

Chapter 2

The Brain—Your Personal Necktop Computer

Abstract The chapter provides an introduction for those who are unfamiliar with the inside of their head. Important concepts related to the anatomy of the brain, and how nerve circuits operate, are explained. Evolution gradually added various functions to the nervous system for the purpose of promoting survival and procreation. I refer to these functions as “apps” (applications) or “modules”. The text moves on to compare the brain with a computer, as this comparison helps us understand both devices.

The Anatomy of the Most Complex Object

In order to understand what goes on in the brain, it is important to know the basics as to what it looks like. Science has generated an anatomical “map” with names of various structures, as well as a terminology that describes the processes taking place in neurons. In this chapter, I shall first introduce relevant features of the brain, and then compare it with a computer. I believe the comparison helps us appreciate both types of devices.

The first part may feel a bit tedious as it is primarily about introducing several labels and concepts. I believe it is useful to have been introduced to these terms, although it is not necessary to remember their exact connotation.

Unfortunately, the map is not that easy to follow. For one, it is difficult to divide the brain into distinct units; and two, various schools of science use different names or different definitions for partly overlapping structures and concepts. The situation is further complicated by there being both an anatomical map and an even more rather inadequate and unfinished functional map. The functional map is necessarily vague because most tasks are not restricted to a particular structure.

Select anatomical components, focusing on the structures I will refer to later in the book, are indicated in Fig. 1. The text moves on to briefly describe these structures. For a better, three-dimensional and interactive map, I recommend the Internet pages *Genes to Cognition* set up by Cold Spring Harbor Laboratory.¹

¹Try <http://www.g2conline.org>.

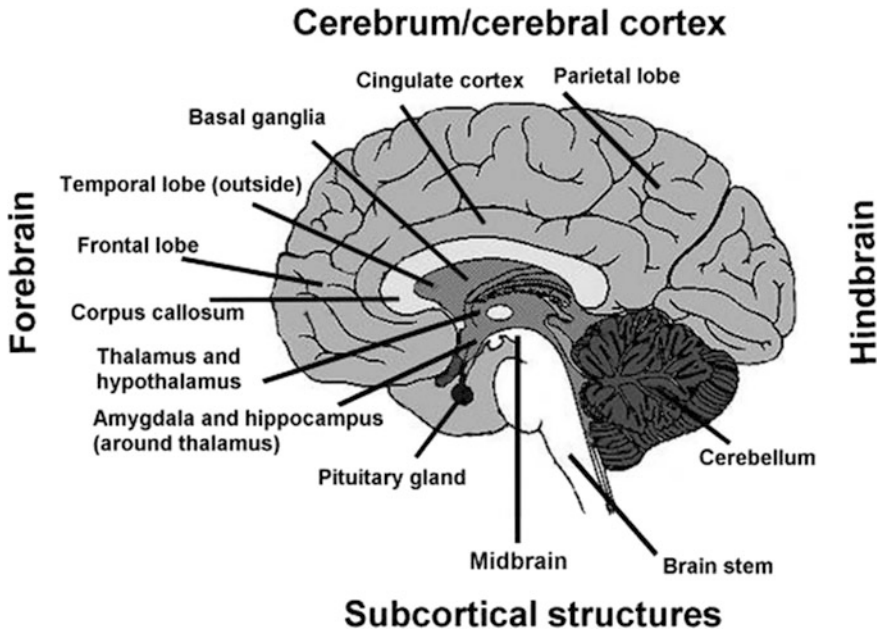


Fig. 1 Cross-section of a brain as seen from the *left*. Structures discussed in the text are indicated. The directions of the lines (*up, down, left or right*) suggest which (two) of the four major categories the structures belong to; for example, thalamus is part of the forebrain and of the subcortical structures. While the real brain is three-dimensional, the lines end at a particular point in a two-dimensional drawing—the map is consequently a gross approximation

The embryonal development of vertebrate nervous systems starts with a linear tube following the length of the early foetus. The brain subsequently develops from four blobs that gradually appear in the frontal part of the tube. One way of portraying the adult brain is to distinguish between which of these four blobs the various structures are derived from. The remaining part of the tube gives rise to the spinal cord and the associated nerve fibres innervating the body.

The two anterior bulbs develop into the *forebrain*. This is considered the home of higher functions such as consciousness. The main component is the *cerebral cortex*, which is what one can see upon removing the skull, and what most people associate with the brain. The power of thinking is generally assumed to depend heavily on the cortex. It consists of a left and a right hemisphere, and each is further divided into lobes based primarily on the deeper furrows (*sulci*) that are visible on the surface. The lobes are split up in sections based on presumed function, for example, the visual cortex and the auditory cortex. A large area in the innermost part is referred to as *cingulate cortex*. Inside that again lies the *corpus callosum*—a “highway” of nerve fibres that connects the two hemispheres.

The cortex, or the *grey matter*, is actually only a sheet of neurons some 2–4 mm thick. It is attached to the *white matter*, which is composed primarily of nerve fibres

rather than the actual cell bodies of neurons. In an analogy to electrical appliances, the grey layer constitutes the actual appliances, while white matter is simply wiring that connects the various units. Together the two layers form a 1.6 m² “blanket” that has been curled up in a somewhat disorderly fashion.

The cortex (including the white matter), as well as the underlying structures referred to as *basal ganglia*, are formed from the first bulb (the telencephalon). Together they form the *cerebrum*, which may be referred to as the “main brain”. The second bulb (diencephalon) gives rise to important *subcortical* structures such as *thalamus*, *hypothalamus*, and (part of) the *pituitary gland*. Some structures surrounding the thalamus have a mixed heritage (stemming from both first and second bulb), the two most relevant for the present discussion are *amygdala* and *hippocampus*. They contain important neural circuits associated with the generation of good and bad feelings. The amygdala is particularly associated with fear, while hippocampus has additional functions related to memory.

The third bulb (mesencephalon) is synonymous with the term *midbrain*. It forms a somewhat inconspicuous area in the interior part of the head. It is, however, an important “relay station” for signals going back and forth between body and brain. Information from sense organs passes here, as do impulses controlling muscular movements.

The final bulb forms the *hindbrain*, which includes the *cerebellum* (meaning “little brain”) as well as structures in the *brain stem*. The latter links the brain with the *spinal cord*. The primary function of the cerebellum is to coordinate muscle activity. It looks superficially like a smaller version of the cortex in that both have two hemispheres and a furrowed surface. The resemblance reflects that both are formed from folded layers of nervous tissue, but while the cortex seems crumpled, the cerebellum is more neatly folded.

Our giant head is primarily due to the size of the cerebrum. This is the part that expanded most dramatically in the evolutionary lineage leading to *Homo sapiens*, and it constitutes the larger part of the 1.3 l human brain. Does this mean that the particular human qualities reside here? The answer is a conditional “yes”: The cortex has important roles in consciousness and in our intellectual capacity; but as we shall see, consciousness apparently does not depend entirely on this structure.

