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Chapter 1

A Quick Trip through the Nervous System

My brain: it's my second favorite organ.

—WOODY ALLEN (*SLEEPER*, 1973)

The brain you are carrying around in your head is by far the most complicated structure known in the universe, and everything you are, have been, and will be arises from the activity of this three-pound collection of 100 billion neurons.

Although this book is about *neuroscience,* the study of the nervous system, it's mainly about the brain, where most of the nervous system action takes place. (The central nervous system consists of the brain, retina, and spinal cord.) If your brain functions well, you can live a long, happy, and productive life (barring some unfortunate circumstances, of course). If you have a brain disorder, you may struggle to overcome every detail of life, a battle that will take place within your brain. So read on for an introduction to the nervous system, how it works, what it does, and what can go wrong.

Understanding the Evolution of the Nervous System

The earth formed 4.5 billion years ago. Evolutionary biologists believe that single-celled *prokaryotic* life (cells without a cell nucleus) appeared on earth less than one billion years after that. What's remarkable about this date is that geophysicists believe this was the earliest point at which the planet had cooled enough to sustain life. In other words, life appeared almost the instant (in geological time) that it was possible.

For unknown reasons, it took more than another billion years for *eukaryotic* life (cells with nuclei) to appear and another billion years for multicellular life to evolve from eukaryotic cells. The processes that lead to multicellular life all took place in the earth's oceans. Finally, it took *another* billion years for humans to appear after plants and animals migrated to the land. Humans finally appeared less than a million years ago.

Specializing and communicating

REMEMBER

In multicellular organisms, the environment of cells on the interior is different from the environment of the cells on the exterior. These different environments required the cells in these multicellular life forms to develop a way to specialize and communicate. Understanding this specialization is one of the keys to understanding how the nervous system works.

Imagine a ball of a few dozen cells in a primitive ocean billions of years ago. The cells on the inside of the ball might be able to carry out some digestive or other function more efficiently, but because they aren't exposed to the seawater they don't have any way to get the nutrients they need from the seawater, and they don't have a way of ridding themselves of waste. To perform these tasks, they need the cooperation of the cells around them. Multicellular life allowed — in fact, mandated — that cells specialize and communicate. Eukaryotic cells specialized by regulating DNA expression differently for cells inside the ball of cells versus those on the outside. Meanwhile, some of the substances secreted by cells became signals to which other cells responded.

Moving hither, thither, and yon — in a coordinated way

Currents, tides, and waves in Earth's ancient oceans moved organisms around whether they wanted to be moved or not. But organisms developed several mechanisms for having some control over their location. For example, organisms specialized for photosynthesis developed buoyancy mechanisms to keep themselves in the upper layer of the ocean where the sunlight is. Some multicellular organisms evolved *flagella* for moving. But, in multicellular organisms, flagella must move in a coordinated way for efficient movement (picture a sculling team that has every member rowing at their own pace). Without some form of communication to synchronize their activity, the boat — the organism in this case — would go nowhere fast. The result? Networks of specialized cells with *gap junctions* between them evolved. These networks allowed rapid electrical signaling around ringlike neural nets that became specialized for synchronizing flagella on the outside of the organism.

Evolving into complex animals

Balls of cells with nervous systems that had become capable of moving in a coordinated fashion in the oceans evolved into complex animals with sensory and other specialized neurons.

About half a billion years ago, invertebrates such as insects crawled onto the land to feast on the plants that had been growing there for millions of years. Later, some vertebrate lung fish ventured onto the land for brief periods when tidal pools and other shallow bodies of water dried up, forcing them to wriggle over to a larger pool. Some liked it so much they ended up staying on the land almost all the time and became amphibians, some of which later evolved into reptiles. Some of the reptiles gave rise to mammals, whose descendants are us.

Enter the neocortex

When you look at a human brain from the top or sides, almost everything you see is *neocortex.* It's called "neo" because it is a relatively recent invention of mammals. Prior to mammals, animals like reptiles and birds had relatively small brains with very specialized areas for processing sensory information and controlling behavior.

What happened with the evolution of mammals is that a particular brain circuit expanded enormously to become an additional processing layer laid over the top of all the older brain areas for both sensory processing and motor control.

