



## PERSPECTIVES: COGNITION

# Out of the Minds of Babies

Steven Pinker

**I**t is a cliché of neuroscience that the brain works differently from a digital computer. But the report by Marcus *et al.* in this issue on page 77 (1) demonstrating “rule learning by seven-month-old infants” suggests that one of the mechanisms that makes computers intelligent—manipulating symbols according to rules—may be a basic mechanism of the human brain as well.

Hundreds of years before anyone knew anything about brains or computers, two very different conceptions arose of how the mind works:

“When a man reasons, he does nothing else but conceive a sum total from addition of parcels, or conceive a remainder from subtraction of one sum from another; which, if it be done by words, is conceiving of the consequence of the names of all the parts to the name of the whole, or from the names of the whole and one part to the name of the other part. ... For REASON is nothing but *reckoning*.”

In this passage from *Leviathan*, written in 1651 (3), Thomas Hobbes uses “reckoning” in the original sense of “calculating” or “computing.” For example, if the definition of “man” is “rational animal,” and we are told that something is “rational” and an “animal” (names of parts), we can deduce it is a “man” (name of whole). If these symbols are represented as patterns of activity in the brain, and if some patterns trigger other patterns because of the way the brain is organized, then we have a theory of intelligence. That theory became the basis of the rationalist philosophy of Descartes and Leibniz, and much later, information-processing models in cognitive psychology, Noam Chomsky’s theory of generative grammar, and programs for language and reasoning in artificial intelligence.

But there is an alternative:

“There appear to be only three principles of connection among ideas, namely, *resemblance*, *contiguity* in

time or place, and *cause or effect*. Experience teaches us that a number of uniform effects result from certain objects. When a new object, endowed with similar sensible qualities, is produced, we expect similar powers and forces and look for a like effect. From a body of like color and consistence with bread we expect like nourishment and support.”



In this passage from his 1748 *Enquiry Concerning Human Understanding*, David Hume summarizes the theory of *associationism*. The mind connects things that are experienced together or that look alike, and generalizes to new objects according to their resemblance to known ones. Replace Hume’s “ideas” or “sensible qualities” with “stimuli” and “responses,” and you get the behaviorism of Ivan Pavlov, John Watson, and B. F. Skinner. Replace the ideas with “neurons” and the associations with “connections,” and you get the neural network models of D. O. Hebb and the school of cognitive science called connectionism.

The theories would not have survived for centuries if they did not account for important phenomena. Associationism captures the tendency of animals to pick up statistical patterns among events and generalize them to similar events. Examples range from the gradient of bar-pressing rates in rats when the surrounding stimuli vary from training conditions to the widely reported demonstration in these pages last year that eight-month-old infants pick up the probabilities of transition between syllables in streams of artificial speech (3).

Moreover, it’s easy to see how the laws of association might be implemented in neural hardware. If, as many neuroscientists believe, neurons that fire together wire together, we have an implementation of Hume’s principle of contiguity in time. If neurons

represent simple properties, and sets of active neurons represent concepts, then concepts that are similar will literally overlap in neural real estate, and anything associated with one concept will automatically be associated with similar concepts. The connectionists Geoffery Hinton, David Rumelhart, and James McClelland, echoing Hume’s remark about resemblance, wrote, “If ... you learn that chimpanzees like onions you will probably raise your estimate of the probability that gorillas like onions. In a network that uses distributed representations, this kind of generalization is automatic” (4).

The theory of symbol processing seems better suited to explaining the brain’s ability to handle complex ideas and the aspects of language that communicate them. People are

not slaves to similarity. We can be told that a whale is not a fish and that Tina Turner is a grandmother, overriding our statistical experience of what fish and grandmothers tend to look like. This suggests an ability to summarize an entire category by a mental variable or symbol, whose meaning comes from the rules it enters into: “a mammal is an animal that suckles,” “a grandmother is the mother of a parent.” These rules support generalizations that work more like deductions than similarity gradients. For example, we can infer that whales have livers or that Ms. Turner has had at least one baby (5).

Language is the quintessential symbol-manipulating system. When we learn that the grammatical object comes after the verb from simple sentences like “Tex hugged *the dog*,” we can generalize that regularity to grammatical objects that are very different in sound (“I like *Joe Bfispk*”), in meaning (“Kant defined *the categorical imperative*”), or in length (“Sheila met a *tall blonde man with one brown shoe*”). The abstractness and open-ended expressive power of human language comes from a system of recursive rules manipulating variables like “noun phrase” and “object” (6).

Although many cognitive scientists believe that the human mind is a hybrid system that uses both associations and rules (5), others want to retain associative networks as the fundamental stuff of cognition (4). They suggest that humans are not naturally good at the kind of reasoning subserved by rules. Rule use emerges late in life as a result of formal schooling and socially articulated rules, or as a result of extensive training that makes an associative network approximate rule-like behavior.

Marcus *et al.* (1) have now shown that infants as young as seven months can abstract simple rules from language-like sounds, suggesting that rule formation is

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not a late add-on but there from the start. Children of that age are just beginning to segment words from ambient speech, although they are several months away from understanding or producing them (6). Marcus *et al.* used a common method in the study of infant cognition: present a stimulus repeatedly until the infants are bored, then present them either with stimuli of the same kind or of a different kind. "Same kind" and "different kind" are in the mind of the beholder, so if infants attend longer to the different kind, they must be telling them apart.

