Eye, Brain and Vision

by the book David Hubel's "Eye, Brain and Vision"

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Intuition tells us that the brain is complicated. We do complicated things, in immense variety. We breathe, cough, sneeze, vomit, mate, swallow, and urinate; we add and subtract, speak, and even argue, write, sing, and compose quartets, poems, novels, and plays; we play baseball and musical instruments. We perceive and think.

How could the organ responsible for doing all that not be complex?

The brain contains 10^{12} (one million million) cells. The total number of interconnections in the brain should be around 10^{14} to 10^{15}. Anatomical complexity is a matter not just of numbers; more important is intricacy of organization, something that is hard to quantify.

The main building blocks of the brain are the nerve cells, or **neurons**.
They are not the only cells in the nervous system: a list of all the elements that make up the brain would also include glial cells, which hold it together and also help nourish it and remove waste products; blood vessels and the cells that they are made of; various membranes that cover the brain; and the skull, which houses and protects it.

The **cell body** (body of neuron) has the usual globular shape and contains a nucleus, mitochondria, and the other organelles that take care of the many housekeeping functions.
From the cell body comes the main cylinder - shaped, signal-transmitting nerve fiber, called the **axon**.
Besides the axon, a number of other branching and tapering fibers come off the cell body: these are called **dendrites**.
The entire nerve cell the cell body, axon, and dendrites is enclosed in the cell **membrane**.
The cell body and dendrites receive information from other nerve cells; the axon transmits information from the nerve cell to other nerve cells.

The axon can be anywhere from less than a millimeter to a meter or more in length; the dendrites are mostly in the millimeter range. Near the point where it ends, an axon usually splits into many branches, whose terminal parts come very close to but do not quite touch the cell bodies or dendrites of other nerve cells. At these regions, called **synapses**, information is conveyed from one nerve cell, the **presynaptic cell**, to the next, the **postsynaptic cell**.
The signals in a nerve begin at a point on the axon close to where it joins the cell body; they travel along the axon away from the cell body, finally invading the terminal branches. At a terminal, the information is transferred across the synapse to the next cell or cells by a process called **chemical transmission**.
Nerve cells come in many different types. No one knows how many types exist in the brain, but it is certainly over one hundred and could be over one thousand. No two nerve cells are identical.

- What happens when information is transferred from one cell to another at the synapse?

In the first cell, an electrical signal, or impulse, is initiated on the part of an axon closest to the cell body. The impulse travels down the axon to its terminals. At each terminal, as a result of the impulse, a chemical is released into the narrow, fluid-filled gap between one cell and the next the synaptic cleft and diffuses across this 0.02-micrometer gap to the second cell.
There it affects the membrane of the second cell in such a way as to make the second cell either more or less likely to fire impulses.

The nerve cell is bathed in and contains salt water. The fluids both inside and outside the cell contain chloride, potassium, sodium, and calcium ions (Cl , K+, Na+ and Ca 2+).
In the **resting state**, the inside and outside of the cell differ in electrical potential by approximately one-tenth of a volt, positive outside. The signals that the nerve conveys consist of transient changes in this resting potential, which travel along the fiber from the cell body to the axon endings.

How the charge across the cell membrane arises.
The nerve-cell membrane, which covers the entire neuron, is very complicated structure. It is not continuous, like a rubber balloon or hose, but contains millions of passages through which substances can pass from one side to the other.
Some are pores, of various sizes and shapes. Some are more than just pores; they are little machine-like proteins called pumps, which can seize ions of one kind and eject them from the cell, while bringing others in from the outside.
Other pores, called channels, are valves that can open and close. What influences a given pore to open or close depends on what kind of pore it is. Some are affected by the charge across the membrane; others open or close in response to chemicals floating around in the fluid inside or outside the cell.

The charge across the membrane at any instant is determined by the concentrations of the ions inside and out and by whether the various pores are open or closed.

- Pores are affected by the charge and the charge is determined by the pores, i.e. these two things can be interdependent.
- In short, the opening of potassium pores results in a charge across the membrane, positive outside.

When the nerve is at rest, most but not all potassium channels are open, and most sodium channels are closed; the charge is consequently positive outside.
Making the membrane less positive outside depolarizing it from its resting state results in the opening of the pores. The effects are not identical for the two kinds of pores: the sodium pores, once opened, close of their own accord, even though the depolarization is maintained, and are then incapable of reopening for a few thousandths of a second; the potassium pores stay open as long as the depolarization is kept up.

For a given depolarization, the number of sodium ions entering is at first greater than the number of potassium ions leaving, and the membrane swings negative outside with respect to inside; later, potassium dominates and the resting potential is restored.

This sequence of events, in which pores open, ions cross, and the membrane potential changes and changes back, constitute an **impulse.**

A depolarization of the membrane making it less positive - outside than it is at rest is what starts up the impulse in the first place.

If a depolarization of the membrane will be small then the membrane come back to the resting state very soon.
If a depolarization will be very large then the membrane potential is reversed in sign, relative to the resting potential: instead of being 70 millivolts, positive outside, it becomes 40 millivolts, negative outside.

