Hello everyone, welcome to another episode of Q&A about science and technology for kids and others.
So, let's see, I see a number of questions saved up here.
Alright, there's a question…
I'm Kathy, why are newer light bulbs so much more efficient than older ones? They both turn electricity into light.
All right, let's talk about that. So, the original light bulbs that were… so, main point is, there are different ways to turn electricity into light, and they're incandescent.
light bulbs, and there are LED light bulbs, and they work in kind of rather different ways. So, the thing that incandescent lights do is they make a filament.
Piece of wire, basically. Very hot.
And it glows. And, you know, if you heat something up, at first, it will glow red-hot.
Eventually, it will glow white-hot, If you heat it up even more, it will glow blue hot.
And eventually, it will start emitting light that's at higher frequencies that's out of even the visible range that we can see.
But…
what was discovered by, well, I think Thomas Edison originally discovered carbon filaments, but in most light bulbs, most incandescent light bulbs, it's a little piece of tungsten filament, and tungsten has a melting point around 60…
what is it, 6,000 degrees, Celsius? And,
The… it… you can heat it up sufficiently hot that it glows white-hot before it melts.
And in an incandescent light bulb, you have to… the filament, the inside of a bulb is a vacuum, or actually it has an inert gas in it.
If it didn't have that, then the filament would just burn up. It would combine, the tungsten would combine with oxygen.
it would, actually make a very… I think it makes a lovely substance called Wolframite.
Because the sort of European original name for tungsten, the element tungsten element 74, was Wolfram. At some point in the 1950s, kind of a deal got made that the American version of tungsten, which is tungsten, was used as the official name, and Wolfram, the European name. was, was deprecated, other than the fact that the symbol is W in the periodic table, whereas niobium, which had been known in the US as Columbium, didn't make it with the US name, and made it instead with the,
The, the European name. Anyway, that's a side point. But, just my, my namesake, favorite element, element 74, tungsten, aka Wolfram.
In any case, the way an incandescent light works is the electricity is used to heat up this filament to the point where it glows white-hot
So that you're getting light that is kind of similar to the light you get from the sun, because the sun is producing light by being hot. The surface of the sun
Is the idea is the surface of the sun is at basically the same temperature as the, as the filament in your incandescent light bulb, and so both glow with the same kind of white-ish light.
white light, because it's a mixture of red to blue in a spectrum. It's a particular spectrum that's a so-called blackbody spectrum. It is the characteristic spectrum that heated objects produce light with that distribution of colors and so on.
So, the idea of an incandescent light bulb is you use your electricity to heat up the filament to the point where it glows, and that glow is where you get the light.
Okay, Plan B is light-emitting diodes, LEDs.

