoms, so we could use slightly blunter wires to create voltage changes across the plates of a small capacitor to generate mechanical forces. Figure 10 shows a schematic of how this could be accomplished. If two 12nm × 12nm plates move from a separation of 3 to 4 nm under 5V, the force exerted is about 1nN.

Electrical motors could be used to drive molecular conveyor belts for material transport and to turn worm drives as part of robotic positioning arms (useful for positional synthesis). A schematic of one possible motor is shown in Figure 11. For a motor with a radius of 195 nm and an applied voltage of 10 V, the angular frequency would be about 5×10^9 radians per second and the rim speed 1000 m/s. The power density is high: 10^{15} watts/m^3, limiting the number of motors in a given volume due to cooling constraints. Bearing drag is estimated to be small, ~1.3 pW, but the sliding tunneling contact may exert a drag associated with electron transfer that could dominate the power losses in the motor. More work needs to be done to characterize the drag mechanisms.

Nanomechanical Computational Systems. The positioning systems in molecular assemblers need devices to direct their programmed movements, and ways to store these programs. Computers and control systems similar to those already devised for macroscale robotic arms can be implemented at the molecular level. While molecular electronic computers for this purpose seem possible [6-10], they are more difficult to analyze. The molecular mechanics approximations used to calculate the minimum energy structures and bond strengths of the components shown previously do not provide enough information to calculate the electronic behavior of molecular electronic devices. But there is no rule that says, '**Computers Have To Be Electronic**.' In fact, the first programmable computer design was a mechanical Analytical Engine conceived by Charles Babbage in 1834. Similarly, molecular mechanical computational devices have been designed.[2]

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[2] While molecular mechanical computers would be slower and less efficient than molecular electronic devices, it is much easier to analyze molecular mechanical systems. By analyzing and assigning lower bounds to molecular mechanical computer performance, we can use these values in the design and performance analysis of other devices that depend on the computers. In practice, molecular machines may turn out to be even more efficient and capable with molecular electronic devices.

Carbyne rods in tension can be used to transmit signals by pulling on them, and molecular groups (based on a pyridazine ring) attached to the rods can serve as gates and probes (Figure 12). Depending on the gate's position, it can either block or allow the probe knob to pass by. In this type of arrangement the logic gate is the equivalent of a transistor. Different configurations can give different types of rod logic gates; Figure 13 shows a NAND (or Not AND) gate. Estimates of the performance of a RISC (reduced instruction set computing) machine based on rod logic yield the following:

- Switching times are on the order of 0.1ns
- The energy dissipation is $\ll kT_{300}$
- Combinational logic systems can achieve four register to register transfers in 1.2 ns
- Nanomechanical RISC machines can achieve clock speeds of ~1 GHz, executing instructions at ~1000 MIPS
- A CPU-scale system containing 10^6 transistor-like interlocks could fit within a 400 nm cube; at 1 GHz it would dissipate 60nW, performing $>10^{16}$ instructions per second per watt
- A forced convection system with fractal plumbing could effectively remove about 100kW from a one centimeter cube at 273K. This would allow $\sim 10^{12}$ CPU scale systems with 10^6 transistors each to operate within that volume.

This 10^{12} CPU system would run at about 10^{15} MIPS. By comparison, personal computers run at about 5-20 MIPS, engineering workstations run at about 200^+ MIPS, supercomputers run at about 10^5 MIPS, and the human brain runs at about 10^9 MIPS. So one of these machines would have the computational equivalent of a million human brains in the volume of a cubic centimeter (in terms of logic operations per second—programming is another matter). Fast molecular tape memory similar to RNA is also possible. It would have a storage density on the order of 5×10^{21} bits per cubic centimeter. That is sufficient density to store the information content of the Library of Congress within the dimensions of a sheet of office paper.

Molecular Sorting, Processing, and Assembly. Molecular manufacturing systems would transform raw materials, in molecular form, into finished products. Impurities could be separated from feedstock molecules using a sorting rotor as shown in Figure 14. The binding site is designed so that specific portions of the desired molecules selectively stick there. The required potential energy of binding is estimated to be -161maJ, based on typical values of entropy loss for organic molecules. Deficits in the binding energy between feedstock molecule and receptor site could be made up by applying hydrostatic pressure or with attractive intermolecular forces.

The purified molecules can be transported away from the sorter system using the molecular equivalent of a conveyor belt (Figure 3). Once on a conveyor belt, the molecules can be transported to other belts, changing speed or frequency if necessary. The estimated belt speed is 0.5 cm/s and the transition time from belt to belt is less than 0.2 μs. A system for transforming a stream of small feedstock molecules into a stream of reagent moieties would be between one million and three million atoms in size. It could deliver the equivalent of its own mass in about 3 seconds. The error rate is estimated to be less than 1 in 10^{15} operations; at 10^{6} operations per second this gives a mean time to failure of about 3000 years.

One possible scheme has reagent moieties transported up through the center of a hollow manipulator arm to a working tip for positional synthesis. One such device has been designed to a moderate level of detail (Figure 4). The arm's design stiffness of 25N/m helps to hold positional errors to below one in 10^{15}. Applying 1 nN of force at the tip would deflect the arm only 0.04 nm.

Parts could be made more rapidly (but less flexibly) with molecular mills, which are well suited to making standard components at high rates. For example, one device might be designed to attach one hydrogen atom to a specific position on the surface of molecular bearings as they move by on a conveyor belt. Mills of this sort could be employed to make blocks of systems up to 1μm, at which point manipulators could fabricate components from these blocks. (Manipulators could also be used to fabricate items of smaller sizes, more flexibly though less rapidly than mills.) The range of systems that can be constructed from a catalog of 10^{6} parts is large, since those small parts can be connected in different ways to form larger parts. By convergent assembly, these many smaller parts could be assembled to form fewer larger parts. A 1 kg structure would contain about 10^{15} blocks made from about 10^{6} separate systems. In Figure 15 we see how a volume could be filled with assembler systems for convergent assembly. The branching pattern could be extended through more than 30 generations, enabling the assembly of objects from more than 10^{27} pieces.

The net result of all this is a system that uses a cheap fuel such as acetone (about 10¢/kg), weighs one kilogram, can produce high purity products at a rate of 1 kg/hr, has a waste product of high purity water, and generates excess power along with waste heat (from release of energy from feedstock molecules).

Design for Reliability. The use of atomically perfect diamondoid structures for walls and seals provides an important advantage to the reliability of the devices described in the preceding sections: virtually no contamination can get into the system. In the case of He contaminant insertion into a seal between two nitrogen-terminated diamondoid surfaces, the energy of the He atom would be ~170 maJ. At typical concentrations of atmospheric He and at 300K, the leakage rate is $\sim 10^{-15}$ atom/nm·s—or one He atom in >10,000 years. In the case of H_2 and larger species, the leakage would be even less. It also turns out that a defect-free diamondoid structure is quite impermeable to gases. The energy to move atomic hydrogen from free space into a minimum energy site is ≥800 maJ, which is thermally prohibitive.

Another advantage to using a covalently bonded material such as hydrogen-terminated diamondoid is that the surface is very stable, even at elevated temperatures. Metal surfaces by contrast are less stable, although a bulk metal could be terminated at the surface by an intermetallic or other compounds like carbides, nitrides, borides and oxides for improved stability.

Another possible mode of system failure is that of photochemical damage. Shielding can effectively exclude light from the system. In order to limit the mean time between photochemical failures to 30 years of terrestrial sunlight exposure, the transmittance through an optical barrier must be limited to 10^{-14}. For aluminum, this translates to a shield thickness of 250 nm. Systems 10 μm or more on a side will not suffer a large volumetric penalty with this shielding.

At sufficient temperatures, thermomechanical damage can cause system failure. Estimates based on the pyrolysis of polymers suggests that 600K can be exceeded without degradation and diamond is stable to 1800K in vacuum, but machine-phase systems may behave differently. For example, mechanical stresses on particular components may be destabilizing; alternatively, constraints on molecules in housings can make them more stable. All the designs described in this paper were developed to be highly stable at 300K.

Radiation damage is inevitable. The probability that a device will be hit by ionizing radiation is roughly proportional to its mass. Based on experimental evidence with enzymes (and assuming that the more tightly constrained design of nanomachines is balanced by the greater radiation tolerance of diamondoid structures), we assume that nanomachines will suffer ~10^{15} inactivating hits per kilogram per rad, under the single-point failure assumption that one cleaved bond will disable a device. At a terrestrial radiation dose of 0.5 rad/year, components on the order of 1 μm^3 would have annual failure rates on the order of several percent. Because ionizing radiation cannot be excluded, good designs should therefore provide redundancy to extend time between failures. The probability that a redundant system will be functional can be estimated by the equation:

$$P_{func}(system) \approx \exp\left\{-N\left[1-\exp\left(-10^{15} D m_i\right)\right]^{n_i}\right\}$$

where N is the number of sets of components, there are n redundant components in each set, each component has a mass m (kg), and the radiation dose is D rads. After 200 years of terrestrial radiation, 4×10^{19} sets of components of 100nm per side (10^{-18} kg) with a redundancy of n=25 will have a failure probability of about one in one million.

Theoretical Properties of Materials

The materials we make are fraught with defects on several scales:

- at the intramolecular or intragranular level, where an atom in a molecule or crystal grain may be missing, out of place, or may be substituted with the wrong kind of atom
- at the intermolecular (or intergranular) level, where molecules (or grains) that could be favorably matched (aligned) with their neighbors, aren't; and where contaminant atoms, molecules, or films can poison the intermolecular boundaries

- at the microscale where large clusters of molecules (such as fibers) or individual crystal grains may be unsuitably sized or aligned; and where microtears, pits, fissures, and cracks can degrade material performance
- at the macroscale where we have visible flaws

These defects exact a major toll on materials properties and performance. Calculations of the theoretical properties of perfect crystals[3] show that if metal and ceramic parts could be made from pure, perfect crystals, their strength would be between 10 and 50 times that of the strongest form of the same material made using today's routine commercial practices. This is illustrated in Figure 16. Use of novel, highly alloyed, and composite perfect materials would push that factor over 100 times the strength of today's commercial materials. The same numbers hold for the maximum elastic strain of conventional vs. theoretical solids (Figure 17).

