JEREMY WOLFE: What I'm going to do for the next three lectures is to talk about how we see. What I'm going to do today is talk about how we take information in. Next Tuesday, I'll talk about the fact that we take in two much information, more information than we can use. And we have to select amongst that information.

And on Thursday of next week, what I'll talk about is the fact that perception is never just a direct somehow registration of the outside world. It's always an act of interpretation of the world, and I'll talk about how we go about interpreting the information that we've gotten from the outside. I will be barely able to scratch the surface of the topic. I will abandon all discussion of the other senses, for instance, which is a great pity.

Now, it's true that I can barely scratch the surface of almost any topic in this course. But here the danger is greater because this is actually what I do for a living. And so on any little bit of this, I can talk forever. And so exactly how much of the surface I scratch will be determined by how far afield I end up going.

This slide is up there to illustrate in some sense those three bits. Let's see if I take the stage chalkboard light off. There we go. You want to go off? Then they can-- oh, then you can see a little bit better.

Well, you know, [INAUDIBLE] you can see stuff. This is Bruegel. Woo, that hurt. That's Bruegel's painting of the battle between the good angels and the bad angels. For me, the purpose is to say, look, it's clear that you see something.

It's clear that what you are seeing is an act of interpretation. In fact, you may not have particularly known that it was a battle between good angels and bad angels before you look at it, and it's also clear that even though you, in some sense, see the whole thing, you're not processing it fully, at least not all at once. So for instance, you may not have particularly noticed-- I don't know what he is. He's a really cool beast. I'm not sure if that's a bad angel falling or something.

But you probably hadn't particularly noticed this fish guy. Actually, in this picture, you're probably still not noticing the fish guy. He just looks like a blob. It's a great picture. Look at it sometime. And this guy's got very bad stomach problems, whatever he's doing.

OK, rather than continuing to try to look at a murky picture, let's go to a less murky picture. And let's start by talking about how you actually get information in from the visual system, which obviously involves-- come on, get off of there-- going through the eye. On the handout, which-- do I have a copy of it here? Yes, OK. A lot of terminology.

Are you responsible for it? Yes, of course. If you miss some little bit of terminology, that's not going to sink you in the course, either on this topic or on any other topic. You want to put your effort into thinking about the broader topic. But it's useful in being able to talk intelligently about it to get a grip on some of this terminology and hence the tour of the visual system that I will now embark on.

From the outside in, the purpose of the eye, or at least the front half of the eye is to form an image on the back half of the eye. Do I have a little cursor here? So all of this, sometimes called the anterior segment of the eye, is there to form an image like a camera would on the back surface of the eye.

Most of the optical power of the eye is at the very front surface of it. That front surface is called the cornea. It has, apart from its virtues as a lens focusing light, it is also one of the two surfaces in the body most sensitive to pain. You may try this out if you want at home. I don't recommend it, but if you scratch your cornea, you will know it, and you will not be happy.

What's the other one? What's the other surface, do you think? Anybody care to venture a guess?

AUDIENCE: Thumbs.

JEREMY WOLFE: Thumbs? No, that's a novel thought. No, look. He's thinking like the cartoons. You hit the thumb with the hammer, and ow, it hurts. Let me tell you. If you hit your cornea with the hammer, it hurts a lot more. Yes.

AUDIENCE: Someplace inside the mouth.

JEREMY WOLFE: Someplace inside the mouth. No, again, you think about that as the inside the mouth as a place where pain happens. But that's because you do stupid things with your mouth, like hey, that pizza looks good. Now, you would never stick the pizza on your eyeball. So again, yeah, it's nicely innervated for pain, but not particularly, not the other great location. I'll take one more here.

AUDIENCE: [INAUDIBLE] at the bottom of your foot.

JEREMY WOLFE: Yeah, same sort of thing, right you step on nails and stuff. Yeah, the bottom of your foot is a good place. No, you-- oh, there's two people here I've just got to take their answers because they're so eager.

AUDIENCE: Yeah, that's what I was going to say, somewhere inside your ear.

JEREMY WOLFE: Somewhere inside your ear is the point, not the chunk that so many people are thrilled with, oh, let's put a hole in this. Oh, that was fun, let's do it again. That obviously hurts, but-- I guess. I've never gone in for this myself. The reason one of the reasons your mother said, don't put anything inside your ear that's bigger than your elbow is because if you put something small and pointy in there, it eventually reaches your eardrum. And that's the other surface.

When you had an ear infection as a kid, the pressure from your middle ear the fluid in your ear stretched that, it hurt. And that hurts a lot. So don't put the hot pizza in your ear either.

OK, the cornea is just a relatively thin layer. It's held in shape by fluid, a watery like fluid, which is known technically as the aqueous humor. Humor in this case has nothing to do with being funny. It's an old word from for a fluid.

It forms a space that separates the cornea from. The iris the iris is that the bit that gives your eye its color. But it's basically a sphincter of muscle with a hole in it, and that hole is the pupil of the eye, which is the aperture of the camera. That's where light's getting in from the outside into the inner portions of the eye.

The pupil changes size because you've got this sphincter of muscle that either relaxes or contracts. What makes it change size?

AUDIENCE: Light.

JEREMY WOLFE: Light. We know that. More light makes it do what? Gets smaller. Why?

AUDIENCE: [INAUDIBLE]

JEREMY WOLFE: Yeah, so there's less light. Sure, it's going to be less light. But why do you have this? What did they teach you in third grade?

AUDIENCE: [INAUDIBLE]

JEREMY WOLFE: Never stick your elbow in your eye. Yes, I know that. No, I need a hand here. There's too many mutterings. There's a hand.

AUDIENCE: Because you don't want to go blind.

JEREMY WOLFE: Because you don't want to go blind. Why would you go blind?

AUDIENCE: There's too much light.

JEREMY WOLFE: There's too much light. See, that's what they teach you in third grade. It's bogus. It sounds good, and it seems to make sense. But ask yourself what level of protection that pupil can give you.