In these experiments, infants were habituated with "sentences" that follow one sequence, such as "ga ti ga" and "li na li" (an ABA pattern), and then were presented with sentences that contained different words and either the same sequence, such as "wo fe wo" (ABA), or a different sequence, such as "wo fe fe" (ABB). The babies listened longer to the "different" sequence, showing that they must have

discriminated ABA from ABB; everything else about the test sentences, such as the actual syllables and their transition probabilities, was the same. Various controls ensured that the children did not simply like the sound of some sequences more than others, or memorize smaller chunks like BA. Marcus has also demonstrated that a kind of associative network frequently touted as a ruleless model of language learning, J. Elman's Simple Recurrent Network, does not discriminate the patterns in the way these infants do.

Marcus *et al.* (1) are careful not to claim that infants lack an ability to form associations, that rule learning is uniquely human, or that the rule-learning mechanism at work in this experiment is the same one that babies use to acquire language later. But their demonstration suggests that the ability to recognize abstract patterns of stimuli that cut across their sensory content is a basic ability of the human mind. How it is carried out in

the brain is still largely a mystery. Research in the neurobiology of learning and in neural network modeling (perhaps searching where the light is best) has tended to focus on simple associative learning mechanisms whose functions would have been recognizable to associationist philosophers writing centuries ago. Marcus *et al.*'s experiment is a reminder that humans also think in abstractions, rules, and variables, and is a challenge to figure out how we do so.

## References and Notes

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4. G. E. Hinton, J. L. McClelland, D. E. Rumelhart, in *Parallel Distributed Processing*, D. E. Rumelhart and J. L. McClelland, Eds. (MIT Press, Cambridge, MA, 1986).
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## PERSPECTIVES: SURFACE SCIENCE

## Driven Liquids

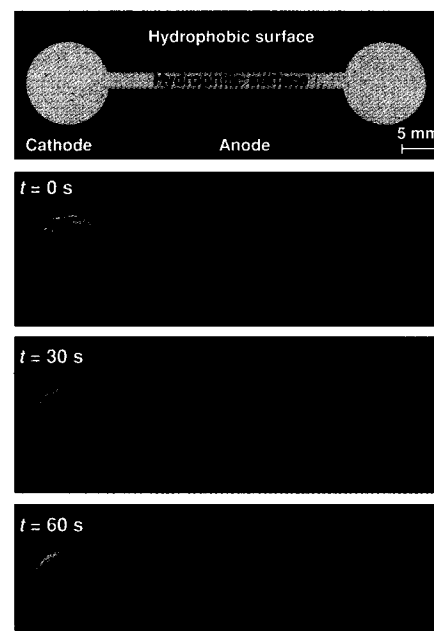
Michael Grunze

It has long been known that a continuous liquid film can spontaneously form into droplets that move freely over surfaces without application of an obvious external force. For example, wine connoisseurs are familiar with the "tears of wine" first explained by James Thomson in 1855 (1). The formation of wine drops from a continuous liquid film spreading over the wineglass surface is driven by the change in surface tension caused by the evaporation of alcohol. Variations in surface tension and the resulting changes in wetting behavior of the liquid by composition or temperature gradients were studied and explained over 100 years ago and are associated with the name of the Italian physicist Carlo Marangoni (2). Two reports in this issue, one by Gau *et al.* (3) on page 46 and the other by Gallardo *et al.* (4) on page 57, bring us up to date on recent studies of liquids moving on surfaces.

Spreading of a fluid or formation of drops from a continuous film is also controlled by the chemical composition of the substrate surface. Young's equation (5) defines the equilibrium contact angles through the interfacial tensions at the solid-liquid, solid-gas, and gas-liquid interface. The contact angle between liquids and solids can be

used to classify a substrate with respect to its wetting and adhesion properties for technical applications (6), but it also indicates whether a surface will be resistant to the adsorption of macromolecules and particles of biological origin (7). A spatial inhomogeneity in surface tension on a substrate to control adhesion and adsorption can be created by several approaches, such as by adsorption of hydrophobic molecules on a hydrophilic support (8) or by mixed hydrophobic-hydrophilic self-assembled monolayers (9). Nonequilibrium contact angles generated on opposite sides of a drop supported on a solid create a directional force and can even lead to the "uphill" movement of a droplet, as demonstrated by Chaudhury and Whitesides (8). Besides the obvious importance of surface tension in understanding interface phenomena, the practical control of wettability is elemental in the design and operation of microfluidic devices for microchemical analysis of complex fluids, flow cytometry, or rapid DNA screening. Any improvements in nonmechanical means to pump and position fluids are expected to have a direct impact on these emerging technologies.

The two reports in this issue describe how fluids and particles suspended in a liquid can be moved by spatially controlled changes in contact angles. Both reports explore the possibilities of controlling wetting and dewetting (and hence flow) by a structural control of the liquid-



**Patterned pump.** Time-elased photographs showing the pumping of green dye in a channel of liquid confined by a pattern of hydrophobic and hydrophilic self-assembled monolayers on a planar gold electrode. The gradient in surface pressure driving the flow is maintained by the generation and consumption of redox active surfactants at the cathode and anode surfaces, respectively.

solid contact line, either by adjusting the volume of the liquid confined to a hydrophilic contact area or by manipulating interface chemistry by adsorption and desorption of surface active molecules.

Gau and co-workers (3) discovered a new general instability phenomenon for a