The reduction in potential across the membrane, with ultimate reversal of potential, doesn't take place all at once along the fiber's length, because transfer of charge requires time.
It starts in one place and spreads along the fiber at a rate of 0.1 to 10 or so meters per second. At any instant there will be one active region of charge reversal and this reversal will be traveling away from the cell body.
This event constitutes the impulse.
One can see that the impulse is not at all like the current in a copper wire. It is the event, the impulse in the nerve, that travel.

One important feature of a nerve impulse is its all - or - none quality.
The magnitude of the reversed potential traveling down the nerve (that is, the impulse) is determined by the nerve itself, not by the intensity of the depolarization that originally sets it going.

It is analogous to any explosive event. How fast the bullet travels has nothing to do with how hard you pull the trigger.

For many brain functions the speed of the impulse seems to be very important, and the nervous system has evolved a special mechanism for increasing it.
Glial cells wrap their plasma membrane around and around the axon like a jelly roll, forming a sheath that greatly increases the effective thickness of the nerve membrane.
This added thickness reduces the membrane's capacitance, and hence the amount of charge required to depolarize the nerve.

The layered substance, rich in fatty material, is called **myelin**. The sheath is interrupted every few millimeters, at **nodes of Ranvier**, to allow the currents associated with the impulse to enter or leave the axon.
The result is that the nerve impulse in effect jumps from one node to the next rather than traveling continuously along the membrane, which produces a great increase in conduction velocity.

White matter in the brain and spinal cord consists of myelinated axons but no nerve cell bodies, dendrites, or synapses.
Grey matter is made up mainly of cell bodies, dendrites, axon terminals, and synapses, but may contain myelinated axons.

- How are impulses started up in the first place, and what happens at the far end, when an impulse reaches the end of an axon?

A nerve impulse arrives at the axon terminal and causes special neurotransmitter molecules to be released.
Transmitter molecules are much smaller than protein molecules but are generally larger than sodium or calcium ions.
Acetylcholine and noradrenaline are examples of neurotransmitters.
When these molecules are released from the presynaptic terminal they quickly diffuse across the 0.02-micrometer synaptic gap to the postsynaptic membrane.

These neurotransmitters act on the postsynaptic membrane either to lower its membrane potential or to keep its membrane potential from being lowered.
If the membrane potential is lowered, the frequency of firing increases; such a synapse is called **excitatory**.
If instead the membrane is stabilized at a value above threshold, impulses do not occur or occur less often; in this case, the synapse is termed **inhibitory**.
Whether a given synapse is excitatory or inhibitory depends on which neurotransmitter is released and which receptor molecules are present.

Any one nerve cell is contacted along its dendrites and cell body by tens, hundreds, or thousands of terminals, therefore at any given time the level of the membrane potential is the result of all the excitatory and inhibitory influences added together.
A single impulse coming into one axon terminal generally has only a minuscule effect on the next cell, and the effect lasts only a few milliseconds before it dies out.
When impulses arrive at a cell from several other nerve cells, the nerve cell sums up, or integrates, their effects. In this case the depolarization will be enough to generate impulses, usually in the form of a repetitive train.

The site of impulse initiation is usually where the axon leaves the cell body.
The more the membrane is depolarized at this point, the greater the number of impulses initiated every second.
Almost all cells in the nervous system receive inputs from more than one other cell. This is called **convergence**.
Almost all cells have axons that split many times and supply a large number of other nerve cellsperhaps hundreds or thousands. This is **divergence**.

Some axons are so short that no propagated impulse is needed; by passive spread, depolarization at the cell body or dendrites can produce enough depolarization at the synaptic terminals to cause a release of transmitter. That is the information can be transmitted without impulses.
In our retinas, two or three of the five nerve-cell types function without impulses.
An important way in which these signals differ from impulses is that their size varies depending on the strength of the stimulus. They are therefore often referred to as **graded signals**.
Remember that impulses, on the contrary, do not increase in size as the stimulus increases; instead, their repetition rate increases.

One can think of the central nervous system (the brain and spinal cord) as consisting of a box with an input and an output.
The input exerts its effects on special nerve cells called **receptors**, cells modified to respond to "outside information".

This information can take the form of light to our eyes; of mechanical deformation to our skin, eardrums, or semicircular canals; or of chemicals, as in our sense of smell or taste.
In all these cases, the effect of the stimulus is to produce in the receptors an electrical signal and consequently a modification in the rate of neurotransmitter release at their axon terminals.

At the other end of the nervous system - the output: the motor neurons, nerves that are exceptional in that their axons end not on other nerve cells but on muscle cells.
All the output of our nervous system takes the form of muscle contractions, with the minor exception of nerves that end on gland cells.
The wiring diagrams for the many subdivisions of the central nervous system one can illustrate by this picture.