So how much light is it going to cut out? The answer is it cuts out a bit more than a factor of 10. From the largest, it can be to the smallest it'll be if you stare at-- if you're out in really bright light. So it can change light levels by about a factor of 10.

If you go from in here right now-- actually, it's fairly dim in here. But if you go from here to just go outside into the courtyard, the change in light level is going to be on the order of a factor of 1,000 right there. The change in light level that your visual system can deal with from, say, a moonlit night to bright sun on a snow field is on the order of 10 to the 12th or 10 to the 13th. So there's no way that the need to protect yourself is going to be taken care of by the pupil of the eye. There's just not enough range there.

Pupillary constriction, what it's probably doing for you, those of you who are photographers, is it's increasing the depth of field on your camera. A pinhole camera will focus many different distances at once. A larger aperture sure will only focus one plane at one time. And so if you've got lots of light, you crank down the pupil in order to be able to focus, in order to get better focus basically.

But the protection thing just doesn't-- I mean, it's not a stupid answer because it's what everybody believes. It doesn't turn out to be a correct answer. Now there's one other-- several other things that will change the size of your pupil, but one other of interest. What else changes the size of your pupil? Anybody know anything else that they can change the size? Yep.

AUDIENCE: Looking all the way down there at you.

JEREMY WOLFE: Looking all the way down there at me. Well, yes, but for reasons that are-- why? Well, no, no, what you're changing-- sorry, that's the next bullet here.

What you're changing when you change focus of the eye is you're changing the shape of the lens. At least you are. I'm not because at my age, the lens has basically become a rigid lump, and so when I want to look from there to here, I use an external lens. Yes, back to the pupil.

AUDIENCE: When you lie.

JEREMY WOLFE: When you lie. Yes, that will work, a little bit. Maybe not reliably enough to-- the CIA or something every now and then gets the idea that really works. But it's on the right general track. Yeah.

AUDIENCE: Some drugs do that.

JEREMY WOLFE: Yep, some drugs will certainly modulate it. And all right, I'll [INAUDIBLE].

AUDIENCE: When you look at the objects of your affection.

JEREMY WOLFE: There you go. That's the one I-- particularly one I was fishing for. Your level of arousal will change the size of your pupil. And notably, if you look at something that you like or someone that you like, your pupils get bigger. You didn't know-- I mean, obviously not everybody here knew that explicitly.

But you knew that implicitly because the result of that is that you think that things with big pupils are cuter than things with little pinhole pupils, right? So that's why sappy cartoons or cards have big pupils. It is also why in years gone by, women would put a drug known as atropine or known as a cosmetic as belladonna for pretty woman, pretty girl, in their eyes. What it did was it paralyzed and relaxed the muscles of the iris and made a great big pupil.

It didn't do anything good for their vision because it made things kind of blurry. It also paralyzes the lens. But it gave them great big pupils. And so they're looking at the guy who may or may not be the object of their desire. They're looking at some guy. They can't see him so well, which who knows. That may have helped, but he's looking at her thinking, implicitly, her pupils are really big. I know what that means.

Well, it turns out following up on whoever it was over there, it actually means she's on drugs. In any case, pupil size is modulated by emotional state. And it's one of these things that we knew implicitly, people know implicitly, and think big pupils are attractive for that reason. But it's only when you show up here, you find out these things explicitly.

All right, I've already said something about the lens. The most notable thing about the lens is it gets harder with age and less-- you can try this out. In fact, here it's a good time in your life to start this experiment. Take something like the handout and ask yourself how close you can get and have the letters still be in sharp focus.

This is so sad. It makes me weep. But I know you're getting there, too. Now what you can do. You could actually if you're a compulsive about these things. Write it down somewhere and just check every year.

This is one of those things where the signs of aging start showing up now. You will be able to see even during the course of your 20s that so-called near point is moving further out. For me without my glasses, we're out here somewhere. And eventually, you're locked at one plane of focus.

And depending on where that is determines which particular set of glasses you need. Do you need glasses to read? Do you need bifocals? Whatever. It's because you've lost the ability to fine tune that focus.

Now, you need something to hold the rest of the eye in shape. What you've got in there is-- it's really a jelly called the vitreous humor for the glass-like substance. And it's for our purposes not desperately interesting. It's there to hold your eye out so that the front end of the eye can make an image on this back surface. The back surface of the eye where the transduction from photons, from light energy into signals in the nervous system, where that takes place, that tissue is known as the retina. The word comes from the word for a net.

The fovea is the point-- fovea comes from the word for pit. It's the point on the retina where you have the highest visual acuity, the strongest, the greatest ability to resolve small details. You don't particularly realize in the course of your normal day to day existence just how bad vision gets away from the fovea.

You have this notion of a highly detailed world that's in focus all over the place, but that-- to jump ahead to the third lecture in this series-- is a construction. It's not reality. And you can prove to yourself. Take the handout again. Hold it at some comfortable reading distance.

Fixate on the L on that second line there, where it says lecture four. If you're fixating on the L, the L is falling in your-- forming an image on your fovea. Ask yourself while you're fixated on the L, how many letters off to the right you can actually read? And the answer is going to be not many. If you think you can read to the end of the line, it's because you're not fixating. You're moving your eyes around.

Again, like the pupil thing, this is something you knew implicitly. Nobody sits there and says, you know, I'm going to read this handout. I can see it. It's there, but I can't read it because the outside of the fovea, I simply don't have the resolving ability to do it.

Why not? Well, I can give you at least one reason. You have about 100 million photoreceptors in your retina. Photoreceptors are the cells that convert light energy into a signal in the nervous system. They're the transduction elements. You have only about a quarter of a million to a million axons, nerve fibers running from the eye to the brain.

So that 100 million has got to get boiled down to the much smaller number that you've got available to you. And so that means you can't treat each photoreceptor as a-- oops, that's not what I wanted to turn full on. That was stupid. I wanted to turn-- where did it go? You need a chalkboard. That one.