Other properties would also benefit from molecular nanotechnology. For example, there are reports of exceptional corrosion resistance when iron is purified to 99.995%; the material is also ductile down to 4.2K [17]. Greater improvements can be expected with the elimination of defects as sites for corrosion attack, and with surfaces constructed to atomic smoothness and appropriately terminated to inhibit chemical reactions. The use of oxides and intermetallics could be greatly expanded in oxidation- and corrosion-resistant applications without the current problem of embrittling impurities, defect structures, and grain boundaries.

Although no material or device of macroscopic dimensions can be made indefinitely defect-free[4] (because of the damaging effects of pervasive high energy background cosmic radiation), molecular nanotechnology will provide us with the capability to produce bulk solids to as near perfection as physics will allow. No existing process can make this same claim.

Applications of nanotechnology to industrial fabrics

Clearly, there are enormous advantages to having materials that are 100 times stronger than we have now. Objects made from these materials could be up to 100 times lighter, using 100 times less material.[5] As a result, ultralight cars, trucks, trains, and planes would use far less energy, especially with atomically smooth surfaces to reduce internal friction and air resistance losses.

Industrial fabrics, and textiles in general, will have similar gains in performance. Today, basic units of fabrics are molecules of natural and synthetic materials such as cotton (cellulose), wool (α-keratins), rayon (cellulose), polyester, and so forth. The

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[3] Measurements of low-defect whisker properties support these calculations, as they approach the theoretical properties. See, for example, references [11-16].

[4] All statements regarding "defect-free" or "atomically perfect" materials and devices in this document are hereby qualified to really mean very low levels of defects consistent with ionizing radiation, thermal, chemical, and photochemical damage from environmental sources which may be detected and self-repaired by systems with such capability.

[5] Even more, about 250 times, by substituting diamondoid composite material.

molecules are tangled together in various ways to form fibers, which in turn can be spun into yarns.

At the molecular level, and given the capabilities of molecular nanotechnology, an obvious approach to improving the strength and toughness of a fabric would be to reinforce the fiber with carbyne molecules. Carbyne is a linear chain of carbon atoms with alternating single and triple bonds. Although carbyne has been known for some time, only within the past year have researchers successfully stabilized the molecule in long (300-500 atoms) chains by capping the ends with trifluoromethyl and nitrile radicals [18]. With molecular manufacturing, arbitrarily long chains will be possible. Carbyne is extremely strong in tension, with an estimated breaking force greater than 6nN [19]. A cubic packed array of carbyne molecules would have a tensile strength greater than 50 GPa (7,000,000 psi). By comparison, commercial rayon has a tensile strength of 0.45 GPa (65,000 psi) and nylon, 0.083 GPa (12,000 psi). Yet the carbyne molecule is quite flexible, allowing many options for twisting into fibers.

A carbyne molecule could be cross-linked to other carbyne molecules using the same sorts of structures that Drexler designed for gate knobs in the mechanical nanocomputer [1, 19]. The strength and stiffness of the resulting array could be adjusted by varying the number, length, and geometry of the cross-links. Carbyne fibers made of non-cross-linked molecular arrays would have an extraordinary degree of toughness since cracks would not propagate from one molecule to the next.
Carbyne has a high thermal conductivity along the axis of the chain of carbon atoms (roughly that of diamond, about 2100 W/m-K—five times that of copper). As diamond is stable in air to 900K (1160°F), carbyne would have a similar high temperature stability as long as the ends are terminated properly. With these properties, carbyne would provide an excellent base for a heat resistant fabric as long as it is not in direct contact with strong carbide forming elements such as tungsten, titanium, tantalum, and zirconium at high temperatures. The high axial thermal conductivity would act as a natural heat pipe to help to dissipate heat from hot spots on the material. Thermal conductivity could be quite low in the transverse plane with an open array of molecules with long, widely spaced cross-links.

Of course, comparing the theoretical properties of carbyne to today's commercial materials isn't quite fair. Today's materials made with molecular nanotechnology would have much improved properties on their own without carbyne. As Roger Soderberg has pointed out, there would be virtually 100% efficiency in converting yarns to fabric tensile strength due to the high level of uniformity in both strength and elongation from one yarn to another [20]. Fiber separation could be eliminated as a failure mode by connecting individual fibers end to end and making them continuous, but still bundled and twisted in the same amorphous way. It seems possible to do this while maintaining the look and feel of current fabrics, if desired.

Smart Materials and Nanotechnology

While synthesis of defect-free materials will lead to substantial improvements in performance, molecular nanotechnology will make more radical changes possible by integrating computers, sensors, and micro- and nanomachines with materials. Here are some ideas:

- Micropumps and flexible microtubes could transport coolant or a heated medium to needed parts of clothing.

- The kinds of sorting rotors shown in Figure 14 could be arrayed as “pores” in a semi-permeable membrane to allow only particular kinds of molecules through. Water might be a useful molecule to select for, to keep one side of a fabric dry or another side wet. On the wet side, the water could be transported away to an evaporator, or stored.

- One of the most intriguing ideas I’ve heard is that of an active, programmable material [21]. The basic idea is to have a material made of small cellular units that connect to each other with screws. Computers would direct the cells, powered with small electrostatic motors, to adjust their relative spacing with the screws. By selecting which screws would tighten and which would loosen, the shape of a item could change to conform to the needs of the user. A solid, rigid object could be made to behave like a fabric by effecting rapid changes in its shape, or with temporary disconnections between some cells. A flexible fabric could turn rigid by having loosely bound cells temporarily connect into a stiff framework. Thus, distinctions between fabrics and other types of materials could blur.

  The programmable material concept is not limited to fabrics but has many potential applications there. One example that Drexler pointed out would be a space suit that would allow nearly as much freedom of movement as one’s own skin. Imbedded computers connected to strain gages could sense the wearer’s intended movement and adjust the material accordingly. Reflectance of the outer layer could be variable to absorb needed amounts of heat from the sun-facing side and transport it to cold spots—although the material’s insulative properties would allow very little of the wearer’s heat to escape. Excess heat could be transported to radiators on the cold side.

- Fabrics could be self-cleaning: robotic devices similar to mites could periodically scour the fabric surfaces and integral conveyors could transport the dirt to a collection site, or the previously mentioned molecule-selective membrane could transport water to one side or the other for a cleaning rinse.

- Fabrics could be self-repairing: sensors would detect discontinuities in the material via loss of signal or a reported strain overload and send robotic “crews” to repair the damage. Self-shaping fabrics would be able to return to their original shape around a tear until repairs are effected.

- Large sections of fabrics could be made without visible seams by joining panels of fabric with microscopic mechanical couplings along their edges. Similarly, surfaces could contain mechanical couplings that, when pressed together would bond with nearly the strength of the bulk material. This ‘smart velcro’ could latch and unlatch at the user’s request.

Conclusions

(1) Engineering calculations based on proven molecular modeling techniques show us that molecular mechanical systems can be designed with general capabilities to manipulate individual molecules and build materials and devices to atomic specification.

(2) Biological examples show us that molecular mechanical systems work in practice, with high levels of reliability. Analysis of potential failure modes shows that mechanical nanosystems could operate reliably for many decades.

(3) Calculations of theoretical properties and measurements of near-perfect whiskers show us that, with the capabilities of molecular nanotechnology, we can expect materials that are 10-50 times stronger and tougher, and 100 times more elastic than today’s commercial products.

(4) Molecular nanotechnology will enable a very fine-grained integration of computers and sensors with materials (intelligent materials systems). The additional integration of electromechanical devices will blur the distinction between materials and machines. Materials will be viewed as active systems with programmable shapes and properties.

Part 2: Economic and Social Policy Issues

In this section I review both historical and recent developments in the field of molecular nanotechnology. Economic and environmental factors will help speed development, but traditional specialization of academic disciplines will impede progress. I argue that the pace of development should be balanced by concern for safe and responsible development, and the need to see benefits within a reasonable development time. Recent trends indicate that the pace of development has quickened measurably over the last five years.

The Origins of Molecular Nanotechnology

In order to appreciate the origins of nanotechnology, its interdisciplinary nature, and its pace of development, it is worthwhile to review some history. A timeline of progress is provided in Figure 18.

Erwin Schrödinger was one of the first to describe life in terms of molecular objects and machinery in his 1944 book, "What is Life?" In the 1950s, John von Neumann realized that machines could be programmed to be self-replicating [22, 23]. Arthur von Hippel, in his 1959 book, "Molecular Science and Molecular Engineering" [24] and later in his 1965 book, "The Molecular Designing of Materials and Devices [25]," took a distinctly interdisciplinary, bottom up approach to materials design. But it was Richard Feynman, in his 1959 talk, "There's Plenty of Room at the Bottom" who specifically described small mechanical objects holding and placing atoms to build up a desired structure [26].

For a number of years after this time, nothing specific happened to advance this concept and Feynman's talk remained largely forgotten. There were, however, significant advances in molecular biology, supramolecular chemistry, and computer science in the intervening years that contributed to the body of knowledge necessary for the right ideas to coalesce. In the spring of 1977 the core ideas of what we now term *molecular nanotechnology* or *molecular manufacturing* came together in the mind of a student at MIT by the name of Eric Drexler. As a biographer later wrote, ". . . consideration of self-assembled systems of molecular machines based on biological models led to the realization that such machines could be used to position reactive molecules, guiding chemical reactions under programmable control so as to build complex structures, not unlike the operation of a ribosome." [27]

In the meantime, work had been underway to develop molecular electronic devices—computational systems employing single molecules to perform switching and signal propagation operations. The first such device was patented by Aviram and Seiden, of IBM, in 1974 [28]. Forrest Carter of the Naval Research Laboratory, as well as others, organized conferences and symposia on this subject during the early to mid 80s [6-10]. When Drexler heard about these ideas he wrote the first technical paper on molecular nanotechnology, which was published in the Proceedings of the National Academy of Sciences in 1981 [2].

It was right around this time that another important milestone occurred. In 1982, Binnig and Rohrer published a description of their new invention, the scanning tunneling microscope [29]. Now it was not only easy, but relatively inexpensive, to image individual atoms. It was apparent that if one could attach tools to an STM tip, it would be possible to directly perform positional synthesis and start to build structures. But it wasn't until late 1987 or early 1988 that we learned it was possible to move atoms around without any special tools attached to the tip [30].