The four bulb plan for brain architecture dates back to the early vertebrates; which means that most of the functions present in the brain have been around, in some form or another, for a long time. The lower and “more primitive” part of the brain, including the midbrain and brain stem, are required to sustain brain activity. Without them the brain cannot function. In that way they are responsible for both consciousness and many other functions; that is, damage to sensitive areas of the brain stem (particularly the reticular formation) means *you* are lost.

Nerve circuits of the brain stem are presumably also responsible for moving your attention toward dangers or other highly relevant features of the environment. If you happen to be asleep, they make sure to wake you up.² Normally you feel in charge

²Steriade M. Arousal: Revisiting the reticular activating system. *Science* 272 (1996) 225–226.

of what you wish to focus your mind on, but these ancient nerve circuits have the capacity to overrule your free will. It makes sense because the unconscious brain has more information about what is going on than you do.

The “little brain” is the bigger one

The cerebellum, or little brain, constitutes, as the name suggest only 10% of the brain volume. Surprisingly it contains 80 % of the neurons! The vast majority of the remaining neurons are in the cortex, thus the subcortical structures are left with only 1 %.

The main task of the cerebellum is to coordinate the use of muscles. It does not necessarily decide on any action to be taken, but helps execute commands stemming from your conscious mind. The command centres are situated primarily in the motor cortex on top of the head, but orchestrating the fine-tuned activity of a large number of muscle fibres is beyond the capacity of these centres. You can decide that your right arm is to swing the racket in order to hit a tennis ball, but to have any chance of hitting the ball the way you desire, the cerebellum must take care of synchronizing the muscle fibres involved.

Most people seem unaware of the complexity of this task. You walk without as much as a thought about how to move your legs, but even on a flat surface the coordination required is a tremendous challenge. An uneven surface requires even more as to fine-tuned control. Playing chess is, in comparison, an easy task. We have computers that can beat the best chess players, but no robot is able to walk on two legs with anywhere near the elegance of a human. In other words, there is a reason why the cerebellum contains the greater share of neurons.

The control of movements is, and has always been, the primary task for any nervous system—perhaps it is also the most complex task. Still, you are probably not impressed. But the lack of admiration for what this clump of nervous tissue is able to accomplish is due to your lack of knowledge. The cerebellum does not inform you about what it is up to, evolution did not find any reason to bother your conscious brain with all the tedious details. Furthermore, you may have noticed that we humans are not particularly good at moving our bodies; a mountain goat will run and jump around in a terrain where you would hardly dare to hike. And as long as we consider ourselves far superior to these animals, the task cannot be anything worth bragging about!?

To the extent that goats contemplate on such matters, I would guess that they are not particularly enthralled by our capacity to move pieces around a chessboard, but do note how clumsy we are in rocky terrain. Actually we do excel in one form of coordinated muscle control—we have the most versatile and dexterous hands and fingers.

The cerebellum certainly deserves more attention, but fortunately it will not get it. Whether you play tennis or go for a walk, you are best served by letting it carry out its work without your involvement and intervention.

Neuron Style Talking

The typical neuron looks like a hairy head on a thin stem (Fig. 2). The hair represents *dendrites* that send signals in toward the head, or cell body; the stem is the *axon* that passes the signal on to other cells. The main function of the neurons is to communicate with each other by sending electrical signals through their dendrites and axons. Upon reaching the next cell the signal is transferred by means of *synapses*.

This continuous “chatting” is the activity responsible for whatever the brain is capable of doing—including anything from the control of breathing to reading the pages of this book. Both conscious experiences and all the unconscious processes that take place within the brain have a *neurological correlate* in the form of activity in particular nerve circuits. Typically, however, the correlate is exceedingly complex as there may be millions, or even billions, of neurons involved. To further complicate the situation, the cells are typically active even when not caring for any particular function.

Actually, the brain contains a lot more than just neurons. Obviously it needs a blood supply. In addition it has a nerve specific support system in the form of *glial cells*; there are, in fact, a lot more of these around than there are neurons. The situation is somewhat like an elite national sports team, for each active performer there are several members of the support group. The performers are the ones doing the job, but their performance relies heavily on the backing they get. Compared to other mammals, the human glial cells are bigger, and the brain contains more of them per neuron; it is tempting to give this “support team” part of the honour for human mental achievements. In fact, mice where the glial cells have been switched with the human counterpart are “smarter” than normal mice.³ As a curiosity, I might mention that in a certain part of Einstein’s cortex the support cells were particularly abundant.⁴

Signals are conducted along dendrites and axons by means of electrical pulses (in the form of ions passing into the cell and thereby causing a voltage change across the membrane). The synapses are either chemical or electrical. In the chemical ones, which are the more common, the transmission to the next cell is by

³Han X et al. Forebrain engraftment by human glial progenitor cells enhances synaptic plasticity and learning in adult mice. *Cell Stem Cell* 12 (2013) 342–353.

⁴Diamond MC, Scheibel AB, Murphy GM, Harvey T. On the brain of a scientist: Albert Einstein. *Experimental Neurology* 88 (1985) 198–204.