Neuroscientists are not exactly sure how and why the neocortex evolved. Birds and reptiles (and dinosaurs, for that matter) did pretty well with their small, specialized brains before the massive expansion of the neocortex that occurred in mammals. However it happened, once mammals arrived, the neocortex enlarged tremendously, dwarfing the rest of the brain that had evolved earlier. This occurred despite the fact that large brains are expensive, metabolically. The human brain consumes about 20 percent of the body's metabolism despite being only about 5 percent of body weight.

Looking at How the Nervous System Works

Look at just about any picture of the brain, and you see immediately that it consists of a number of different regions. The brain does not appear to be an amorphous mass of neural tissue that simply fills up the inside of the skull.

Given the appearance of the brain, you can ask two very important and related questions:

- Do the different regions of the brain that look different really do different things?
- Do the regions that look the same do the same thing?

The answer to both questions? Sort of. The next sections explain.

FIELDS AND BUMPS: EARLY THEORIES ABOUT HOW THE BRAIN WORKS

The early history of neuroscience saw a number of brain function theories that have been shown to be incorrect. Two of the more interesting are *phrenology* and the *aggregate field* theories.

The aggregate field theories supposed that, for the most part, the brain is a single, large neuronal circuit whose capabilities are related mostly to its total size. These theories assumed that the brain's internal structure is of little consequence in understanding its function.

At the other extreme were the phrenologists, who believed that almost every human characteristic, including attributes such as cautiousness, courage, and hope, are located in specific parts of the brain. These folks believed that the development of these attributes can be determined by measuring the height of the skull over those areas (bumps), the presumption being that the underlying brain grows and pushes the skull upward for traits that are highly developed. You can read more about phrenology in Chapter 12.

The important role of neurons

The nervous system, explained in detail in Chapter 2, consists of the *central nervous system* (the brain, retina, and spinal cord), the *peripheral nervous system* (the sensory and motor nerve axons that connect the central nervous system to the limbs and organs). The peripheral nervous system also includes the *autonomic nervous system* (which regulates body processes such as digestion and heart rate), and the enteric nervous system, which controls the gastrointestinal system.

All the divisions of the nervous system are based universally on the functions of neurons. *Neurons* are specialized cells that process information. Like all cells, they are unbelievably complicated in their own right. All nervous systems in all animal species have four basic types of functional cells:

- **Sensory neurons:** These neurons tell the rest of the brain about the external and internal environment.
- **Motor (and other output) neurons:** Motor neurons contract muscles and mediate behavior, and other output neurons stimulate glands and organs.
- **Projection neurons:** Communication neurons transmit signals from one brain area to another.
- **Interneurons:** The vast majority of neurons in vertebrates are interneurons involved in local computations. Computational interneurons extract and process information coming in from the senses, compare that information to what's in memory, and use the information to plan and execute behavior. Each of the several hundred distinguishable brain regions contains several dozen distinct types or classes of computational interneurons that mediate the function of that brain area.

What really distinguishes the nervous system from any other functioning group of cells is the complexity of the neuronal interconnections. The human brain has on the order of 86 billion neurons, each with a unique set of about 10,000 synaptic inputs from other neurons, yielding about a quadrillion synapses — a number even larger than the U.S. national debt *in pennies!* The number of possible distinct states of this system is virtually uncountable.

You can read a detailed discussion on neurons and how they work in Chapter 3.

Computing in circuits, segments, and modules

The largest part of the brain, which is what you actually see when you look at a brain from above or the side, is the neocortex. The neocortex is really a 1.5 square foot sheet of cells wadded up a bit to fit inside the head. The neurons in the neocortex are organized in complex neural circuits that are repeated millions of times across the cortical surface. The repeated neural circuits are called *minicolumns.*

REMEMBER

The brain contains many specialized areas associated with particular senses (vision versus audition, for example) and other areas mediating particular motor outputs (like moving the leg versus the tongue). The function of different brain areas depends not on any particular structure of the minicolumns within it, but its inputs and outputs.

So, even though the cell types and circuits in the auditory cortex are similar to those in the visual and motor cortices, the auditory cortex is the auditory cortex because it receives inputs from the cochlea (a part of the ear) and because it sends output to areas associated with processing auditory information, using it to guide behavior.

Many other parts of the nervous system also are made up of repeated circuits or circuit modules, although these are different in different parts of the brain:

- **The spinal cord** consists of very similar segments (cervical, thoracic, lumbar, and so on), whose structure is repeated from the border of the medulla at the top of the spinal cord to the coccygeal segments at the bottom.
- **The cerebellum,** a prominent brain structure at the back of the brain below the neocortex, is involved in fine-tuning motor sequences and motor learning. Within the cerebellum are repeated neural circuits forming modules that deal with motor planning, motor execution, and balance.

