Despite the appeal of this picture to theorists, experimentalists remain skeptical about the importance of the oscillations—even for visual binding. "I think it's an ingenious idea, but I'm not completely sold on it," says Harvard neurobiologist David Hubel. "And what I don't find so great is the philosophical tangents . . . equating it with consciousness and every other thing." Rockefeller's Gilbert describes his position as agnostic. "I would like to be open minded," he says, "but it requires a lot more backup information to know what the significance [of the oscillations] is, and whether it's not just something artifactual that is not used by the brain."

One reason Gilbert and others remain lukewarm is that they suspect the oscillations are merely a side effect of neuronal activity, rather than a key element in brain function. In experiments in which he has recorded from the same brain regions as Singer, Gilbert says he only occasionally has seen synchronous oscillations. "We tended to interpret it as a funny state the cortex had gotten into," he says.

That "funny state" could be an epiphenomenon, or nonfunctional by-product, of the firing of neurons linked together in a network. Computer simulations by several groups have shown that oscillations can easily arise in active neural networks, a fact that Singer readily acknowledges. "I am entirely open to the possibility that it is an epiphenomenon," he says. "We have to go on and collect more evidence which suggests that the brain may actually be using it."

Gathering that evidence will require experiments on waking monkeys. Both Andreas Kreiter in Singer's lab and Singer's former postdoc Gray (now working independently at the Salk Institute) have observed the oscillations in monkeys, although they are more transient and harder to detect. Next, both labs plan to devise images that can be altered to appear as one object or two, show them to monkeys and test whether the oscillations between columns go in and out of phase-lock depending on whether the monkey perceives specific features to be part of the same object or not.

These experiments will address not only the binding issue, but also a major charge that has been leveled against Koch and Crick's consciousness theory: that it is based on data taken largely from anesthetized (that is, unconscious) animals. How, the critics ask, can a theory of consciousness be based on observations of animals that are not conscious? Though Singer and Gray have observed the oscillations in waking cats, most of their characterization has been done with anesthetized cats, because it is technically easier. And they agree that if the oscillations are contributing to any conscious process, whether it be simple binding or something grander, they must be confirmed to not only exist but to play a role in alert animals.

As the experimentalists pursue the oscillations in their biological context, the theorists are cheering from the sidelines. Von der Malsburg, for one, is eagerly awaiting the next round of results. "Wolf Singer and the others are onto something extremely important," he says. "If this experimental-theoretical story materializes even further, it will open the door to a completely new era."

■ MARCIA BARINAGA

ADDITIONAL READING


C. von der Malsburg and W. Schneider, "A neural cocktail-party processor," *Biol. Cybern.* **54**, 29 (1986).

F. Crick, "Function of the thalamic reticular complex: The searchlight hypothesis," *Proc. Natl. Acad. Sci. U.S.A.*, **81**, 4586 (1984).

D. Y. Ts'o, C. D. Gilbert, T. N. Wiesel, "Relationships between horizontal interactions and functional architecture in cat striate cortex as revealed by cross-correlation analysis," *J. Neurosci* **6**, 1160 (1986).

C. D. Gilbert and T. N. Wiesel, "Columnar specificity of intrinsic horizontal and corticocortical connections in cat visual cortex," *ibid.*, **9**, 2432 (1989).

R. Eckhorn, *et al.* "Coherent oscillations: A mechanism of feature linking in the visual cortex?" *Biol. Cybern.* **60**, 121 (1988).

C. M. Gray, A. K. Engel, P. Konig, W. Singer, "Stimulus-dependent neuronal oscillations in cat visual cortex: Receptive field properties and feature dependence," *Eur. J. Neurosci.* **2**, 607 (1990).


# A New Wave in Applied Mathematics

*A technique called wavelets may upstage Fourier analysis in a multitude of applications—from CAT scanning to locating subs*

WAVELETS ARE MAKING A BIG SPLASH in mathematics. Despite the diminutive name, wavelet theory is something of a tidal wave breaking over a venerable technique that has been king of the hill for a century and a half: Fourier analysis. Almost since the day in 1822 when French mathematician Joseph Fourier first published a treatise on the theory of heat, the technique he introduced in that treatise revolutionized mathematical physics. The technique—Fourier analysis—rapidly came to dominate the analytic approach to scientific problems from acoustics to quantum mechanics to climatology to crystallography.

Now a new theory—wavelets—has appeared, one its enthusiasts see as a significant advance over Fourier analysis. They believe it will help solve pressing problems in many branches of engineering and physics. Among possible applications: data compression for storing and transmitting digitized images; music and speech synthesis; seismic exploration; detecting engine problems or submarines gliding through deep waters; analyzing the dangerous downdrafts known as microbursts that are associated with thunderstorms; and improvements in medical imaging from CAT scans and nuclear magnetic resonance.

"Never before in anything on which I've worked have I had contacts with people from so many different fields," says Ingrid Daubechies, a leading wavelet theorist at Bell Laboratories. "Because you have everybody interested and everybody has a different way of looking at it, you have all these ideas brewing together, and it's very fertile for everybody concerned."

