Brain and Evolution

In 1972, Gerald Edelman (b. 1929) received the Nobel Prize in Physiology or Medicine for his discovery of *somatic selection* in the immune system of mammals. It was his answer to the question of how our bodies manage to produce so many different antibodies, each geared against a particular invader.

Previously, it had been thought that the blueprints of all antibodies were encoded somewhere and were activated during an infection. But the number of all possible infectious agents that our species has encountered in the past and may yet encounter in the future is so staggering that this assumption strained credulity. Moreover, different people produced very different antibodies in response to the same invader.

Gerald Edelman showed that the immune system works by the evolutionary principle. While any other cell in the body carries the same genes, certain immune cells are an exception to the rule. Their genetic composition allows variation. When a new infectious agent is encountered, the immune system's engine guns itself into a frenzy, busily trying different combinations of immune cells' genes, until a fit is made.

This architecture allows a quick response to *any* invader that may *ever* be encountered. In only a few days, evolution does what may have taken rational design decades to accomplish.

But Edelman didn't rest on his laurels. He proposed that the brain too works by the evolutionary principle. This was the birth of the Neural Darwinism paradigm in neuroscience.

Evolution manifests itself in the brain in several ways. Firstly, as far as its structure is encoded in the genes, the brain is a product of the evolution of the species—*natural selection.*

A neuron that has failed to make any connection commits suicide by a mechanics called *apoptosis*.

Secondly, in a growing organism, neurons compete to make connections between each other. Again we see how evolution is superior to rational design. Instead of pre-programming a specific rigid structure, neural evolution allows the competition to self-optimize the connectivity pattern. This *developmental selection* ensures that even identical twins or clones would never have identical brains. Yet the randomness is not allowed to run amok; the general, high-level structure of the brain is kept intact—a sort of combination of "free market" and control, honed to perfection over the eons of evolution.

Thirdly, in a functioning brain, neurons compete for a chance to fire; that is, to send signals to other neurons. There are two kinds of neurons in the brain: excitatory and inhibitory. When an excitatory neuron sends a signal to another, it encourages the target to fire in turn, whereas an inhibitory neuron tries to silence its target (whether or not either succeeds depends on the current conditions and a variety of thresholds).

If we only had excitatory neurons, they would have quickly synchronized, all neurons in the brain firing in perfect unison, as pendulums that stand on the same floor influence each other via mutual feedback to spontaneously synchronize their oscillations in a process called *entrainment.* Their clocks begin to tick together. But perfect unison is an extremely simple structure; it does not support complexity. Neuronal oversynchronization is, in fact, what happens during an epileptic fit (*grand mal*); predictably, the person is unconscious while it lasts.

Inhibitory neurons create complexity, by enabling competition. When an excitatory neuron fires to another, it wakes up its inhibitory allies, which try to silence other neurons that want to send similar signals. The winner takes all. Moreover, the winner is rewarded further: the firing neuron-to-neuron synapses get stronger, so that they are more likely to win in the future. Synapses get weaker if they don't fire for a while. This process is called *brain plasticity*—the brain keeps modifying itself to get smarter, better at reacting to new situations. This is how, for example, we can learn tasks to such a level of perfection that we can perform them on auto-pilot—learning new faps, getting rewired.

In the brain, massively parallel neuronal ensembles thus compete to deliver the best results, comparing their predictions with the feedback from external action, making corrections. The impression that our brain is "single-threaded" is an illusion, for we only perceive the results of massively parallel computations, like many teams that work on the same task. And if you think that our memory capacity is low just because we can juggle only a handful of objects in our mind at the same time, consider how much information is involved in just one object, taking into account all sensory inputs, not to mention interaction with the object, such that the number of forking paths—decisions made on the basis of the object's properties—can grow exponentially. As Daniel Dennett (b. 1942), one of the proponents of Neural Darwinism, put it in [10]:

> Throw a skeptic a dubious coin, and in a second or two of hefting, scratching, ringing, tasting, and just plain looking at how the sun glints on its surface, the skeptic will consume more bits of information than a Cray supercomputer can organize in a year.

NEURONS ARE NATURAL OSCILLATORS OF ELECTRICAL potential across the cellular membrane. When they fire to each other, they can synchronize, producing what we call *brain oscillations,* or brainwaves.

The random variations, necessary to drive the *neuronal selection,* follow the pink noise distribution as $1/f$, the amplitude (strength) of oscillations being inversely proportional to

$1/f$ noise is called *pink* because, if the frequencies were those of visible light, the resulting color would be closer to the red part of the spectrum, intuitively expected to be pink. Although calculations show that the color is closer to golden tan, no one is about to rename pink noise.

their frequency. A noise following a more general $1/f^a$ distribution is called *fractal noise,* where the number a is its *fractal dimension.* When $a<1$, chaos is stronger than order; when $a>1$, order is stronger than chaos. But when $a=1$, this is the zone of the highest complexity, if complexity is measured by the number of states that the system can tell apart from each other. In other words, $a=1$ is when the butterfly effect is most strongly felt. Of course, the higher the number of states the system can distinguish between, the higher the amount of information the system can contain. Pink noise is the most informationally dense noise in the universe.