At the Second International Symposium on Molecular Electronic Devices in 1983, Drexler presented the most complete description of a molecular computer (electronic or otherwise) up to that time[31]. In 1985 Buckminsterfullerene was discovered [32], and—although this particular molecule may have no direct application in molecular manufacturing—it has certainly generated much interest in carbon-based molecular structures and has got a lot of people thinking about making similar structures (such as nanotubes) that might somehow be useful.

The Foresight Institute was founded in 1986 to provide both a forum and a framework for preparing for the consequences of nanotechnology. Because of publication of the first book on nanotechnology, *Engines of Creation*, [33], plus some added publicity from an article in the Boston Globe [34] that was picked up by the major wire services, there was a strong surge in media attention that year. In October, Drexler presented another, more rigorous, paper on mechanical nanocomputers at the third MED conference [19]. There was also a major advance in instrumentation with the advent of the atomic force microscope: now non-conductive atoms and molecules could be imaged [35].

One of the problems with acceptance in the scientific and engineering communities up to this point was that there were no drawings of assemblers or their components, and it was difficult for people to visualize the machines. That changed to some extent in 1987 with the publication of two papers, one with some information on electrostatic nanomotors [36] and the other on molecular gears and bearings [37]. Another significant accomplishment was the first protein designed from scratch and synthesized in the laboratory [38], silencing a frequent criticism up to that point.[6]

Signs of mainstream acceptance appeared in 1988 with the publication of an article in Scientific American [39], and the teaching of a course on nanotechnology at Stanford University [40].

In 1989 the first technical conference on molecular nanotechnology was organized by the Foresight Institute, and the proceedings were published some years later [41]. In 1990 there was a lot more involvement by other researchers. Ted Kaehler, a programmer on sabbatical from Apple Computer, spent time at the Foresight Institute designing a library of molecular brackets [42]. Ralph Merkle, at Xerox PARC, began work on computational nanotechnology [43, 44]. Drexler was invited to give a talk on nanotechnology in Japan at the invitation of MITI (Ministry of International Trade and Industry) and was surprised to find that they had organized an entire conference around his talk. It was not long after that MITI announced major funding for a series of related projects. Also that year STM technology had advanced to the point where Don Eigler's group at IBM could manipulate individual atoms to sub-nanometer precision and spell out "IBM" [45].

In 1991 the second technical conference was held, and included an important paper by Charles Musgrave of Caltech on hydrogen abstraction [46] which showed how one could add and remove individual hydrogen atoms from a hydrogen terminated diamondoid surface. Japan's MITI announced $185M program to develop related technologies [47, 48]. In the U.S. a much more modest (but nevertheless formal) effort was undertaken: the Institute for Molecular Manufacturing (IMM) was founded [49]; it is a non-profit institution who's goal is to advance the development of molecular nanotechnology. Eric Drexler received the first doctorate degree to be awarded in molecular nanotechnology (MIT) [50]. A non-technical book was published [51]. Xerox PARC funded an intern to develop software to automate

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[6] Some critics of nanotechnology had pointed to the difficulties associated with determining the structure of proteins as a reason why nanotechnology would be too hard to develop in the near future. The flaw in this reasoning was that the problem of designing proteins that are easy to design and synthesize is very different from the problems associated with the determination of the structure of large, complex proteins.

atomic placement in molecular modeling software [44]. A course on nanotechnology was taught at Cornell University by Prof. Dean Taylor [52].

In 1992 the first general conference was held, again organized by the Foresight Institute. Significant government awareness occurred when Drexler testified at a senate subcommittee hearing chaired by Al Gore (who seemed to have a reasonable grasp of the concept), a pentagon briefing, and at a briefing for the White House Office of Science and Technology Policy. The Japanese translation of *Engines of Creation* was published (and is now out-selling the American copies by a two-to-one margin on a *per-capita* basis [53]). A major milestone in nanotechnology development was the publication of *Nanosystems: Molecular Machinery, Manufacturing, and Computation.*, which provides a very rigorous engineering analysis of molecular mechanical devices and manufacturing systems [1].

The third technical conference was held in 1993 and the theme was "Computer-Aided Design of Molecular Systems [54]." Computational tools for the design of molecular systems were reviewed, as well as IMM's progress on the design of intermediate assembler devices, a virtual reality manipulation of an STM probe with force feedback was described, and a Nanotechnology Collaboratory is being organized by Argonne National Laboratory to share computational resources. Also at the conference the first Feynman prize in Nanotechnology was awarded to a doctoral student at CalTech. Crystal Clear, a molecular CAD tool, was developed by Geoff Leach interning at Xerox PARC [55]. The most important news of 1993 was the announcement of plans to build the first laboratory in U.S. dedicated to molecular nanotechnology research [56]. The laboratory is headed by Prof. Richard Smalley (the Nobel Laureate co-discoverer of Buckminsterfullerene) at Rice University and will support undergraduate teaching, graduate level training, and research.

In 1994 Ari Requicha established the Molecular Robotics Laboratory at the University of Southern California, the Beckman Institute (U. of Illinois at Urbana-Champaign) performed work on molecular nanostructures, and Jack Gibbons (U.S. Science Advisor) advocated nanotechnology research.

In general, nanotechnology development is accelerating due to the introduction of new tools for atomic imaging which are being adapted for positional synthesis, progress in supramolecular and protein engineering techniques [57, 58] for the synthesis of molecules and assembly into larger structures, and improved capabilities for molecular design as well as less expensive hardware.

State-of-the-Art

Computational tools for molecular design and property prediction continue to improve. A series of mergers in the industry recently culminated in two of the largest players, Biosym and Molecular Simulations, joining to form one company. Mathematical techniques such as density functional theory allow the calculation of systems with larger numbers of atoms, as does the ever-increasing speed of hardware. While use of these sorts of software packages has historically been directed toward drug design and polymer research, new initiatives in computational materials science and chemistry reflect a trend toward broader applications.

With the scanning tunneling microscope (STM) and atomic force microscope (AFM), we have rudimentary tools for positional synthesis. There are recent reports of the use of an AFM to fashion a 0.2 micron wide transistor on amorphous silicon [59] and the use of an AFM to catalyze reactions at specific points on a chemical surface [60].

Work on molecular electronic devices seems to have slowed after the death of Forrest Carter in 1987, but it hasn't stopped. There are still significant efforts on conducting polymers and molecular electronic devices [61-65].

In Japan, efforts such as the Aono Atomcraft project, the Kunitake molecular architecture project, the Atomic Arrangements: Design and Control project, the Yoshida Nanomechanism Project, and a fifteen year project at Riken on self-assembling molecular ultracircuits put the Japanese clearly in the lead. In 1990, an interdisciplinary team of researchers at the Protein Engineering Research Institute constructed the largest designed protein then known [27]. MITI has committed $185 million to projects in molecular design, measurement, and manipulation, including the Angstrom Technology Project. While these projects have a large degree of overlap with the technologies needed to develop molecular manufacturing, they do not yet have this as a specific goal.

There are some European and Australian efforts as well: Switzerland has a five year nanosciences program [66], Sweden has a "Micronics" project [27], the University of Cambridge is a partner with the Japanese in the Atomic Arrangements: Design and Control project [67], there is the Ludwig Boltzman Institute for Molecular Nanotechnology in Vienna [68], and Australia's Cooperative Research Centre for Molecular Engineering and proposed Nanotechnology Facility [66].

Advances continue in the area of protein engineering, as others have followed DuPont's lead in designing proteins from scratch. Xerox PARC has one of the most focused efforts toward designing assembler systems with its computational nanotechnology project, and Apple Computer seems to be devoting some resources with the participation of one of its more accomplished programmers (Ted Kaehler). The Foresight Institute and Institute for Molecular Manufacturing continue to focus attention on molecular nanotechnology, and to fund research. And with the involvement of Rice University, the Beckman Institute, and the USC Molecular Robotics Laboratory, larger efforts are now finally underway in the U. S.

Driving Forces for (and against) Development

There are many economic and environmental motivating forces to encourage development of molecular nanotechnology. One envisioned result of the technology is a portable manufacturing system able to build a wide range of useful products to atomic specification, including a copy of itself. A system capable of building a copy of itself to atomic specification—as well as a wide range of other products from clothing to food to computers—would have important economic consequences. Many goods would no longer need to be transported from remote locations but could be fabricated in one's home, saving the time, energy, and waste associated with transportation, packaging, and storage in warehouses and shops. Besides the waste reduction, the environment would benefit from a form of manufacturing that produces no toxic waste, and the technology could be applied to both purify and mine existing waste sites.

The energy savings associated with improved material strength and performance was mentioned previously. The wide availability of inexpensive solar cells, inexpensive ultra high efficiency insulation, atomically smooth surfaces to reduce friction losses, and lighter vehicles will translate to a major decline in our dependence on fossil fuels.

Computer processors more powerful than the ones found in today's fastest engineering workstations could be made smaller than a typical human cell, as could micro-robots. These would have applications in medicine, where the general capability to repair damaged cellular structures to atomic precision would provide cures for many important illnesses [33, 39, 51].

Facing off squarely against these expected benefits is the potential for abuse. Without good ways to limit the functionality and deployment of molecular machines we would be facing serious threats to both individual and national security. In the design of nanomachines there are many ways to limit the extent of damage that a system could do if it malfunctions: test the system extensively in computer simulations and small sealed laboratories, have the system rely on rare chemicals not available in the environment, have counters to limit the number of generations of replication, confine most systems within sealed enclosures, and so on. As in the mechanical systems of today’s technology, most malfunctions would generally result in lack of function instead of dangerous conditions. By incorporating well-tested consensus standards in system designs, most dangerous conditions could be avoided. But because not all situations can be foreseen, and because there will always be the threat of an *intentionally* destructive system, further measures are necessary. Development of a fine-grained active shield to defend against accident or malice must go hand in hand with development of the technology [33].

As always, there must be balance in the pace of development. Those who fear the potential dangers and might seek to block development in our open society should realize that a greater danger would be to have the technology developed first elsewhere—such as in a closed society away from public scrutiny. Those who seek fast development to attain the economic and medical benefits as quickly as possible should realize the dangers of failing to develop adequate safeguards at the same time.

