A Radical Computer Learns to Think in Reverse

By George Johnson

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When people hear the words ''computer scientist,'' they might imagine a white-coated figure carefully arranging chips into circuitry. Or they might picture a bleary-eyed programmer trying to exterminate a bug from glowing lines of code on a video screen. But at the upper reaches of the craft, computer science can be as ethereal and abstract as theoretical physics, driven by thought experiments as bold as those of Einstein, who imagined what it would be like to ride a light beam through the sky.

What is the most powerful computer the laws of physics would allow? When computer scientists entertain this question, they are not simply wondering how great a machine mere mortals might build someday. They are imagining an almost angelic device that meshes so perfectly with the very structure of nature that it works with the highest efficiency possible, an ideal the engineers can then strive to match.

In fact, the universe itself can be thought of as a giant computer, orchestrating the movements of the stars, the planets, even the subatomic particles. The goal then is to learn to compute the way nature does.

An important step toward this goal was recently taken at the Massachusetts Institute of Technology's Artificial Intelligence Laboratory, where scientists have developed a radically different kind of experimental computer chip called Flattop. In the device, named after a local pool hall, Flattop Johnny's, the problem to be solved is converted into a vanishingly tiny billiard game. Bits of information bounce around like billiard balls, carrying out calculations far more efficiently than in an ordinary computer.

''It would be a lie to say it's bug free,'' said Dr. Tom Knight, the leader of the project, which also included Dr. Norman Margolus and M.I.T. students Michael Frank, Carlin Vieri, M. Josephine Ammer and Nicole Love. ''But it's a convincing enough demonstration. It's a stake in the ground. It says, 'Here, look, you can do it.' ''

The most intriguing thing about billiard ball computers -- first envisioned in the 1970's -- is that they are, like the universe itself, reversible. If you observe the solar system, you can work backward from any point and determine where the planets were days, centuries or millennia ago. The information is conserved. The same is true of perfectly elastic billiard balls on a frictionless surface. At any moment, you can reverse the action, re-creating the starting position of the game.

But an ordinary computer is irreversible, grating against the natural grain of the universe. Once it churns out an answer, there is no way to go back and find out what the question was. Suppose you pick up a pocket calculator someone has left on a table and the display says ''4.'' Did someone punch in 2 + 2, 3 + 1, 438,988 - 438,984, or 239,465 X 0 + 4? There is no way to know. The information describing the history of the calculation has been discarded.

The data have not disappeared from the universe, which would violate a law requiring that information be conserved. According to the second law of thermodynamics, every one of those lost bits is shed as a minuscule puff of heat. The information is out there in the air somewhere but beyond any reasonable hope of retrieval.

In a modern digital computer, this shedding of information occurs at every step in the long, rapid chains of calculations. Seemingly useless, intermediate results are discarded to reset the memory registers, adding to the heat that must be removed from the machine to keep the parts from malfunctioning.

Other sources of heat -- like that caused by the drag of electrical resistance on electrons moving through wires -- can be reduced indefinitely as technology improves. (In superconducting components, electricity moves unimpeded.) Or one can reduce resistance simply by running a machine more slowly. But in the early 1960's, Dr. Rolf Landauer of the I.B.M. Thomas J. Watson Research Center in Yorktown Heights, N.Y., proved that no matter how close engineers come to eliminating these other sources of waste, a minimal, irreducible amount of heat must inevitably be shed whenever a computer clears its memory by erasing a one or a zero. Dr. Landauer, who died in April, showed that this loss per bit, the ''thermodynamic cost of forgetting,'' is required by the laws of physics.

It was not until 1973 that Dr. Landauer's colleague, Dr. Charles Bennett, found a way around this problem. If the unwanted bits were never discarded, then this final source of waste would disappear. A specially designed computer could grind through a chain of calculations, saving every intermediary result in its memory. There would be no heat-wasting erasures.

Unless such a machine had an infinitely large memory, however, it would eventually become clogged with this extraneous data. To continue, the computer would have to be reset. That is where reversibility comes in. The computer, having saved everything, would have a complete record of its history, how it got from the beginning to the end of the calculation. So, one could simply run it backward, rewinding the machine to the beginning of the problem, without erasing a single bit.

Around the same time as Dr. Bennett's insight, an M.I.T. scientist, Edward Fredkin, realized a particularly elegant way to think about reversible computation -- as a cybernetic billiard game. The essence of any digital computer is its ability to convert a problem into a sequence of ones and zeroes, shuffling them to produce the answer. In the imaginary Fredkin machine, the green felt of the billiard table is scored off into a grid. At each intersection, the presence or absence of a ball represents a one or a zero. A problem to be solved is converted into a pattern of balls, which then ricochet off one another and bounce against reflecting ''mirrors'' like those in a pinball machine. The final configuration represents the answer.

If the balls were perfectly elastic and the table surface friction-free, then the billiard ball computer would operate with no loss of energy whatsoever. That is impossible, of course. But the point was that, through clever engineering, there was no limit to how closely one could approach this ideal. Because the system was reversible, the mandatory energy loss from erasing bits would not be a problem.

Efficient as such a system would be, there would still be drawbacks. In a complex calculation, the extra memory needed to save all the intermediary ''garbage bits'' can grow wildly. As a compromise, Dr. Bennett devised a memory-saving method in which a computer would carry out a few steps of the calculation, copy the result and rewind. Then, starting with the copied result, it would take a few more steps. He likened the method to crossing a river using just a few stepping stones: one must backtrack to pick up the stones left behind, placing them in the path ahead. While the procedure would consume less memory, it would require more computational steps, slowing down the calculation. To computer scientists, this was a classic tradeoff: pay the computational cost with either memory space or processing time.

Over the years, the idea of reversible computation was further developed by other researchers, including Dr. Margolus and Dr. Tommaso Toffoli at M.I.T. But even with the refinements, reversible computers remained academic. How would you actually design a billiard table that computed? The problem was to map the metaphor of ricocheting balls onto the fluctuating voltages inside a silicon chip.

Small strides have been made in recent years with so-called adiabatic circuits, which cleverly avoid some of the costly erasures. (In thermodynamics, ''adiabatic'' refers to reactions that happen without the loss or gain of heat.) If a computer needs to clear a register that says ''1,'' for example, it might simply subtract the digit instead of erasing it and expending the heat.

''Reversibility felt like an austerely beautiful thing,'' Dr. Bennett said. ''It seemed like almost a math game that had its own elegance. Then people started building real computer circuits.''

It was not until the recent development of Flattop that a fully reversible chip existed. The device, only about as complex (and not as powerful) as the 8080 chips that drove the first PC's, is purely experimental, an ''existence proof'' that such things can be made. But the scientists have plenty of time to tinker with improvements. Today's inefficient computers cast off far more heat than what is lost from the thermodynamic cost of forgetting. Reducing this waste will occupy engineers for at least another decade.

''For now the dumb way of doing this -- dumping the energy onto the floor -- is still probably the best,'' Dr. Knight said. ''I tend to look not at what the problems are today but what the problems are going to be.''

As computers get smaller and faster, engineers will eventually have to confront the limit discovered by Dr. Landauer. For many scientists though, the larger motivation remains philosophical: bridging the divide between physics and computer science, between the natural and the artificial.

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