That means you can't treat each photoreceptor as a pixel with a private line to the brain. You do have something approximating this in the fovea, where you have fine detailed resolution. But in the periphery, away from the fovea, what you have is many, many, many, many photoreceptors that are all ganged together to send their signal off to the central nervous system. And so you lose resolution out there in the periphery.

Well, let's say a little more about the details of that retina. Oh, the optic nerve is the bundle of fibers going off from the eye to the brain. I'll say a bit more about that in a minute or so. Quick tour of the retina itself.

Up at the top there, you've got the photoreceptors, these transduction elements. There are two flavors of them called rods and cones, named rods and cones because under the microscope, rods are rod-shaped, and cones are cone-shaped. They are different in their functions and capabilities.

Cones operate in bright light at daylight levels. They do mediate color vision, and they are concentrated at the fovea. They are most densely represented at the fovea.

Rods work in dim light levels. They are not able to mediate color vision, which is why on a moonlit night, you don't see colors. It's not because color somehow drained out of the world. It's because the visual system that's looking at that world can no longer analyze the input for color information but only for grayscale information.

And rod photoreceptors are concentrated away from the retina. I'm sorry, away from the fovea. They are in fact absent from the central fovea so that if you go-- the best place to see this actually is if your room gets dim enough at night, if your room is dim enough at night that you can't see color, you're working in the rod realm. And then you will discover that if you fixate on a dim spot of light, you can't see it, that there might be something out here. You notice it, and then you move your eye to look at it, and it'll disappear because the image, if it's small enough, will now fall into the fovea, and there are no rods there, and you can't see it.

This is why if you're a stargazer, and you're looking at a dim star, you want to look at that star out of the so-called corner of your eye. The corner of your eye is about 20 degrees away from straight ahead because that's where the density of rod photoreceptors turns out to be greatest. I was going to say something else about Rod photoreceptors, but that has disappeared from my mind.

So I will say that the rest of this is a collection of nerve cells, of neurons. It's really a little chunk of brain. Developmentally, the retina is a chunk of brain that's pushed out into the eye. And this is the start of the visual nervous system. For present purposes, it's worth thinking about two aspects of this organization.

One is a through path that runs from-- do I have a little-- it's coming back. Where did my little cursor go? There we go-- from the photoreceptors through so-called bipolar cells to ganglion cells, a vertical path in this picture heading from the photoreceptors out to the brain. And then there are cells whose processes are sitting here and here, making horizontal connections so that photoreceptors don't behave like isolated pixels, so that they can talk to each other, and so you can start doing some calculations if you like.

And those are cells like horizontal cells that have their processes up here and amacrine cells that have their processes down here. So those are things making horizontal connections across the retina, photoreceptors, bipolar cells, ganglion cells are forming this through pathway going from eye to brain.

Now, if you were to look at this, and I was to say where is light coming from in this picture, the reasonable answer would be-- a reasonable answer would be [INAUDIBLE]. It would seem like a reasonable answer would be like it's coming from the top, hitting the photoreceptors, and heading off to the brain and out the bottom. But in fact, light's coming from there.

The retina is put on backwards in an interesting kind of a way or intuitively backwards at least, so that light shines through all of this stuff before actually getting to the photoreceptors. Why is that? Well, there are a variety of possible answers. But one of the answers is-- let's see, the remaining term on the list that I haven't mentioned in that retina list, which is actually at the top of the list. It says pigment epithelium.

Come back little cursor. It doesn't-- oh, there it is. Here we go. Up here, there would be a layer of what boils down to black gunk coating the back surface of the eye. And the photoreceptors are stuck into that. That's the pigment epithelium.

What it's there for is-- well, let's suppose that all of you guys are photoreceptors. And here I am. I'm a photon, and I'm part of this image of the world on the outside, and I'm coming flying in. And with luck, I'll be absorbed by mister photoreceptor here. But suppose I don't.

Suppose I hit over here. Well, I don't want to-- well, I. Photons don't have much conscious life as far as we know. You, the owner of this visual system, don't want that photon bouncing around anywhere else. You want it either to be absorbed by a photoreceptor or to be gone because if it bounces and hits up there somewhere, it's going to degrade the image. It's going to be like haze across the image if it's not landing where it should to make a nice sharp image.

And so this black gunk is there to soak up extra photoreceptors. A very good idea if you are a diurnal animal, an animal who works out in bright light, and not such a good idea if you're an animal who is nocturnal or running around in dim light. There what you want to do is catch every photon that you can possibly catch.

And so if you're a cat, for example, you do this differently. Instead of a pigment epithelium at the back of your eye, you have a structure known as the tapetum. It's actually very beautiful. It looks like mother of pearl, but you only get to see that if you take it out of the cat, which makes the cat less beautiful.

But it's a reflective surface. This is why if you get a cat in your flashlight beam, its eyes seem to glow at you because the light comes in. If it doesn't get absorbed by, say, the photoreceptors, it can bounce, and an amount of it will bounce back out. Some amount of light will bounce back out of your eyes. That's what you see as red eye in an unlucky photograph, for example. Is that a hand?

AUDIENCE: Wouldn't that distort the image?

JEREMY WOLFE: For the cat.

AUDIENCE: Yeah.

JEREMY WOLFE: Yeah, absolutely. That's why you almost never see cats reading *The New York Times.* No, cat visual acuity is pretty lousy. But a cat has different visual desires than you and I do. The cat's not big on sweating the visual acuity thing.

The cat wants to know, "Did it move? Can I jump on it? Can I bite it? Is it another cat? Can we do stuff?" All this stuff. This thing doesn't require a lot of visual acuity, and the cat wants to be able to do it in dim light.