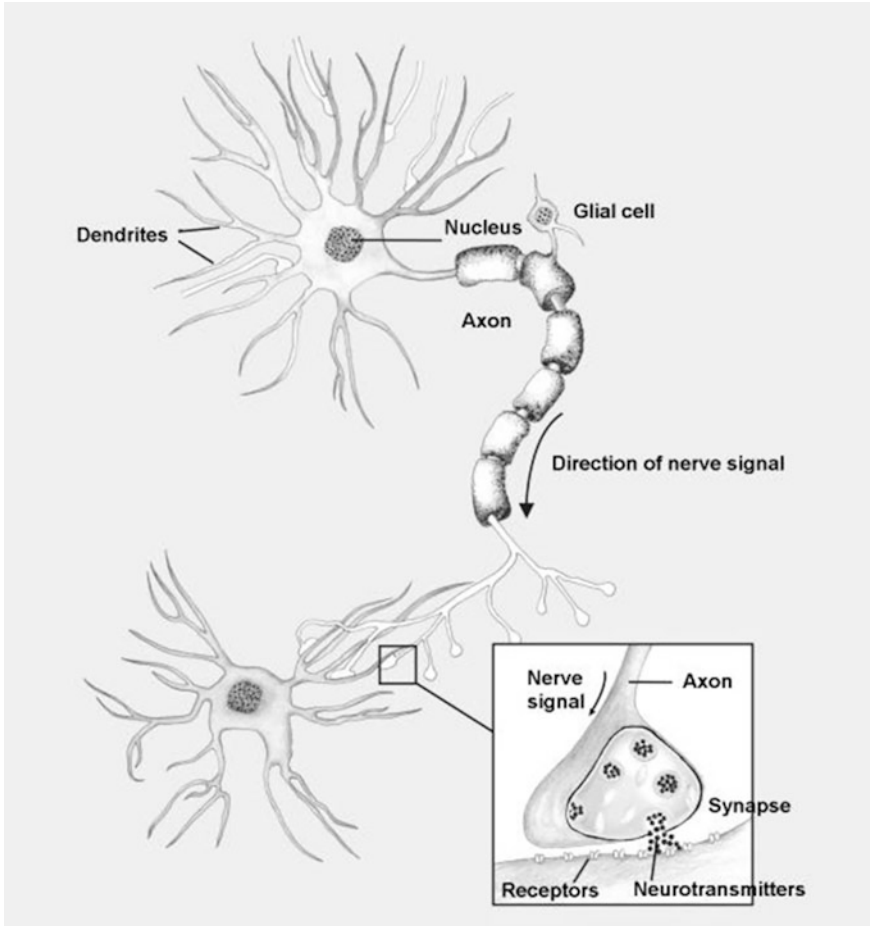


Fig. 2 A neuron (nerve cell) and its connections. The neuron receives signals from other cells through the dendrites. These impulses may or may not trigger a response in the form of a signal to be initiated by the cell body and passed down its axon. Within dendrites and the axon the impulse is passed on by a form of electrical current; but in order to move on to another cell, the signal must pass through a synapse. This typically implies the release of neurotransmitters from the sending cell; the receiving cell is triggered when the neurotransmitters bind to its receptors. The lipid sheet surrounding the axon is formed by glial cells (indicated to the *top right*) and helps speed up the signal. (Drawing Anette Mehl Landmark)

means of messenger molecules referred to as *neurotransmitters*. The neurotransmitters are released as the electrical signal reaches the synapse, and they are registered by *receptors* on the receiving cell. The *electrical synapses*, on the other hand, stands for a more direct transfer, what may be pictured as a plug somewhat loosely stuck into an outlet.

The electrical synapses stand for a fast and simple transmission, while the slower chemical synapses allow for a lot more options in terms of modulating the signal. The neurotransmitters may, for example, either stimulate or inhibit the receiver as to whether the signal should be passed on. The complexity, and opportunities, embedded in chemical synapses is reflected in the variety of chemicals involved. There are at least 60 different neurotransmitters, and a substantially larger variety of proteins that can affect how they function. The proteins include multiple receptors for each neurotransmitter, as well as proteins involved in the recycling and release of neurotransmitters. This system allows us to develop medications aimed at alleviating disorders affecting the nervous system. Pretty much all the *psychoactive substances* we know act in, one way or another, by either stimulating or inhibiting the transfer of neurotransmitter signals.

The most common neurotransmitters are *glutamate* and *GABA*. The former is stimulatory while the latter inhibits the release of further signals from the receiving cell.

Each neuron may obtain input—through its incoming chemical and electrical synapses—from more than a thousand other neurons. Whether it will pass on the signal depends on the sum of the input. If the stimulatory signals are sufficiently dominating (compared to inhibitory signals), an electrical signal is sent down the axon. It is somewhat like Facebook. You receive messages from various friends, and decide whether you want to pass them on to other friends. If an invitation to participate comes from a number of sources, the neuron, and perhaps a Facebook member, is more likely to pass it on.

Also like Facebook, neurons (at least in one part of the cortex) respond more strongly to those “closely related” (as to distance apart and/or subtype of nerve cell). Actually, most of the connections of an individual cell may be more or less dormant. Apparently the brain constructs a vast number of connections, and then uses the flexibility inherent in this somewhat redundant system to modulate activity. That is, the synapses are activated or inactivated in order for the brain to adapt, or learn.⁵ Having a variety of synapses preformed means new connections (required for novel learning) can proceed without the lag required to grow novel axons or dendrites—just changing the relative importance of different synapses can have drastic ramifications for the circuits involved. On a negative tone, the wiring also means that even if we do obtain a detailed overview of how the brain is wired, including all possible nerve circuits, we still are a far cry from having a description of how nerve activity actually generates consciousness. We would need to know the individual role of each connection.

Neurons form a grey mass (once the blood has been washed away), while areas dominated by wiring (axons and dendrites) form white matter. This is because the fibres are covered with layers of cell membranes formed by glial cells. Membranes consist primarily of fat, and as you may have noticed on a strip of bacon, fat is

⁵Cossell L et al. Functional organization of excitatory synaptic strength in primary visual cortex. *Nature* 518 (2015) 399–403.

generally white. It is worthwhile to note that compared to our closest relatives, chimpanzees and gorillas, the human brain does not contain that much more neurons—the increase in size reflects primarily more connections and glial cells.

During the latter part of gestation and the first two years of life, there is a massive growth in links connecting various neurons. According to the Japanese scientist Tomoko Sakai this is the salient feature causing humans to outperform any other animal in cognitive tasks.⁶ In other words, the white matter, or the complexity of neuron communication, is where our unique talents rest. Hercule Poirot kept pointing to his “little grey cells” while he probably should have referred to his “vast white mass”.

Even taking the complexity of chemical synapses into consideration, the working of the brain is reasonably simple. Our present knowledge is relatively detailed and comprehensive. The miracles resulting from this activity, like the dreams and visions you have, are a completely different challenge. They are presumably a product of the extraordinary complexity of nerve signalling between billions of neurons, but regrettably we only have vague ideas as to how these wonders are achieved.

People studying complexity theory likes to make diagrams consisting of boxes connected together with lines. They will tell you that even relatively simple diagrams, perhaps a few dozens of boxes and their connections, can give rise to highly intricate activities. No wonder the processes going on in the brain, with its billions of boxes, are difficult to both outline and comprehend. The big problem, however, is that even if we could delineate the precise neurological activity behind a particular percept, we still might not understand why this activity results in something as intangible as an experience. That is, how can nerve activity, however complex it may be, give rise to consciousness?

We have just started to describe the relevant neurology. This task has been referred to as *The Easy Problem*, while the leap from this description to an actual comprehension is *The Hard Problem*.⁷ Perhaps refining the description will yield the best possible answer science can ever offer; or perhaps a detailed account of the activity behind consciousness will open the gates to a higher level of insight.

The electrical transfer of signals involves the opening of gates for Na^+ -ions in the cell membrane. These ions are more abundant outside the membrane, and the subsequent influx neutralizes the typical negative electrical charge present on the inside. When this happens at a particular spot in an axon (or dendrite), the effect is to open the next Na^+ -gates downstream. In that way the signal is passed on. Obviously, the cell needs to pump the Na^+ -ions out again to be ready for a new signal, which sets a limit to the frequency of signals going down a particular fibre.

⁶Sakai T et al. Developmental patterns of chimpanzee cerebral tissues provide important clues for understanding the remarkable enlargement of the human brain. *Proceedings of the Royal Society B* 280 (2013) 2398–2407.

⁷Chalmers DJ. *The Conscious Mind*. (1996, Oxford University Press).

The pertinent points for the present discussion are; for one, that we can measure this change in electrical potential across the membrane with electrodes connected to a voltmeter; and two, that it is possible to manipulate the nerve cell into firing, or not firing, by applying an electrical charge to the electrodes.