Time Frame, Rate of Progress

There are various reasons why I expect development efforts to proceed rather quickly now that properly focused laboratories have been established. First of all, no new science is required in order to proceed with development. Atomic bonding and molecular interactions are sufficiently well understood that we can proceed with design, and where uncertainty exists parts can be overdesigned for their purposes. At the same time, progress does not stand still and any new advances will only accelerate development. Furthermore, there does not seem to be a single enabling path to development: self-assembly techniques, positional synthesis using scanning probe technology, synthetic chemistry, protein engineering, and even micromachines could conceivably (and individually) lead to molecular manufacturing in time. In combination, development can proceed much faster.

It is worth noting that the specialization of discipline that is so rooted in our academic institutions, as well as our government and industrial environments—and that has provided us with such rapid technological progress in this century—has probably slowed development efforts. Successful development and rapid progress will come with the formation of interdisciplinary teams, and cross-education of specialists in fields like molecular chemistry and mechanical engineering.

There are several quantitative measures that point to development as soon as 15 years from now. Keyes [69] has plotted the number of atoms needed to store one bit of information vs. time (Figure 19): if the trend continues, we will reach the molecular mechanical device regime between the years 2010 and 2020. The same holds true in plotting the amount of energy dissipated per logic operation (Figure 20). Taniguchi [70] has traced the precision of our ability to machine objects, and in Figure 21 we once again see that we will reach single atom precision between the years 2010 and 2020.

The exact timing is largely dependent on how much overall effort we (as a global community) expend in this endeavor, and on the quality and focus of the effort. Given sufficient resolve, there is reason to believe that the technology could be developed within ten years.

Conclusions

A review of the history traces molecular technology's roots back to Richard Feynman in the 1950s; progress in molecular biology, molecular electronics, and mechanical engineering led to development of the concept by Drexler in 1977. Significant progress has been made in recent years in both design advances, and in tools for the imaging and synthesis of molecular structures. Within the past five years, the pace of development has increased with more efforts specifically focused on developing capabilities to manipulate individual atoms and molecules, and to create structures to atomic specification. There are many important incentives which make it seem likely that the pace of development will continue to grow. Accordingly, the technology is expected to mature within 15 years and this will impact the textile industry by bringing new tools for the manufacture of fabrics, order of magnitude improvements in material properties and performance, but a decentralization of manufacturing. There is every reason to believe that the intellectual property of future nanomechanical fabric manufacturing systems (decentralized in consumer's homes and businesses) can be maintained, as well as patent protection of novel fabrics and materials.

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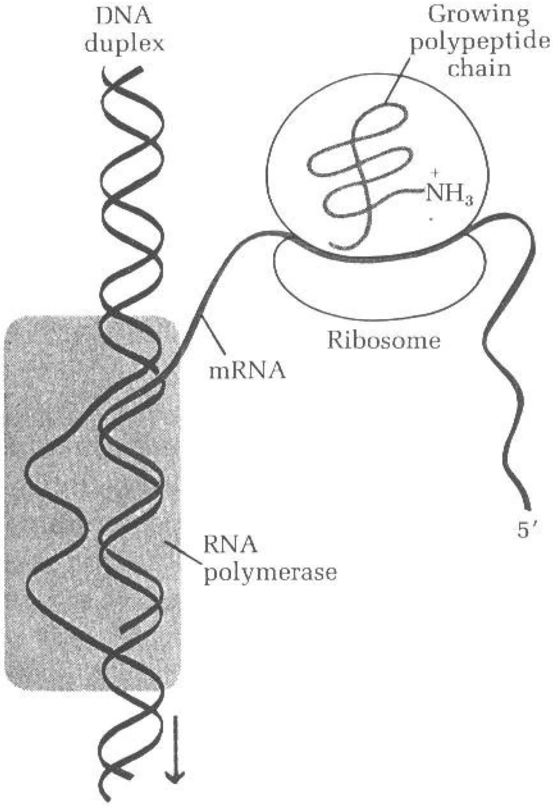


Figure 1. Ribosomes are examples of molecular machines that synthesize structures using molecular building blocks. Source: Principles of Biochemistry, by A. L. Lehninger: Worth Publishers, Inc., New York, N.Y., p. 891, 1982. Reprinted by permission of the publisher.

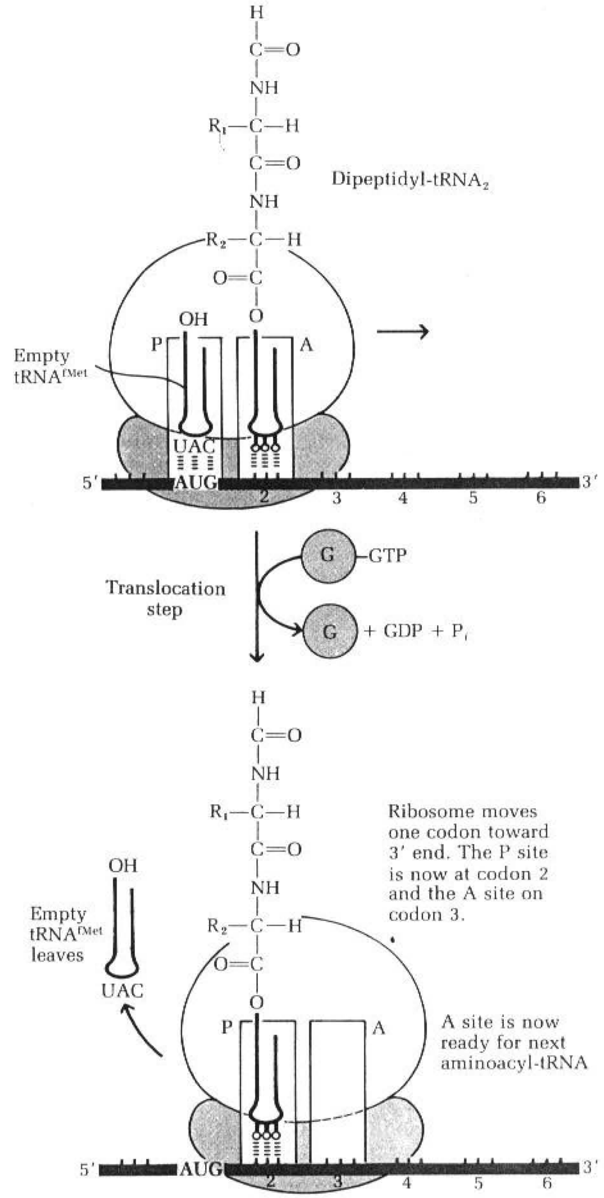


Figure 2. An empty transfer RNA detaches from its site on the ribosome, which moves forward along the mRNA to wait for the next tRNA with its bound peptide. The bound peptide will attach to the growing polypeptide chain. Source: Principles of Biochemistry, by A. L. Lehninger: Worth Publishers, Inc., New York, N.Y., p. 889, 1982. Reprinted by permission of the publisher.

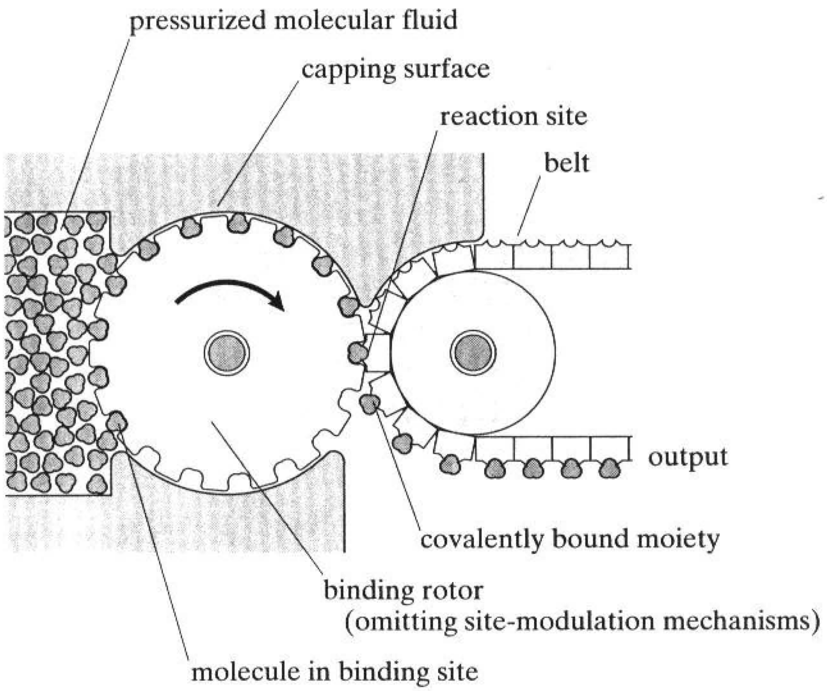


Figure 3. Schematic diagram of a mechanism for removing molecules from a liquid phase and covalently binding them to a moving belt. This diagram omits mechanisms for modulating the properties of the receptor; these would be necessary in order to approach thermodynamic reversibility (exposure of an empty receptor as shown would be inherently dissipative). Generalized mechanisms for modulating the receptor can also relax constraints on reaction geometry and conditions (for example) by forcing compression and motion of the confined molecule. Source: Nanosystems: Molecular Machinery, Manufacturing, and Computation, by K. Eric Drexler: John Wiley & Sons Inc., New York, N.Y., p. 384, 1992. Reprinted by permission of the publisher.