We have this notion that cats can see in the dark, which of course, is not really true. No light, no vision. But cats-- people think cats can see in the dark because cats can see stuff in dim light that you and I can't. And part of the reason for that is that they are willing to let stray photons go where they will. Because in fact, I gave a radical example, if my hypothetical photon missed my hypothetical photoreceptor here, odds are it's not going to go out to outer Mongolia. It's going to get absorbed someplace nearby. And so the effect will be a blurring, not a complete degradation of the image. The cat can cope. The cat doesn't mind too much.

By the way, if you're interested in design, taking a look at the design of eyes across the animal kingdom is a beautiful business. The number of different ways that evolution or the hand of God, you can take your pick, has chosen to solve the problem of collecting light in an amazing array of possibilities. Once you start-- cats are one thing, but you go off into insects and other beasties, and it's great, wonderful stuff. If you want to be an engineer, probably lots of good plans, lots of good industrial design there.

All right, let me take a quick trip up into the rest of the visual system here. This picture that's up on the screen now is mimicking the picture on the upper left of the second page of the handout. It's showing the connections-- oh, I just remembered. I want to do a quick demo here before I do that. Let's go back and do that. Whoops, not that way, this way.

If the retina is on backwards, you've got this interesting problem. Let's go forward. So there are those optic nerve, nerve fibers to the optic nerve. How are they going to get out of the eye if light is coming from there? What they do-- come back, there we go-- is they run across the surface of the retina until they reach the optic nerve, and then they go out, up to the brain.

Where are the photoreceptors at the optic nerve? The answer is there aren't any photoreceptors at the optic nerve. If there aren't any photoreceptors at the optic nerve, what do you see there? Well, the answer isn't nothing because you're not aware of the fact that there's some big hole in your visual field, but there is. You automatically fill it in because if it's green here and green here, and there's no information there, it's a good bet that it's probably green all the way across and your visual system can figure this out.

But it's worth it to prove it to yourself that there is a blind spot there. Let's see on the handout. Well, flip to the back of the handout where you got a little extra white space and put an X. Put an X on the handout here like this. And a little ways away like about that, put a little black dot or a little dot. I don't care if it's Black.

And then what you want to do-- so the dot is to the right of the X. Close the left eye. Cover your left eye. Look at the X. Hold it so that the dot is straight out to the right and then move the paper back and forth, and you will find that there's a spot where the dot completely disappears.

What you've done at that point is moved the dot into the optic nerve head, the place where the optic nerve is leaving the eye. If you're saying, I can't do this, I don't see a blind spot, it's not because you're special and don't have one. It's because you're doing it wrong.

Well, there is an alternative. I'm given to understand that the octopus retina is not put on backwards in this way. And so perhaps you're an octopus.

OK, let's go back to this wiring diagram here. What I want to-- you can play with this later. It's cool. Do things like-- well, if you flip it around, you can find that you got one in the other eye, too. You can also do things draw a line with a hole in it.

If you draw a line with a gap in it and put the gap in the hole, the line will appear to complete. If you get really adept at this, you can do what King Charles II of England was reputed to have liked to do, which is can look at your friends and put their heads in blind spots and watch their heads disappear. Charles II didn't get to chop off as many heads as his predecessors had, so this was the best he could do, I guess.

All right. How do the axons from the optic nerve feed the visual centers of the brain? You will recall, from the first lecture perhaps, that everything from the right side of my body on the skin senses gets represented in the sensory homunculus on the left and everything from the left in the sensory homunculus on the right.

The way to not do this in the visual system would be to have let's have everything from my right eye go to my left hemisphere and everything from the left eye go to the right hemisphere. That wouldn't be any good. Isaac Newton figured out, without bothering to do any anatomy, Isaac Newton figured out that wouldn't be any good because I want to look out at the world with two eyes, and I want to see one world.

So I'm going to have to do something that brings the information from the two eyes together. What you actually do is the following. Everything from the left side of each retina ends up in the left hemisphere, and everything from the right side of each retina ends up in the right hemisphere. The image on the eye is flipped.

That's just simple-- simple lenses do that. So I've got a simple lens in that anterior portion of my eye. That means that the image of you guys landing on my retina has your feet up, your head down, and left and right reversed. So what that means here is-- what have I done? What that means here is, OK, if I stare at the person wearing yellow here-- if I stare at the person wearing yellow, she'll look embarrassed. It always works, but that's a different phenomenon.

All right, but I'm staring at you, but I'm not actually paying any attention to you. What I'm actually doing is looking at-- my acuity is so bad, it's a black blob right about there. I assume she's a person, or he's-- yeah, she's a person. OK. Anyway, acuity is very bad.

But the image of-- if you're on my fovea, the woman to the right is in the right half of my visual field landing on the left side of my retina. She lands on the left side in both eyes. And as a result, she's landing in my left hemisphere. If I'm looking at you, some arbitrary blob-- there's a blob that just moved over there. Oh, she's a person, too.

This person in the left visual field ends up on the right retina in each eye and in the right hemisphere. And in that way-- so there's only one of her, in a sense, up in my brain and only one of her up in my brain. And they're getting together in that-- and the result is that half the fibers from each retina have to cross to the other side. That's what this cute little map on page two is telling you.

But the important thing not to get confused about is don't tell us on some exam that your left eye goes to your right hemisphere or something. It's left half of each retina goes to left hemisphere. Left half of each-- right half of each retina goes to the right hemisphere.

What it does once it gets there is-- this is a monkey brain. And what you're looking at is the cortical surface here. Let's see. That must be the outside surface, and this is the inner surface of the hemisphere if there are two hemispheres. The one on the bottom is looking at the inside surface.

The colored areas are ones that are important in vision. I talked at the beginning about the fact that primary visual cortex is right here at the back of the brain. But it's amazing how much of the brain is devoted to vision. It's very hard to look at in a picture. It's very hard to look at period.

