

## Molecular Manufacturing

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The fundamental concepts of molecular manufacturing spring from Richard Feynman's famous 1959 talk, "There's Plenty of Room at the Bottom", which envisioned using productive machinery – factories – to build smaller factories, leading ultimately to nanomachines building atomically precise products. Although inspired by biology (where nanomachines regularly build more nanomachines despite quantum uncertainty and thermal motion), Feynman's vision of nanotechnology is fundamentally mechanical, not biological. Molecular manufacturing concepts follow this lead.

Hence, to visualize how a nanofactory system works, it helps to consider a conventional factory system. The technical questions you raise reach beyond chemistry to systems engineering. Problems of control, transport, error rates, and component failure have answers involving computers, conveyors, noise margins, and failure-tolerant redundancy. These issues are explored in technical depth in my book *Nanosystems: Molecular Machinery, Manufacturing, and Computation* (Wiley/Interscience, 1992), which describes the physical basis for desktop-scale nanofactories able to build atomically precise macroscopic products, including more nanofactories.

These nanofactories contain no enzymes, no living cells, no swarms of roaming, replicating nanobots. Instead, they use computers for digitally precise control, conveyors for parts transport, and positioning devices of assorted sizes to assemble small parts into larger parts, building macroscopic products. The smallest devices position molecular parts to assemble structures through mechanosynthesis – 'machine-phase' chemistry (see illustration and caption below).

Machine- and solution-phase chemistry share fundamental physical principles, yet differ greatly. In machine-phase chemistry, conveyors and positioners (not solvents and thermal motion) bring reactants together. The resulting positional control (not positional differences in reactivity) enables reliable site-specific reactions. Bound groups adjacent to reactive groups can provide tailored environments that reproduce familiar effects of solvation and catalysis. Positional control itself enables a strong catalytic effect: it can align reactants for repeated collisions in optimal geometries at vibrational (>terahertz) frequencies. Further, positional control naturally avoids most side reactions by preventing unwanted encounters between potential reactants. Transition state theory indicates that, for suitably chosen reactants, positional control will enable synthetic steps at megahertz frequencies with the reliability of digital switching operations in a computer. The supporting analysis for this conclusion appears in *Nanosystems* and has withstood a decade of scientific scrutiny.

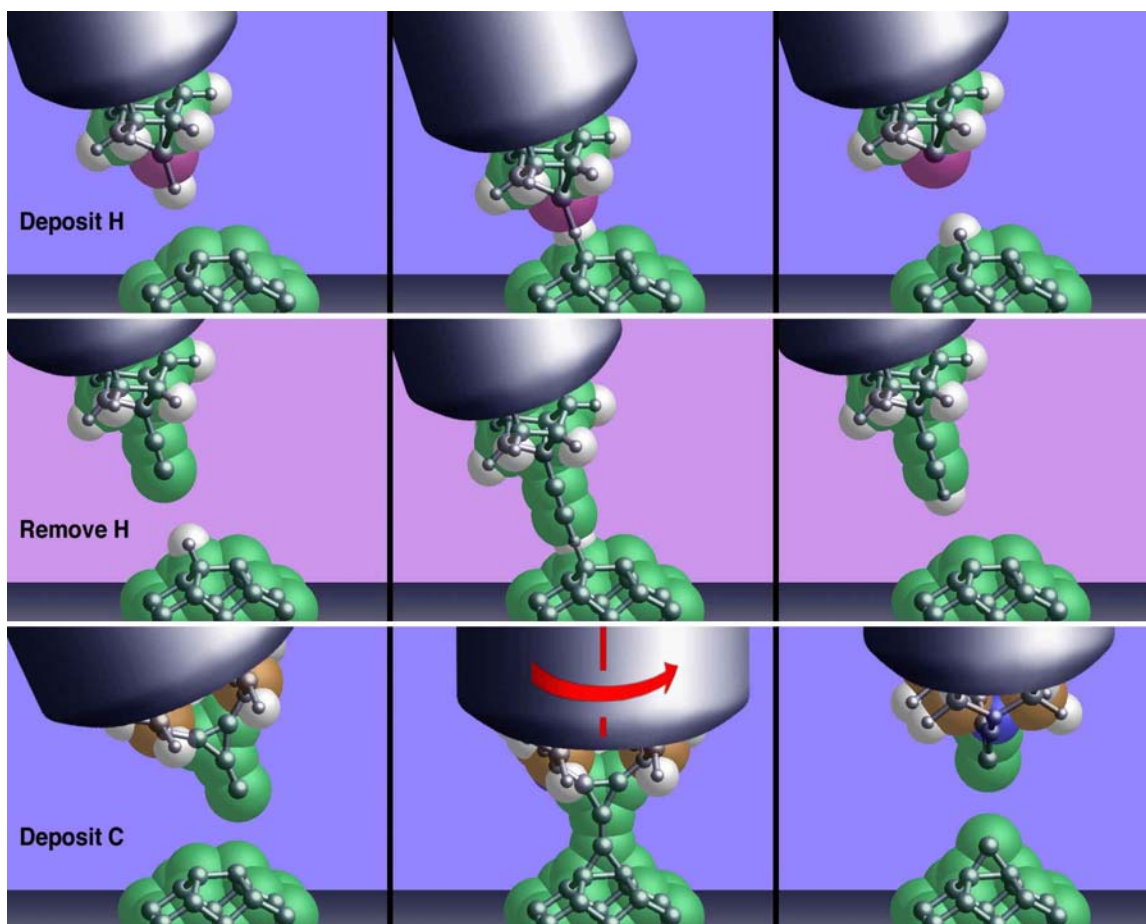
It should be clear that chemical reactions (whether machine-phase or conventional) need no impossible fingers to control the motion of individual atoms within reactants, as suggested by misstatements in the U.S. press. As molecules come together and react, their atoms (being 'sticky') stay bonded to neighbors, and thus need no separate fingers to hold them. Direct positional control of reactants is both achievable and revolutionary; talk of additional, impossible control has been a distraction.