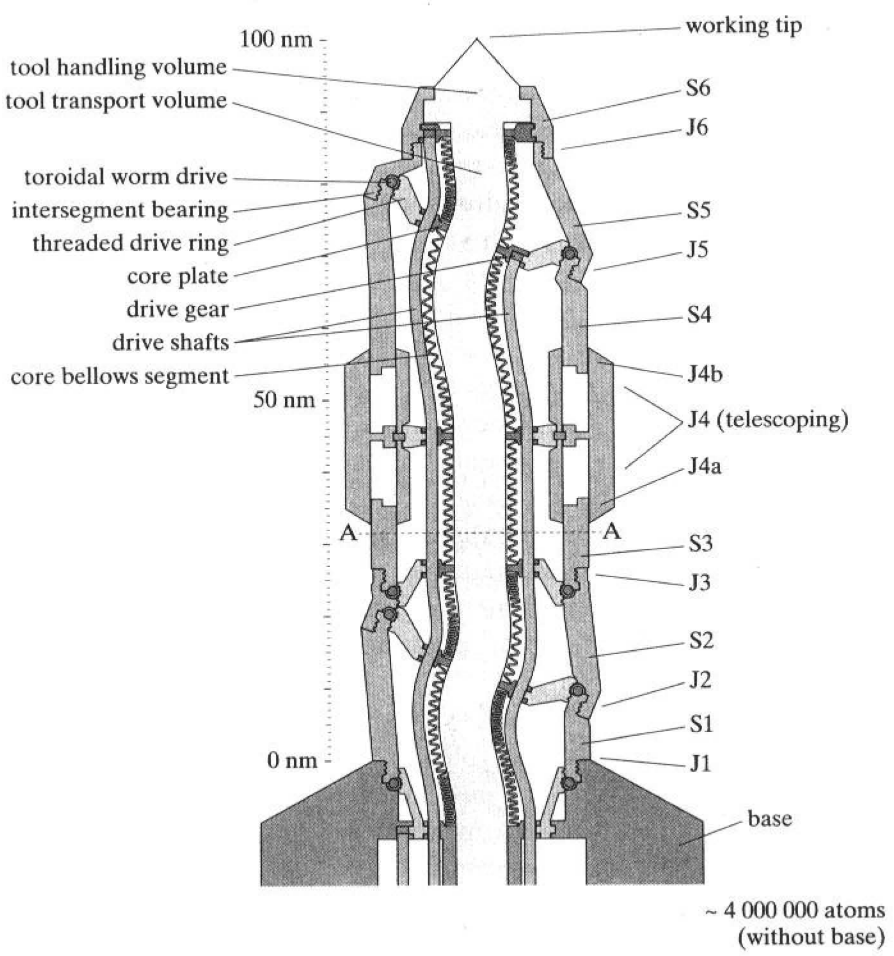


Figure 4. Cross section of a stiff manipulator arm and identification of parts (schematic). Source: Nanosystems: Molecular Machinery, Manufacturing, and Computation, by K. Eric Drexler: John Wiley & Sons Inc., New York, N.Y., p. 401, 1992. Reprinted by permission of the publisher.

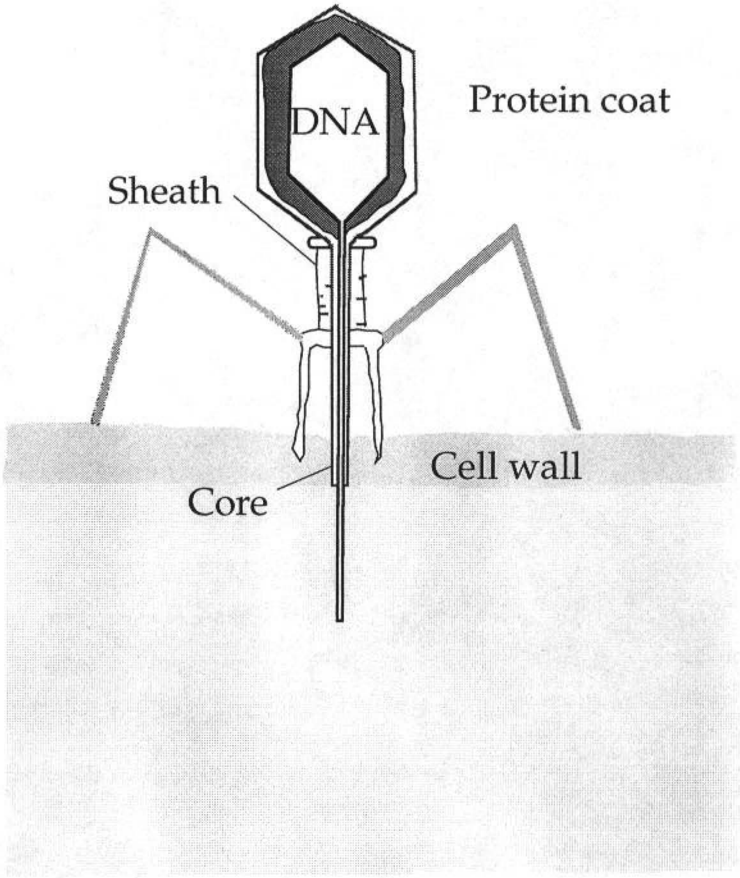


Figure 5. A T4 bacteriophage and its method of injecting DNA into a bacteria cell [After Wood and Edgar, Scientific American, July 1967].

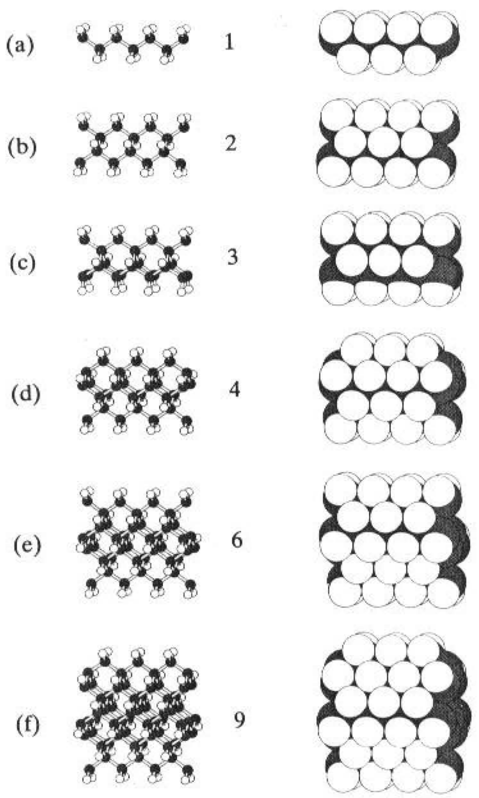
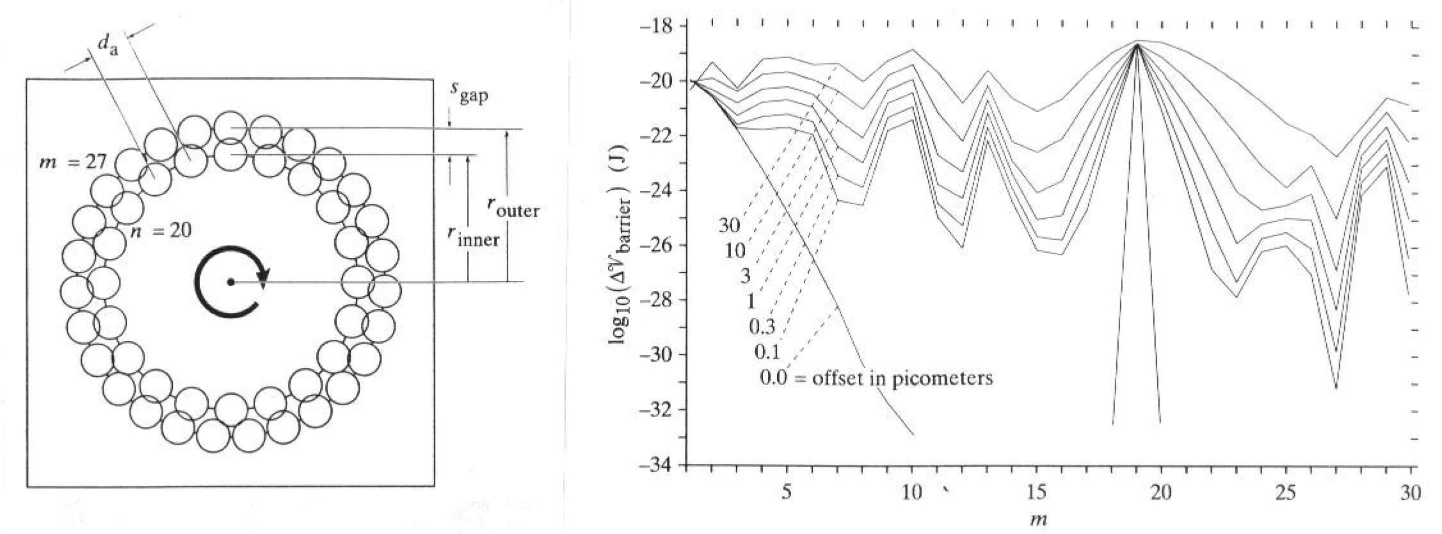


Figure 6. A series of rod structures, most consisting of a hydrogen-terminated region of the diamond lattice. Rod (a) is a polyethylene chain; (b)–(f) can be described as additional chains linked side by side (the digits to the right indicate the number of such chains in the corresponding rod). The structure of rod (c) departs from the diamond pattern, adding bonds perpendicular to the rod axis to replace nonbonded H | H contacts. Source: Nanosystems: Molecular Machinery, Manufacturing, and Computation, by K. Eric Drexler: John Wiley & Sons Inc., New York, N.Y., p. 259, 1992. Reprinted by permission of the publisher.



(a) **(b)**

Figure 7. (a) Coplanar ring model for a symmetrical sleeve bearing. (b) Barrier heights for rotation in the coplanar-ring model, based on the MM2 exp-6 potential for the H | H interaction; n = *19.* Source: <u>Nanosystems: Molecular Machinery, Manufacturing, and Computation</u>, by K. Eric Drexler: John Wiley & Sons Inc., New York, N.Y., p. 285 & 289, 1992. Reprinted by permission of the publisher.