REMEMBER

All the modules that make up the central nervous system are extensively interconnected. If you were to take a section through about any part of the brain, you'd see that the brain has more *white matter*, or pale-appearing *axon tracts* (the neural "wires" that connect neurons to each other) than darker *gray matter* (neural cell bodies and dendrites, which receive inputs from other neurons and do the neural computations). Here's why: The brain uses local interconnections between neurons to do *computations* in neural circuits. However, any single neuron contacts only a fraction of the other neurons in the brain. To get to other brain modules for other computations, the results of these computations must be sent over long distance projections via axon tracts of communication neurons.

What a charge: The role of electricity

Most neurons are cells specialized for computation and communication. They have two kinds of branches: *dendrites* (which normally receive inputs from other neurons) and *axons* (which are the neuron's output to other neurons or other targets, like the muscles) emanating from their cell bodies.

Neuronal dendrites may be hundreds of micrometers in length, and neural axons may extend a meter (for example, axons run from single cells in the primary motor cortex in your brain down to the base of your spinal cord).

Neurons use electricity to communicate between different parts of the neuron. The basic idea is that synaptic inputs spread out all over the dendrites cause currents to flow from the dendrites into the cell body. The cell body converts this changing electrical current into a set of pulses (spikes) sent down its axon to other neurons. To find out more about how neurons communicate in general, head to Chapter 3. The chapters in Part 2 explain the specific details for each of the sensory systems.

Understanding the nervous system's modular organization

The nervous system has an overall modular organization. Neurons participate in local circuits consisting of several hundred neurons consisting of different types. These local circuits perform neural computations on inputs to the circuit and send the results to other circuits as outputs via projection (communication) neurons.

Local circuits form modules that perform certain functions, like seeing vertical lines, hearing 10,000 Hz tones, causing a particular finger muscle to contract, or causing the heart to beat faster. Groups of similar modules form major brain regions, of which there are several hundred, give or take. Modules in the brain, spinal cord, peripheral nervous system, and autonomic nervous system all work together to maintain your survival by regulating your internal environment and managing your interaction with the external environment.

Of course, humans use their nervous systems to do more than just survive. We have feelings and memories and curiosity and spiritual yearnings. We are capable of language, self-reflection, technology, and curiosity about their place in the universe.

Looking at the Basic Functions of the Nervous System

Animals have nervous systems, but plants don't. The question is why not? Both plants and animals are multicellular, and many plants, such as trees, are far larger than the largest animals.

EAT YOUR BRAIN OUT, YOU (SEA) SQUIRT!

Sea squirts are filter feeders (they filter nutrients out of ocean water) that live on the ocean floor. What's interesting about these organisms is that during development they have a mobile, larval form with a cerebral ganglion that controls swimming, but the adult form is *sessile* (anchored, like a plant).

During metamorphosis to its adult form, the sea squirt digests this central ganglion and thus "eats its own brain," because, as a plant form, it no longer needs it.

The key difference, of course, is movement. All animals move, but almost no plants do. (Venus Flytraps have a bi-petal leaf that snaps shut on insects, but we won't count that.) Nervous systems enable movement, and movement is what separates plants and animals.

Sensing the world around you

Sensory neurons detect energy and substances from inside and outside our bodies. Energy detectors include photoreceptors in the eye that detect light (Chapter 5), auditory hair cells in the cochlea that detect sound (Chapter 6), and mechanoreceptors in the skin that detect pressure and vibration (Chapter 4). Sensory cells that detect molecules include olfactory neurons in the nose and taste buds in the tongue (Chapter 7).

We also have detectors inside our bodies that detect body temperature, CO_2 levels, blood pressure, and other indications of body function. The central and autonomic nervous systems (discussed in Chapter 11) use the outputs of these internal sensors to regulate body function and keep it in an acceptable range *(homeostasis)*. This typically occurs without our conscious awareness.

REMEMBER

Sensory neurons are the most specialized of all neurons because they have unique mechanisms for responding to a particular type of energy or detecting a particular substance (as in smell and taste receptors). For example, some animals can directly sense the earth's magnetic field. They do this because they have cells that have deposited little crystals of magnetite in their cytoplasm that react to the magnetic field force of the earth to generate an electrical signal in the cell. This electrical signal is then communicated to other cells in the animal's nervous system for navigation.

