By Richard E. Smalley

Of Chemistry, Love and Nanobots

How soon will we see the nanometer-scale robots envisaged by K. Eric Drexler and other molecular nanotechologists? The simple answer is never

WHEN A BOY AND A GIRL fall in love, it is often said that the chemistry between them is good. This common use of the word "chemistry" in human relations comes close to the subtlety of what actually happens in the more mundane coupling of molecules. In a chemical reaction between two "consenting" molecules, bonds form between some of the atoms in what is usually a complex dance involving motion in multiple dimensions. Not just any two molecules will react. They have to be right for each other. And if the chemistry is really, really good, the molecules that do react will all produce the exact product desired.

Near the center of the typical chemical reaction, the particular atoms that are going to form the new bonds are not the only ones that jiggle around: so do all the atoms they are connected to and the ones connected to these in turn. All these atoms must move in a precise way to ensure that the result of the reaction is the one intended. In an ordinary chemical reaction five to 15 atoms near the reaction site engage in an intricate three-dimensional waltz that is carried out in a cramped region of space measuring no more than a nanometer on each side.

In recent years, it has become popular to imagine tiny robots (sometimes called assemblers) that can manipulate and build things atom by atom. Imagine a single assembler: working furiously, this hypothetical nanorobot would make many new bonds as it went about its assigned task, placing perhaps up to a billion new atoms in the desired structure every second. But as fast as it is, that rate would be virtually useless in running a nanofactory: generating even a tiny amount of a product would take a solitary nanobot millions of years. (Making a mole of something—say, 30 grams, or about one ounce—would require at least 6×10^{23} bonds, one for each atom. At the frenzied rate of 10^9 per second it would take this nanobot 6×10^{14} seconds—that is, 10^{13} minutes, which is 6.9×10^9 days, or 19 million years.) Although such a nanobot assembler would be very interesting scientifically, it wouldn't be able to make much on its own in the macroscopic "real" world.

Yet imagine if this one nanobot were so versatile that it could build anything, as long as it had a supply of the right kinds of atoms, a source of energy and a set of instructions for exactly what to build. We could work out these detailed instructions with a computer and then radio them to the nanobot. If the nanobot could really build anything, it could certainly build another copy of itself. It could therefore self-replicate, much as biological cells do. After a while, we'd have a second nanobot and, after a little more time, four, then eight, then 16 and so on.

For fun, suppose that each nanobot consisted of a billion atoms (10^9 atoms) in some incredibly elaborate structure. If these nanobots could be assembled at the full billion-atoms-per-second rate imagined earlier, it would take only one second for each nanobot to make a copy of itself. The new nanobot clone would then be "turned on" so that it could start its own reproduction. After 60 seconds of this furious cloning, there would be 2^{60} nanobots, which is the incredibly large number of 1×10^{18}, or a billion billion. This massive army of nanobots would produce 30 grams of a product in 0.6 millisecond, or 50 kilograms per second. Now we're talking about something very big indeed!

Nanobots in general may not be terribly interesting as a way of making prodigious amounts of things, but self-replicating nanobots are really interesting. If they are feasible, then the notion of a machine that can build anything from a CD player to a skyscraper in a remarkably short time doesn't seem so far-fetched.

But these self-replicating nanobots can also be quite scary. Who will control them? How do we know that some sci-

> Manipulator fingers on the hypothetical self-replicating nanobot are not only too fat; they are also too sticky. Both these problems are fundamental, and neither can be avoided.

