Ripples and Puddles

by Hans Moravec

Computers were invented recently to mechanize tedious manual informational procedures. Such procedures were themselves invented only during the last ten millennia, as agricultural civilizations outgrew village-scale social instincts. The instincts arose in our hominid ancestors during several million years of life in the wild, and were themselves built on perceptual and motor mechanisms that had evolved in a vertebrate lineage spanning hundreds of millions of years.

Bookkeeping and its elaborations exploit ancestral faculties for manipulating objects and following instructions. We recognize written symbols in the way our ancestors identified berries and mushrooms, operate pencils like they wielded hunting sticks, and learn to multiply and integrate by parts as they acquired village procedures for cooking and tentmaking.

Paperwork uses evolved skills, but in an unnaturally narrow and unforgiving way. Where our ancestors worked in complex visual, tactile and social settings, alert to subtle opportunities or threats, a clerk manipulates a handful of simple symbols on a featureless field. And while a dropped berry is of little consequence to a gatherer, a missed digit can invalidate a whole calculation.

The peripheral alertness by which our ancestors survived is a distraction to a clerk. Attention to the texture of the paper, the smell of the ink, the shape of the symbols, the feel of the chair, the noise down the hall, digestive rumblings, family worries and so on can derail a procedure. Clerking is hard work more because of the preponderance of human mentation it must suppress than the tiny bit it uses effectively.

Ripples

Like little ripples on the surface of a deep, turbulent pool, calculation and other kinds of procedural thought are possible only when the turbulence is quelled. Humans achieve quiescence imperfectly by intense concentration. Much easier to discard the pesky abyss altogether: ripples are safer in a shallow pan. Numbers are better manipulated as calculus stones or abacus beads than in human memory. A few cogwheels in Blaise Pascal's seventeenth century calculator perform the entire procedure of addition better and faster than a human mind. Charles Babbage's nineteenth century Analytical Engine would have outcalculated dozens of human computers and eliminated their errors. Such devices are effective because they encode the bits of surface information used in calculation, and not the millions of distracting processes churning the depths of the human brain.

The deep processes sometimes help. We guess quotient digits in long divisions with a sense of proportion our ancestors perhaps used to divide food among mouths. Mechanical calculators, unable to guess, plod through repeated subtractions. More momentously, geometric proofs are guided (and motivated!) by

our deep ability to see points, lines, shapes and their symmetries, similarities and congruences. And true creative work is shaped more by upwellings from the deep than by overt procedure.

Calculators gave way to Alan Turing's universal computers, and grew to thousands, then millions and now approaching billions of storage locations and procedure steps per second. In doing so they transcended their paperwork origins and acquired their own murky depths. For instance, without great care, one computer process can spoil another, like a clerk derailed by stray thoughts. On the plus side, superhumanly huge searches, table lookups and the like can sometimes function like human deep processes. In 1956 Allen Newell, Herbert Simon and John Shaw's Logic Theorist's massive searches found proofs like a novice human logician. Herbert Gelernter's 1963 Geometry Theorem Prover used large searches and Cartesian coordinate arithmetic to equal a fair human geometer's visual intuitions. Expert systems' large compilations of inference rules and combinatorial searches match human experience in narrow fields. Deep Blue's giga-scale search, opening and endgame books and carefully-tuned board evaluations defeated the top human chess player in 1997.

Despite such isolated soundings, computers remain shallow bowls. No reasoning program even approaches the sensory and mental depths habitually manifest at the surface of human thought. Doug Lenat's common-sense encoding Cyc, begun in the 1980s and about the most ambitious, would capture broad verbal knowledge yet still lack visual, auditory, tactile or abstract understanding.

Many critics contrast computers' superiority in rote work with their deficits of comprehension to conclude that computers are prodigiously powerful, but universal computation lacks some human mental principle (of physical, situational or supernatural kind, per taste). Some Artificial Intelligence practitioners profess a related view: computer hardware is sufficient, but difficult unsolved conceptual problems keep us from programming true intelligence.

