some wavering, for almost half a century has stood us in good stead. It was an enlightened policy. The question seldom asked by those who advocate more attention to "strategic research goals" rather than "curiosity driven" science is, *Which policy in fact more effectively produces the goal of strong science and technology?*

While, no doubt, we at universities need to pay more attention to training students in applied scientific directions, and industrial corporations need to return to policies with a longer view—paying more attention to applied research rather than only to immediately needed development—it would undermine the entire edifice of science and technology to turn off the wellspring of it all by denigrating the prime force motivating most scientists: curiosity. Although following our curiosity may appear frivolous to outsiders, very few fundamental discoveries in physics have been made by researchers pursuing a strategic plan with a goal that is deemed useful to society. (Saying that curiosity is the driving force is not the same as saying that we rely on serendipity, though that is also an element that should not be neglected.) To rely on the self-indulgence of individual curiosity in basic science to arrive at the socially desirable goal of useful applications is no more paradoxical than to rely on the destructive emotion of individual greed to drive the capitalist market economy. A wise policy does not try to inhibit either (as the failure of Communism showed for the case of economics) but instead steers both into socially beneficial directions. (Curiosity about what makes nature tick is surely more socially useful than curiosity about the foibles of our neighbors or leaders, which our society seems to encourage at present to a self-destructive degree.)

A policy that does not feed the flowering of natural human curiosity and channel it into creative fundamental scientific productivity will result in the withering of the whole scientific enterprise. For a number of years we have been seeing a very worrisome dwindling of the number of American students who are interested in science. Among the many causes of this phenomenon, surely one is that science, and particularly physics, has been presented to students in the media and in the schools as a discipline pursued mainly for the purpose of making better weapons and neater gadgets. It is a mistake with grave social consequences not to tap the natural curiosity among the young for science. We should, in fact, encourage this curiosity by emphasizing that it is the very heart of science.

To do research in basic physics we do not first find out what technological progress is needed, then devise a good strategy to get there and finally think about what new fundamental ideas are needed to implement it, although there may be a very small fraction of research physicists who are able to function fruitfully in that manner. There is no historical evidence that such an approach produces results comparable to letting those who are good at it do what their curiosity leads them to do. The "strategic planning" approach has already filtered into the culture of writing far too many grant proposals. A science policy that discourages "curiosity driven" research will become even more oppressive, and what used to be a flourishing enterprise full of originality and imagination will become a business of dry drones churning out routine products. We need to return to an American science policy that taps into the natural motivation of human beings and supports a basic science that is *curiosity driven.*

Roger G. Newton
Indiana University
Bloomington, Indiana

Might Neuronal Spikes Permit a Binary Brain?

A good mystery is worth exploring. So while I enjoyed John Hopfield's elegant exposition of the computational power of analog "neurons" (February 1994, page 40), I would like to encourage further exploration of neural biophysics by mentioning some problems in applying simple analog theories to the brain.

We know that neurons in mammalian cerebral cortex communicate by means of spikes (action potentials). The difficulty lies in the spikes' interpretation: Do they approximately form a slow analog average-rate code (Hopfield's main emphasis)? Or a fast binary pulse code, in which changing rates are only an epiphenomenon? Or something in between, like Hopfield's example of multiplexed visual processing?

To be fair, no paper has yet shown single spikes in neurons of visual cortex (the best-studied area) responding reliably to stimuli; only the slowly varying *probability* of firing a spike seems related to the flickering patterns shown the animal. Evidently rates do—and single spikes do not—code for such obvious properties of the stimulus as brightness, shape and location.

But most of such neurons' inputs come from *other neurons* in a highly interconnected network. Those neurons fire with significant and precisely timed synchrony;[1] we cannot measure how such synchrony in input affects a single cell. On the one hand, such synchrony creates problems for cells that average out presumably uncorrelated inputs;[2] in a pulse code, on the other hand, single-spike synchrony might be the *signal* (not correlated noise),[3] performing a subtle computation like figure–ground computation.