Moving with motor neurons

Most neurons are computation interneurons that receive inputs from other neurons and have outputs to other neurons. However, some neurons, like those listed in the preceding section, are different:

- **Some neurons are specialized for sensation.** The input for these neurons comes from the world, not other neurons.
- **Some neurons send their output to muscles, glands, or organs instead of other neurons.** In this way, they spur action, which can be anything from secreting a particular hormone to regulate a bodily process to darting out the front door and across the lawn when you hear the ice-cream truck.

REMEMBER

Our bodies execute two very different types of movement. *Voluntary movement*, which is what most people normally think of as movement, is controlled by the central nervous system whose motor neurons innervate *striated muscles* (these same muscles and neurons are involved in reflexes, too). We also have *smooth muscles* controlled by neurons in the autonomic nervous system, such as in the digestive system or those that control the pupil of the eye. Movement is such an important topic in neuroscience that I devote all of Part 3 to it.

Deciding and doing

Central nervous systems are complex in mammals because large areas of the neocortex conduct motor control, sensory processing, and, for lack of a better term, what goes on in between sensory input and motor output. Devoting a large amount of brain tissue to motor control allows sophisticated and complex movement patterns. Large brain areas processing sensory inputs can allow you to recognize complex patterns in those inputs.

Brain areas not devoted directly to controlling movement or processing sensory input have traditionally been called *association cortex.* Although lumping all non-sensory, non-motor cortex together under this term is not very accurate, it is clear that association cortex allows very complex contingencies to exist between what is currently being received by the senses and what behavior occurs as a result. In other words, a large neocortex allows a lot of deciding to go on about what it is you will be doing.

Among mammalian species, those that we tend to think of as the most intelligent, such as primates, cetaceans, and perhaps elephants, have the largest neocortices. It's not just the neocortex that impacts intelligence; it's the size of the frontal lobe in particular. The most intelligent among the animals just listed (primates) have the largest frontal lobes relative to the rest of the neocortex.

REMEMBER

The most anterior (meaning, toward the front) part of the frontal lobe is called the *prefrontal cortex.* This area is highly expanded in primates and particularly in humans. The prefrontal cortex is responsible for the most abstract level of goal planning.

If you don't have large frontal lobes (or the axons therein are not yet myelinated, as with teenagers), your behavior tends to be dominated by your current needs and what is currently going on in the world around you. If you're a lizard, you're either hungry or cold or hot or seeking a mate or in danger of being caught by a predator. You have a number of behavioral repertoires, and your brain selects among them. For example, you may be seeking a mate, in which case you're following the looking-for-love motor program, when you spot a hawk circling overhead, at which point you switch to the avoiding-hawks motor program and seek a rock to crawl under.

Mammals, with their frontal lobes, have the capacity to plan complex, multistep action sequences. They can avoid hawks and still remember where the potential mate was and return to mate pursuit after the hawk leaves. Mammals can interact in large social groups in which their relationship to every other member is individualized, not just based on who's bigger or smaller or receptive to sexual advances at the moment.

Processing thoughts: Using intelligence and memory

When thinking about intelligence, we typically think about the differences between humans and animals, although some animal behavior is certainly acknowledged as being intelligent. Two attributes — our capability for language and our *episodic* memory — are associated with human intelligence. The following sections give a very brief outline of key points related to memory, language, and intelligence. For a complete discussion of the hierarchy of intelligence — and the key discoveries and remaining conundrums — head to Chapters 12 through 15.

Language

One attribute associated with human intelligence is language, which, when defined as the use of sign sequences within a complex grammar, appears to be uniquely human. What's interesting about language — at least from a neuroscientist's perspective — is that it resides primarily on only one side of the brain (the left side in most right-handers).

What makes it mind-boggling is that the two sides of a human brain appear nearly identical in both large- and small-scale organization. In other words, there appears to be no significant physical difference between the two halves. Neuroscientists know of no circuit or structure or cell unique to the left side of the brain that would explain its language capacity compared to the lack of it on the right side. Yet, as seen in patients whose left and right brain halves have been disconnected for medical reasons, the left side is capable of carrying on a conversation about recent experience, but the right side is not.