But what vision researchers like to do is to make maps like this, where you take the cortical surface and flatten it. It's all this wrinkly curve, involuted structure. Use a variety of techniques to flatten it out like a map, and then you see that this is the piece that's at the back of the head, V1 primary visual cortex. Then you've got all these gazillion other regions that are important in visual processing, some of them for rather precise things. Where did MT go? I lost my cursor again. Come back.

There it is. I think right there is MT, for example, which is important in motion processing. Lots of work being done trying to figure out what different bits of it do. Look, let me give you a broad organizing scheme for how to think about this. It's not perfect, but it ain't bad.

From primary visual cortex where very basic information about spots and lines and primitive bits of motion gets pulled out, more advanced processing can be thought of as in two large streams. One large stream going up towards the parietal lobe is telling you things about where stuff is in the world, how is the world laid out. So my notion that this space is laid out as a big slanted plain in front of me probably has counterparts in-- is probably a product of this sort of a pathway.

A second pathway going down into the temporal lobe is very concerned with what stimuli might be. So there, if you're a monkey, and I spear individual cells, it might be where I would find a cell that was particularly interested in a hand, a monkey hand, or a hairy leg or something like that. It turns out that the hairy part can be important.

When this work was first being-- some of the work on things like monkey hand detectors was being done by one of my professors at Princeton. And actually my TA in intro psych when I was an undergrad was a grad student who was working on this. And he reported to us that he was recording the-- if you go spear a cell, it's one thing if you're just trying to figure out if it likes spots of light. But how do you figure out if the cell likes something like a hand?

Well, they had in those days drawers full of stuff. And you waved all this stuff in front of the monkey and see what makes the cell go. And these experiments in the good old days tended to run for a very long time because this was an anesthetized monkey. And the monkey wasn't going to wake up from this particular operation. And you ran the experiment for days and days and days. And you stayed up the whole time.

So Bob Desimone, now a famous visual neuroscientist, is up late at night with this stupid monkey, with his stupid cell. And the cell isn't doing anything. He's waving everything at it. So finally, he took off his pants, wrapped a towel around his waist, and did a little dance in front of the monkey. The cell went nuts.

Being a good scientist, he then narrowed this down to the notion that this was a cell that actually seemed to be interested in hairy legs. And the hairy part turned out to be important. I feel free to tell this story about Bob Desimone because Bob Desimone is running around the country with a talk at the moment that has a picture of me in it kissing a wombat. So don't ask.

It all seems fair to me. All right, well, so if you go up into way down here in the temporal lobe, you might find cells that respond only to something like a hairy leg or a monkey hand or something like that. If you're hanging out back here in primary visual cortex-- well, actually, let's go back and hang out in the retina even. Look at that. We'll hang out right there.

If you're hanging out in the retina, the cells have-- if you like much simpler needs than this hairy leg detector somewhere up in the temporal lobe, I mentioned before that you might be bringing together a whole bunch of photoreceptors through, say, a bipolar cell to a ganglion cell to bring together a whole bunch of them to send a signal off to the brain. But what I didn't mention is that not all the photoreceptors that are hooked up to stimulate a ganglion cell are going to excite that cell.

Let's draw some pictures over here. What actually happens-- and I'm just going to mimic this over here-- is that you'd have some photoreceptors who are set up to excite a ganglion cell and then some other guys around them who would be set up to inhibit it. And so here's this.

The result is that what this cell-- so that's a one-dimensional slice. And this would be a two-dimensional picture. The retina is after all a two-dimensional surface. So what you'd really get is some region of photoreceptors that excite the cell and some surrounding region where light inhibits the subsequent ganglion cell. And then light out here does nothing.

So this is the receptive field of this cell. This is the only part of the retina that this cell over here cares about. And it's going to send its signal off to the brain. And so now what does this cell do?

Well, among the things that this cell can do, is it can tell you I am most excited by a spot that's exactly this size. If the spot gets any bigger, it's going to encroach on this inhibitory stuff and reduce my excitation. If the spot's any smaller, I'm not going to get all of my excitatory guys excited, and the response gets more.

So I'm most excited by a spot of exactly this size. If I build receptors with different sized centers, now this guy is only going to be excited by a little spot. And I can make one that would be excited by a bigger spot. And so even at the level of the retina, you can start to get cells that are telling you more than just light on, light off. They're starting to tell you something about the size of things in the visual field.

When you get up to the cortex, you find that now cells come to be interested in things like lines, not just a spot, but a line. And it'll say-- this cell will say I like lines in this orientation. I don't like lines in this orientation. In fact, I like lines in this orientation only if they move this direction.

And so you can imagine that what you start to do early in the visual system is to pull out a whole bunch of little features, if you like, that you can then use subsequently to try to figure out is there a monkey hand here, is there a laptop computer, or something like that. So you've got this-- early in the system you've got basic features being pulled out of the image.

Now, this presents a problem. Suppose that what you want to do-- well, let's start with orientation. Suppose you want to decide that a line is a particular orientation. How good are you at that? The answer turns out to be that you are good enough to be able to tell roughly one-degree increments. How are you going to do that?

Well, you could have a cell specifically designed to look for zero degrees vertical, one degree, two degree, three degree, four degree. And you need one of those everywhere in the visual field and at all different sizes. A little line that's vertical, a big line that's vertical. You're going to need an awful lot of cells then.

That's not what we do. What we seem to do all over the place in the visual system and in sensory systems in general is to make comparisons, that comparisons are very powerful in this game. So how do you decide that something is vertical? To a first approximation, what you do is you look at whether or not the left tilted guys and the right tilted guys, the cells that like stuff, well, that's going to be right tilted. The cells that look for something that's tilted a little to the right, cells that are interested in stuff that's tilted to the left, are they roughly equally excited?

If they're roughly equally excited in balance one with the other, then odds are that you're going to see-- that you're looking at a vertical stimulus. If the right tilted stuff is stronger than the left tilted stuff, so that balance gets tilted, you're going to say that the stimulus is tilted. It turns out that if you do something to make-- let's say you go off and you make the left tilted stuff weak by tiring it out. How do you tire it out? Show it a bunch of left, show a bunch of left lines. That makes this weaker.

