Vision

The theme of the next two lectures is vision. It has some technical material about neurons and brain anatomy. You can skip this if you like; that won't handicap your understanding of the rest of the material, but hey! – there are no exams; you might as well go along for the ride. Before I get into the technical stuff however, I would like to tell you two stories. You can think of them as background material for vision in particular and consciousness in general. Then I want to review briefly the plot from my last lecture and that will take us naturally into the subject of vision. The first story concerns a construction worker named Phineas Gage. On September 13 of the year 1848, Gage was setting explosives to make way for a railroad track. The procedure was to drill a hole in the rock and drop in the explosives. Then sand was poured down the hole and compacted with a tamping iron. The point of this of course, was to prevent the explosion from venting through the hole. Gage was distracted momentarily and did not realize that the sand had not yet been poured. He tried to tamp it and the gunpowder fired shooting the tamping iron through his skull. The rod was 1 ¼" in diameter and about 3 ½ feet long. It passed through the side of his face, through his brain, through the top of his skull, and off into space. As you might expect, this had some effect on his personality. He was still an intelligent and able-bodied adult; he had no impairment in movement or speech. He had no memory problems regarding his life either before or after the accident. However, he had been a diligent and self-disciplined worker before the accident. Afterwards, according to one of his contemporaries, he was fitful, irreverent, indulging at times in the grossest profanities, impatient of constraint or advice, obstinate, capricious, and vacillating.

What are we to make of this bizarre incident? Evidently, the brain has a lot of redundancy. I have a hole in my brain about the size of a ping-pong ball where a brain tumor used to be growing many years ago. Perhaps this has affected me in some way, but my friends have been too nice to point it out. The second point is that the brain goes in for distributed intelligence. If you are looking for one spot in the brain where personality is stored or one place where consciousness takes place, you will be disappointed. This is certainly true of vision. Seeing, as you will see, takes place all over the brain.

My next story tends to a slightly different conclusion. Einstein died on April 17, 1955 of a burst aortic aneurysm. He had specifically requested that his remains be cremated and scattered in secret. He hated being idolized and was afraid that some weird cult would idolize his remains. The autopsy on Einstein was performed by Thomas Stolz Harvey, a young pathologist. Despite the fact that Harvey was not in any way a brain specialist, he removed Einstein's brain. He also removed his eyes and gave them to Einstein's ophthalmologist who put them in a safe deposit box in New York City. So far as I know they are still there. He dissected the brain into about 240 distinct blocks encased in a plastic-like material called *celloidin*. Within months, he was fired from his job at the hospital for refusing to surrender the specimen. Harvey then took the brain with him to a new job in a biological testing lab in Wichita, Kansas. It was kept in a cider box stashed under a beer cooler. From there, he moved to Weston, Missouri, and practiced medicine until he failed a state competency exam. He started working on an assembly line in Lawrence, Kansas, and again, he took the brain with him. He claimed that he was studying the brain in his spare time and would soon publish a report. He kept saying that for 43 years.

In the early 1990's, Harvey returned to Princeton. He met a magazine writer named Michael Paterniti. They decided to take the brain with them on a cross-country trip to California to meet Einstein's granddaughter. The brain made the trip in the trunk of a Buick Skylark. Paterniti eventually published a book about the trip called *Driving Mr. Albert.* During these years, Harvey would offer pieces of the brain to various neuroscientists, but eventually he returned what was left of the brain to the pathology department at the University Medical Center at Princeton.

So was Einstein's brain like everyone else's? No, it was not. There is a region just above and behind your ears called the parietal lobes. There is a portion of Einstein's brain there – the inferior parietal lobe – that is 15% larger in Einstein's brain than in yours. There's a neighboring region in yours – the parietal operculum – that's missing in Einstein's brain. The usual interpretation is that during early childhood development one region of his brain grew at the expense of the other.

What does this mean in terms of mental functioning? The enlarged region is an area associated with mathematical thought, visual-spatial cognition, and the imagery of movement. The fact that the enhanced area is associated with mathematics is hardly surprising and Einstein was noted for using visual imagery together with mathematics in formulating his theories. The missing area may be associated with speech production. We know that Einstein didn't start talking until the age of three and he failed the Technology Institute language exams when he was 15. At any rate, the loss was not permanent. He was famous for his elegant prose in later life.

