Amazing algorithms

Biological computation

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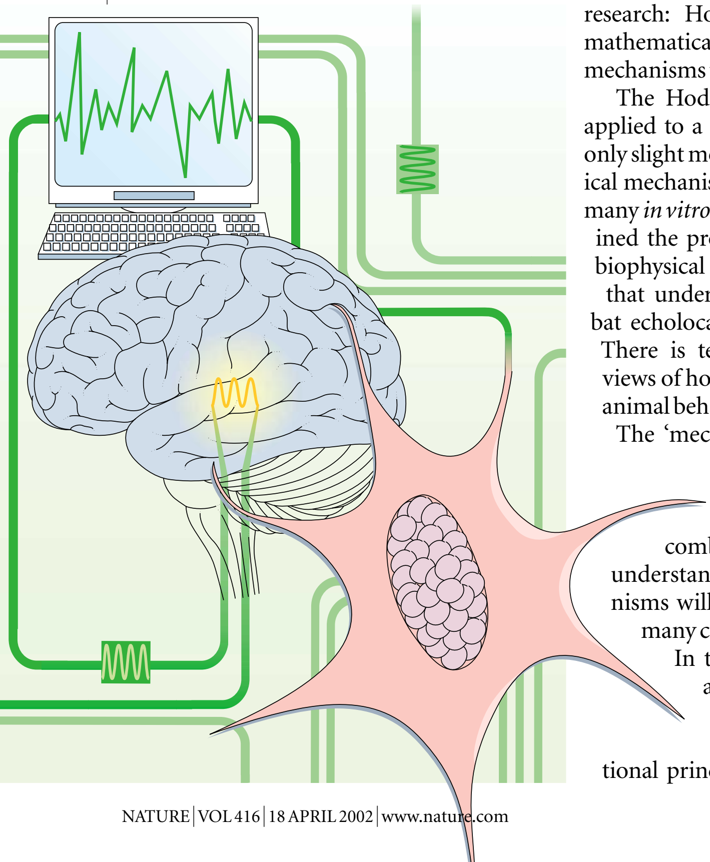
When can a physical system be said to perform a computation? In the broadest sense, every physical system performs a computation by realizing a solution to the dynamic equations that govern its physical behaviour. However, physical computing is more interesting in the narrower domain in which a set of physical variables represents the values of another set of mathematical ones. A physical variable might be a voltage within a digital computer, the height of a stack of poker chips, or a chemical concentration in a biological cell. These variables are then dynamically transformed by physical processes, in a way that represents algorithmic manipulation of the mathematical variables.

For physical computing systems that are also biological, it is often fruitful to view the organism as the 'user' of the computation. Natural selection has created many species in which individual survival rests on effective, often remarkable, computations performed by the organism's own physiology. For example, many bats locate insect prey by emitting ultrasonic pulses and detecting the echoes. By detecting small Doppler shifts in the frequency of the returning pulses, the bat's nervous system can discern acoustic 'texture' and so distinguish prey from inanimate objects. Such elegant calculations suggest some of the selection pressures that may have shaped the underlying computational mechanisms, and can help to guide future research.



Further understanding of such computations would come from a knowledge of how acoustic variables are represented in the bat brain, of the mathematical algorithms that describe the transformation of these variables, of the biophysical mechanisms by which the transformations are performed, and of the computational errors that these mechanisms introduce in the presence of noise. These issues also concern natural selection. Algorithms should facilitate competent, or even near-optimal, computation. Theoretical engineering tools can help us to appreciate constraints on biological designs and to evaluate computational performance in relation to physical limits. Furthermore, because computations are carried out using biological molecules and cells, the physical properties of this hardware must also have constrained natural selection.

To date, most research on biological computation has been concerned with representation. For instance, *in vivo* studies have shown how acoustic variables are represented in the electrical 'spikes' emitted by neurons. The electrical waveforms of these spikes all have a similar shape, so the acoustic variables are probably represented by the number of spikes and their arrival times. How the arrival times of spikes can represent physical variables is an area of more general debate. Nevertheless, there is widespread agreement over one of the greatest triumphs in this arena of research: Hodgkin and Huxley's classical mathematical description of the ion-channel mechanisms that underpin spike generation.

The Hodgkin–Huxley equation can be applied to a wide range of organisms, with only slight modifications. Are other biophysical mechanisms also widespread? Although many *in vitro* mechanistic studies have examined the properties of single neurons, the biophysical properties of neuronal circuits that underlie animal behaviours such as bat echolocation are less well understood. There is tension between two common views of how computations and associated animal behaviours should best be studied.

The 'mechanistic view' is that complex computations, such as those that control dancing, are implemented as hierarchical combinations of simpler ones, so an understanding of basic neural mechanisms will be a key that helps to unlock many complex phenomena.

In the 'algorithmic view', complex algorithms cannot be deduced from simple mechanisms as there are emergent computational principles that cannot be found by combining biophysical components. By analogy, the mathematics involved in rendering three-dimensional graphics on a computer do not follow from the workings of transistors. Hence, we should study the representations and algorithms used by systems that exhibit rich computational behaviour. One might try to deduce the algorithms used by the brain to recognize objects in a visual scene by manipulation of visual stimuli and analysis of neuronal spike patterns.

There is merit in both views, and no doubt a variety of research strategies will be needed to understand the range of biological computations. Yet it is interesting to examine the history of other areas of biological research, in which debates over the relevance of simple models to complex phenomena are more mature. What has been remarkable, and largely unanticipated, is the success of mechanistic discoveries, often concerning molecular genetics, in unravelling intricate phenomena and unifying seemingly distant research areas. Examples include the importance of yeast genetic studies for human disease and of fruitfly embryonic studies for human development.

A shared evolutionary history has often given rise to similar molecular and genetic mechanisms across a wide range of organisms, allowing us to study experimentally amenable systems and to apply the findings to other organisms. However, the physical properties that underpin the algorithms used in the brain are probably established through a complex mixture of genetic and environmental influences, so the degree to which common mechanisms will prevail remains to be seen. ■

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FURTHER READING

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