This is just one of the indirect indications that cortical neurons may compute with single spikes rather than with temporal averages of them. Let me highlight two others:

▷ *All neurons are not created equal.* The behavior of a canonical "neuron" (as shown in Hopfield's figure 4) bears little relation to that of neurons in visual cortex. The canonical neuron—typically a motor or sensory neuron—behaves like a "relaxation oscillator" (as Hopfield reminded me during my thesis exam): Its voltage ramps steadily upward until it reaches a "threshold," at which it fires and resets to a low voltage. But when a *cortical* neuron is visually stimulated, the voltage inside it has strong and apparently random fluctuations, without ramping, and returns to *near* the threshold (rather than far below it) right after a spike is fired, as shown in many published records.[4]

The fact that intricately branched cortical neurons bear little resemblance to the "compact" canonical ones may help explain this difference. The presence of positive-feedback properties in these electrically remote branches[5] makes them capable in principle of performing very fast temporal discriminations,[6] which may appear as strong fluctuations in the cell's voltage. This idea remains speculative, because the most numerous of the branches are so much thinner than a recording electrode that no one has yet directly recorded their fastest electrical behavior.

▷ *The source and function of firing irregularity are not understood.* While a canonical neuron fires fairly regularly at all but its slowest rates, cortical neurons seem to fire very irregularly—almost randomly—at *all* rates. It is very difficult to reconcile this irregular output with a neuron model that performs significant temporal averaging.[7] In fact, despite order-of-magnitude disagreements about many key parameters, no published realistic model has yet produced realistic, fast firing patterns. In general, any neuron model that *can* produce strong firing irregularity (without resorting to *ad hoc* random numbers) is also capable of discriminating at single-spike time scales.

This irregularity is usually viewed as noise that contaminates an average-rate code. It might equally well be viewed as high-bandwidth *information* in a binary pulse code, if cells have the temporal precision to make use of it. A simple estimate[8] indicates that such a pulse code can carry at least a hundredfold more information than a purely analog rate code using the same irregular spikes. Could Nature be making use of the extra bandwidth of irregular spiking, in accordance with Hopfield's dictum that "if some quirky detail of neurobiology is useful in an important but special computation, that detail can be selected for and improved by evolution"?

At the moment, our knowledge of single neurons in cortex is much like the knowledge one gets of a computer's disk drive by watching the flickering light on its front: We observe the time-averaged activity and try to infer what caused it. But in cortex we do not yet know the detailed mechanisms producing that activity or their temporal precision. Without that knowledge it may be premature to accept the simplification that cortical neurons use a slow average-rate code while ignoring their strong, unexplained high-frequency signals as "inconvenient details."

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William Softky
California Institute of Technology
Pasadena, California

Polymers' Progress as Efficient Diffractors

Anthony Garito, Rui Fang Shi and Marvin Wu (May 1994, page 51), discussing the photorefractive effect in organic polymers, state, "These devices have shown response times and diffraction grating efficiencies . . . close to those of inorganic devices." The paper cited in this context is the first demonstration of the photorefractive effect in a polymer, performed in 1991. The diffraction efficiencies observed in that work were very small (on the order of 10^{-5}) and should not be compared to the performance of inorganic photorefractive materials. Since then, rapid progress in the field of organic polymer photorefractive materials has led to diffraction efficiencies as high as 35%, which do rival or in some cases exceed the performance of inorganic photorefractive materials.[1] Work in progress shows diffraction efficiencies approaching 100%. These results make organic photorefractive materials an exciting new prospect for nonlinear optical devices.

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Klaus Meerholz
Sandalphon
University of Arizona
Tucson, Arizona

North Dakota Firing Was Faculty Fueled

As members of the physics department at North Dakota State University, we feel it necessary to respond to the letter (October, page 90) protesting the dismissal of Manuel de Llano, a tenured professor in our department. Since none of the authors of that letter contacted any of us, we presume that they based it on information provided them by de Llano. Whoever controls your information can easily persuade you.

The letter strongly implies that de Llano's dismissal is a punishment for his public criticism of the NDSU administration. However, the process actually began with a *unanimous* request from the physics department faculty for his dismissal. We presented that request to the administration over three months before the state legislative audit committee hearing at which de Llano gave the testimony that the letter's authors suggest was one of the causes of his dismissal. The major cause, however, is his conduct within the department, which has been consistently disruptive and has interfered not only with his own functioning as a faculty