These two anecdotes taken together are puzzling. On one hand we know that damage to specific regions in the brain create a variety of neurological problems. If you have read "The Man Who Mistook His Wife for a Hat" by Oliver Sacks, you will know of some of the more bizarre cases. We can also speculate that the extra 15% in the inferior parietal lobe was responsible for Einstein's powers of mathematical imagination. On the other hand, P. Gage's injury left most of his mental functioning intact. You will see as we go along that the brain uses distributed parallel processing on a massive scale. We also know that the brain is sometimes "rewire" itself to work around damaged regions. We call this ability *plasticity*. Whether these two features together account for the remarkable case of Phineas Gage is another matter.

Now let's get back to last week's lecture. I introduced you to Descartes and his dualism. He claimed that there were two "substances" as he called them. Today we might say that there are two realms or two ways in which things might exist. He called them body and mind. Body refers to everything physical but particularly the brain with all its neurons, synapses, glial cells, etc. "Mind" refers to another kind of reality. This is the realm of the soul, the realm of thinking and praying, it is the same realm as God and the heavenly powers. There is nothing physical about mind and it has no location in space. This makes good intuitive sense until you start to think about how something purely non-physical is going to interact with something completely physical. Then you have to allow for philosophical zombies and ghosts and suddenly dualism seems like a bad idea. The main alternative to dualism is monism. This comes in many varieties but the basic idea is that there is only one kind of stuff and it's all physical. I'll talk more about this in later lectures.

Descartes left us with two other issues however. He was fascinated with automatons, or as we would call them, robots. He thought that perhaps we are just sophisticated organic automatons. In modern terms – perhaps our minds are really computers, and to push this idea a little further, perhaps we could build and program computers that would be conscious. Nowadays we call that idea "strong AI." That will be my next topic after vision.

The other problem had to do with vision. Descartes had an idea that the image that is projected on the retina was somehow projected again somewhere inside the brain. We called that the Cartesian theatre and it didn't seem like a very promising idea. But now the ball is in our court, how do we see? This is an important question for at least two reasons. The brain is a very complicated place, I'll describe in a bit just how complicated, and we probably know more about vision than anything else that goes on there. If we could just understand vision then we might have a leg up on understanding the brain as a whole. The second reason is that vision is still mysterious. Apparently, visual processing goes on at something like 20 separate locations in the brain and we have only vague ideas about what goes on in them.

So what does the thinking in your brain? It turns out that all the thinking is carried out by one very special kind of cell called a neuron. Neurons are ordinary in the sense that they have all the usual apparatus that a cell needs to carry on business: a nucleus, DNA, organelles, etc., but there are two additional structures that will concern us. On one end of the cell there is a "bush" of protruding structures call dendrites. They are actually extensions of the cell and there are very many of them, a typical neuron might have 10,000. On the other end of the neuron is a long structure that looks like some kind of cable. These are called axons. Neurons just have one each, but they can be very long. The nerves in your spinal column for example, are axons that originate in neurons in your brain. The neuron is basically an electrical device. Electrical signals come in through the dendrites, are analyzed in the body of the cell, and depending on what the neuron decides, a signal will or will not be propagated down the axon where it will eventually make contact with other dendrites. Here is a very fanciful description of what happens. Suppose one dendrite gets a signal that signifies “grey,” another gets the signal for “big ears,” another for “trunk,” and still another for “tusks.” The neuron considers all this information and sends a signal down it’s axon signifying “elephant!” I suppose that if you are in elephant country that information would be useful for many reasons, so the axon will contact the dendrites of many other neurons, which will consider the matter further.