What can be made using mechanosynthesis? Organic and organometallic reactions in solution-phase and chemical vapor deposition systems can, in the hands of skilled chemists, produce a vast diversity of structures. These include all the products of organic synthesis, as well as metals, semiconductors, diamond, and nanotubes. Augmenting such chemistries with positional control of reactants will enable the fabrication of macroscale products containing chemically diverse structures in complex, precise, functional arrangements. Nanofactories based on mechanosynthesis thus will be powerful enablers for a wide range of other nanotechnologies.

Synthetic reactions and molecular machinery of the sort required for nanofactories have parallels in known systems, and have been explored using computational chemistry by professor Ralph Merkle and others. The physical realization of nanofactories, however, will require a multi-stage systems engineering effort. In 1959, Richard Feynman suggested scaling down macroscopic machines. In 2003, the flourishing of nanotechnologies suggests a bottom-up strategy: using self-assembly (and perhaps scanning probes) to build solution-phase molecular machines, using these to gain limited positional control of synthesis, and then leveraging this ability to build systems enabling greater control. Thus, multiple areas of current research (in computational chemistry, organic synthesis, protein engineering, supramolecular chemistry, and scanning-probe manipulation of atoms and molecules) constitute progress toward molecular manufacturing.

However, because it is a systems engineering goal, molecular manufacturing cannot be achieved by a collection of uncoordinated science projects. Like any major engineering goal, it will require the design and analysis of desired systems, and a coordinated effort to develop parts that work together as an integrated whole.

Why does this goal matter? Elementary physical principles indicate that molecular manufacturing will be enormously productive. Scaling down moving parts by a factor of a million multiplies their frequency of operation – and in a factory, their productivity per unit mass – by the same factor. Building with atomic precision will dramatically extend the range of potential products, and decrease environmental impact as well. The resulting abilities will be so powerful that, in a competitive world, failure to develop molecular manufacturing would be equivalent to unilateral disarmament.



MECHANOSYNTHETIC REACTIONS on a diamond (100) surface in vacuum, from computational models. Depositing and removing hydrogen protects and activates surface sites; depositing carbon extends the structure. To deposit H, a positioner presses a weakly bonded Ge-H tip into a strained alkene. To remove H, a positioner uses a strongly bonding alkynyl radical to abstract the target atom. To deposit C, a positioner moves a vinylidene carbene along a barrier-free path to insert into the strained alkene, twists  $90^\circ$  to break a pi bond, and then pulls to cleave the remaining sigma bond.