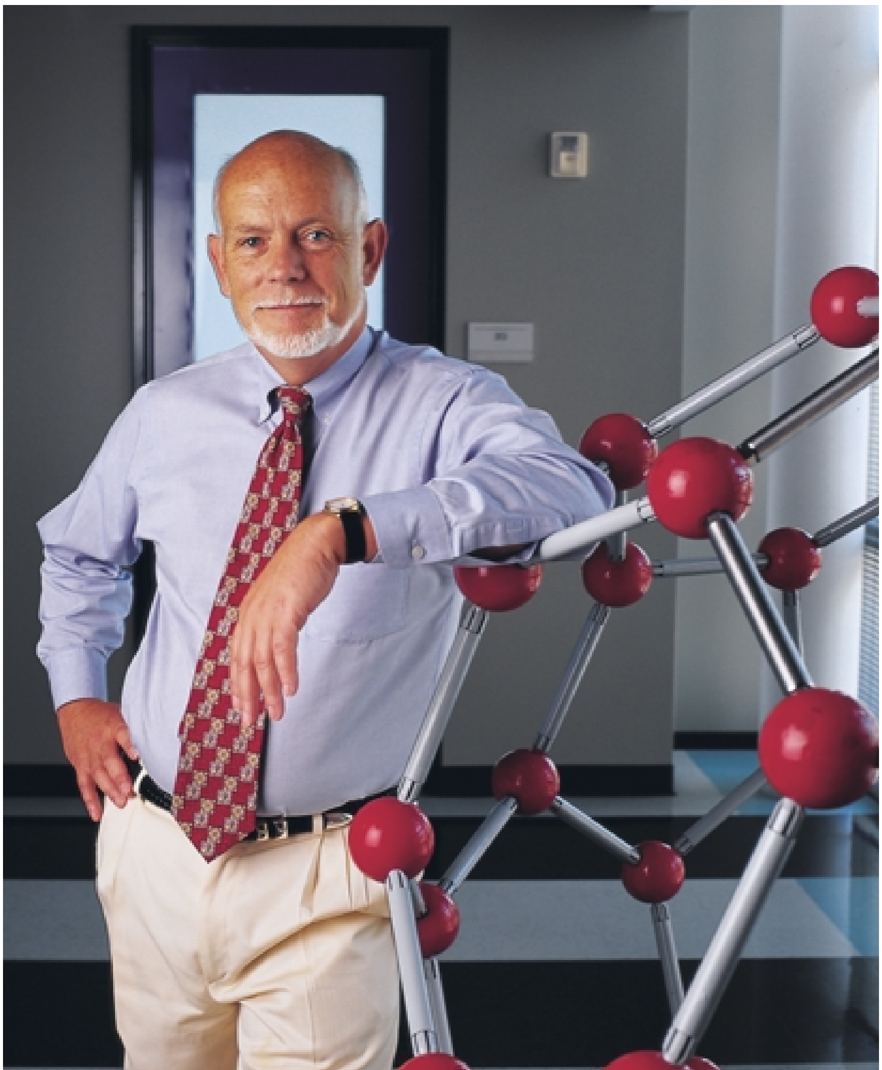
ABOUT THE AUTHOR

RICHARD E. SMALLEY is the Gene and Norman Hackerman Professor of Chemistry and Physics at Rice University. He received the 1996 Nobel Prize in Chemistry for the discovery of fullerenes.

entist or computer hacker won't design one that is truly autonomous, carrying a complete set of instructions for itself? How do we know that these nanobots won't mutate and that some of these mutants won't achieve the ability, like cancer cells, to disregard any signals that would otherwise trigger self-destruction? How could we stop them once they reached this malignant state? Self-replicating nanobots would be the equivalent of a new parasitic life-form, and there might be no way to keep them from expanding indefinitely until everything on earth became an undifferentiated mass of gray goo.

Still more frightening, they would by either design or random mutation develop the ability to communicate with one another. Maybe they would form groups, constituting a primitive nervous system. Perhaps they would really become "alive" by any definition of that term. Then, in the memorable words of Bill Joy, the chief scientist at Sun Microsystems and someone who has worried in print about the societal implications of proliferating nanobots, the future simply would not need us.

But how realistic is this notion of a self-replicating nanobot? Let's think about it. Atoms are tiny and move in a defined and circumscribed way—a chemist would say that they move so as to minimize the free energy of their local surroundings. The electronic "glue" that sticks them to one another is not local to each bond but rather is sensitive to the exact position and identity of all the atoms in the near vicinity. So when the nanomanipulator arm of our nanobot picks up an atom and goes to insert it in the desired place, it has a fundamental problem. It also has to somehow control not only this new atom but all the existing atoms in the region. No problem, you say: our nanobot will have an additional manipulator arm for each one of these atoms. Then it would have complete control of all the goings-on that occur at the reaction site.



NOBELIST Richard E. Smalley dismisses the notion of out-of-control nanorobots.

PAM FRANCIS

But remember, this region where the chemistry is to be controlled by the nanobot is very, very small—about one nanometer on a side. That constraint leads to at least two basic difficulties. I call one the fat fingers problem and the other the sticky fingers problem. Because the fingers of a manipulator arm must themselves be made out of atoms, they have a certain irreducible size. There just isn't enough room in the nanometer-size reaction region to accomodate all the fingers of all the manipulators necessary to have complete control of the chemistry. In a famous 1959 talk that has inspired nanotechnologists everywhere, Nobel physicist Richard Feynman memorably noted, "There's plenty of room at the bottom." But there's not *that* much room.

Manipulator fingers on the hypothetical self-replicating nanobot are not only too fat; they are also too sticky: the atoms of the manipulator hands will adhere to the atom that is being moved. So it will often be impossible to release this minuscule building block in precisely the right spot.

Both these problems are fundamental, and neither can be avoided. Self-replicating, mechanical nanobots are simply not possible in our world. To put every atom in its place—the vision articulated by some nanotechnologists—would require magic fingers. Such a nanobot will never become more than a futurist's daydream.

Chemistry is subtle indeed. You don't make a girl and a boy fall in love by pushing them together (although this is often a step in the right direction). Like the dance of love, chemistry is a waltz with its own step-slide-step in three-quarter time. Wishing that a waltz were a merengue—or that we could set down each atom in just the right place—doesn't make it so. SA

MORE TO EXPLORE

The author's Web site can be accessed at **cnst.rice.edu/reshome.html**