Under special conditions, chemistry can build stable nanostructures.
K. Eric Drexler

I have been asked to reply to the preceding critique and have done so in a hypertext style (to refer to Simson Garfinkel's comments).

1 — What is nanotechnology?

Simson Garfinkel says that Howard Craighead defines nanotechnology as advanced micro technology, while Rick L. Danheiser defines it as synthetic organic chemistry. As this shows, these fields already have names. So far as I can tell, it was I who introduced the term "nanotechnology" into general use, and as Mr. Garfinkel's paragraph on my usage suggests, there is no commonly accepted alternative name for the capabilities that "nanotechnology" is generally taken to describe. If this technology is important, then it needs to be discussed and it needs a brief, unambiguous name. Sticking with the original meaning of "nanotechnology" would be useful for this reason. (There is no perfectly clear line between synthetic organic chemistry and nanotechnology, but neither is there a perfectly clear line between night and day; they are distinct, though one leads to the next.)

2. Why are computer scientists prevalent among those interested in nanotechnology?

Chemists and physicists are best placed to critique proposals in nanotechnology, but their orientation is that of scientists, not of engineers. The tend to focus on what can be studied today, not on what can be built tomorrow. Computer scientists (despite their name) are, in this sense, engineers. Further, they recognize the value of tiny, fast, controllable things, and they are habituated to technological revolution.

4. Can gears turn on frictionless pivots made from single chemical bonds?

All pivots (or bearings) have some sliding friction, or drag, though they can be made to have a negligible amount of static friction, or stickiness. Single chemical bonds are too weak and elastic to use as bearings for the gears mentioned here, but there are other, more adequate approaches based on sliding surfaces. Like many of the points that follow, this was discussed in my course at Stanford, "Nanotechnology and Exploratory Engineering."

5. Will assemblers build devices a single atom at a time?

in general, probably not, though I have sometimes used language that may suggest literal atom-by-atom construction. A more accurate statement would be something like "Assemblers will maneuver reactive chemical elements to tenth nanometer precision, effecting a series of elementary chemical reactions, each of which adds one or several atoms to a workpiece, giving precise control of the resulting molecular structure." And even this is a simplification, since a typical operation will often do something a bit more complex, such as adding three atoms while removing one. The shorter description gives a clear picture of the net effect.

6. Will assemblers do all these things?

Not directly. Assemblers will be general-purpose manufacturing machines, able to make almost anything so long as they are given the right raw materials, fuels, operating conditions, and instructions. They will be used to make many special-purpose machines, and the latter will do most of the work. To make a particular product in quantity, it will make no sense to use general-purpose assemblers; these will instead be used to build a special-purpose production line, like an engine fabrication line in Detroit. These production lines will then be used to turn out devices like Simson Garfinkel's hypothetical diamond-coating-appliers (perhaps formulated into a rub-on paste?), or the more desperately needed devices able to clean up the mess made by 20th-century industrial technology.

Weapons are among the potential products we need to worry about, but ripping attacking armies apart atom by atom is rather too crude and too dramatic; one suspects that the military mind will find other applications for a manufacturing technology characterized by the construction of precise and sophisticated devices. In general, having an image of assemblers doing everything in the future would be a bit like having an image of lathes and milling machines doing everything today.

7. What does nonotechnology assume about how atoms and molecules work?

Gears, motors, mechanical nanocomputer parts, and Simson Garfinkel's proposed drill would work in an extentially mechanical fashion, as would the positioning operations of assembler arms (resembling those of industrial robot arms). The actual chemical transformations effected by assemblers, however, have little resemblance to familiar mechanical operations.

8. What about elasticity and vibrations?

Every physical object is a collection of atoms; nanomachines will simply be very small physical objects. Everything vibrates, everything bends, and machines work regardless; the differences here are more quantitative than qualitative. On a very small scale, the vibrations associated with heat itself become of tremendous importance, and are a crucial issue in nanomachine design and operation. I mention this issue in Engines of Creation, and have done quantitative analyses of thermal vibrations in both logic systems for mechanical nanocomputers and in assembler arms.

9. What about problems with picking up and placing lone atoms?

See (5).

