geology, biology, reactions, compounds, bond enthalpies, and so on. This site contains enough information to keep any student occupied for quite a while. Indeed, I've bookmarked it for my own further use.

This is just the kind of question that the Web is very good at answering, and in my experience, information can be found on just about any subject, whether it's "Where is the fluorine atom in fluorene?" (answer nowhere; there isn't any) or "What is the current phone number for that motel I stayed at 10 years ago in Green Valley Lake?"

Yes, it takes some ingenuity to select search parameters judiciously, and yes you can get a lot of chaff with the wheat on some subjects, but I've been pleasantly surprised at how useful the Internet is.

Where I think we probably agree is in the assertion that simply having access to the Internet is no substitute for critical thinking and enough general knowledge that one can evaluate information intelligently.

John Wheeler
(jcw@chemj2.ucsd.edu)
University of California, San Diego
La Jolla, California

Hammond replies: I would like to thank John Wheeler and Steven Ryan for their suggestions about searching on the Internet. My search for europium, while a real one, was meant to be taken metaphorically. Physicists can avoid most hazards on the Internet, but when material is dispensed freely without formal review or refereeing, our students can be vulnerable targets to misinformation and, plainly, junk. I did another search, this time using Google. Moving up the periodic table, I chose silver, and the results were even worse than those for europium. I found everything for sale, from thermal products to machines that make colloidal silver for snorting (and if you doubt the health benefits of this miraculous device, you can order the descriptive pamphlet for only $3.50). In summary let me reemphasize the value of the Internet when used as an appropriate tool in research and teaching, and warn again that its value is jeopardized by its growing commercialization.

Richard Hammond
(rich_hammond@ndsu.nodak.edu)
North Dakota State University
Fargo

More on Moore's Law

Without entering into the different points of view concerning Moore's Law expressed by Joel Birnbaum and R. Stanley Williams in their article (Physics Today, January 2000, page 38) and Igor Fodor's letter (Physics Today, October 2000, page 106), I must comment more generally on the observation called Moore's Law.

In figure 3 of the Birnbaum and Williams article, the standard growth curve is shown for Intel processor chips from the 4004 of the early 1970s to the Pentium models of the late 1990s. The slope of the curve as drawn shows a doubling time constant of about 26 months; the caption, in contrast, describes the growth as "a factor of four every three years," or a doubling time constant of 18 months! This inconsistency is a frequently promulgated misinterpretation of the observation of Intel Corp's founder Gordon Moore.

In the article, Birnbaum and Williams use a 3.4-year time constant for the factor-of-four increase in the number of bits stored on a memory chip. This corresponds to a 20-month doubling time constant. Indeed the slope for memory chip growth has been and continues to be steeper than for processor chips.

Moore, commenting on the growth of the microelectronics industry in 1964, noted a doubling of the number of elements on a produced chip once every 12 months.[1] For a decade, that meant a growth factor of approximately 1000. Today, when Moore's Law is quoted, the time constant typically quoted is 18 months. Actually, it was 18 months starting in the mid-1970s, approximately 10 years after the original observation. For a decade, then, the growth factor was approximately 100.

The 18-month time constant was no longer valid by the end of the 1980s. For example, from 1980 to 1990 the number of transistors in the Intel-80x processor chips grew from about 29 000 to approximately 1.2 million—substantially less than a factor of 100. In the 1990s, the doubling time constant has been closer to two years. This gives a decade growth factor of approximately 32.

As the industry approaches the physical limits of the complementary metal oxide semiconductor (CMOS) technology curve we have been riding so effectively, let alone the economic limits that are also at work, the rate of growth of the number of transistors on a chip will further decrease. The Semiconductor Industry Association's road map[2] shows a growth of about a factor of 24 for microprocessors in the decade between 1999 and 2009. That implies a Moore's Law time constant for doubling of about 2.5 years.

References

1. R. N. Noyce, *Sci. Am.*, Sept 1977, p. 63. *Information Technology and R&D: Critical Trends and Issues*, rep. no. OTA-CIT-268, US Congress, Office of Technology Assessment, Washington, DC, (February 1985), p. 324.
2. *International Technology Roadmap for Semiconductors: 1999 Edition*, Semiconductor Industry Association, San Jose, Calif. (1999), p. 3. Also available at http://public.itrs.net/Files/1999_SIA_Roadmap/ Home.htm.

Alfred E. Brenner
(abrenner@ida.org)
Institute for Defense Analyses
Alexandria, Virginia

Seeing Atoms More Clearly

In his otherwise excellent review of x-ray holography (Physics Today, April 2001, page 21), Richard Fitzgerald writes, "Lens aberrations in electron microscopes have prevented . . . atomic resolution in electron holography." However, this is no longer true. Alexander Orchowski, Wolf-Dieter Rau, and Hannes Lichte[1] describe experimental off-axis electron holography with atomic resolution. This is the first paper that actually does what Dennis Gabor wanted to do—correct electron-optical aberrations to see atoms. Other groups have also done this since. The resolution of the best electron microscopes is now about one angstrom (better if in-line holography is used), which is sufficient to "see atoms."

Reference

1. A. Orchowski, W.-D. Rau, H. Lichte, *Phys. Rev. Lett.* **74** 399 (1995).

John Spence
(spence@asu.edu)
Arizona State University
Phoenix, Arizona

Correction

March 2001, page 96—In the obituary for Louis Goldstein, the credit for liquefying the helium-3 isotope should have gone to Edward R. Grilly, Edward F. Hammel, and Stephen Sydoriak. ■