The latter premise can seem plausible for reasoning, but it is preposterous for sensing. The sounds and images processed by human ears and eyes represent megabytes per second of raw data, itself enough to overwhelm computers past and present. Text, speech and vision programs derive meaning from snippets of such data by weighing and reweighing thousands or millions of hypotheses in its light. At least some of the human brain works similarly. Roughly ten times per second at each of the retina's million effective pixels, dozens of neurons weigh the hypothesis that a static or moving boundary is visible then and there. The visual cortex's ten billion neurons elaborate those results, each moment appraising possible orientations and colors at all the image locations. Efficient computer vision programs require over 100 calculations each to make similar assessments. Most of the brain remains mysterious, but all its neurons seem to work about diligently as those in the visual system. Elsewhere I've detailed the retinal calculation to conclude that it would take on the order of 100 trillion calculations per second of computing -- about a million present-day PCs -- to match the brain's functionality.

That number presumes an emulation of the brain at the scale of image edge detectors: a few hundred thousand calculations per second doing the job of a few hundred neurons. The computational requirements would increase (maybe a lot) if

we demanded emulation at a finer grain, say explicit representation of each neuron. By insisting on a fine grain we constrain the solution space and outlaw global optimizations. On the plus side, by constraining the space we simplify the search! No need to find efficient algorithms for edge detection and other hundred-neuron-scale nervous system functions. If we had good models for neurons and a wiring diagram of a brain, we could emulate it as a straightforward network simulation. The problems of Artificial Intelligence would be reduced to merely instrumentally- and computationally-daunting work.

Alternatively we could try to implement the brain's function at much larger than edge-detector grain. The solution space expands and with it the difficulty of finding globally efficient algorithms, but their computational requirements decrease. Perhaps programs implementing humanlike intelligence in a highly abstract way are possible on existing computers, as AI traditionalists imagine. Perhaps, as they also imagine, devising such programs requires lifetimes of work by world-class geniuses.

But it may not be so easy. The most efficient programs exhibiting human intelligence might exceed the power and memory of present PCs manyfold, and devising them might be superhumanly difficult. We don't know: the pool is extremely murky below the ripples, and has not been fathomed.

(Very powerful optimizing compilers could conceivably blur grain sizes by transforming neuron-level brain simulation programs into super-efficient code that preserves input-output behavior but resembles traditional AI programs. Such compilers would surely need superhuman mental power (they would be singlehandedly solving the AI problem, after all), but perhaps of a relatively simple, idiot-savant, kind.)

Puddles

Each approach to matching human performance is interesting intellectually and has immediate pragmatic benefits. Reasoning programs outperform humans at important tasks, and many already earn their keep. Neural modeling is of great biological interest, and may have medical uses. Efficient perception programs are somewhat interesting to biologists, and useful in automating factory processes and data entry.

But by which will succeed first? The answer is surely a combination of all those techniques and others, but I believe the perception route, currently an underdog, will play the largest role.

Reasoning-type programs are superb for consciously explicable tasks, but become unwieldy when applied to deeper processes. In part this is simply because the tasks deep in the subconscious murk elude observation. But also, the deeper processes are quantitatively different. A few bits of problem data ripple across the conscious surface, but billions of noisy neural signals seethe below. Reasoning programs will become more powerful and useful in coming decades, but I think comprehensive verbal common sense, let alone sensory understanding, will continue to elude them.

Entire animal nervous systems, hormonal signals and interconnection plasticity included, may become simulable in coming decades, as imaging instrumentation and computational resources rapidly improve. Such simulations will greatly accelerate neurobiological understanding, but I think not rapidly enough to win the race. Valentino Braitenberg, who analyses small nervous systems and has designed artificial ones, notes the rule of "downhill synthesis and uphill analysis" -- it is usually easier to compose a circuit with certain behaviors than to describe how an existing circuit manages to achieve them. Meager understanding and thus means to modify designs, the cost of simulating at a very fine grain and ethical hurdles as simulations approach human-scale will slow the applications of neural simulations. But robot toys following in Aibo's pawprints should be interesting!

No human-scale intelligence (as far as we know) ever developed from conscious reasoning down, nor from simulations of neural processes, and we really don't know how hard doing either may be. But the third approach is familiar ground.

Multicellular animals with cells specialized for signaling emerged in the Cambrian explosion a half-billion years ago. In a game of evolutionary one-upmanship (there's always room at the top!) maximum nervous system masses doubled about every 15 million years, from fractional micrograms then to several kilograms now (with several abrupt retreats, often followed by accelerated redevelopment, when catastrophic events eliminated the largest animals).

