emphasized the importance of the program FRODO (*1*) in their work. However, interactive three-dimensional molecular graphics did not begin with FRODO in 1978, but in 1964 with work on the Project MAC display at the Massachusetts Institute of Technology (MIT) (*2*) by the late Cyrus Levinthal (then at MIT) and me (then at Harvard University) (*3*).

The project MAC system was one-of-a-kind, but once commercial interactive three-dimensional computer graphics displays began to appear in 1967–1969, the Division of Research Resources of the National Institutes of Health encouraged both Levinthal and me to establish computer graphics laboratories at Columbia University and Princeton University, respectively. This earlier work had the same motivation as FRODO—to eliminate the use of large and clumsy wire models.

Hall lists molecular graphics programs now routinely used in structural biology and states that "All these programs are, in a sense, the children of FRODO." They are all, including FRODO, descendants of our earlier work.

Robert Langridge
Computer Graphics Laboratory
University of California,
San Francisco, CA 94143, USA

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■

Three Presidents

Craig Halvorson and his colleagues (Reports, 26 Aug., p. 1215) describe the design and fabrication of a novel and extremely fast optical image processor that uses the nonlinear optical properties of conjugated polymers. The device was demonstrated by optical correlation of an image of U.S. President George Washington, with a second image bearing likenesses of presidents Washington, Thomas Jefferson, a rotated Washington, and John Adams (clockwise from top of illustration, p. 1892). Halvorson and his colleagues conclude that the reference image of Washington is correlated best with the unrotated likeness of Washington in the second image (autocorrelation), as one would expect. However, they also find that the next largest peak in the correlation intensity is between the image of Washington and that of Jefferson, followed by Washington and a rotated image of Washington, and last between the images of Washington and Adams (*1*).

We performed a similar correlation analysis, using conventional computational tools, on the images used in Halvorson *et al.*'s demonstration. We digitized the images appearing in the article and computed the correlation intensity as a function of relative image shift. We found a maximum correlation intensity corresponding to the unrotated image of Washington, as did Halvorson *et al.* However, we found the next largest peak in the correlation intensity corresponding to the image of Adams, not Jefferson, and the smallest peak corresponding to Jefferson, not Adams. This result is reasonable, given that both Washington and Adams are looking to their right and shadowed on their left, whereas Jefferson is looking to his left, and shadowed on his right. For this heavily shadowed black-and-white image, the correlation intensity is more sensitive to the subject's orientation and illumination angle than it is to subtle differences in facial features.

Halvorson *et al.*'s demonstration of their novel optical correlator remains an impressive feat of engineering, in that they achieved a result in 160 femtoseconds; our analysis required seconds.

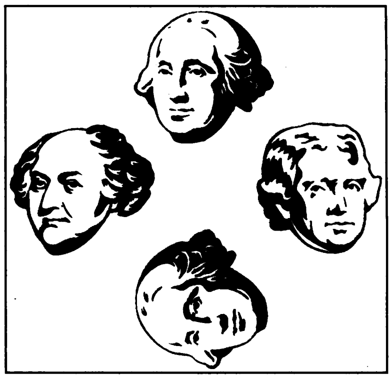
J. E. P. Connerney
T. Satoh
Goddard Space Flight Center,
National Aeronautics and
Space Administration,
Greenbelt, MD 20771, USA

Note

1. In spite of their political differences, John Adams, a Federalist, probably had more in common with Thomas Jefferson, an early leader of the Democratic-Republicans, than did Washington with either man. Washington regarded himself first and foremost as a military man, whereas Adams and Jefferson were political theorists, diplomats, and philosophers.

Exaggerated statements and unwarranted extrapolations are problems in all areas of science, but seem to be particularly endemic in the field of optical computing. It is common in this field for authors to quote "potential performance" or "theoretical limits" several orders of magnitude higher than what they have actually demonstrated. The recent report by Halvorson *et al.* is a case in point.