In order to measure the signal as it passes through a single cell, one electrode needs to go inside the cell. However, a large number of cells in a particular area tend to fire in synchrony. The total variation in extracellular ion concentration is sufficient to be measured by electrodes in that area—or even attached to the outside of the skull. The latter way of measuring is referred to as *EEG* (electroencephalogram). The fluctuations in voltage, normally measured between one electrode on the head and another elsewhere on the body, change more or less regularly as the (millions) of cells located near the electrode (which means a particular part of

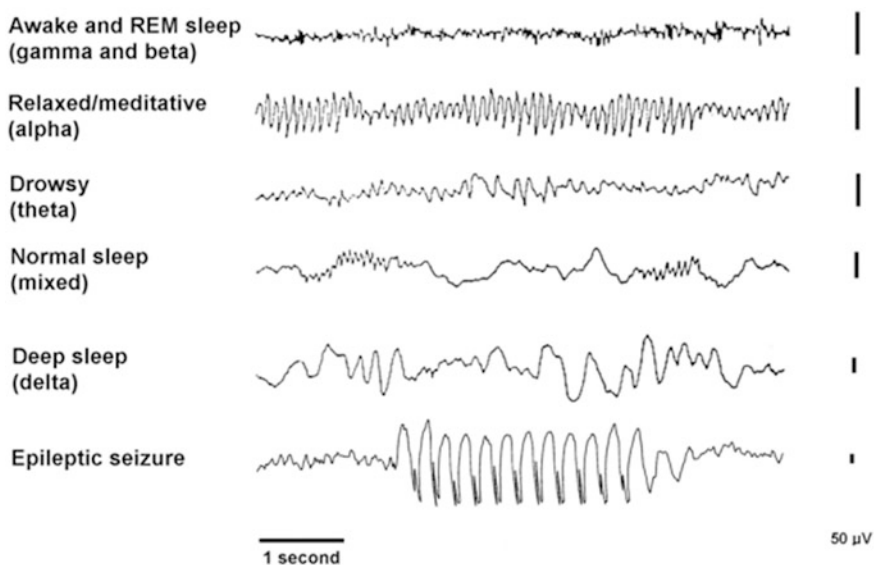


Fig. 3 EEG patterns associated with different brain states. The neurons in any particular part of the cortex tend to fire more or less in synchrony. The combined influx or outflux of ions from a large number of cells allows us to measure variations in voltage by means of electrodes attached to the head. As the variations tend to be somewhat regular, we talk about oscillations. The oscillations are named according to their frequency measured in Hertz (Hz), which means oscillations per second. The spectrum of frequencies is divided into *delta* (0.1–4 Hz), *theta* (4–8 Hz), *alpha* (8–15 Hz), *beta* (15–30 Hz), and *gamma* (30–100 Hz). Both the frequency and the amplitude (each vertical line to the right represents 50 μV) depend on the state of mind. Note that the EEG while awake looks similar to what we find during REM sleep. At the bottom is shown a brief epileptic seizure (an absence)

the cerebral cortex), either fire a signal or pump ions back out. The oscillations are usually between 4–40 Hz (beats per second). The amplitude, the speed, and the regularity of the oscillations reflect the sort of activity going on in that particular part of the brain. Moreover, the overall pattern, which tends to be reasonably consistent across much of the cortex, reflects the sort of mental state you are in. Figure 3 illustrates the point.

The neurons rarely stop completely their activity. If they do, it most likely means you are dead. Otherwise the chatting goes on—even when there really is nothing that “needs to be said”. This basal activity is particularly well synchronized, which is seen on the EEG as slow and somewhat regular oscillations (such as the delta waves associated with deep sleep).

Ever so often certain nerve circuits get particularly intense in their chatting. The set of neurons involved presumably reflects those required for a particular task, conscious or unconscious, the brain is working on. The more fervent activity is recognized on EEG as a more arbitrary pattern, largely replacing the synchrony of the resting state. While awake, most of the cortex seems to be more or less engaged, which is seen as the more disorganized EEG pattern on top of the figure. The activity adds up to rapid and low amplitude oscillations, what is referred to as beta or gamma waves. The amplitude is low because the neurons are less synchronized.

The tendency to fire in synchrony is a key aspect of all advanced nervous system. It is an intrinsic feature of the brain, perhaps one day it will prove to be the core clue in our quest to understand how consciousness is generated. Millions of neurons coordinate their actions, so obviously some form of regulatory mechanism is required. Engrained in the nerve circuits there are, in other words, stimulatory processes that ignite cells to fire together; as well as inhibitory processes that stop the process from getting out of control. We know a little bit about how this regulation is obtained.⁸ The underlying neurological machinery is not constant, but amenable to external input, which means it is part of the brain’s capacity to learn and adapt to changing conditions.

Sometimes this basal feature of the brain goes awry. We see that in the condition referred to as *epilepsy*. A part of the brain gets stuck in strong and highly synchronous firing. It is interesting to note that the result may be either to activate or to inactivate functions. The former may cause uncontrolled jerking movements or strange sensations; the latter, if the attack spreads to a sufficient part of the brain, may result in loss of consciousness.

Although many neurons have long-distance connections, a considerable fraction of the cells responsible for a specific task are typically localized in a particular region. It means that this region will light up as being more active than neighbouring parts of the brain when engaged in that particular task. By measuring

⁸Turrigiano G. Keeping a lid on it. *Nature* 511 (2014) 297–298.

activity we can therefore pinpoint brain structures that act as hotspots for various assignments.

Overall the brain is only slightly more active when you are awake as compared to in deep sleep.

Lots of things can go wrong in a system as complex as the human brain. Epilepsy reflects one type of vulnerability; I shall later describe other disorders as they constitute an important source of information. They help us understand what sort of functions evolution has incorporated in the brain, as well as pinpointing the actual neuronal structures involved.

The Concept of Brain Modules

Although the human brain may easily pass as the most complex structure in the Universe, science has not given up on a detailed description. There is, after all, a compelling precedence for obtaining insight by not giving up. Describing the complete DNA sequence of the human genome seemed an impossible task some thirty years ago, but now it is simple routine. Genetics is moving on to map mutations and other individual variations in the genome, and to find the role of each gene present. One important point is that no one can read this sort of information. The genome sequence alone would cover a book of a million pages, not to mention all the other data, thus the only way to analyse and extract meaningful information is with the help of computing power. Gone are the days when all relevant facts could be either in the head of a scientist or on his bookshelf.

A related mapping effort is being undertaken concerning the brain. Large consortiums of scientists are trying to chart all the neurons as well as all their connections.⁹ Another approach is to create computer simulation of what is going on, assuming that an *in silico* brain will open the gates of comprehension.¹⁰

Besides the problem of extracting true insight from these fountains of data, the projects need to take into account that the brain is continuously changing, and that even at birth no two individuals are identical. The proteins and other molecules that build the brain are typically broken down and resynthesized within hours, but the neurons tend to be reasonably long-lived. Relatively few neurons are formed after birth, and although they do die off as we age, most are present from cradle to coffin. The connections between the cells, however, are continuously formed and moulded, and it is the connections that constitute the working power of the brain.