And if you were to In an incandescent light.
it's producing, kind of, all possible colors. It's producing photons of all possible frequencies.
Photons that have lower frequency, correspond to things like red light. Protons with higher… higher frequencies produce green light, and so correspond to green light. Still higher frequencies, blue light, and so on. When you go beyond blue light, you get to ultraviolet.
Eventually to X-rays and so on, as you go up to higher energies of photons.
Well, so, an incandescent light bulb is producing this whole range of energies of photons, whole range of colors. The combination makes what we perceive as white light.
It's kind of…
the thing to realize is when it comes to humans, the way we tell what color something is, is by seeing how it affects the three kinds of cone cells we have in our eyes. We have cells that detect the redness of a color, the greenness of a color, the blueness of a color.
And, so we're taking whatever the range of energies of photons is, we're just saying how much redness is there there, how much greenness, how much blueness.
There are other kinds of animals that have different numbers of color sensor… color receptor cells in their eyes. Things like cats and dogs only have two rather than three color receptors, so they can't tell such a range of colors.
There are other creatures, I think the record is held, as far as people know right now, by the mantis shrimp, which has 15 different color receptors.
So, for a mantis shrimp, the distribution of colors that you see in a heated filament or from the sun, it'll have all those different colors that we don't, that, are being detected by different parts of its retina.
Okay.
So, there's a big hack that's used for LED lighting.
Which is to say, all we notice is how much redness there is in light, greenness and blueness. So forget all the other intermediate colors. Just have light that has a certain amount of red, a certain amount of green, a certain amount of blue.
And it turns out that you can have a device, I'll describe how it works, an LED, that basically just emits red light.
So, for a long time, it was known how to make LEDs that would emit red light, LEDs that would emit green light, but that kind of wasn't enough.
Because while there were some displays people had, which were red displays or green displays, if you really want to make, kind of, general-purpose light for humans, you also need a blue light.
And so then, at some point in the 1980s, I guess, the blue LED was discovered. And so very quickly, there started to be LED lights that have combinations of red, green, and blue. So for us humans.
That seems to be just like white light. It seems to be like all possible frequencies of light, seems like it's a good way to illuminate anything.
For the mantis shrimp market, which I think is rather limited right now, mantis shrimps are not, don't have a lot of purchasing power, but for the mantis shrimp market, our LED lighting that has just a red, a green, a blue component will be a total lose.
The mantis shrimp would be complaining, where is that color in the middle that we can perceive?
And this doesn't look right at all. This doesn't look like white light at all.
It's just like in the time when there were red and green LEDs that could be produced, but not blue, I suspect one could have made something which would be a perfectly adequate light

as far as a cat or dog is concerned, which has only two different kinds of color receptors. It just wasn't adequate for us. We were like, that's not a reasonable… that's not reasonable light that has a reasonable way of giving us different colors.

Okay, so how do LEDs work?

So, the basic idea is that you're… okay, so what is electricity, what's light?

Electricity is a flow of electrons in a material.

So, in the most common case is electrons in a wire. A wire is a metal. The characteristic of metals is that electrons can flow freely through a metal.

So normally electrons, if you just have, sort of any old material, the electrons are part of atoms. And they're sort of captured, they're localized within atoms. So there might be, you know, in a hydrogen atom, there's an ordinary hydrogen atom, there's one electron, one proton, and the electron is just stuck there in the hydrogen atom.

What happens in metals is that you have a bunch of atoms, let's say of copper or something, if it's a piece of copper.

And the copper atoms are pretty close together, but they're electrons that are sort of on the outer parts of the copper atoms. The copper atom has a whole bunch of electrons in it, but the outer copper atoms are kind of being shared between different copper atoms in the metal.

The metal has what in condensed matter physics, is called a conduction band. It's a, it's a place where electrons that have a certain energy are capable of roaming freely through the metal.

And so that's a feature of… it's a feature of metals. The atoms are close enough together, they share electrons. The electrons are a part of the conduction band, where they are sort of… they can just move from the position of one atom to the position of another atom. The electrons are kind of delocalized throughout the metal.

When you put an electric field on the metal.

which you do by putting a voltage across the metal, that electric field will move the electrons.

And that's why when you put a voltage across a metal, across something, you'll be causing a current, a flow of electrons, that are following that voltage.

So, this idea that electrons flow freely in metals is more or less true. It's not precisely true, because there are always, the fact that the metals at, like, room temperature, are always… the atoms are always jiggling around. That means that the electron that was trying to have a smooth ride through the metal will keep on running into these things that come from, sort of, the jiggling around.

so-called phonons in the material, and the electron will keep on scattering against phonons. It will keep on not really having a smooth road, a smooth path through the metal.

You can get things called superconductors. At very low temperatures, you get rid of those phonons and so on, and you can have a situation where electrons can just roam completely freely through a material.

and you have the electrons just, you start them going with some little sort of nudge of voltage, and then the electrons will just keep going, and you can have a sort of ring of superconductor, and the electrons will just keep going. The currents in the electrons will just keep going around and around that ring for months at a time in a superconductor. This is a thing that's used in MRI machines.

they'll typically have superconductors that they use to make their magnets, and it's a big deal to sort of shut down an MRI machine, because that's all this current that's just circulating in its superconductor. And it's that persistent, so to speak. But an ordinary metal.