On the left of the figure there are the receptors, an array of information - transducing nerves each subserving one kind of sensation such as touch, vibration, or light.
These receptors form the first stage in some sensory pathway.
Fibers from the receptors make synaptic contacts with a second array of nerve cells, the second stage in our diagram; these in turn make contact with a third stage, and so on.
Sometimes three or four of these stages are assembled together in a larger unit, which is called a structure. These structures are the aggregations of cells, usually plates or globs.

When a structure is a plate, each of the stages forming it may be a discrete layer of cells in the plate.
A good example is the retina, which has three layers of cells and, loosely speaking, three stages.
When several stages are grouped to form a larger structure, the nerve fibers entering from the previous structure and those leaving to go to the next are generally grouped together into bundles, called **tracts**.
Remark, at the input end we have not just one but many sensory systemsvision, touch, taste, smell, and hearingand that each system has its own sets of stages in the brain. When and where in the brain the various sets of stages are brought together, if indeed they are brought together, is still not clear.

In tracing the visual system from the receptors further into the brain, one may find that it splits into separate subdivisions. These subsystems might deal separately with eye movements, pupillary constriction, form, movement, depth, or color. Thus the whole system diverges into separate subpathways. Moreover, the subpaths may be many, and may differ widely in their lengths. Some paths have many structures along the way and others few.

When the path from input to output is very short, we call it a **reflex**.
In the visual system, the constriction of the pupil in response to light is an example of a reflex, in which the number of synapses is about six.
In the most extreme case, the axon from a receptor ends directly on a motor neuron, i.e. we have from input to output, only three cells (receptor, motor neuron, and muscle fiber) and just two synapses, it is called a **monosynaptic reflex arc**.
That short path is activated when the doctor taps your knee with a hammer and your knee jumps.

At the output end, we find not only various sets of body muscles that we can voluntarily control, in the trunk, limbs, eyes, and tongue, but also sets that subserve the less voluntary or involuntary housekeeping functions, such as making our stomachs churn, our water pass or bowels move, and our sphincters (between these events) hold orifices closed.
We also need to qualify our model with respect to direction of information flow. In almost every case in which information is transferred from one stage to the next, reciprocal connections feed information back from the second stage to the first.
Further, we will speak about the visual system.

When we look at the outside world, the primary event is that light is focused on an array of 125 million receptors in the retina of each eye.
The receptors are nerve cells specialized to emit electrical signals when light hits them.
The task of the rest of the retina and of the brain proper is to make sense of these signals, to extract information that is biologically useful to us.
The result is the scene which we see, with all its intricacy of form, depth, movement, color, and texture.

The receptors and the next two stages are contained in the retina.
The receptors are the **rods** and **cones**; the optic nerve, carrying the retina's entire output, is a bundle of axons of the third - stage retinal cells, called retinal ganglion cells.
Between the receptors and the ganglion cells are intermediate cells, the most important of which are the bipolar cells.
The optic nerve proceeds to a way station deep in the brain, the lateral geniculate body.
After only one set of synapses, the lateral geniculate sends its output to the striate cortex, which contains three or four stages.
Each of the columns in our diagram is a plate of cells in cross section. Each of the columns of cells in the figure represents a two-dimensional array of cells.

All the cells feeding into a single cell at a given stage (such as the bipolar cells that feed into a single retinal ganglion cell) are grouped closely together.
In the case of the retina, the cells connected to any one cell at the next stage occupy an area 1 to 2 millimeters in diameter; they are certainly not peppered all over the retina.
Thus there is no the connections within the retina are longer than about 1 to 2 millimeters.
For most retinal ganglion cells the best stimulus turns out to be a small spot of light of just the right size, shining in just the right place.

Consider how our eyes move. Each eye is roughly a sphere, free to move like a ball in a socket.
Each eye has six extraocular muscles attached to it and moves because the appropriate ones shorten.
Easily see from the picture that for one eye, say the right, to turn inward toward the nose, a person must relax the external rectus and contract the internal rectus muscles.
Consequently any eye movement is made by contracting one muscle and relaxing its opponent by just the same amount.
The same is true for almost all the body's muscle movements.

Furthermore, any movement of one eye is always part of a bigger complex of movements. If we look at an object a short distance away, the two eyes turn in; if we look to the left, the right eye turns in and the left eye turns out; if we look up or down, both eyes turn up or down together.
All this movement is directed by the brain. Each eye muscle is made to contract by the firing of motor neurons in a part of the brain called the **brainstem**.

To each of the twelve muscles there corresponds a small cluster of a few hundred motor neurons in the brainstem.
Each motor neuron supplies a few muscle fibers in an eye muscle.
These motor neurons receive inputs from other excitatory fibers.
To obtain a movement such as convergence of the eyes, we would like to have these antecedent nerves send their axon branches to the appropriate motor neurons, those supplying the two internal recti. We would like both antecedent sets of cells to fire together, to produce the contraction and relaxation in the same time.
This is one way in which one can get coordinated movements involving many muscles.
Practically every movement we make is the result of many muscles contracting together and many others relaxing.