10. Is an arm bond needed with any arbitrary piece of an arbitrary molecule?

Assembler arms will wield a variety of tools, each with a standard "handle" fitting a standard "hand"; the tools themselves will be specialized. Further, only a limited range of tools would be needed to build a wide variety of products, since even a complex product can be built through a complex series of simple operations. All this is familiar from macroscopic manufacturing technology.

11. Will nanomachines use x-ray or electron-beam "radar" to spot molecules?

Surely not, for reasons well-stated here (I have not seen this proposed elsewhere). Further, freely moving molecules would elude grabbing even if they could be seen; assembler arms would simply be too slow. Industrial robots typically pick prepositioned, preoriented parts off something like a conveyor belt, rather than rummaging around in a bin — and this despite the greater ease of vision on a macroscopic scale. I expect that assemblers will work in a similar fashion.

12. Will nanomachines rely on diffusion?

There is a distinction to be drawn between relying on diffusion somewhere, and relying on it everywhere. Assemblers will enable precise construction of large, complex molecular systems because they (i.e. their positioning arms) will be able to direct chemical reactions with a specificity and reliability that cannot be achieved when molecules are free to bump together in all possible positions and orientations. Thus, they avoid diffusion when moving molecules to the site of reaction.

13. How complicated are assemblers?

Assemblers and nanocumputers will be roughly as complex as industrial robots and microcomputers, because they will contain similar numbers of parts performing similar functions. All these devices, however, will be far less complex (and adaptable) than living organisms; they will have broader capabilities in some respects, but not in all.

14. Can these anti-aromatic structures exist?

For quantum-mechanical reasons, some molecules that can be drawn as rings with alternating double and single bonds are especially stable (like the six-membered benzene ring) and others are especially unstable (like the four-membered cyclobutadiene ring). One of my nanomechanical designs contains a ring resembling the latter; it has the advantage of having a useful shape for the purpose. Is its "instability" a problem?

Chemists regard chemicals as unstable when (for example) they spontaneously dissociate, or rearrange, or react with themselves at a high rate, or when they readily react with a variety of other molecules. This final process is not intrinsic to the molecule, but results from the presence of other reactive molecules. In a different environment, the molecule will be stable. Chemists ordinarily work with molecules in solution, and in vast numbers; these molecules are free to encounter others of the same kind, so any reactions that occur will be unavoidable. This is a stronger kind of instability, typically dealt with by studying molecules under low-density, near-vacuum conditions, or in solid matrices of noble gases at temperatures near absolute zero.

Under the latter conditions, cyclobutadiene exists, but it begins reacting with itself on even slight warming (to 25 degrees Kelvin). In a nanomachine, of course, molecules do not wander freely; they encounter only certain other structures in certain orientations. Under these conditions, the cyclobutadiene ring can indeed be stable (as it is at room temperature when surrounded by bulky, branched side-chains).

16. Should one talk about what has not been demonstrated?

James S. Nowick is correct that predictions are not publishable in many fields of science. However, nanotechnology is not a branch of science (as I have taken pains to point out in Engines of Creation); it is an engineering discipline based on established science. Engineering projects are often discussed and written about before they are undertaken. Indeed, in the 1930's members of the British Interplanetary Society performed feasibility studies which argued that one could fly to the moon with rockets. With care, feasibility studies can be done today in the field of nanotechnology. The required intellectual discipline includes strict avoidance of areas of scientific uncertainty (or pursuit of designs which are robust despite a given range of uncertainty); it is thus closer to engineering than it is to science. To scientists, engaged in learning new facts about nature, talk of future knowledge is speculative and often pointless. To engineers, engaged in building new devices, talk of future possibilities grounded in established science need not be speculative and is often essential.

17. Are we doing nanotechnology today?

The developments and goals cited here are relevant, and show how short-term objectives are leading toward steadily more sophisticated molecular devices. In my work I have focused on long-term developments, and have described devices that no one would consider trying to build today (because we lack the tools) and that no one is likely to build tomorrow (because we will then have better designs). Still, even the crude nanotechnology I am able to describe and defend would have capabilities far beyond what has been achieved today. We are speaking of the difference between a mousetrap on the floor and a gripper on an industrial robot arm backed up by a computer.

In closing …

I thank Simson Garfinkel for a stimulating critique of my work, it has provided an occasion to explain several points previously made only in teaching or in conference proceedings.