At ordinary room temperature and so on, there is a resistance, a resistivity to the metal, so you, you don't, you don't get to completely have the,
the electrons flow freely. What happens when the electrons don't flow freely? Well, they're kind of colliding with these phonons. These phonons are little lattice vibrations. They're kind of the particles of lattice vibrations. They're kind of little elementary amounts of lattice vibration. Lattice vibration is what eventually turns into… that corresponds to heat.
Heat is this microscopic motion of atoms. You can think about as microscopic deformations of the lattice that makes up the metal, or whatever.
That… that… that… well, that corresponds to heat. So, when you put a current, through the metal.
then you're… every so often, the electrons and the current are hitting these lattice vibrations, and the momentum, the energy of the electron is getting transferred to the lattice vibration. So, in other words, you're going from the, kind of, the energy of the electron to energy in the wiggling around of the crystal lattice, or
effectively the heat in the material. And that's actually how an ordinary incandescent light bulb works. It's putting, it's making the filament glow by putting current through the filament.
But because there's resistivity in the filament, in the piece of tungsten wire or whatever, because there's that resistivity, that corresponds to the electrons not really going freely, but keeping on hitting things that are causing the material to heat up. And that's why, when you put the current through the electric light bulb, it causes the electric… the filament in the electric light bulb to heat up. That heating up
Causes the filament to glow, and you get light.
Okay. Well, with this picture, how does a light-emitting diode work? Well, light-emitting diodes don't use metals, they use semiconductors instead.
So, I mentioned in a metal, there's… so, normally in an atom, the electrons are just captured in the atom, they're localized to the atom.
In a metal, there's the so-called conduction band in which the electrons can roam freely throughout the metal, or more or less freely. They keep on getting, sort of, scattered by things, and that's the thing I was just mentioning in terms of resistivity.
But roughly, there are sort of some electrons that roam fairly freely.
And…
It's… that's… that's the way it is in a metal. So a semiconductor, a metal, is a conductor. It conducts electricity. Electricity can sort of flow through it freely. There are also materials that are insulators, like glass, for example, is a pretty good insulator.
Those are so-called dielectric materials, or insulator materials. In those materials, there aren't electrons that flow freely through the material.
All the electrons in that material are localized in their atoms, and so if you try and get an electric current of a flow of electrons, it doesn't work, because instead, every electron is just localized to an atom.
Okay, there is an intermediate case, so-called semiconductors, and semiconductors have electrons where they're normally localized in their atoms, but with a fairly small push
they can be pushed into the conduction band. And so for silicon, for example, sort of the most famous and widely used semiconductor, it takes 6 volts to push 6 volts of energy, in terms of electrons, 6 electron volts of energy.
To push an electron from where it is in a silicon atom into the conduction band.
So, if you… if you put,

