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TODAY'S LEADING THINKERS ON THE UNTHINKABLE

Edited by John Brockman

With an Introduction by Steven Pinker
and an Afterword by Richard Dawkins

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When Will the Internet Become Aware of Itself?

Terrence Sejnowski

TERRENCE SEJNOWSKI *is a computational neuroscientist at the Howard Hughes Medical Institute. He is coauthor (with Steven R. Quartz) of* Liars, Lovers, and Heroes: What the New Brain Science Reveals About How We Become Who We Are.

I never thought I would become omniscient during my lifetime, but as Google continues to improve and online information continues to expand, I have achieved omniscience, for all practical purposes. The Internet has created a global marketplace for ideas and products, making it possible for individuals in the far corners of the world to automatically connect directly to one another. The Internet has achieved these capabilities by growing exponentially in total communications bandwidth. How does the communications power of the Internet compare with that of the cerebral cortex, the most interconnected part of our brains?

Cortical connections are expensive, because they take up volume and cost energy to send information, in the form of spikes along axons. About 44 percent of the cortical volume in humans is taken up with long-range connections, called the white matter. Interestingly, the thickness of gray matter, just a few millimeters, is nearly constant in mammals that range in brain volume over five orders of magnitude, and the volume of the white matter scales approximately as the 4/3 power of the volume of the gray matter. The larger the brain, the larger the fraction of resources devoted to communications compared to computation.

However, the global connectivity in the cerebral cortex is extremely sparse: The probability of any two cortical neurons having a direct connection is around 1 in 100 for neurons in a vertical column 1 mm in diameter but only 1 in 1,000,000 for more distant neurons. Thus, only a small fraction of the computation that occurs locally can be reported to other areas, through a small fraction of the cells that connect distant cortical areas.

Despite the sparseness of cortical connectivity, the potential bandwidth of all of the neurons in the human cortex is approximately 1 terabit per second, comparable to the total world backbone capacity of the Internet. However, this capacity is never achieved by the brain in practice, because only a fraction of cortical neurons have a high rate of firing at any given time. Recent work by the neurobiologist Simon Laughlin suggests that another physical constraint—energy—limits the brain's ability to harness its potential bandwidth.

The cerebral cortex also has a massive amount of memory. There are approximately 10^9 synapses between neurons under every square millimeter of cortex, or about 10^{11} synapses overall. Assuming around a byte of storage capacity at each synapse (including dynamic as well as static properties), this comes to a total of 10^{15} bits of storage. This is comparable to the amount of data on the entire Internet. Google can store this in terabyte disk arrays and has hundreds of thousands of computers simultaneously sifting through it.

Thus, the Internet and our ability to search it are within reach of the limits of the raw storage and communications capacity of the human brain, and should exceed it by 2015.

The biophysicist Leo van Hemmen and I recently asked twenty-three neuroscientists to think about what we don't yet know about the brain and propose a question so fundamental and difficult that it could take a century to solve—in the spirit of David Hilbert's twenty-three problems in mathematics. Christof Koch and Francis Crick speculated that the key to understanding consciousness was global communication: How do neurons in the diverse parts of the brain manage to coordinate despite the limited connectivity? Sometimes, the communication gets crossed, and V. S. Ramachandran and Edward Hubbard asked whether synesthetes—rare individuals who experience crossover in sensory perception, such as hearing colors, seeing sounds, and tasting tactile sensations—might give us clues to how the brain evolved.

There is growing evidence that the flow of information between parts of the cortex is regulated by the degree of synchrony of the spikes within populations of cells that represent perceptual states. Robert Desimone and his colleagues have examined the effects of attention on cortical neurons in awake, behaving monkeys and found the coherence between the spikes of single neurons in the visual cortex and local field potentials in the gamma band, 30–80 Hz, increased when the covert attention of a monkey was directed toward a stimulus in the receptive field of the neuron. The coherence also selectively increased when a monkey searched for a target with a cued color or shape amid a large number of distracters. The increase in coherence means that neurons representing the stimuli with the cued feature would have greater impact on target neurons, making them more salient.

The link between attention and spike-field coherence raises a number of interesting questions. How does top-down input from the prefrontal cortex regulate the coherence of neurons in other parts of the cortex through feedback connections? How is the rapidity of the shifts in coherence achieved? Experiments on neurons in cortical slices suggest that inhibitory interneurons are connected to each other in networks and are responsible for gamma oscillations. Researchers in my laboratory have used computational models to show that excitatory inputs can rapidly synchronize a subset of the inhibitory neurons that are in competition with other inhibitory networks. Inhibitory neurons, long thought to merely block activity, are highly effective in synchronizing neurons in a local column already firing in response to a stimulus.

The oscillatory activity that is thought to synchronize neurons in different parts of the cortex occurs in brief bursts, typically lasting for only a few hundred milliseconds. Thus, it is possible that there is a packet structure for long distance communication in the cortex, similar to the packets that are used to communicate on the Internet, though with quite different protocols. The first electrical signals recorded from the brain in 1875 by Richard Caton were oscillatory signals that changed in amplitude and frequency with the state of alertness. The function of these oscillations remains a mystery, but it would be remarkable if it were to be discovered that these signals held the secrets to the brain's global communications network.

Since its inception in 1969, the Internet has been scaled up to a size unimagined even by its inventors, in contrast to most engineered systems, which fall apart when they are pushed beyond their design limits. In part, the Internet achieves this scalability because it can regulate itself, deciding on the best routes to send packets depending on traffic conditions. Like the brain, the Internet has circadian rhythms that follow the sun as the planet rotates under it. The growth of the Internet over the last several decades more closely resembles biological evolution than engineering.

How would we know if the Internet were to become aware of itself? The problem is that we don't even know if some of our fellow creatures on this planet are self-aware. For all we know, the Internet is already aware of itself.

Democratizing Access to the Means of Invention

Neil Gershenfeld

NEIL GERSHENFELD is *a physicist and the director of the Center for Bits and Atoms at MIT. He is the author of* Fab: The Coming Revolution on Your Desktop—From Personal Computers to Personal Fabrication.

The elite temples of research (of the kind I've happily spent my career in) may be becoming intellectual dinosaurs as a result of the digitization and personalization of fabrication.

Today, with about $20,000 in equipment, it's possible to make and measure things from microns and microseconds on up, and that boundary is quickly receding. When I came to MIT, that was hard to do. If it's no longer necessary to go to MIT for its facilities, then surely the intellectual community is its real resource? But my colleagues and I are always either traveling or overscheduled; the best way for us to see one another is to go somewhere else. Like many people, my closest collaborators are distributed around the world.

The ultimate consequence of the digitization of communications, then computation, and now fabrication is to democratize access to the means of invention. The third world can skip