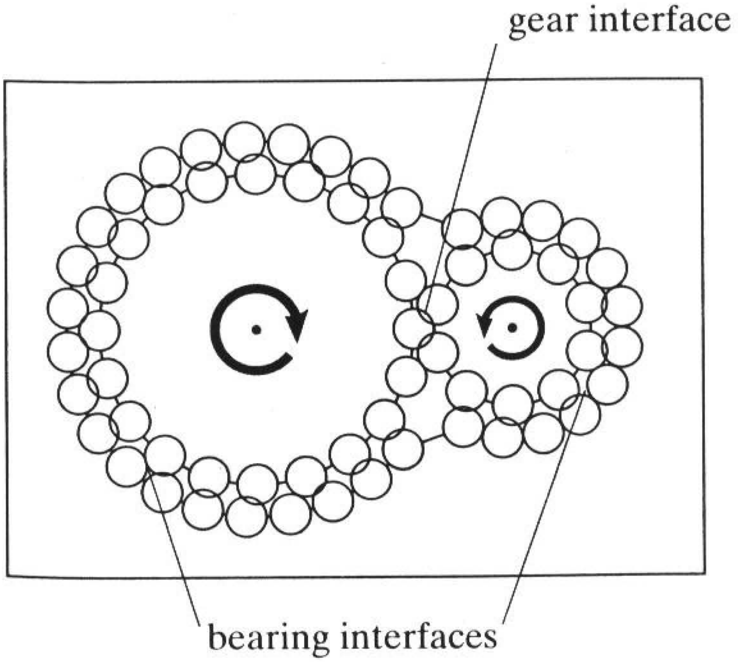


Figure 8. Schematic diagram of two gears supported by bearing surfaces. Source: Nanosystems: Molecular Machinery, Manufacturing, and Computation, by K. Eric Drexler: John Wiley & Sons Inc., New York, N.Y., p. 307, 1992. Reprinted by permission of the publisher.

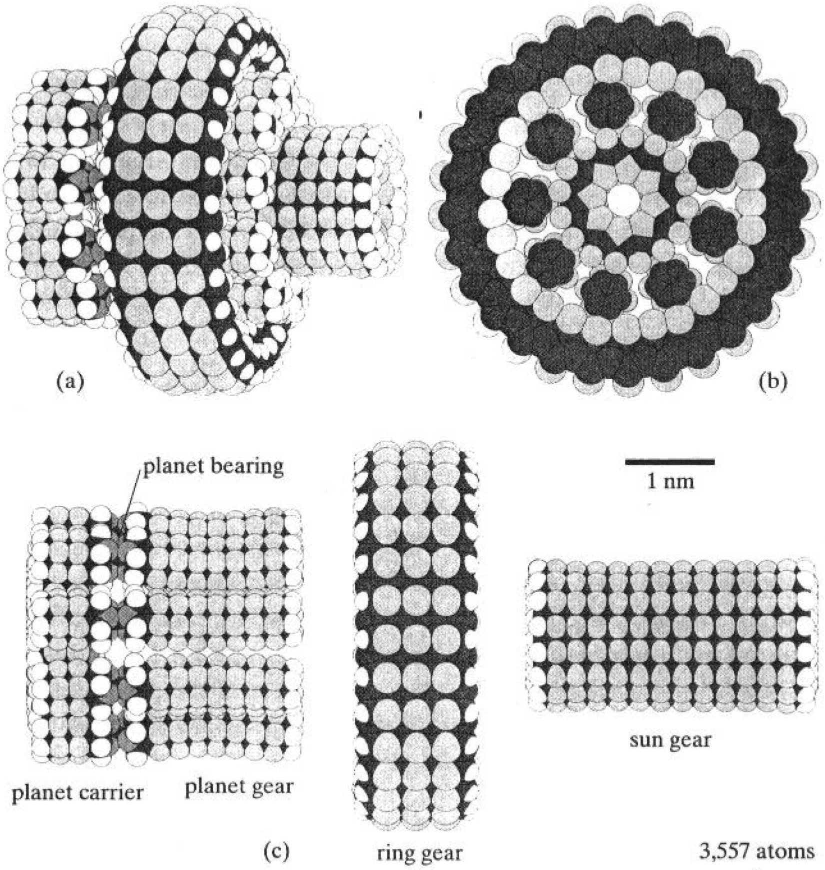


Figure 9. A planetary gear, (a) end view, (b) side view, (c) exploded view. The ring gear structure is a strained Si shell with S termination; the sun gear is a special-case structure related to an O-terminated (100) diamond surface; the planet gears resemble multiple hexaasterane structures with O (rather than CH_2) bridges between the parallel rings; view (c) retains elastic deformations occurring in (a), hence gears are bowed. Source: Nanosystems: Molecular Machinery, Manufacturing, and Computation, by K. Eric Drexler: John Wiley & Sons Inc., New York, N.Y., p. 312, 1992. Reprinted by permission of the publisher.

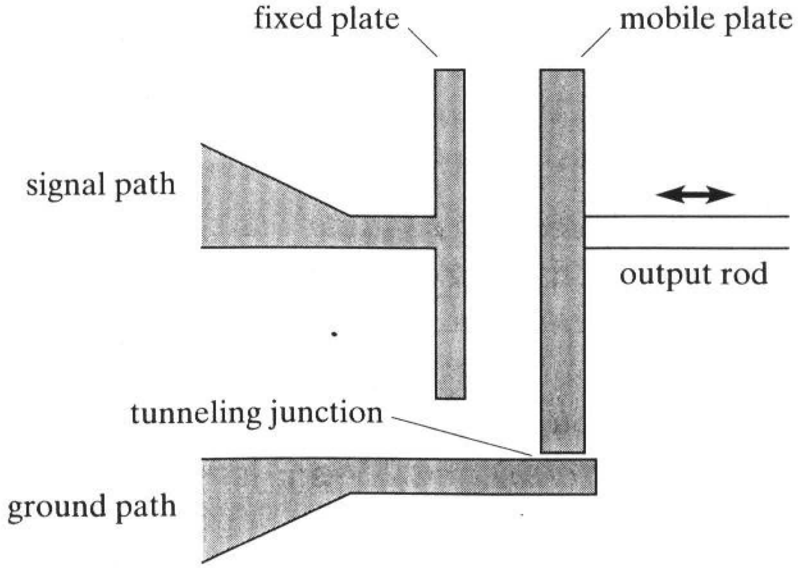


Figure 10. Schematic diagram of an electrostatic actuator for interfacing electrical inputs to mechanical outputs. Source: Nanosystems: Molecular Machinery, Manufacturing, and Computation, by K. Eric Drexler: John Wiley & Sons Inc., New York, N.Y., p. 335, 1992. Reprinted by permission of the publisher.

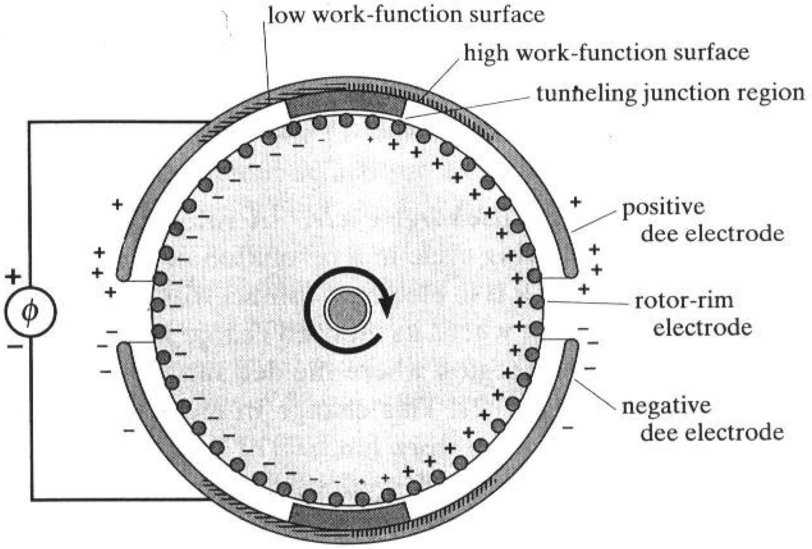


Figure 11. Schematic diagram of an electrostatic motor (not to scale). The dee electrodes and rotor-rim electrodes are conducting, the rotor structural material is insulating. Rotation and torque are in the direction shown. Source: Nanosystems: Molecular Machinery, Manufacturing, and Computation, by K. Eric Drexler: John Wiley & Sons Inc., New York, N.Y., p. 337, 1992. Reprinted by permission of the publisher.

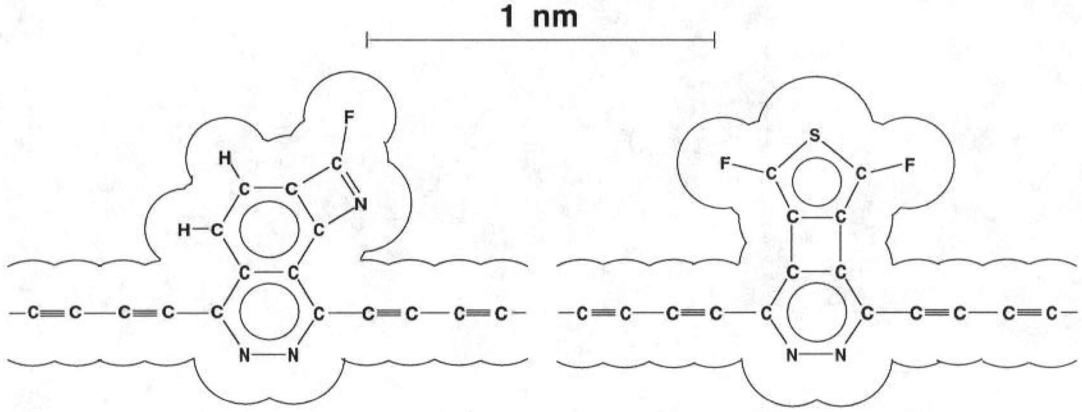


Figure 12. Some components of a rod logic system. Within a constraining housing, the gate knob (right) can either block the probe knob (left) or move aside. (After Drexler in [12].)

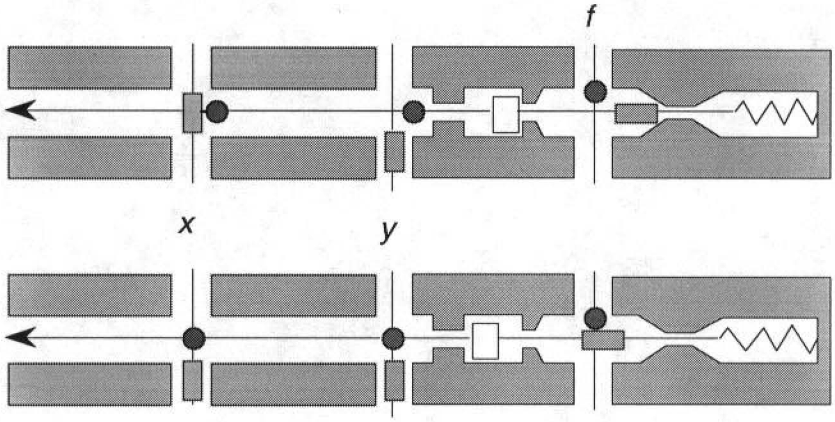


Figure 13. A rod logic implementation of a NAND gate. When both x *and* y *gates do not block the probes, tension on the rod pulls a gate over to block a probe knob on the output rod* f. (After Drexler in [12].)