If you push it with 6 volts, you'll get the thing to effectively act like a conductor.
Okay, so… the… That's… Okay, so then…
Let's see, what ends up happening is…
So that's, that's what happens in a raw semiconductor, like silicon.
The next idea is so-called doped semiconductors that are sort of P or N-type doped semiconductors. So,
Boy, this is a good exercise for me, having to think this through in real time. So, silicon…
In the kind of crystal structure of silicon.
a silicon atom is a valence 4 thing, so that means every silicon atom wants to be kind of connected to four other silicon atoms.
It has, they're a kind of, it's going to make bonds, it's going to have sort of electron-swapping bonds with four other atoms, so-called covalent bonds, with four other atoms.
Okay, so… If you introduce some other material that has valence 3 or valence 5,
Oh, gosh, what are the usual ones? I think,
Oh my gosh, is it some…
10, maybe, as well? I've forgotten.
Gosh, I should know that. Anyway, there are… if you look in the periodic table, the kind of columns of the periodic table
tell you about the valence, the number of, number of bonds that things will make, for those kinds of atoms. And what you want to do is go from the silicon column to the column either to the left or to the right.
And then you'll get things that sort of expect 3 bonds or expect 5 bonds. And those… if it expects 5 bonds, it kind of is… is… has an extra electron that doesn't have a place to go.
And that extra electron is important because it's kind of, you can think of it as being sort of closer to the conduction band. It doesn't have a place to go. It could almost be delocalized.
Well…
Okay, maybe we don't need to get into all the details of that. The main point is that,
When you end up with a situation where there can be an electron that is kind of promoted from where it was, kind of happily sitting in an atom, to something that is essentially in the conduction band.
Where it's roaming freely and so on. But you can have a situation where the electron kind of gets locked back into where it was in an atom. It goes from its kind of higher energy state, where it's kind of roaming freely, back into the sort of the hole that was left
In an atom where the electron went missing and went sort of roaming freely.
Okay, so what happens when an electron falls back down into this,
into its ordinary place. Well, the electron had more energy, it has to lose that energy somehow.
And the way it loses that energy is by emitting a photon, and it emits a photon of a frequency that corresponds to that energy difference.
And so, that's basically how LEDs work, is you're using electric current
To promote electrons into the conduction band, and they're falling back down, and as they fall back down and lose energy, they get rid of that energy by emitting a photon, and that's the photon we see.
And so what's happening is, you're, rather than just jiggling the material around and, making it so that, oh, I should have explained. When you jiggle the material around.

You're jiggling atoms around, and as you jiggle the atoms around, the electrons in those atoms are being pushed into higher energy states, and they're then falling down into lower energy states, and that's what's emitting the light that comes when you heat something up.
The heating… okay. So, in an incandescent light bulb, for example, you're using electricity to produce heat. You're using heat
To make the electrons and atoms kind of
bounce around, and within their atoms, go to higher energy states, that then… then the things will go from the higher energy state, they'll be sort of kicked, the atom will be kicked, and as the atom is kicked, the electron will go within the atom into this higher energy state.
And then, after a very small amount of time, often, something like,
let's see, a billionth of a second, this kind of time frame. The electron will kind of go back down to the lower energy state, always staying within the atom, and when it goes back down into that lower energy state, it will emit a photon.
The photons that it will emit have a whole range of different, energies, and that's what leads to, kind of, the sort of the glow that you get when you heat a material up.
So… Actually, the,
Yeah, I'm eliding several features of how this actually works, but that's more or less the right picture. It's a little bit trickier than that. Yeah, basically, right, that's more or less the right picture. But,
That's… that's how you get this whole range of different, energies in, in an incandescent light bulb. So you're going from electricity to heat back to… back to… and then to heat, then that's affecting the electrons, the electrons are then emitting photons, and you're getting light.
In the case of an LED, you're going directly from electricity to move electrons to higher energy states that then fall back down
to directly produce light, but it's only light of particular frequencies, and because we now know how to make red, green, and blue frequencies, we can make white something which, at least for us humans, approximates white light, and we have an LED light bulb.
So… so that means, basically, all the energy that's going into the LED is basically going into making photons, whereas
In the case of an incandescent light bulb, a lot of that energy is just going into heating up the material and emitting, for example, photons that are in the infrared, which are not… we don't… aren't useful. It's producing heat.
Radiant heat corresponding to infrared light, rather than light that we can see.
I suppose that's a much simpler summary of what's going on. In an incandescent light bulb, you produce all these different kinds of photons from ones that we can see that span the visible spectrum from red to blue and so on, along with things like infrared photons that we can't see and that just correspond to heat. Whereas in the case of an LED, we're producing just specifically frequencies of photons that correspond to light
That we can see, and that's where all the energy is going.
That was trickier than I thought.
Let's see… Well, there's a question here.
if… Humans saw in a completely different wavelength range. Would our physics look different?
You know, I have a little device that I can hook on a cell phone, and it's an infrared… it sees the world in infrared.

And things are really different in infrared. I mean, like, you look at a person with glasses, the glasses are really cold, the skin is at, you know, standard body temperature. You see different parts of your skin are at different temperatures.