⁹Look up “Human Connectome Project” or “Brain Activity Map Project” on the Internet.

¹⁰This is the European Union approach under the umbrella “Human Brain Project”.

Nerve circuits that are regularly engaged tend to create new and strengthened connections. These changes are typically accompanied by an increase in the size of the brain areas involved. It is possible to study such changes. Neuroscientists have, for example, shown that two hours of video games are sufficient to cause detectable modifications in the parts of the brain that these games engage.¹¹

The modifications due to use, or lack of use, are referred to as *brain plasticity*. You might call it “learning”. The human brain is probably more plastic than any other brain, which means not only are we able to gain more knowledge, we are also better at adapting to changes in our environment or life situation. The good news is that this plasticity implies that *the brain can be exercised, and thus fashioned, to the desire of the beholder*.



Which one is more important for moulding our brains—nature (genes) or nurture (environment)? (A shepherd family in Kyrgyzstan)

¹¹Sagi Y et al. Learning in the fast lane: new insight into neuroplasticity. *Neuron* 73 (2012) 1195–1203.

Nature and nurture

Disputes as to whether genes or the environment are responsible for various aspects of human behaviour have troubled the scientific community for too long. The either-or debate can safely be buried. The question is not whether a particular trait depends on genes or upbringing; for most practical purposes, all features of adult humans are shaped by interactions between the genetic constitution and the conditions of life. As to some features, the environment is the more important factor, for instance choice of language or eating utensils; while other attributes depend more on genes. The feeling of pain upon bruising a knee is an example of the latter. The relevant question, and the one I as a biologist try to answer, is: How do the genes influence the way the environment shapes us? Or vice versa.

The combined impact of these two factors makes each of us a unique person. As a biologist, however, I am primarily tuned toward understanding the typical or “average” person—not so much the peculiarities of the individual.

You need to accept your genetic constitution. There is, at least so far, not much you can do to change it. Accordingly, the environment is what we should focus on; but fortunately this offers a rich source of options and opportunities. We ought to ask questions such as: What sort of environment serves us best, and what is required to mould the brain in a direction that brings happiness? Phrased differently: What types of internal and external impressions will exercise the mind to the effect that conscious experiences are flavoured by positive affect?

We are all unique, so we all need to find personal answers. On the other hand, genetically speaking we are relatively similar. Consequently we start out life with pretty much the same options. A general understanding of the human species is therefore useful when it comes to finding personal answers.

It is the extreme plasticity of the human brain that has caused the nature versus nurture controversy. Social scientists tend to see plasticity, and conclude that humans can be shaped in any conceivable way. As a biologist, I focus on the role of the genes. They do set limits, and they push the mind in particular directions. The genetic factor may be more obvious in other species of animals, but it is definitely present in humans as well.

The information obtained by the grand brain projects is likely to prove useful, but even an exact map, and a precise simulation, will not necessarily reveal the more interesting aspects of what is going on. A complementary, and perhaps equally useful but a lot cheaper, approach is to try to outline the various utilities the process of evolution added to the brain. The fundamental functions are presumably pretty much the same in each individual, although they are moulded by life in various ways.

The overriding principle used by the process of evolution (when forming the nervous systems of various species) is that the functions created should be useful tools for the genes. In the case of humans, this implies a flexible and adaptable brain. It is inherent in the design that we are influenced and shaped by the environment. This lack of determinism explains why the methods of social sciences are required to understand human behaviour, but not the behaviour of insects. On the other hand, we are not born like blank slates. The genes do guide us in our walk through life. Evolution has equipped the brain with a lot of functions; some are reasonably constant as to how they perform their objectives, while others are meant to be more versatile. In order to understand human psyche, we need to recognize these functions and study how they unfold over the span of a lifetime.

A good starting point for organizing our knowledge is consequently to ask: How does our brain contribute to survival and procreation? The question can be answered by describing all the tasks cared for by a human brain. I like to use the term *module* for the components, or nerve circuitry, in the brain that handles various functions. In advanced nervous systems such as ours, the brain is given a substantial list of tasks, including anything from lifting the left index finger, increasing the heart rate in times of danger, and make you fall in love. For each function there is a designated module. In short, the brain can be compared to a pocketknife. Like the brain modules, the various tools of the knife are activated when needed. However, while the knife may have a dozen tools, the brain can be divided into thousands of modules; how many depends primarily on to what extent one split up or lumps together the various tasks cared for. Moreover, the brain modules are not neatly organized side by side, but overlap in their use of nerve circuits; thus a single neuron may be involved in a range of functions. In some cases we can pinpoint a particular part of the brain as the main site for a given task; occasionally due to the consequences of having this part destroyed. For example, damage to a particular area of the frontal lobe of the cortex (Broca's area) affects our capacity to speak.

Perhaps a more trendy comparison is to consider brain modules as analogues to apps (applications) on a smartphone. You activate the various apps when needed. The brain is plastic, so it is fair to claim that new apps can be added—such as an app for understanding Chinese or performing a summersault. As in the case of the brain, the apps make use of overlapping electronic circuitry in the phone.

The brain is to some extent organized in a way that allows us to create a functional map, the cortex apparently more so than the subcortical parts. Yet, even in cases where we can point out the seat of a particular function, the local nerve circuits are most likely unable to handle the allocated task without the help of other parts. I use the term “module” regardless of whether the neurological correlate is gathered in a specific location or smeared all over the brain.

Another important difference in the comparison between brain and knife is that while the knife retains its particular qualities, the brain has the capacity to improve its modules. They are not cast in steel. It might be added that in both cases the tools will tend to become blunted in the long run. We all age.

Obviously the brain is not designed with the human desire for categorization in mind. The module concept is artificial, the real brain is just a mash of activity that somehow manages to care for certain requirements of living. In fact, it is the lack of orderliness in the brain that makes the module concept useful. If we could isolate the various tools, as in the case of the knife, understanding the brain would have been a lot easier. Instead we need to opt for insight gained by considering putative functions added by evolution.

Any description of the brain is necessarily a simplification. We will never have a complete and perfect understanding, but the concept of modules offers, in my mind, a strategy to attain at least a vague impression of what the brain is like.

One type of experiments has won great popularity in recent years: By means of brain scanners, scientists try to plot features onto the functional map.¹² The subject is, for example, asked to focus on a particular task—such as lifting a finger, performing a calculation, or engage in feelings for a loved one—the scanner will tell the scientists which parts of the brain are the most active. It is typically a question of finding what parts of the brain have the highest level of metabolism, which can be done by following how blood or oxygen is redirected to particular areas. We are reasonably sure that the areas that light up are in fact engaged, but it is more difficult to rule out the involvement of other regions of the brain.