Episodic memory

Another, less appreciated distinction between human and animal intelligence is human's capacity for episodic memory. *Episodic memory* is the memory of a particular event and its context in time. It can be contrasted with *semantic memory,* a kind of associative memory involving the general knowledge of facts or associations. It's the difference between knowing *when* you learned the capital of Alabama was Montgomery (episodic) versus knowing the fact that the capital of Alabama is Montgomery (semantic).

Even primitive animals can form associative memories, such as in classical or operant conditioning (does the name Pavlov ring a bell?), but there is virtually no accepted evidence that animals other than humans have episodic memories, which depend on the operation of working memory in prefrontal cortex. The fact that your dog has learned what to do when you utter the word *sit* suggests that animals have a memory function something like what is called *semantic memory* in humans.

The prefrontal cortex is larger in humans than other primates, but even non-primate mammals have prefrontal cortices, so the question becomes, does episodic memory depend on language? What neuroscientists do know is that the complex planning that humans are capable of depends on executive functions in the prefrontal cortex.

When Things Go Wrong: Neurological and Mental Illness

Given the enormous complexity of the brain, it should not be surprising that sometimes it gets broken. Mental disorders range from those with a clear genetic basis, such as Down and Fragile X syndromes, to disorders with high but not complete heritability, such as schizophrenia and autism, to conditions that may be almost completely attributed to life events, like some types of depression.

Some mental disorders are also associated with aging, such as Alzheimer's and Parkinson's diseases. These diseases have no clear genetic basis, although increasing evidence points to associations between some genetic constituencies and risk for these diseases. Huntington's disease is genetic, but its symptoms typically don't appear until adulthood.

What can go wrong with the brain can occur at multiple levels. The following is just a sampling of mental and neurological illnesses that can occur:

- **Developmental errors in gross structure:** Genetic mutations or environmental toxins can lead to defects in gross brain structure. Defects can include missing, abnormally small or disorganized brain areas, such as in the cerebellum, or diminished axon tracts connecting brain areas.
- **Developmental errors in specific local circuits:** Some recent theories for autism suggest that, in people with autism, the balance between short and long range neural connections is skewed toward an excess in the short range. This is hypothesized to lead to over-attention to details and inability to respond well to the big picture.
- **Dysfunctional neural pathways:** Mutations in genes that specify neurotransmitter receptors may lead to brain-wide processing deficits. While some brain areas may compensate with other neuronal receptors, other areas may not. Excitatory/inhibitory receptor balance may be implicated in epilepsy and some forms of depression.
- **Environmentally caused organic dysfunctions:** The brain can be damaged by overt injury, such as by a blow to the head. It can also be damaged by toxins such as lead and mercury that produce developmental delays and other mental incapacities without overt signs of brain damage.
- **Environmentally caused psychological dysfunctions:** Sometimes mental illnesses, such as some types of depression, occur after environmental triggers in people who have had no previous indications of mental problems. A crucial question in mental illnesses such as depression is whether non-organic causes, such as loss of a loved one, produce depression primarily by changing brain neurochemistry.

For more information on these types of diseases and disorders, head to Chapter 17.

Revolutionizing the Future: Advancements in Various Fields

Revolutions in neuroscience that will have significant ramifications on humanity will occur within 20 years in these two areas:

- Treatments and cures for dysfunctions
- Augmentation of the brain beyond its heretofore "normal" capabilities

I discuss both in the following sections.

Treating dysfunction

Until the last quarter of the 20th century, attempts to treat brain problems were a lot like trying to fix a computer with a hammer and a hacksaw. We simply lacked the appropriate tools and the knowledge about how to use them. Research on the brain has started to change this, and the change is now happening very rapidly.

Pharmacological therapies

Most major mental disorders, including depression, schizophrenia, anxiety, and obsessive-compulsive disorder, are currently treated primarily with drugs. Most of these drugs target neurotransmitter systems.

Pharmacological therapies vary in their effectiveness and side effects. Lessons learned from first- and second-generation drugs are being used to design and screen third- and higher-generation agents. Although the cost of bringing a major new drug to market is currently on the order of one billion dollars, there are extensive international, privately and publicly funded efforts to develop new drugs. Drugs that are effective in eliminating most mental illness, substance abuse, or sociopathy would transform humankind.

Transplants

Neural transplants offer great hope for treating neurological disorders such as Parkinson's disease, which are caused by the death of relatively small numbers of cells in specific brain areas (the *substantia nigra,* in the case of Parkinson's). Transplants may consist of either donor tissue or stem cells that can differentiate into the needed cell types when transplanted into the affected region.