This ubiquitous appeal arises from wavelet theory's way of rearranging data to reveal key features of a physical or mathematical system—features that might otherwise be hidden. Fourier analysis shares that essence, but the big difference between the two methods is in how they tackle the data.

Fourier analysis assumes the world is made of sine and cosine curves—the simple, undulating functions of high-school trigonometry. This might seem to limit the method to studying smooth, periodic phenomena, but in fact it works in many settings. That was the nub of Fourier's innovation and the reason Fourier analysis has occupied center stage for so long.

Starting with an arbitrarily complicated function, the Fourier analyst looks for a collection of sines and cosines of varying frequencies and amplitudes that, when added together (or more precisely, integrated), reproduce the original curve. The assignment of an amplitude to each frequency is a function in its own right; mathematicians call it the Fourier transform of the original function.

A large amplitude at a particular frequency indicates something important is happening there. For example, a Fourier transform of weather data—the temperature in Detroit as a function of time, say—is likely to have a large amplitude for the frequencies corresponding to 24 hours and 365 days, because the temperatures are likely to be quite similar at those intervals. In many applications the original function is essentially ignored, because the Fourier transform contains the same information in more manageable form.

Useful as this method is, it does have drawbacks. If, for example, the temperature readings in Detroit are found to be in error, even for a single hour, it is necessary to recompute the amplitudes for *all* frequencies in the Fourier transform. Even worse, Fourier analysis grinds to a halt if there are gaps in the data; the gaps must be filled in by some sort of mathematical guesswork before the transform can be computed.

That's where the advantages of wavelet theory become apparent. Using wavelets, the analyst can "zoom in" on details, much like a camera with a zoom lens. Wavelet theory can also work around any gaps in the data, in effect postponing the guesswork until after the transform has been taken.

These advantages are made possible by the fact that the wavelet transform uses different building blocks than Fourier's method. The problem with sines and cosines, the units of Fourier analysis, is that they undulate forever in both directions. The units of wavelet analysis, however, are concentrated in short intervals. Starting with a "mother wavelet" concentrated on one interval (generally between 0 and 1), other building blocks are typically created by moving the mother wavelet left or right in unit steps and dilating or compressing it by repeated factors of 2.

The mother wavelet can be likened to a musical whole note played at middle C, and its "children" to half notes played one octave higher, quarter notes two octaves higher, and so forth (for example, a double whole note at the C below middle C, and so forth). In fact, the analogy with musical notation is so close that one group in France is exploring the use of wavelets to automate the production of printed scores from live music.

In visual terms, the dilated and compressed versions of the mother wavelet correspond to low-resolution and high-resolution details of a picture. Indeed, Stephane Mallat and Sifen Zhong of the Courant Institute at New York University are exploiting this analogy to develop a two-dimensional wavelet approach to data compression of digitized images. The basic idea is simple: compute the wavelet transform to a certain level of resolution and record only the coefficients that are above a certain threshold. Since most images have large regions where the texture doesn't change, only a relatively few coefficients survive the cutoff.

**Edgy image.** *Sifen Zhong and Stephane Mallat created a wavelet analysis that is particularly responsive to edges and used it to analyze a photograph at three levels of sensitivity. The lowest sensitivity analysis (upper right) was then used to reconstruct the image (upper left).*

Mallat and Zhong have also refined the method to be especially sensitive to edges, which often spell the difference between sharp and blurry reproductions. The early results are encouraging: compression ratios of around 40 to 1 with reconstructed images that are nearly indistinguishable from the original. Their edge detection algorithm may eventually find applications in robotics and artificial intelligence.

Ronald Coifman and colleagues at Yale University and elsewhere are working on applications of wavelets to acoustic signal compression and fast numerical algorithms. They use "packets" of wavelets, chosen by a special optimizing algorithm from a library of possibilities, to reproduce digitized speech at a fraction of the cost in terms of information bits—an important consideration when you want to cram as many signals as possible into a telecommunication system. The technique also can be used on other types of signals, including digitized images. "The next generation of modems will use wavelet packets," confidently predicts Victor Wickerhauser, a collaborator with Coifman at Yale.

The most far-reaching application of wavelets could be in the development of fast numerical algorithms for scientific computation. The Fourier transform is currently used to simplify and thereby speed up computations in a certain class of problems in mathematical physics. Coifman and Gregory Beylkin, a mathematician at Schlumberger Doll Research in Ridgefield, Connecticut, have shown that wavelets can serve the same purpose in a wider class of problems. The new technique could allow researchers in many areas of physics and engineering to tackle more ambitious computer analyses and simulations.

While excitement runs high, the wavelet experts are quick to caution that wavelets are not the answer to everything. A good many applications may die quietly when it's found that other techniques work better. "As the saying goes, 'When you first pick up a hammer, everything looks like a nail,' " explained one participant at a conference on wavelets at the University of Lowell in Massachusetts. However, researchers say, it's clear that wavelets are here to stay, and the challenge now is to decide what the nails really are. ■ Barry A. Cipra