Since we are talking about electricity, I need to adopt the persona of an electrical engineer for a moment. The signals coming down the dendrites are analog signals. That is to say they can have any value, negative or positive, within some range. Some of these signals are excitatory, that is to say they make things happen. Others are inhibitory, they tend to prevent things from happening. And when you add them together they tend to cancel one another. You might think of the excitatory signals as simply positive and the inhibitory signals as negative. You add positive and negative together and you get something closer to zero. (This is a slight oversimplification, but it makes the whole operation easier to explain.) The other important point is that they are decremental, that is to say they tend to die out as they propagate down the dendrites. Signals that start closer to the cell body will arrive stronger than those that start out farther away.

So all these signals coming down 10,000 dendrites arrive at the cell body and are simply added up, a simple mathematical operation. Depending on what the sum is, the neuron will send out a signal down its axon, and here begins a new phase in the operation: the signal isn’t analog but digital. More precisely, it consists of a series of spikes. The spikes are all the same amplitude, but they come at varying intervals almost like Morse code, a series of dots and dashes. Part of the reason for making this switch is that digital signals travel faster, farther, and with less noise than analog signals, and the axon signals may have a long way to go.

Finally, the signals arrive at the end of the axon and here begins the most interesting part of the journey; the digital signals are converted to chemical signals! Now I have to abandon my role as an electrical engineer and momentarily become a chemist. There is a small gap called the synapse between the end of the axon and the beginning of the dendrite. The taxon terminates in a little bulb called the presynaptic cell, wrapped up in a thin membrane. Inside the cell are little vesicles. You might think of them as miniature water balloons, but in this case they are not filled with water but with one of several neurotransmitters. All this is immersed in a kind of a chemical soup containing a myriad of protein molecules and some simple metallic cations. The one that concerns us here is calcium. A calcium ion has two electrons removed so it has a doubly positive charge. When the axon signal arrives at the end of its journey it attracts Ca ions into the cell where they break open the vesicles and release the neurotransmitter into the synaptic cleft. Depending on what chemical it is, it might produce an excitatory or inhibitory signal in the dendrite. The signal then propagates down into the cell body and the whole process starts over again.

Why bother? Why go to all the trouble to convert an electrical signal into a chemical signal and back again to an electrical signal? The answer is astonishing. It’s possible to do mathematical calculations with chemicals! In principle, anything you can do with your pocket calculator can be done with protein molecules. Even take logarithms and exponentials, evaluate polynomials, and solve quadratic equations. It’s not clear how many of these features the brain actually uses, but certainly some of them. So when I said that neurons did the thinking, that was not the whole truth. Some thinking takes place in the chemical soup surrounding the synapse. This is especially important for memory. I will get around to that at the end of the talk.

There’s one more thing I need to tell you about neurons: there are a lot of them! Roughly 100 billion. This is a famous number. There are 100 billion stars in our galaxy and 100 billion galaxies in the visible universe. Now remember each neutron has 10,000 synapses and each synapse has the capability of a small calculator. That means that your brain contains 10,000 times 100 billion small calculators. I have heard it claimed that this is roughly the number of all the leaves on all the trees in the Amazon River basin. It is also claimed that if we were to think of a light that was proportional in intensity to complexity, then a galaxy would shine like a dim bulb and our brains would be beacons visible across the universe. I don't know exactly what this means, I don't know how to quantify complexity, but at least it's fun to think about.

It's hard to think about thought and consciousness because of the enormity of this complexity in somewhat the same way that it is hard to think about evolution because of the enormity of the time span. That's one reason why I would like to concentrate on vision. It focuses our attention on a simpler subset of what goes on in the brain, somewhat like thinking about the evolution of a single species might give us some insight on how evolution works.