Many laboratories are working on transplanting tissue containing foreign secretory cells shielded from the recipient's immune system by membranes that allow the secretory products out but not the host's immune cells in. If the encapsulated cells respond to circulating levels of neurotransmitters in the host in an appropriate way, they may be able to regulate the levels of what they secrete more accurately and effectively than can be done by taking pills.

Electrical stimulation

Deep brain stimulation (DBS) is a technique in which the balance of activity in a neural circuit involving several brain areas is altered by continuous stimulation of neurons in one part of the circuit. This technique evolved partly from attempts to achieve the same ends by surgically removing brain areas that were thought to be over-activated in the basal ganglia circuit in Parkinson's disease.

DBS has seen extensive success in treating Parkinson's disease and certain kinds of tremors. DBS has also shown promise in treating certain kinds of depression.

Another kind of electrical stimulation is transcranial magnetic stimulation (TMS). TMS uses a strong, pulsed magnetic field generated just outside the skull to produce localized currents within the brain areas underneath the coil. These currents initially excite and then shut off brain activity for some period of time. Despite the short duration of the direct effects, long-term benefits have been observed in situations such as intractable depression. In this, TMS appears to act somewhat like the old "shock therapy" (electroconvulsive therapy, or ECT), but without producing seizures and some other unintended side effects.

An electrical stimulation technique called transcranial direct current stimulation (tDCS) has also shown promise in enhancing learning, reducing depression, and possibly increasing self-control. tDCS involves injecting about 2 milliamps of current between anode (positive) and cathode (negative) electrodes placed on different brain areas, depending on what brain area is to be modulated. Most studies suggest that brain activity under the anode is enhanced, while brain activity under the cathode is depressed. As with TMS, effects seem to last much longer than the treatment time, which is usually about 20 minutes for tDCS.

Neural prostheses

Paralysis from spinal cord and brain injuries has been almost impossible to treat because the motor neurons that would activate the muscles were either killed in the original injury or degenerate from lack of use afterward. A long-time rehabilitation dream has been to intercept brain signals commanding movements, relay them past the interruption, and drive muscles directly with electrical stimulation.

Another type of neural prosthesis is for sensory replacement. By far the most successful of these is the cochlear implant for deafness. More than 700,000 of these have been implanted worldwide at the time of this writing. In most cases these prostheses allow the recipient to carry on normal conversations, even on the telephone.

Prostheses for vision have been less successful. This is partly due to the fact that the information channel is so much larger (1 million ganglion cell axons versus 30,000 auditory nerve fibers), and partly because the cochlea presents a unique environment suitable for the introduction of a stimulating prosthesis. Demonstration projects for visual prostheses have implanted them in both retina and visual cortex, but neither approach has achieved clinically relevant effectiveness. Work continues, however.

Genetic therapies

Much psychological and neurological dysfunction occurs because some neurotransmitter systems are overactive, underactive, or out of balance with other systems. Given that neurotransmission is regulated by gene expression, modification of that expression is an obvious therapeutic target. The insertion of new genes in adult animals and humans has been accomplished with viral transfection therapies, such as modifying *adenoviruses* (the viruses that produce the common cold) to insert a desired gene in a patient's genome that will then be expressed like the patient's own native DNA but will correct the neurotransmitter imbalance. More recently, the CRISPR/Cas9 technique allows the editing (removing/replacing) of virtually any sequence in a cell's DNA. Genetic therapies such as this are likely to revolutionize medicine and neuroscience research and therapy in the next decades.

Augmenting function: Changing who we are

Humans are now beginning to augment ourselves. This augmentation will go far beyond the vaccines, surgical procedures, and prosthetics that alter our bodies, because it will involve our brains being directly connected to electronic circuits and, through those circuits, to the universe.

Using likely extensions of current technology, imagine using an implanted neural prosthesis to access the Internet just by thinking about it. Similar prostheses could translate languages in our heads or allow us to do complex mathematical calculations. They could allow us to communicate with anyone on earth simply by thinking about that person.

Sound far-fetched? Consider that neuro-prostheses consisting of hundreds of electrodes have already been experimentally implanted in a few people who were either paralyzed or blind. The principles involved in recording from or stimulating individual neurons in the brain are well within current technology. Genetic modulation of the nervous system may greatly enable the compatibility between it and implants. What remains to be done is to achieve better resolution and signal processing and longer lasting implants, which no doubt will happen in 20 years.