You see a lot of things in the world that sort of look different when you're looking in the infrared.

In terms of what things will be important to us if we saw in the infrared, clearly there's a different range of, quotes, colors that you can see in the infrared, that, you know, color is this different, you're, you're sensing

The amount of redness, greenness, blueness, which correspond to the amount of different frequencies of light.

different frequencies of photons that are being emitted or reflected from a particular kind of object. And in the infrared, there are very different kinds of distributions of colors for things, or I say colors in quotes, because they're not ordinary colors that we perceive.

They're just different distributions of the amount of the light that's emitted at a certain, or the infrared light that's emitted at a certain frequency, and so on.

Well, I don't actually know whether the world is more or less diverse in our band of frequencies corresponding to visible light, or in the infrared, or in the ultraviolet.

So, for example, bees see substantially in the ultraviolet, and so when they're recognizing different, types of plants and so on, different flowers and such like.

The bright colors that we see in flowers, bees will see a different part of those… that… those colors, because they're seeing in the ultraviolet as well.

So, the band of frequencies, if you look at all possible photon frequencies, the band that we perceive with our eyes as visible light is very, very narrow. And it's a question of, if you are trying to tell, is this a good thing to eat, a bad thing to eat, is this a this or a that?

How much that sort of peephole of information

in energies of photons, how much do we get from visible light? And how much would we instead get if we were seeing in infrared, for example? I actually don't know the answer to that.

The kind of mechanics of how different materials emit or reflect different kinds of light is a bit different in the infrared than it is in the visible spectrum. And you're more going to be, as you get down towards

Well, in the visible part of the spectrum, it's really mostly about properties of atoms. As you go down to, sort of, lower frequency.

Lower energy electro… photons, you're more sensitive to properties of molecules.

So when you get down to the level of, beyond, infrared, you get to microwaves, at that point, you're… you're seeing the vibrations of molecules and things like that. That's determining the… for a particular material, whether there is, emission at different frequencies or absorption at different frequencies is determined by,

by this kind of vibrations of molecules and rotations of molecules. Actually, vibrations of molecules is more in the infrared, rotations is more in the microwave.

So in… if we saw in, kind of, the microwave… in the infrared part of the spectrum, my guess is we'd be much more sensitive to, sort of, the properties of materials as revealed by molecular vibrations than the properties of materials as revealed by things like

The amount of different kinds of atoms.

So, for instance, there are many kinds of bright colors in things like gemstones and so on that are produced by specific little… by tiny crystal defects where there are particular atoms there that emit and absorb light at particular frequencies, making kind of a ruby red or a, an emerald green, things like this.

Those are associated with, sort of, light interacting with atoms. If we were sensitive more to the vibrational aspects of molecules, whole molecules, we would have sort of a different perception, I think, of different materials. It might be a little bit more like

there might be more diversity for us in the… and perhaps in the colors of things. I mean, a lot of stuff out in the world, you know, is… is… most powders, for example, tend to be white.

Because, that's, that's where, the,

Because that's the, the size of the powder granules is such that, it's,

it's reflecting light in such a way that we get this whole spectrum of possible colors. I don't know whether the same is true. I actually should have looked at that through infrared. I haven't done that, I don't really know what it looks like.

But in any case, so I would think

we might have more discrimination of different kinds of materials, and we might be more used to that if our, sort of, vision was shifted into the infrared. I think, at least into the far infrared. It's a little bit, maybe more, a little bit more like our sense of smell.

Where, whereas in… I mean, again, it depends on other sort of features of what our sensory apparatus will be like.

In the case of vision, as I mentioned, we have just red, green, and blue feature detectors. In the case of smell, we have hundreds of different feature detectors that are detecting, essentially. roughly the shapes of molecules, and we're sort of sensitive to hundreds of different kinds of shapes of molecules, and that determines sort of our smell landscape. And maybe if we were sort of seeing in the far infrared, we would be more sensitive to… we'd be sort of more discriminating of different kinds of materials, and we might not have as much of, oh, it's just… a generic thing. It might be more… it's a… it's a, it's something of this type versus that type, and so on. A few speculations about that, I'm not sure.