The natural starting point for any discussion of vision is the eyeballs. They are really parts of the brain that happen to protrude through two holes in the skull. The lens focuses an image of the outside world on the retina. Incidentally, the image is upside-down and it's projected on a two-dimensional surface. The fact that you see things right side up in 3-D should tell you that the brain has done some serious repackaging, but that is just the beginning. The inner surface of the retina is lined with little photoreceptors called rods and cones. The cones work in bright light and are sensitive to color. There are 5 million of them tightly clustered around the most sensitive part of the eye. There are 100 million rods more widely spread around the retina. They only see in black and white but are much more sensitive in dim light. In fact, these detectors are so sensitive that we have to take a brief look at quantum mechanics. We normally think of light as being composed of electromagnetic waves but in quantum mechanics we like to think of it as a stream of a vast number of particles called photons. The key idea here is that the rods and cones are so sensitive that they can respond to a single photon. This represents to a huge amount of data. To give you an idea of how much it's useful to use computer language. The basic unit of memory in a computer is the bit. A bit is either on or off, either yes of no. A byte is 8 bits and most modern computers use words that are 4 or 8 bytes long. In normal light your eyes would be taking in data at the rate of a billion bits per second. But your typical long novel only takes several megabytes to store, so your eyes are recording data at the rate of 20 or 30 copies of Tolstoy's *War and Peace* PER SECOND! It has probably occurred to you that nothing else in your brain works anywhere near that fast, so we have a serious problem. The serious problem the brain faces when it comes to visual processing is just this, how with its limited resources is it going to analyze this data quickly and comprehend it usefully? This question takes us into unchartered territory, and what we find there is profoundly mysterious. I would like to take you on a tour at least to the boundary of this region. We have already taken the first step, what are we to do with that billion bits of information?

Suppose you were designing a computer to analyze this data. How would you begin? I would like to throw out a few ideas. Here's one idea: discard redundant information. Let me show you what I mean by this. Take for example a stop sign. The one I have in mind has white lettering on a red background. Let's say that you see this on the street and one million of your cones register exactly the same shade of red. That's redundant information. It would only take a few neurons to say, "this is mostly red but some of it is white." The only places where we really need the information is at the edges between the colored regions. Let's see how the brain goes about finding edges.

The header for this podcast is a cartoon drawing of the retina. The first thing to notice is that it's hooked up backwards. Light has to pass through the yellow and blue layer to finally reach the rods and cones which are at the extreme right of the picture. When one of the photoreceptors picks up a photon it sends a signal "backwards" through the blue layer of bipolar cells. The bipolar cells in turn send a signal to the ganglion cells. The optic nerve is just the bundle of the axons of all the ganglion cells. There are two other kinds of cells in the picture, the horizontal cells and the amacrine cells. There are actually 20 different kinds of amacrine cells and they are not well understood, so I propose to ignore them completely. The horizontal cells are easier to understand. Remember the stop sign. We don't want to process the information from a million cones that are all saying "red." So the horizontal cells just average over a large number of adjacent cones and then subtract the average from the same cones so that all the cones that were seeing red are now not seeing anything. In this way we have discarded a lot of redundant information. The bipolar cells come in two varieties, ON cells and OFF cells. The ON cells respond when they see a bright spot on a dark background, the OFF cells respond when they see a dark spot on a light background. Of course there are red, green and blue cones, so there are bipolars that only see red spots, some that only see green spots and some that only see blue. At this point the data stream consists of millions of flickering spots.

Next come the ganglion cells; there are three different kinds that have come to be called M, P, and k cells. The bipolar cells connect to the ganglions in a very clever way so the myriad of flickering spots turn into three kinds of data. First there are the P cells. They carry information about color. They also have fine spatial resolution. You might say that P stands for presence. These cells tell where things are and what color they are. The M cells on the other hand have no color sensitivity and they have rather crude spatial resolution, but they are sensitive to motion: M for motion. This is hard to grasp; P cells know where the spot is but don't know if it moving. M's know that it's moving but don't know where it is!

The next stop is a small region in the thalamus at the back of the brain called the lateral geniculate nucleus or LGN for short. The optic nerve is wired up so that the right halves of the visual fields of both eyes are routed to the LGN on the left side of the brain and the left visual fields go to the LGN on the right. At this point there are eight streams of data on each side: red and green P cells, blue k cells, and the M cells from the right (or left) eye. The M and P cells are mapped to six layers in the LGN with k cells making thin layers in between. Until recently it seemed that the LGN had no function except as a kind of relay station to send signals to various parts of the brain. Now it's clear that it is much more than a passive relay. It serves to further eliminate redundancy, improve signal to noise ratio and, "repackage" the data for the brain's various agendas.