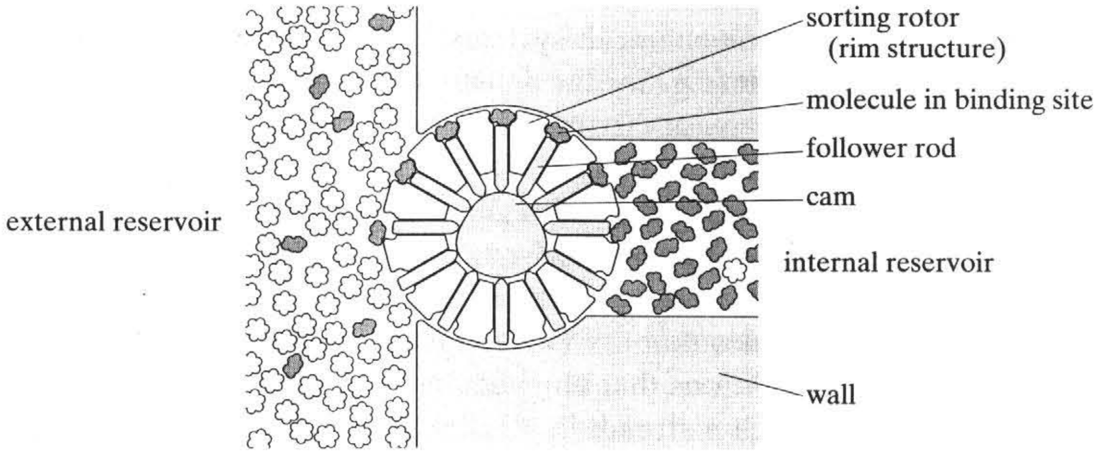


Figure 14. A molecular sorter. As the rotor moves about the cam, follower rods push the molecules out into the reservoir. The figure shows an error, where the wrong molecule has gotten through. To reduce errors, an auxiliary rotor could bind the other side of the molecule which then passes through in a totally enclosed state. Placing the sorting rotors in a series of cascades would allow arbitrary levels of purity. Source: Nanosystems: Molecular Machinery, Manufacturing, and Computation, by K. Eric Drexler: John Wiley & Sons Inc., New York, N.Y., p. 374, 1992. Reprinted by permission of the publisher.

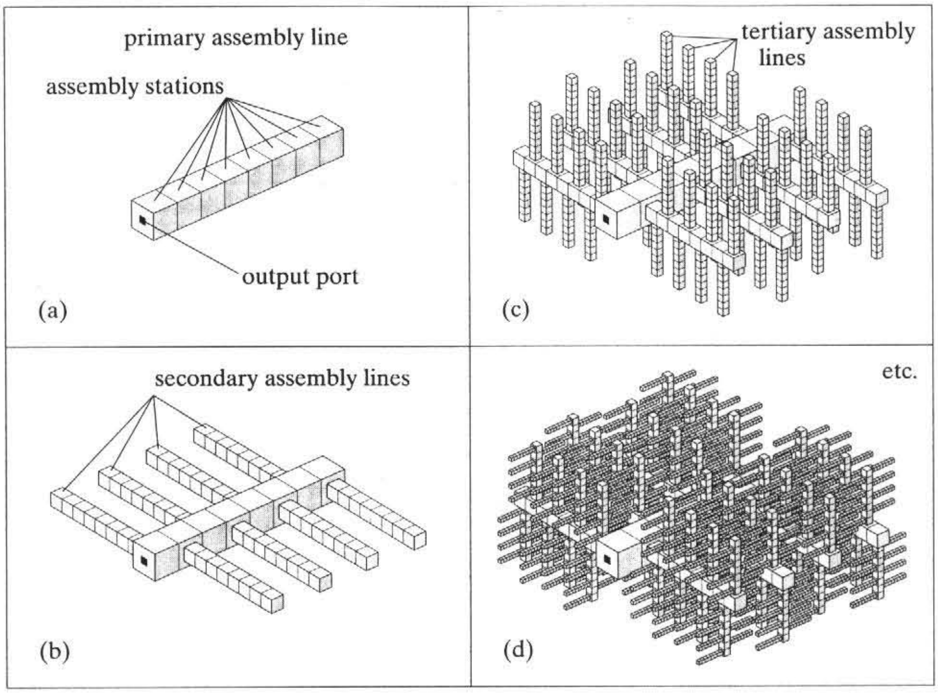


Figure 15. A simple model of a spatial arrangement for a hierarchical, convergent assembly process; panel (a), (b), (c), and (d) provide successively more detailed diagrams. In (a), a primary assembly line consisting of a series of 8 assembly stations (drawn as cubes) performs the final 8 assembly operations in a hypothetical manufacturing process. In (b), 8 secondary assembly lines provide parts to the final lines; (c) and (d) illustrate tertiary and quaternary assembly lines. Since each level of lines contains an equal volume, this pattern cannot be indefinitely extended without self-intersection (the maximum radius of expansion is bounded). With local rearrangements to postpone self-intersection until the available volume is nearly full, a branching pattern of this sort can be extended through >30 generations, enabling the assembly of objects from >10^{27} pieces. This structure demonstrates that certain geometrical constraints can be met, but does not represent a proposed system. Source: Nanosystems: Molecular Machinery, Manufacturing, and Computation, by K. Eric Drexler: John Wiley & Sons Inc., New York, N.Y., p. 418, 1992. Reprinted by permission of the publisher.

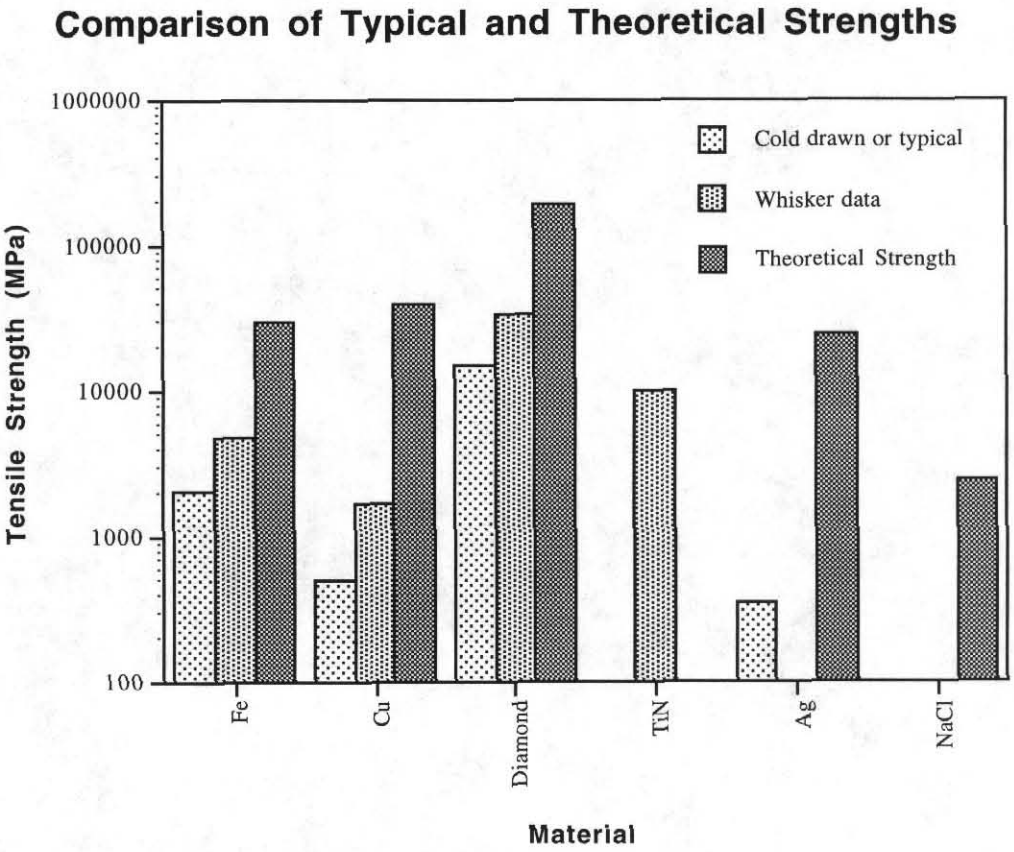


Figure 16. If materials could be made pure and atomically perfect, they would be 10-50 times stronger than today's strongest (though most brittle) form of the same substance. Suitable alloying of the atomically perfect material would increase that differential by more than a factor of 2.

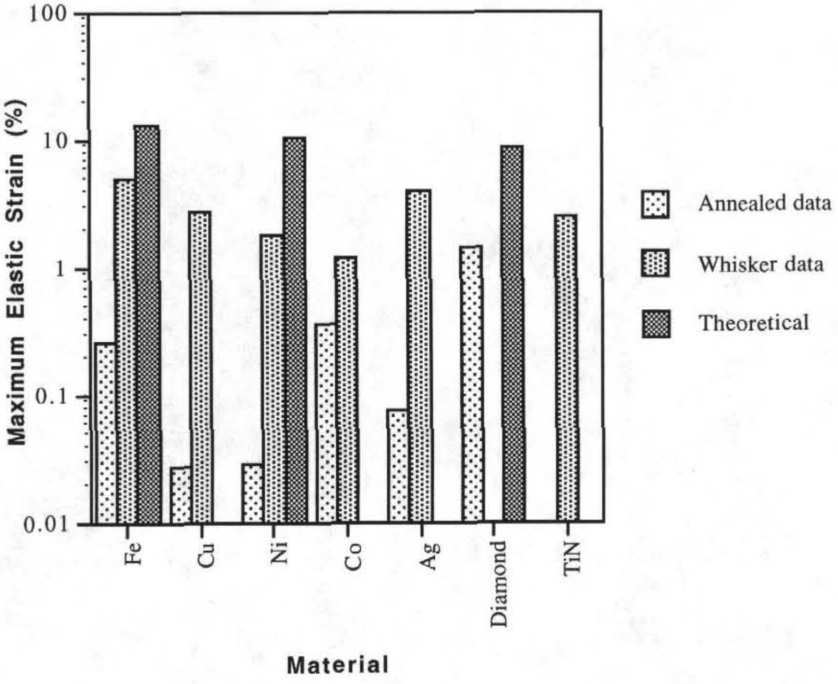


Figure 17. If materials could be made pure and atomically perfect, they would be about 100 times more elastic than today's most elastic (though softest) form of the same substance.