The human brain modules were formed gradually over several hundred million years by the process of evolution. Occasionally novel needs gave rise to truly original constructs, but more often the needs were catered to by reshaping modules already present. This process would be the equivalent of the pocketknife producer designing a screwdriver by cutting the tip off a knife rather than by assuring an optimal design based on functional requirements. It has, for example, been suggested that the capacity for language evolved by reshaping brain modules originally set up for detailed control of arms and hands.¹³ The utility of the arms required for throwing an object, such as a spear, may have led to gesturing, and then again to oral dexterity.

Humans are a rather special case. More so than any other animal we have an overarching module that has been given considerable power; that is, consciousness. Human consciousness is designed to be involved in a large variety of tasks, the concomitant level of free will is sufficient to allow for extensive personal control. In a way, consciousness is the hand that uses the pocketknife. It can choose to activate particular tools. True, many of the modules are not directly available for the mind, including the control of bowel movements, but we still reside over a rather versatile “knife”.

In this book, I am particularly interested in *one* module—the one that creates the good or bad aspects of feelings. I refer to it as the *mood module*. It may be divided

¹²Neuroimaging includes functional Magnetic Resonance Imaging (fMRI), which pinpoint areas that are more active; and Computed Tomography (CT), which can be used to detect injuries responsible for behavioural changes.

¹³See Corballis MC. *From Hand to Mouth*. (2002, Princeton University Press).

into various submodules engaged in offering various rewards or punishment, I consequently quite often refer to the mood *modules*; the choice of singular or plural depends on the context. The potential for conscious impact on the activity of the mood modules is, of course, highly relevant when discussing life quality.

Whether a task is initiated by the conscious or unconscious brain, it will typically require the engagement of several modules. In the analogy with the pocket knife it means you will need screwdriver, knife blade, and pliers in order to change an electrical socket. Your conscious experiences similarly depend on input from a large number of modules: Visions mingle with distant memories, and reading the newspaper may be accompanied by music. The mood module tends to contribute, either vaguely or distinctly, implying that most experiences are somewhat pleasant or unpleasant.

In contrast to the pocketknife, one module may actually disturb, or impact on, the output of other modules. The sight of a talking mouth can, for example, change what you hear! The modification takes place during the processing of the auditory signal. The psychologist Harry McGurk published an example many years ago under the title “Hearing lips and seeing voices”.¹⁴ He showed subjects a film of a person saying “ga”. If they simultaneously heard the same person say “ba”, they would consistently claim the sound was “da”.

Peculiarities, such as the tendency for mixing up various sensory inputs due to extensive and somewhat haphazard processing, set the brain apart not only from the pocketknife, but also from a computer. In the remaining part of Chapter I shall discuss other features that make the brain different from your laptop.

What does it mean to have a feeling?

The word “feeling” is a bit ambiguous. The meaning tends to depend on the context. For me the term stands for one of the major types of contribution that feed into conscious experience. The function of feelings is to encourage behaviour in a way that is expected to benefit the genes. Feelings are there to guide us by creating a sense of something positive or negative, and by indicating how we should proceed to improve our net score of mood. For example, feeling thirsty is somewhat unpleasant, but the discomfort is alleviated by drinking.

It should be noted that the human repertoire of feelings is not always appropriate in terms of survival and reproduction in an industrialized society. Jealousy and the tendency to fear strangers are not necessarily to the benefit of the genes today (nor to the benefit of life quality), but evolution installed these traits because the behaviours they instigate once were useful for the propagation of our genes.

¹⁴McGurk H, MacDonald J. Hearing lips and seeing voices. *Nature* 264 (1976) 746–748.

A variety of elements are combined into a unified experience in the brain. We see the texture and colour of an object; sometimes additional features are added, including an aroma, sounds, and perhaps some sort of feelings. The contribution offered by the latter can be divided into two components. The mood module(s) represent one component in that they generate a sense of good or bad. The second component is more complicated, it is what gives the feeling a particular content—a “flavour”. The mood part is there to create a common currency that can be used to weigh various options against each other; the more specific (flavour type) content is there to point behaviour in the right direction. Different action is required to satisfy thirst as compared to exploiting an opportunity to procreate.

Psychologists tend to classify feelings, or emotions, based on their flavour. The flavour may be described in terms such as anger, fear, worry, grief and sadness—each of these terms may be referred to as a particular module. The anger module and the grief module, for example, are presumably based on different neural circuits. I emphasize the mood modules as separate units, because they apparently use independent neuronal circuits that are largely shared for the various types of emotions or flavours.¹⁵ Moreover, the mood modules are the ones that ultimately determine the level of happiness. It is important to note that certain types of emotions, such as fear and grief, may activate either punishment or reward—though usually only one of the two at the time.

In order to simplify the text, I sometimes combine the emotional content with the mood content by writing, for example, about “how the fear module contributes to the quality of life”. When there is a need to specify, I refer to the basal mood component as opposed to the sensory or emotional component. All the different constituents are anyway mixed together in a conscious experience. Consequently we do not always acknowledge the reward or punishment parts as distinct elements. You probably *do* notice the pleasant taste of sweetness when munching a cake, thus in this case it is easy to envision the activation of a brain reward. On the other hand, although you enjoy chatting with friends, you probably do not think in terms of activity in the mood module. That is, the contribution made by the mood module is often difficult to distinguish from other aspects of life.

¹⁵The concept of mood modules will be further discussed in Chapter 7.



Is the brain like a pocket knife or a computer? Evolution gradually added novel function to the brain—what I refer to as modules or apps. In this respect a comparison with the knife seems appropriate, the major difference being that the brain's modules are not as distinct or neatly separated as the tools of the knife. Moreover, for the brain to execute a task typically requires the concerted effort of a number of modules. Another option is to compare with a computer. Here too there are similarities and differences; both devices process vast amount of data, but the computer goes about the task in a different way than the brain

Brain Versus Computer

The brain is good for a lot more than opening bottles or tin cans; so if you find the comparison with a pocketknife somewhat degrading, perhaps you prefer to compete with a computer. Here too there are significant similarities—as well as important differences. For one, the brain structure is a lot more complicated. While we know exactly how the computer is set up, we are nowhere near a similar overview of the brain. Furthermore, you have the capacity to think, experience, and control muscles in a way your laptop could only dream of. Yet, the comparison, or competition, between brain and computer is worth a closer look. Not only can the effort increase our understanding, and appreciation, of the brain; but perhaps even lead to better machines. Besides, the computer does have the upper hand when it comes to certain tasks: It will navigate databases, and perform complicated calculations with a zest and speed overpowering any human.¹⁶

One important difference rests with the overall strategy employed. While the computer has separate units for storing and processing, these two tasks are delegated to intermingled neuronal networks. We do not have a hard-disk on which we can store information at a safe distance from our executing powers. On the contrary, the connections between neurons are responsible for both memory and the implementation of an assignment. The strengthening of neural circuits consequently impacts on both storage of memory and our capacity to utilize that memory.

¹⁶For more on the comparison try: Sejnowski T, Delbruck T. The language of the brain. *Scientific American*, October (2012) 54–59.