Our gadgets, too, are growing exponentially more complex, but 10 million times as fast: human foresight and culture enables bigger, quicker steps than blind Darwinian evolution. The power of new personal computers has doubled annually since the mid 1990s. The "edge operator" estimate makes today's PCs comparable only to milligram nervous systems, as of insects or the smallest vertebrates (eg. the 1 cm dwarf goby fish), but humanlike power is just thirty years away. A sufficiently vigorous development with well-chosen selection criteria should be able to incrementally mold that growing power in stages analogous to those of vertebrate mental evolution. I believe a certain kind of robot industry will do this very naturally. No great intellectual leaps should be required: when insight fails, Darwinian trial and error will suffice -- each ancestor along the lineage from tiny first vertebrates to ourselves became such by being a survivor in its time, and similarly ongoing commercial viability will select intermediate robot minds.

Building intelligent machines by this route is like slowly flooding puddles to make pools. Existing robot control and perception programs seem muddy puddles because they compete in areas of deepest human and animal expertise. Reasoning programs, though equally shallow, comparatively shine by efficiently performing tasks humans do awkwardly and animals not at all. But if we keep pouring, the puddles will surely become deeper. That may not be true for reasoning programs: can pools be filled surface down?

Many of our sensory, spatial and intellectual abilities evolved to deal with a mobile lifestyle: an animal on the move confronts a relentless stream of novel opportunities and dangers. Other skills arose to meet the challenges of cooperation and competition in social groups. Elsewhere I've outlined a plan for commercial robot development that provides similar challenges. It will require a large, vigorous industry to search for analogous solutions. Today the industry is tiny. Advanced

robots have insectlike mentalities, besting human labor only rarely, in exceptionally repetitive or dangerous work. But I expect a mass market to emerge this decade. The first widely usable products will be guidance systems for industrial transport and cleaning machines that three-dimensionally map and competently navigate unfamiliar spaces, and can be quickly taught new routes by ordinary workers. I have been developing programs that do this. They need about a billion calculations per second, like the brainpower of a guppy! Industrial machines will be followed by mass-marketed utility robots for homes. The first may be a small, very autonomous robot vacuum cleaner that maps a residence, plans its own routes and schedules, keeps itself charged and empties its dustbag when necessary into a larger container. Larger machines with manipulator arms and the ability to perform several different tasks may follow, culminating eventually in human-scale "universal" robots that can run application programs for most simple chores. Their 10-billion-calculation-per-second lizard-scale minds would execute application programs with reptilian inflexibility.

This path to machine intelligence, incremental, reactive, opportunistic and market-driven, does not require a long-range map, but has one in our own evolution. In the decades following the first universal robots, I expect a second generation with mammallike brainpower and cognitive ability. They will have a conditioned learning mechanism, and steer among alternative paths in their application programs on the basis of past experience, gradually adapting to their special circumstances. A third generation will think like small primates and maintain physical, cultural and psychological models of their world to mentally rehearse and optimize tasks before physically performing them. A fourth, humanlike, generation will abstract and reason from the world model. I expect the reasoning systems will be adopted from the traditional AI approach maligned earlier in this essay. The puddles will have reached the ripples.

Robotics should become the largest industry on the planet early in this evolution, eclipsing the information industry. The latter achieved its exalted status by automating marginal tasks we used to call paperwork. Robotics will automate everything else!

[Hans Moravec is a Principal Research Scientist in the Robotics Institute of Carnegie Mellon University. He has been thinking about machines thinking since he was a child in the 1950s, building his first robot, a construct of tin cans, batteries, lights and a motor, at age ten. In high school he won two science fair prizes for a light-following electronic turtle and a tape-controlled robot hand. As an undergraduate he designed a computer to control fancier robots, and experimented with learning and automatic programming on commercial machines. During his master's work he built a small robot with whiskers and photoelectric eyes controlled by a minicomputer, and wrote a thesis on a computer language for artificial intelligence. He received a PhD from Stanford University in 1980 for a TV-equipped robot, remote controlled by a large computer, that negotiated cluttered obstacle courses, taking about five hours. Since 1980 his Mobile Robot Lab at CMU has discovered more effective approaches for robot spatial representation, notably 3D occupancy grids, that, with newly available computer power, promise commercial free-ranging mobile robots within a decade. His books,

Mind Children: the future of robot and human intelligence, 1988, and *Robot: mere machine to transcendent mind*, 1998, consider the implications of evolving robot intelligence. He has published many papers and articles in robotics, computer graphics, multiprocessors, space travel and other speculative areas.]