The, let's see… Carol is asking, why did humans never develop night vision?

well, I mean, things… critters like cats and so on have

sort of better night vision, I think, they have, you know, they're… I think they have, sort of the… what do you need to have good night vision? You need to collect a lot of photons. You need a big eye to collect lots of photons. And, it's also the case that

On our retinas, we have 4 different kinds of receptors for light. We have red, green, and blue cone cells, and we have rod cells.

And cone cells have this sort of specific sensitivity to different colors. Rod cells are more generic. I think they're more sensitive in red than in other parts of the spectrum.

But fundamentally, rod cells just sense the overall intensity of color, and… but rod cells are more sensitive, and they work even at lower light levels. So you need more photons to kind of excite the red, green, blue cone cells than you do the rod cells.

Now, in our vision system, the, on our retina.

there's a central spot, the so-called fovea, which is chock-full of red, green, blue cells, and then the periphery, we're… it's a lower density of cells altogether, and they're more rod cells in the periphery. So we're… we're more color-sensitive, looking kind of, sort of straight ahead in the central part of our vision than we are, in the, in the periphery.

And for example, when you're… when you're looking at things at low light levels.

you lose your color vision, and you really can… you can sense light intensity through the rod cells, but you can't discriminate red, green, and blue. I have to tell a weird story from when I was probably 7 years old or something. I was on some…

on some little boat somewhere, and, I managed to cut myself.

And we get to the, kind of, dock.

And there's sodium lights there. Sodium light is, a kind of light I didn't describe in talking about light bulbs and so on, but it's, in sodium light, you are getting your, your, it's,

You, you're, you're exciting a particular,

a particular atomic transition in sodium, the D lines of sodium. You're making electrons, you're putting an electric current

through a sodium gas to make, sodium atoms, kind of go into a state, an excited state, and then when they decay from that excited state, they emit photons of a particular frequency. So sodium lamps, old-fashioned,

street lamps and so on, were… had this orangish color. That color was a single frequency.

Okay, so here,

Here I am, actually, this is… I guess the story is actually telling… talking about something slightly different, which is because all I could see was, okay, I've got something which looked like oil, you know, all over my arm, it looked black to me in sodium light.

In fact, it was blood, and it was red, but I couldn't tell it was red, because I was looking at it with monochromatic light, single frequency light, and so my… it's actually a slightly different point from the point I was making. My usual ability to tell the color of things by saying, well, there's a certain amount of red, a certain amount of green, a certain amount of blue, doesn't work if there's only

One… if there's only just one frequency of light that you're using to illuminate the thing you're looking at.

So, so I couldn't tell that I had…

blood all over everything. I just thought it was… I thought it was oil. Any case, irrelevant to… to the thing I was, I was just reminded of that story from a

Close to 60 years ago now. But,

In any case, the, what happens in low light for humans is, we are mostly using our rod cells.

That's why when you have, kind of, some fancy cars and planes and things, tend to have, kind of, red light.

I guess that's because one is more sensitive… that's right. You can use red light for the display, because you can have a lower intensity of light altogether, and still be able to see it, because the rod cells are more sensitive to red light.

So, I think one thing cats do is to have more rod cells and fewer cone cells.

And that allows them to operate in lower light levels.

The… the real winners for low light are things like king crabs, horseshoe crabs, things like this.

The eye has evolved several, 3 or 4 different times in the history of life on Earth.

the trilobites, I think, were the first ones to have them 450 million years ago or something. Now, to have these light-sensitive sensors. But…

Our eyes, our compound eye, different from the eyes of insects and things like this, but our eyes kind of evolved separately from the eyes of crabs, and in our eyes, there's a ridiculous design mistake.