Then something that's vertical is going to turn out to look tilted to the-- you're not going to believe that. Let me show this to you. I'll show it to you in-- I'm going to jump to. OK, we'll jump here. Well, we'll jump here first. Look at that.

OK, here are very boring-- very boring picture. It will be even more boring if I turn out a little more of the lights here. I'm going to a chalkboard. There we go.

How do you know that something is white or gray or achromatic? Again, in this case, you've got color mechanisms that say how red or green-- it turns out that what you've got is how red or green is this. If the answer is, well, it's balanced between red and green, then it might be. And you also ask how blue or yellow is this? If it's not blue, and it's not yellow, and it's not red, and it's not green, well, you know what, it's probably white.

So here, let's take this red green thing, and let's make the green side weak by wearing it out. We'll show you some green. Now I'm going to show you something white. The green is weak. The red is strong. The balance goes this way, and you think that something that was once white now looks kind of green.

There, see? Isn't that amazing? They're not convinced. The ones who are convinced are confused. Stare at the black dot at the center here. You just want to stare at the black dot and think about, say, that red dot up at 12 o'clock. What you're doing is you're tiring out the red side of this red green equation in this particular case, and just keep staring there. And then I'm going to go boink.

[INAUDIBLE]

So the people who went ooh, presumably saw colors. Let's do that again here. What you ought to notice is that you're seeing-- what you want to notice is that the color is this opposite color. It's going the other direction. So the red one will turn green. The yellow one will turn bluish. The green one will turn reddish. So stare at the center, boink. Yeah. Yeah it works.

There we go. That's what's known as a negative afterimage. You can just toggle back and forth. If you look at the black dot on the-- why am I pointing at my computer? That's useless. If you look at the black dot on the right and then move your eyes to the left, you'll see the colors show up in the left hand circles because that afterimage is essentially cooked onto your retina. It's there in retinal coordinates and moves with your eyes.

All sorts of good-- all right, now, let me illustrate to you that this is a ubiquitous phenomenon that shows up for basic phenomena all over the place by turning this back on. Is that going to be enough light for this? Yeah, I'm sure.

All right, so I won't show you the orientation one even though I managed to get a PhD studying it. But I'll show you the motion equivalent of it. Here's what you want to do. Here's some good bright light. You'll still see it over there, except for the guy who's asleep behind the pillar. That's his tough luck.

Anyway, don't all stare at him. It'll just embarrass him. Stare at this because it's much more interesting. So look at this. And we're doing the same game. We're just taking the game and transferring from the color realm or the orientation realm down to the motion realm. So this is contracting.

Yeah, yeah, stare at the center. That's important. So stare at the center. Again, think about 12 o'clock. All the contours are moving down. You know that something's stationary because it's not moving up, down, left or right, but at 12 o'clock, I'm wearing out your down detectors, and at 6 o'clock, I'm wearing out your up detectors, and so on. The consequences of this evil act of mine will be seen vividly if when I take it away what you do is look at my nose.

[INTERPOSING VOICES]

Of course-- of course, what really worries me here is that I-- several people's pupils got much larger, which means they think I look better that way. OK, now, a word of warning. Two words of warning. This is the best demo in the whole class. It's all downhill from here.

The other word of warning is it's a very salient demo, but it's there for a purpose. And it's really lame on the midterm or the final when some motion-- this is called a motion after effect-- when a motion after effect question shows up to say, oh, man, it was cool, man, his head was shrinking and stuff because you don't get much points for that. What you want to know is why this is actually interesting, which I will reiterate by going the other direction since it seems a pity not to.

OK, so again, the way you figure out that something is, in this case, stationary is by making a set of comparisons. And I am using this clever little tool to systematically distort the comparisons that you're making. By the way, I'm also causing you to make one of these inferences that we'll talk about next week. By seeing all these various bits of odd motion, you are making the conclusion that my head is shrinking or growing or something like that. So this is expanding. So this is the amazing pinhead version, ready.

[INTERPOSING VOICES]

So the original version of this, by the way, is known in this is known in the literature as sometimes as the waterfall illusion because it gets described multiple times in the literature. But one of them is by a Scotsman named Adams, who was staring at a waterfall and then noticed that the rocks on the side of the waterfall seemed to be drifting up, and this is a known waterfall and a known spot in Scotland. And there's a group of vision researchers who meet there every year, and the entry requirement for joining this particular elite group is a bottle of scotch of a variety that they have not tried before, which I think helps make the rocks move in all sorts of interesting ways, though they've never invited me, so how would I know?

All right, let's see. OK, this is what I'm going to do. Let me follow up-- so you've seen a negative color after image. You've seen a negative motion after effect. I've asserted that these exist in orientation. You can show this off. You show somebody big stuff and then medium stuff looks small. It's ubiquitous. It shows up all over the place.

I want to show you one more version of this kind of effect. And that's going to take a certain amount of build up here. So the first thing to do is say the vertical and horizontal stripes, do they look different to you? If they look different, somebody raise their hand, tell me what the difference is. What's the difference?

AUDIENCE: The horizontal ones are horizontal.

JEREMY WOLFE: Yeah, all right, in their color or shading in some fashion. Yeah.

AUDIENCE: The vertical ones look a little blurry.

JEREMY WOLFE: The vertical ones look a little blurred. They do look a little blurry. That may be the-- yeah.

AUDIENCE: The [? purple ?] ones with the black lines look a little thicker.

JEREMY WOLFE: Look thicker. We're not getting a lot of vivid color reports here.

AUDIENCE: The horizontal lines look brighter.

JEREMY WOLFE: Brighter. Nobody knows what the word color means. Last try.

AUDIENCE: The vertical lines are grayer-- I mean, the horizontal lines are grayer, and the vertical lines are--

JEREMY WOLFE: I would-- OK, look, this makes the point just fine. Now, never mind, guys. There's no general consensus here. I am about to produce a general consensus. That's the motivational part of today's lecture.