Another point is that the synapses change their “status” continuously. By status I mean how they react to incoming signals, and how likely they are to pass on a signal. The brain is organic and unpredictable—constantly renewing itself. Buy a laptop, and it has the same electrical circuits ten years later. You may, of course, add a memory card, upgrade the programs, and add all your photos; but the machine itself is pretty much the way it was when you bought it. Most likely it is outdated, if ten years old, but the problem is solved by buying a new one—your head is constantly updated and can thus serve you (reasonably) well even if it is a hundred years old. Fortunately, because you cannot exchange it for a newer version.

The brain is not set up to detect and process information in a “logic” and orderly fashion. Our eyes do not scan the field of vision for all possible details, but are tuned to find useful features such as colours that suggest the presence of fruit (typically red and orange). In a similar fashion the hearing system is tuned to sounds deemed particularly relevant, especially the sound of a human voice. Various processes, including those driven by emotions or hormones, modulate our senses in order to skew focus toward what is most pertinent for survival.¹⁷

The number of synapses is estimated at a hundred trillion (10^{14}). This is comparable to the size of memory (bytes) in supercomputers. The brain, however, has a speed problem in that the communication between neurons is slow. The neurons require a few thousands of a second to react on an incoming message, and the axons can at the best transmit a few hundred signals per second—typically a lot less. In comparison, it takes only a billionth of a second to turn on or off a particular computer switch. Not surprisingly, the computer wins in well-defined tasks requiring speed.

The brain demands an immodest share of the body’s nutrients and oxygen: some 20 % even though it only stands for 2 % of body mass. Yet, compared to a computer it is economical. It runs on the equivalent of 20 W, which is roughly what is required to keep your laptop going—the more comparable supercomputers require a lot more.

Conscious processing only deals with one thing at the time, while your unconscious brain uses massive parallel processing. The latter is true for advanced computers as well, but the brain has an edge—at the least in certain situations. The brain has a way of considering a variety of solutions simultaneously; which is why you, and not the machine, can recognize a friend at the market in Marrakech, even if you only spot a glimpse of a face that you have not seen for years.

We humans follow instincts and gut feelings—whatever seems reasonable at the spur of the moment—while computers tend to finish their analysis before considering a conclusion. We have a fast and efficient system of evaluation, based on the parallel processing of the unconscious brain, and a slower alternative where consciousness grabs control. The unconscious takes care of numerous processes, including breathing and reflexes, but it also helps out in situations where the

¹⁷See, for example, Theunissen FE, Elie JE. Neural processing of natural sounds. *Nature Reviews Neuroscience* 15 (2014) 355–366.

conscious brain is pondering particular problems. I sense it when I try to solve a sudoku. In order to find the missing number in a field, it is sufficient to take a quick look at the set of eight numbers present and “ask the unconscious”. Normally it comes up with the right digit in the blink of an eye. However, I do not always trust this part of the brain—after all, it is not “me”—and consequently end up carefully counting from one to nine in order to spot the missing number.

Consciousness is a slow and cumbersome entity, but it does give you a chance to evaluate situations. It also gives you an illusion of being in charge.

Several scientists, Stanislas Dehaene in particular, have demonstrated that you can take advantage of information that was never passed on to your conscious mind.¹⁸ Consider a situation where you are presented with a printed word but only for 30 ms, which is too short to read the word. Alternatively the word is directed to only one eye while the part of the brain engaged in visual processing is busy interpreting signals from the other eye. In situations like these, you have no clue as to what the word is; yet the text may help you answer other questions. If the word was “six”, people are more likely to respond correctly to the question, “How many legs do an insect have?” Your unconscious brain holds information that is not passed on to you, yet the information is accessible when deemed useful by the unconscious brain. The example accentuates the relevance of listening to intuition before offering an answer. Then again, if the visual glimpse was of the word “eight”, the answer suggested by your intuition could easily be wrong.

The fact that the same structures of the brain are responsible for both memory and processing creates a problem. The computer may hold on to a formidable database without that hampering its processing because the memory is gathered on a separate disk. The processors are free to work elsewhere. Searching through a database may take some time, but the search should not block the progression toward a sensible response. In the brain, memory and processing is a question of activity and modulations in “all purpose” neurons. This situation requires a strict balance: If synapses and nerve circuits are designed to be highly stable, the memory is safely stored, but new information is hard to add and the processing may be hampered. On the other hand, if the system is too plastic, we may adapt easily, but have limited capacity for memory. Novel information will tend to wipe out the old one. The point has been demonstrated by looking at the hippocampus. Adult neurogenesis here promotes the formation of new memories, but whether in infancy or adulthood, it is accompanied by the loss of established memories.¹⁹

It should come as no surprise that the brain turns gradually less plastic as we age. Infancy is designed to absorb information—to learn and get wise—while in adult life one ought to hang on to knowledge that has proven useful. The capacity for

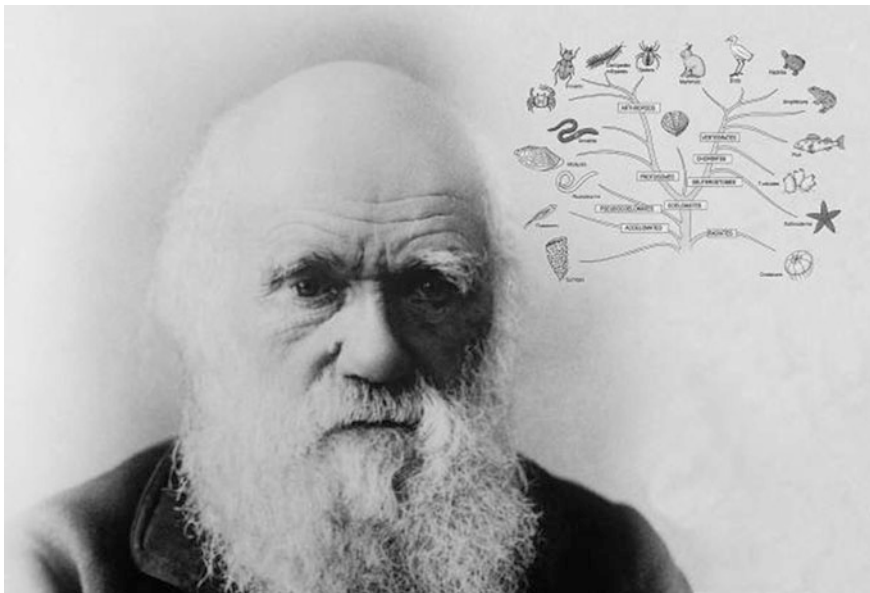
¹⁸Dehaene S. *Consciousness and the Brain: Deciphering How the Brain Codes Our Thoughts*. (2014, Viking).

¹⁹Akers KG et al. Hippocampal neurogenesis regulates forgetting during adulthood and infancy. *Science* 344 (2014) 598–602.

learning new trades is given up for the capacity to retain information already present.