Once again, the evolutionary process has spontaneously established a perfect balance between order and chaos. On one hand, the oscillations in the brain *must* synchronize, for this is precisely how the inputs from disparate sources combine in order to produce a cognitive event. Yet on the other hand, oversynchronization brings epilepsy, a state of mind when large groups of neurons fire in unison—too simple a structure to sustain consciousness.

In a normal waking brain, synchronization must be transitory. The waking (or dreaming) brain is always in a phase change state, like a ball at the top of a hill in an unstable equilibrium, choosing which way to fall—the state of maximum complexity, driven by and driving constantly the butterfly effect.

I suggest that the idea that we do not need to know how the brain works in order to simulate its functionality, currently prevalent in the AI research community, is misguided. We would do better to learn from the brain.

Until we harness deterministic chaos, we will never create a true artificial intelligence. Let's call this the *neuromorphic principle.*

But how did the brain evolve? And why? Neurons are extremely hungry, energetically expensive cells, yet the brain kept growing in size, from one species to another. What is the evolutionary advantage of consciousness?

One of the fathers of modern neuroscience, Rodolfo Llinás (b. 1934) proposed that the brain evolved in actively, *purposely* moving organisms in order to predict results of movement. Plants don't move purposely, so they don't need—and therefore, don't have—a brain. Tellingly, sea squirts spend the first brief stage of their lives as actively moving larvae—animals, with tiny brains. But as soon as they find a good place to settle down, they turn into plants, digesting their own brains.

We tend to underestimate the complexity of our movement. If you take into account the number of muscle groups in just one hand, and the number of motor neurons activated every tenth of a second in various sequences, then the number of degrees of freedom in moving just that hand becomes so enormous that a CPU-based computer would need to have a truly astronomical CPU frequency to handle it, and at 100% CPU, besides. Yet our brain performs the task effortlessly, with only a small portion of its neurons, leaving a lot of processing power for other things—like thinking.

The computational power of the brain is staggering. It may not be adding numbers very fast, but as a movement and decision making processor it beats a computer anytime. Robots can be programmed to perform well, with repeatable precision in predictable environments. In contrast, the brain never repeats itself exactly, thanks to its evolution-driven architecture. But, for the same reason, it is capable of reacting reasonably fast in *any* situation in various environments that the members of the species may find themselves in over many millions of years.

Faps—fixed action patterns—and emotions are certain *necessary* "optimizations" of the brain's predictive engine. Consciousness is necessary to survive in an unpredictable world, taking over from the auto-pilot when something unexpected happens. Thus, neither emotions nor consciousness are limited to humans. Many animals must have them simply to be functional. I suspect that our first AI children will be more ruled by emotions than we are, because emotions come first, well before reason.

In order to predict, the brain builds an internal model of the world. In the course of action, the observed results are compared to the prediction, and the model is spontaneously modified, via plasticity, to predict better the next time around.

It is important to understand that this model is internally generated. Sensory input from the outside world modifies but doesn't fully define the model, which can function based on internal input (like it does in dreams or, say, in planning for the future), even in the absence of any sensory input from the outside. The brain is a virtual reality machine.

How, then, can we understand each other? Why aren't the internal models of different brains so different as to be mutually incomprehensible? Well, they are incomprehensible across different species. But within a species, the foundation of the model has the same evolutionary history. The model, after all, must adequately reflect the shared outside world for survival.

Via the action–feedback–action loop, the universals of the world are embedded, in the course of evolution, in the very structure of the brain. In [19], Llinás offers the metaphor of a gelatinous cube of electrically conductive material with electric contacts on its surface. The gelatin condenses into filaments if current passes often between the contacts but relaxes back to the amorphous state if no current flows for a while.

In this, you may already recognize the brain plasticity at work.

If the current is based on the sensory input from, for example, playing soccer, then eventually our cube of gelatin would develop a structure that, in a certain sense, *encodes* the rules of playing soccer, though it would be very different from the familiar game, with a ball, a team of players, and a referee.

Likewise, the brain encodes our experiences in a different format. It is meaningless to ask where exactly in the brain the images we see or our thoughts are to be found, for they are products of the entire process, encoded in our brain through *interaction* with the world—the action–feedback–action loop.

Though many degrees removed, our thinking is ultimately an internalization of our movement.