No, actually, what it is what I have to do now is for the next few minutes, what you want to do is keep your head upright. You don't have to stare at any one spot. I don't care. You don't even have to keep your head upright. Just keep it in the same orientation.

If you flop all over the place and fall asleep, nothing good happens. So you're going to look at these green vertical lines and these red horizontal lines and see I also have to go back one just so that I remember which way I have to go. But all I need to do here is toggle back and forth between them. Now you can see the negative afterimage here.

If you stare at this green-- oh, I should have done it quickly before. So stare at this green thing for a while. Do you see they get a nice purpley red thing. OK, well-- so that's just the negative afterimage, but we're not that interested in the negative afterimage anymore. Actually we are.

There's an aspect of the negative afterimage that's really cool here, which you may start to notice shortly. During the blank period, shout out the orientation that you see.

AUDIENCE: Vertical. Horizontal. Vertical.

JEREMY WOLFE: That's a little weird. Wouldn't you think? Now that's a little weird because if you stare at these horizontal stripes-- in fact, I should be able to get you back to seeing horizontal. So stare at these. Don't fixate. Don't move your eyes around. And we'll just stare at that for a minute or so.

And then, [INAUDIBLE], is that long enough? Yeah, look horizontal. Still look vertical. Oh, boy. Here's the get rich quick part of this lecture, assuming that you're unscrupulous. You can use this to make your fortune claiming that you can teach people to be psychic. What's the next orientation I'm going to show? What's the next orientation I'm going to show?

If you can make your fortune out of that, well, just send me 10%. But what's really going on here, what this is actually illustrating, this aspect of it is illustrating, is that you're seeing with your whole visual system, not with your retina all by itself or something like that. So each time you look at, say, the red horizontal, you're building up a green horizontal negative afterimage on your retina.

And this is building up a red vertical kind of afterimage on your retina. And if you go back and forth, [INAUDIBLE], this is fun. You build up a plaid. So think about your retina as having a plaid on it.

Now you don't see it here, but the plaid is-- when you're looking at a blank screen, it's just that plaid that's getting shipped up to your brain basically. Well, what else is happening? Well, when you're staring at this green vertical thing, up in your brain, the cells that are interested in vertical are saying we're getting tired. Go to the blank part. Tired vertical guys and more awake horizontal guys are looking at this week plaid, and they're only seeing the horizontal part.

Now. You look at the horizontal, the horizontal guys get tired out. Oh, we can only see the vertical and so on. Let's see. You may ask, isn't it about time we saw something interesting here? The answer is undoubtedly so, but this particular effect takes a few minutes to build up.

And so you got to keep looking at this. Oh, you've got to ask yourself what the effect ought to be what. What I'm building up here is an effect called the McCollough effect named after Celeste McCollough, who unlike most people who discover visual effects, was actually looking for this. She knew what she was looking for, and she knew what she could find.

Now, I already showed you that the pattern you're going to look at again. It was that black and white pattern of vertical and horizontal lines. What do you think the vertical lines should look like when we're done?

AUDIENCE: Red.

JEREMY WOLFE: They should look kind of reddish maybe, and the horizontal should look--

AUDIENCE: Green.

JEREMY WOLFE: Green. Let's see. Well, we might have done this long enough. This is one of these things where if I do it long enough, I can hit absolutely everybody. And if I quit too soon, not everybody will see the effect. Go for it. All right.

So now it's 3:08. All right, here we go. So close your eyes because that will let me get to the right slide. But it will also let you perhaps see that checkerboard floating there in the dark. Murmur if you can see a checkerboard floating in the dark.

OK, good. That's the negative afterimage thing. OK, now take a look at this test pattern again.

[INTERPOSING VOICES]

How many people think that the vertical and horizontal look different now in terms of their color? How many people think it might look a little maybe kind of different, but it's not exactly biting me on the posterior? All right, that's a better test.

Now, the way to find out whether you've actually got the right effect is without knocking out your neighbor, tilt your head 90 degrees. See, that's cooler.

[INTERPOSING VOICES]

OK, I'll say a word more about this, but I won't say a word more about this until you've had a chance to get up and stretch for a second. Look at that. Isn't that nice? We'll leave him up there, too.

OK. That's not what I want to do. Stop, stop. How many people when they look at these dots still see reasonably compelling colors? Not many. How many people when they look at my head still see it shrinking?

Yeah, except for the weird people. Yeah, yeah, yeah, yeah. That's because these-- your visual system is continuously regenerating itself. You stare at the red thing. You wear out in a sense the red detecting chunk of your visual system. And then if you flip your eyes over, you find out that you see a white thing is green.

But then you recover from it. Good. How many people still see this effect? Yeah. Tilt your head just to make sure if you think it's there. Little weak today. We probably should have gone a little bit longer.

Those of you who are seeing it, and perhaps even those of you who are not-- did I put a test pattern on the handout? I forget. No, OK, I'll just bring the PowerPoint back next week.

Not only are you still seeing this some minutes afterwards, but particularly if I don't show you the test pattern a lot, you may see it for days and weeks. The longest report in the literature for the McCullough effect is three months. The only reason it's only three months is because at that point, the undergraduates who, of course, were the subjects went away on vacation. And the experiment ended.

The evidence suggests that if we locked you in the dark that the McCullough effect would last forever. We won't lock you in the dark. And those of you-- I teach this up at Harvard where there are many more pre-law students, and the immediate reaction to this news is half of them consider filing suit. But this will not, in fact, ruin your life in any fashion.

In fact, it'll only be noticeable if you happen to end up looking at a test pattern like this or perhaps serving time in the near future. But this was something that McCullough was not expecting. McCullough thought that what she had done here was, OK, you've got-- you can fatigue color. You can fatigue orientation. Well, I'll fatigue the cells in the brain-- and there are cells in the brain-- that are interested in red vertical lines.