The point is particularly relevant when it comes to babies. Their brains have a strong penchant for learning. Various lines of research suggest that for the first two years of life, we can only generate brief memories (referred to as infantile amnesia).²⁰ At 2–3 years the infant may recall facts and events a bit longer, but memory is still ephemeral because the hippocampus has not yet matured. The capacity to form memories that can later be recalled improves slowly from then on. In other words, the infants are tuned to learn (motoric and related knowledge that is not meant for conscious recall) rather than to gather recallable information, and for this purpose they generate new neurons. The production of neurons slows down after the age of three, which corresponds to the age from which adults have their first recollection.

There is no exact limit as to storage space in the brain, but it is designed to constrain storage in order to secure power of processing. Yet, the restrictions, as to how much knowledge we have, seem to be primarily a question of problems with *retrieving* information rather than of *storing*.



Neither pocket knife nor computer share the brain's aptitude to experience events and deliberate on matters. The brain also wins when it comes to creativity and finding strange associations. (The photo of Darwin is Public Domain)

²⁰Callaghan BL, Li S, Richardson R. The elusive engram: what can infantile amnesia tell us about memory? *Trends in Neuroscience* 37 (2014) 47–53.

The brain will never operate like a computer, the question is whether we can make computers operate more like brains? Several scientists are working on that assignment because they realize that *neuromorphic* machines have certain advantages.

The traditional switch that forms the core of computers can take on two values; on or off, 0 or 1. We refer to this as a *digital* system. The neurons, on the other hand, receive stimuli from a range of synapses, and it is the combined sum of these signals that guide the cell toward firing, or not firing, its own signal. Besides, each synapse can have an adjustable impact. This is a typical *analogue* system in that it is based on continuous variables. Neuromorphic computers aim toward a similar analogue modality.

One advantage of this strategy is that the system is less vulnerable. In a digital unit, having one switch in the wrong position may create havoc to the whole system, while it matters less if one of the many components delivering input to the analogue cell should malfunction. The final decision to pass on or not to pass on a signal is likely to be right anyway. The system is consequently less susceptible to damage. You lose neurons every day throughout your adult life, but the brain still functions reasonably well. As neuromorphic units do not separate stored memory from required processing, they also waste less time on retrieving information and require less energy.

The benefits of a neuromorphic design have led NASA to support work on this strategy with the idea of creating control units for their next Mars vehicle.²¹ So far, the best neuromorphic chip is arguably a design named TrueNorth, which is constructed by IBM.²² It contains 5.4 billion transistors wired together to form an array of one million “neurons” that talk to one another via 256 million “synapses”. A machine based on this chip performs complex tasks, such as face recognition, both faster and with less use of energy than conventional computers.

It has been claimed that computers only perform tasks that a human also could do—if equipped with pen and paper as well as an infinite amount of patience and time. Human imagination, on the other hand, bestows us with true creativity in a way that surpasses machines. Perhaps neuromorphic machines some day will narrow this gap.

The way I see it, there is primarily one advantage and one disadvantage of having a head full of neurons rather than chips: The brain offers us respectively good and bad feelings. You can design computers that pretend to have feelings. People who are easily fooled, or particularly empathetic, may try to comfort an apparently sad robot—but they are duped. There are no feelings inside that box. Neither does the robot *know* that it exists. I believe we will never create artificial intelligences with the capacity to experience anything—at least not in the meaning of the word “experience” that we humans are accustomed to. It is a faculty unique to the process of evolution. Consciousness, in my terminology, is what makes us different from machines. Your laptop is subject to the whims of *your* feelings.

²¹Check the Internet page of Massimiliano Versace (<http://maxversace.com/news>).

²²Service RF. The brain chip. *Science* 345 (2014) 614–616.

That said we already do an excellent job of designing robots that *appears* to be pretty much like us. So far nobody have collected the Loebner Prize set up in 1990 for the first computer to really fool the scrutiny of professional judges; that is, to pose as an adult, reasonably intelligent human. Subtleties of language seem almost impossible to program. On the other hand, most people are easy to fool; in fact, they quite often prefer it that way. When reading a novel or watching a movie we like to believe what we see—regardless of the improbability of the story. Thus many people are happy to let a robot be part of the family, for example Jibo,²³ or to have a lasting love affair with a voice fit, animated character taken from cartoons (it responds to your oral or written messages).²⁴

Theoretically, it should be possible to reconstruct a nervous system, molecule by molecule; or design a computer with the exact qualities of a human brain. For all practical purposes, however, this seems impossible. The situation is comparable to the question of whether we can travel to the furthest galaxies. We can hardly state that this is theoretically impossible, but with 12 (or more) billion light years to go, the task still stands as unfeasible.

Although some people worry about super-intelligent machines,²⁵ I do not lie awake fearing that the latest version of supercomputer decides to conquer the world. Even after having viewed all the Matrix films, I consider this a highly unlikely scenario. Occasionally it may seem difficult to turn the device off, but most things can be easily killed. Bullets and bombs do it for living organisms, cutting the power supply stops artificial intelligence. There are ethical reasons to shy away from the former, while few people feel morally obliged to maintain life-support for a malevolent computer. This planet continues to belong to us (or other biological forms of life)—for good or bad.

Computers are tools, and as such they are becoming ever more indispensable—that too for good or bad. We have developed a possibly dangerous dependency. They are increasingly integrated into human bodies, for example, in the form of pacemakers and hearing aids. In the future, people may receive a computer implant in the head as a baptism present—not to control their life but rather to help them. If so, health and happiness will require not only medical assistance, but also computer expertise, which is a problem if one suddenly finds oneself without these services. Thus in a way computers may conquer the world, in the sense that we, and perhaps the stability of the entire biosphere, will be at great perils without them. They take on an ever larger portion of human work tasks. In the future I would not be surprised to see a job advertisement with the note, “Humans need not apply”.

²³Jibo is arguably the best “family” robot around. See <http://www.newscientist.com/article/dn25881>.

²⁴In Japan this has become a trendy option, or a serious problem, depending on perspective. In a population already infatuated with their Anime and Manga industry, the obvious next choice is to let followers match up with their character of choice. Apparently men are particularly happy with this sort of affair—which, if it spreads outside Japan, may solve the problem of overpopulation.

²⁵Bostrom N. Get ready for the dawn of superintelligence. *NewScientist*, July 5 (2014) 26–27.

One last parallel. If the computer has problems, you may try to fix it yourself, but you will often need the help of someone with more competence. The expert is unlikely to know the details of your computer, but by possessing general computer skills, he may still be able to solve the issue. When suffering from mental disorders people seek the help of a psychologist or a psychiatrist. The more knowledge you gain as to how the brain (or the computer) operates, the more likely you are to avoid or cure nuisances yourself. As too many people have experienced, the brain is more difficult to mend than a computer; which is why you ought to go on reading this book.



Life on Earth appeared soon after the conditions required for life became available, but intelligent life took close to four billion years. Was it an obvious, or necessary, consequence of the conditions on this planet?

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