What these authors actually demonstrated is that a certain nonlinear optical material has a response time of 160 femtoseconds (fs) and that it can be used to correlate two low-resolution images of about 5000 pixels each. Had they left it at that, it would have been an interesting and useful contribution. They went further, however, and converted their data to a "peak processing rate" and compared it to the performance of a Cray supercomputer. To do so, they divided the number of pixels in the image by 160 fs, arriving at a rate of 3×10^{16} "operations per second," which they then compared to "a theoretical maximum processing rate of 1.55×10^{10} floating point operations per second" for a Cray C916. This comparison appears to be meaningless.



Founding fathers. Quickly: Which pair has peak correlation intensity?

The actual processing rate of their system is the number of pixels per image divided by the time required to input an image with a spatial light modulator (SLM). While the authors do not give specifications for the SLM they used, typical devices of this type operate at about 30 frames per second. Thus the *demonstrated* processing rate is about 30 frames per second times 5000 pixels per frame, or 1.5×10^5 operations (*not* floating point operations) per second. This actual number is more typical of a personal computer than of a Cray, but the important point is that it is 11 orders of magnitude below the quoted "peak processing rate."

Halvorson *et al.* include the disclaimer that "faster SLMs will be required before actual processing rates can match the peak rate," implying that it is somehow possible to reach the rate claimed. Even a factor of 10 improvement in SLM performance will be difficult to achieve, and a factor of 10^{11} is required to justify the statement in the text and the abstract (and even repeated in This Week in *Science*, 26 Aug., p. 1153).

Perhaps we in the optics community should agree not to extrapolate our achievements by more than, say, a factor of 1000. Would that help our credibility?

Harrison H. Barrett
Optical Sciences Center,
University of Arizona,
Tucson, AZ 85721, USA

Response: The "actual processing rate" calculated in Barrett's letter is based on the performance of the input device rather than on the performance of the optical processor itself. The SLM on which Barrett's calculation is centered does not, in fact, do the processing; it simply introduces the data into the four-wave mixing processor. Focusing on the "actual processing rate" is like calculating the speed of a computer on the basis of the typing speed of the person entering the data. We calculated the processing speed; Barrett has calculated the data input speed.

The processor described in our report used four-wave mixing to implement the operation of image correlation; this is the fundamental mechanism. The measured four-wave mixing response time was less than 160 fs, and this response time is fixed by the fundamental physics of four-wave mixing in conjugated polymers; it is not dependent on the type of input or output device used.

SLMs are important devices in their own right, and we feel that Barrett is unduly pessimistic about their potential. Traditional nematic liquid crystal SLMs operate by aligning molecules in an applied field, and this is a slow process. However, SLM can be based on many different physical principles. For instance, a recent paper by D. Fichou *et al.* (*1*) reports a photochromic SLM with a response time of less than 10 picoseconds (ps), which was the detection limit of their equipment. This paper also gives an excellent and up-to-date overview of SLM technology. A group at the University of Rochester has recently proposed a field-effect SLM with a response time estimated at 25 ps (*2*). The SLM made by Fichou *et al.* is more than 10^9 times faster than the nematic liquid crystal SLMs that Barrett mentions as the apex of technological achievement.

We used floating point operations to characterize the speed of the electronic computer as this is a traditional measure of processing speed. A correlation operation on an electronic computer is composed of many floating point operations. We expressed the speed of the optical processor in correlation operations, as the optical computer does not use floating point operations. Our comparison is therefore conservative, favoring the electronic computer.

We demonstrated an optical image processor based on four-wave mixing in conjugated polymers that processed entire images in less than 160 fs. There were no "exaggerated statements" or "unwarranted extrapolations."

Craig Halvorson
Andrew Hays
Brett Kraabel
Rulian Wu
Fred Wudl
Allan J. Heeger
Institute for Polymers and Organic Solids, University of California, Santa Barbara, CA 93016, USA

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Corrections and Clarifications

In This Week in *Science*, 10 March, page 1401, under the title "Knowing when to go," the name of the nematode *Caenorhabditis elegans* was misspelled.