They'll get tired. I'll see white vertical as green. They'll recover. I'll see white vertical as white. But what happened was looked at red vertical lines for a while, white vertical looked green, and white vertical looked green for like a really, really long time thereafter. What seems to be going on here is something like this.

Let's suppose-- you know, I've been lecturing from this side of the class almost all day today. I'm worried that somebody's busy reinforcing me to stand over here. Let's see. Actually it's them. No, never mind.

So suppose that the way you decide that something is white vertical is by looking at the balance of-- well, here, let's draw it this way. You know you've got red vertical input, and you've got green vertical input. And they're being like some-- well, let's put a little dial here.

If they're roughly equal, you decide something looks white. So I show you red vertical for a while, and this thing gets weak and cruddy. And now something that should be producing equal input gets more from there. And it ends up looking a little green.

All right, that's fine. What happens if this cell gets sick? It's not going to be one cell. But suppose that this process gets weak in some fashion, not because you were looking at some stimulus, but because you went out and ate the mushroom that you shouldn't have eaten or whatever. And this cell just took a hit, and so now this is kind of a cruddy cell.

Well, there are a couple of possibilities. One of them is that for the rest of time, you're going to end up seeing white things as looking green. That's not going to be good. You don't want that to-- you don't want that to happen.

So if you decided that this was the situation, what you would want to do is choose change the gain on here. So if this was previously just equal gain, let's crank this up a little bit so that we can drag that back up to being equal. That sounds OK. That seems like a clever enough thing to do.

But how are you going to do that? How are you going to figure out that you're broken? How would you know that your visual system was not reporting the truth to you? Well, I mean, one way would be you're saying, hey, that looks white to me, and somebody else says that looks green, and they laugh at you or something. No, it doesn't work. No evidence that that works.

What you do is that you seem to have some notion of the statistics of the world, the way the world ought to be. If the world is systematically different from that, you draw the conclusion that you've got trouble here of some variety or other. Well, not necessarily-- you don't necessarily draw the-- let me give you a non troubled version of this.

How many people have been to one of these omni theater kind of movies? The main reason for going to an omni theater movie is what? You want to feel like you're moving right when you're not moving because all the movies that they ever show you at the science museum are things where you go driving around in race cars, stuff like that, or something like-- anyway, why does this work?

You're sitting in this huge screen, looking at this huge screen. And everything in your visual field is moving in the same way. You know something about the world. The world on average is stationary. If the whole world is moving, there's a good explanation for that typically. The answer is it's not the world. It's you.

What is it that causes the whole world to slide across your retina? This is what causes the whole world to slide across the retina? Sit in the omni, and the world is sliding across your retina. Your brain says, uh-uh, the world isn't moving. I'm moving, and I think I'll throw up now for a while or something like that. That's a separate interesting question.

What is it here that could tell you that you're out of whack? Well, what is the normal relationship between color and orientation in the world? Typically in the world, if you see something that's vertical, what do you know about its color? That's right, nothing.

So what's going on here. Whoops. If it's vertical, it's green. If it's horizontal, it's red. If it's vertical, it's green. If it's horizontal, it's red. You do this for long enough, and a little chunk of your brain, rather like the little chunk of your brain that's saying I ate the cupcakes, I threw up, I'd better do something about this, this little chunk of your brain is saying, there's a correlation between color and orientation.

The only way that happens is if I'm broken. And the only thing to do about that is to adjust the gain on chunks of my visual system. So everything looks green. All the vertical things look green. Oh my goodness, what am I going to do?

Well, I better crank down the gain on the green side. It's obviously too high, and I crank up the gain on the red side. Unfortunately, that was a goof. And it was wrong. So then when you look at a white thing, it now looks red because you cranked the gain up too much over here.

How do you recover from this? Well, if I show you the opposite one, what were we doing before? What was it green vertical? If I show you red verticals and green horizontals for a while, that'll push it back the other way. But that doesn't typically happen in the world.

Simply being exposed to a world where there's no correlation will slowly push you back. But the reason the effect lasts so long is that the evidence from the real world is kind of weak compared to this artificial situation that I cooked up here. The way of thinking about this is like-- here's another way of thinking about this.

Suppose-- all right, I'll go over here just so they don't feel bad or maybe so they don't feel bad. Suppose you're measuring average weight of people. I'm just going to keep weighing people. And I'm going to keep-- what's the average weight of people? It'll bounce around a little bit.

All right, this is how much people on average weigh. Now, what I do is what happens is the amazing 1,000 pound guy comes into my experiment. What happens to the average? Now, I start weighing normal people again. Does it just go-- no, it'll take weighing regular people, it'll take a long comparatively long time for me to get back to normal.

So that's what's going on here. The McCullough effect, adapting stimulus is the 1,000 pound guy that's causing you to think that your brain is broken. You go and readjust your brain, and now slowly it will get better. How's it look there?

Not better yet. How many people have a nice after effect still? Nice McCullough effect? Celeste McCullough would be so proud. OK, you will notice that I have not said a word about signal detection theory. I noticed that, too.

There is a chunk in [? Gleitman ?] about it. I might decide to talk about it on Thursday. Oh, you may also notice that you have lost your cell phone. If that is true, come and talk to me about it because we found it.

One last thing. How many people know what that is? [INAUDIBLE] Shush. I didn't ask you what it was. I just wanted to know if you knew what it was. How many people recognize this? Only a few. OK, now you can shout out.

AUDIENCE: It's a dog.

JEREMY WOLFE: It's a dog. How many people does that help?

AUDIENCE: [INAUDIBLE]

JEREMY WOLFE: Maybe, OK. Wait, wait, wait. Its head is-- well, wait a second, maybe I can get my little-- there we go. There's its head, foot, back paw, its back. It's sniffing at a ground plane that's like here.

[INTERPOSING VOICES]

So you can store that one away till next week, and we'll talk about it.