We were faced with the challenge of dealing with the vast amount of data taken in by the photoreceptors in your retina. Now the solution is beginning to emerge. First take the image apart and combine the "pixels" in such a way that no important information is lost. So far the process is fairly well understood. The next step is to put the picture back together but selecting only that part of the data that are important to what you are doing at the moment. To see how profound the selection process is – you know that when the ophthalmologist looks into your eye, he or she sees a network of blood vessels invaginating your retina. Chances are that you have never seen them despite the fact that you are looking through them. Your brain simply realizes that since they are always there, they are not important and so discards that part of every image you have ever looked at. How it makes such decisions is quite mysterious.

The first step in reassembling the image takes place in a region at the back of your brain variously called V1 or the primary visual cortex. We have a vague idea of what goes on here. V1, among other things, looks for arrays of spots that might line up to make edges.

At this point I have to stop and tell you a story. In 1959 David Hubel and Torsten Wiesel Were young postdocs at Harvard Medical School. They were doing experiments in which they placed microscopic electrodes in the visual cortexes of cats. The electrodes were so small that they could read the signal from a single neuron. They showed the cats things that might interest them, fish, mice, etc. There was no response except when the slide projector changed slides. Then an edge passed across the visual field and the neuron responded. They went on to win the Nobel Prize in 1981.

It then passes the information on to a region called V2, which tries to assemble the edges into coherent outlines. From there the data fan out to some 30 separate processing centers. Neuroscientists have tried to establish wiring diagrams for the brains of macaque monkeys by dissecting out the various neural pathways. The complexity of the wiring is baffling. We don't know exactly what signals are being passed through the various regions, but a vague pattern is apparent. The flow of visual information from V1 and V2 to other cortical areas depends on the type of information being processed. Information used to locate objects and detect their motion is sent to a more superior cortex; this is called the dorsal stream. Neurons in this region have binocular receptive fields and process P-channel information about object location and M-channel information about object movement. These neurons are responsible for producing our sense of spatial orientation, depth perception, and movement of objects in space. You might say that the dorsal stream is concerned with the “whereness” of objects. Information necessary to detect, identify and use color and shape information is sent to inferior cortical areas; this is the ventral stream. These neurons are responsible for processing information necessary for our abilities to recognize objects and colors, read text and learn and remember visual objects, e.g. words and their meanings. In the same sense that the dorsal stream is concerned with the “whereness” of objects, the ventral stream deals with the “whatness” of things.

And then a miracle occurs. All this comes together and we can read text and understand the words. We can recognize the face of a friend and discern her mood from subtle changes in expression. We can see an object and coordinate its image with our motor neurons in such a way that we can grasp it. We have only the vaguest idea how all this happens. But one thing is very clear and very important to my theme of consciousness: it does not happen all at one place. It is simply not true that all this visual stuff finally comes together in one small region of the brain and this is where consciousness “happens.” We now have the technology called functional MRI to see, and least crudely, where and when things happen in the brain. As it happens, it takes oxygen to think, and the process of removing oxygen from hemoglobin and metabolizing it creates a signal that can be detected with MRI technology. There is a tradeoff between spatial and temporal resolution, but the technology is good enough to make my point very forcefully. A subject was asked to look at faces and again at houses. Two quite different regions of her brain were “lit up.” Where then is consciousness? There is another point that is only apparent when we look at the engineering details of the brain. There are many parallel processes going on, but they are not all going on at the same rate. The time differences are small, less than one second, but they raise another problem, when is consciousness? The fact that all these various processes arrive at our consciousness as one integrated experience is what the philosophers call the “binding problem.”

Finally, the biggest question of all. What is the connection between all these neural processes and the actual experience of being conscious and seeing? Let’s say that I look at something that's red. All my red-sensitive bipolar cells spring into action. My ventral stream picks up the chorus. These are the *neural correlates* of seeing red. There is a *correspondence* between this brain activity and the experience of seeing red. What exactly is buried in those words "correlates" and "correspondence"? This is the central question in the philosophical study of consciousness; it's the problem of qualia to which I will return in a later lecture.