Nanotechnology and the information age

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The information technology industry owes its success in large part to the ability of scientists and engineers to make the physical manifestation of information, the devices and *bits*, ever smaller. In both semiconductor and storage technology, we can now make structures with vertical dimensions of a few nanometers. In that sense nanotechnology has been a reality for several years now. In the lateral dimension, however, current manufacturing processes cannot build much structure into an object at length scales less than the minimum lithographic dimension. This is a practical limit though, not an ultimate physical limit. There is no *a priori* reason why we cannot design and build objects with complex structures down to atomic length scales.

Various solutions are being proposed to the problem of fabrication at the nanometer scale, ranging from extending lithography to chemical self-assembly to *nanobots* and *molecular assemblers*. It is important to note in considering the alternatives that the often purported contention between *top-down* and *bottom-up* approaches is a false dichotomy; a hybrid of both approaches is used even in today's manufacturing processes. What matters is the perfection of fabrication.

Stated in general terms, one must consider the defect or error rate with which structural information can be imparted to an object by some dynamical process. *Digital* processes, that is, processes involving a few discrete energetically accessible states, can have very low error rates, but are energetically costly. *Analog* processes with many accessible energy states, such as chemical reactions, have higher error rates, but can be very efficient. The trick is to combine the two modes of imparting structural information so that the complex, hierarchically-organized systems of information technology can be manufactured at minimum cost.

By combining conventional processes, such as optical lithography, with increasingly sophisticated chemical and physical processes in which kinetics and thermodynamics are fully exploited, it should become possible over the next few decades to design and control the structure of an object on all length scales, from the macroscopic to the atomic, and to do so cheaply and reliably in manufacturing. The emergence of such a mature nanotechnology would ensure continued exponential reductions in the cost of information technology hardware, and generate yet unimagined new products and industries.

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