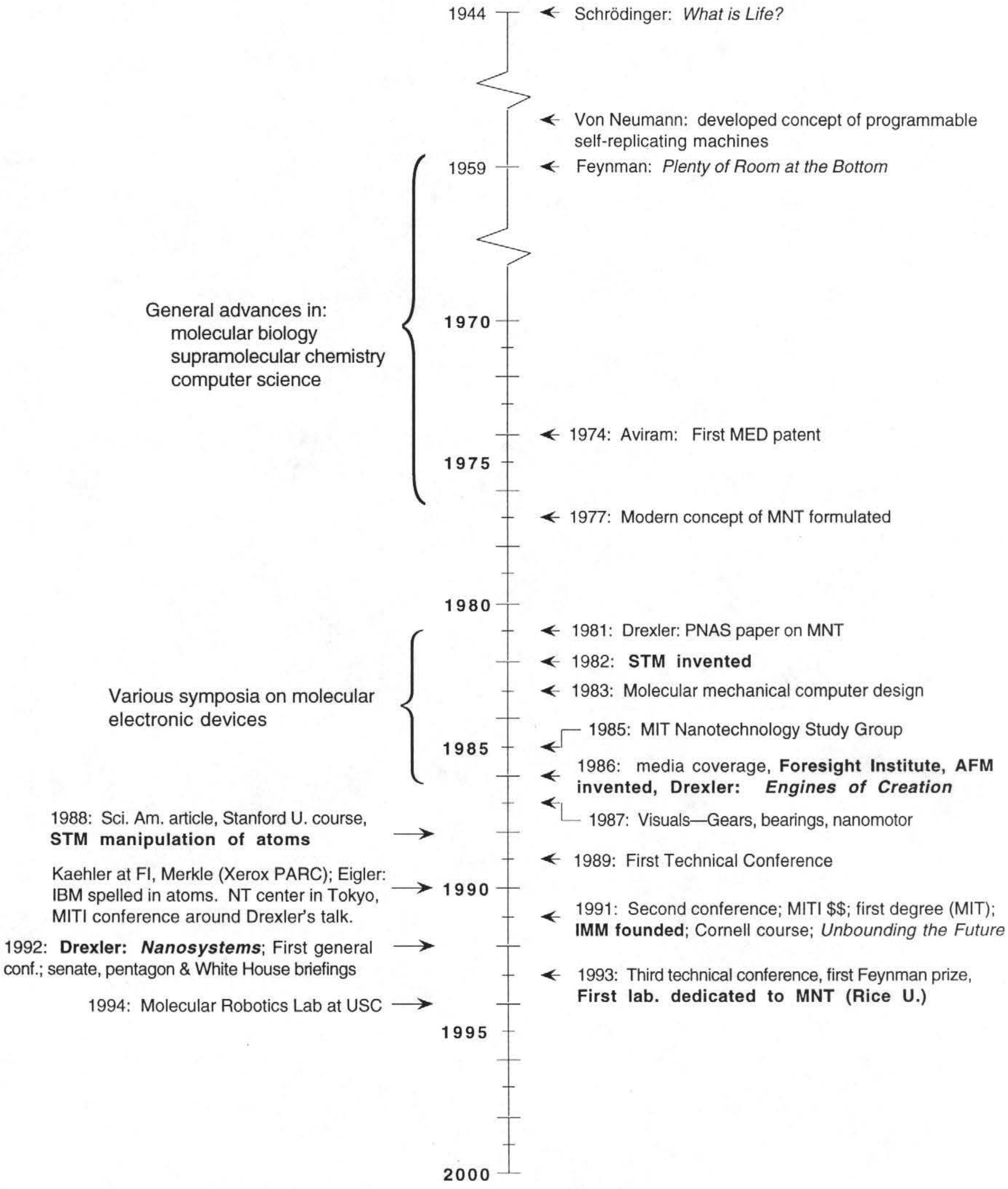


Figure 18. A Timeline of Progress in Molecular Nanotechnology

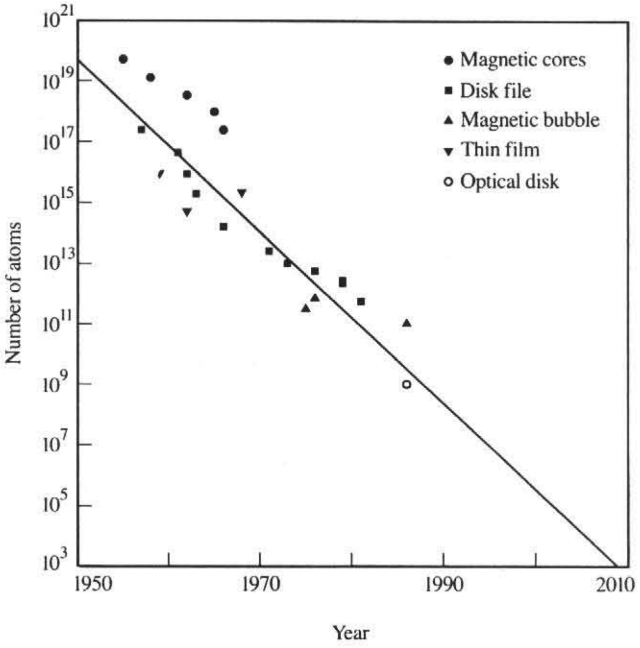


Figure 19. Historical progress in the number of atoms used to store one bit in discrete magnetic entities and in file technologies.

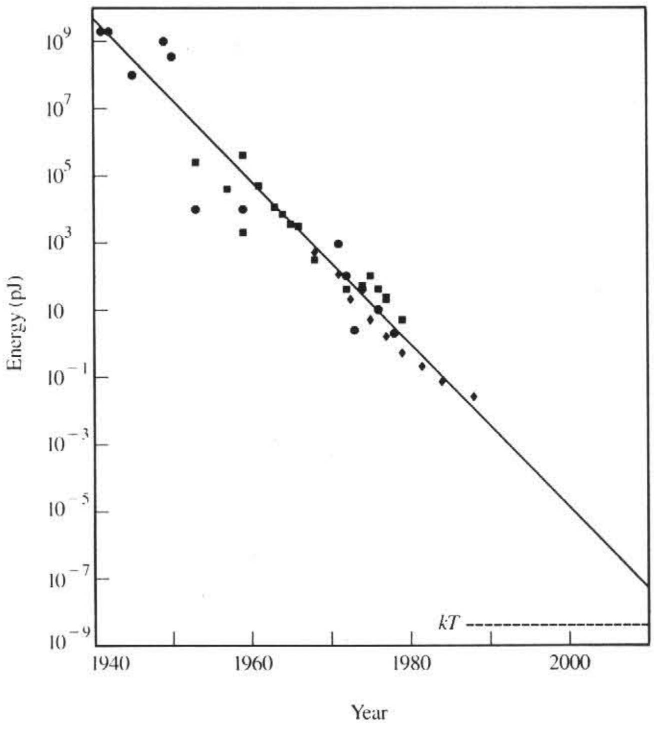


Figure 20. Historical progress in the decrease in energy dissipated per logic operation.

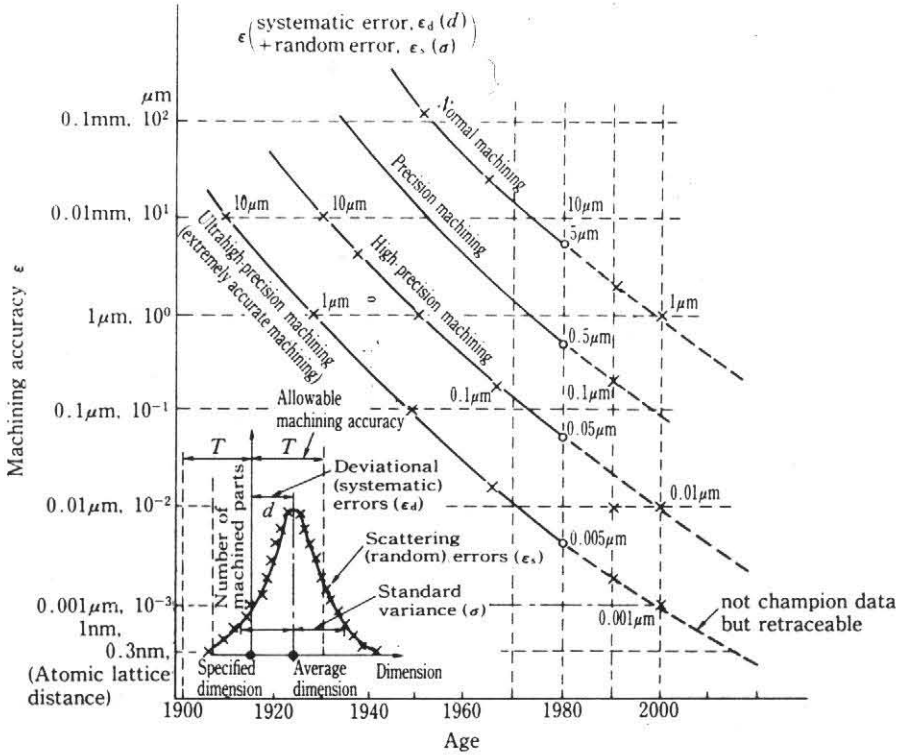


Figure 21. Historical progress in machining accuracy points to molecular precision by the year 2010.