Which is that, if you look at our retinas, there are light-sensitive cells, but they're behind a bunch of cross-connection cells. So the light has to go through the cross-connection cells to get to the cells that are actually sensitive to photons, which is a stupid design mistake.

Presumably. In the case of the horseshoe crab, that mistake was not made, and so its cross-connections are behind the layer of photoreceptors that detect photons.

And…

In fact, in those kinds of creatures, they're sufficiently sensitive to light that it's at least claimed that a single photon

is sufficient to trigger a response. Whereas for us, it's like 50 photons or something that you need to be able to actually record that you see something, you know, a flash of light, a pinprick of light, or something like this.

It is an interesting point that in very low light levels.

of the, you know, 10 million or so cells on our retinas, that each individual cell is not getting that many photons. And so there's an important question. Why is it the case that in low light levels, we're not seeing something that looks like a bunch of pinpricks of light kind of filling in from all the individual, you know, clumps of photons? And I think the reason is that it takes, you know, maybe 50 photons at a time to really

register, and things are sort of getting averaged out, and our brains do that averaging, so we don't see this kind of pointillistic picture of what the scene looks like.

I think, in terms of why…

different species are more successfully kind of see at night than others, it's, I mean, it's just a question of, did they evolve to be nocturnal? Did they evolve to… to be able to

sort of discriminate colors and see all the things that you can see during the day. And there's trade-offs. You can't kind of do both.

You either have to have photoreceptors that are good for, sort of, daytime viewing and color discrimination, or you have photoreceptors that are good for sensitivity to photons, I think. I mean, it is remarkable that the light levels that we can deal with vary dramatically. I mean, over many orders of magnitude.

We can deal with a very dark room, we can deal with very bright sunlight.

you know, the pupils of our eyes contract down in bright sunlight, so that we let less light through, so we don't have to deal with sort of a cascade of lots and lots of photons. They open up when it's dark, so that we get to see more photons, but even so, our retinas still manage to,

to deal with a huge range of different levels of light. So what happens when a photon, interacts with a photoreceptor, it, there's this, it's called visual purple, is the pigment, effectively, that, that absorbs the photon, it

Causes, in the end, that…

That protein has the feature that when it absorbs a photon, eventually it will produce an electron that's then transported by a chain of other proteins, and winds up as a nerve impulse

That, well, winds up being a sort of electrical, electrochemical nerve impulse that eventually gets onto the optic nerve.

But what happens is, once…

a particular rhodopsin, a particular one of these proteins, a photon has been absorbed, that particular piece of rhodopsin is not ready to absorb another photon until it's kind of recovered. It's kind of rebuilding itself to be able to absorb another photon.

And that takes some amount of time. I mean, it takes,

I think it's a time… I mean, in the end.

That's a time of all the seconds, I think.

Because that's what leads to afterimages. When you look at a bright light and you look away, the reason you're getting afterimages is that the rhodopsin on your retina has been kind of saturated with photons, and it takes a while to replenish itself to be ready to absorb more photons.

So… In any case, the,

By the way, that visual purple is what leads to red eye in old-fashioned photographs. You'd have a flash, for example, and the reflection of the flash from your retina would produce this kind of red color, which is the visual purple of the pigment.

And so, for example, you know, cats at night, you'll often see, kind of, their eyes will look… have this pink, red, purple color. That's because you're seeing the color of this pigment in the back of their eyes.

So… I think in,

I think there are simply trade-offs in whether you've set yourself up to be able to deal with high light levels.

Where the pigment is constantly being replenished and so on, or low light levels where it's like, you know, make that, make every photon count, so to speak. That's my guess as to why one doesn't have, you know, one has critters that are either nocturnal or not, so to speak.

I think in the way that we make night vision goggles, things like that, we're using… image intensifiers work by going

using photomultiplier tubes, basically, going from, actually, I suspect they're now done with semiconductors, so maybe it may have changed. I mean, I think effectively, okay, in the past, what was done…

was you would use the photoelectric effect to go from a photon… in a photon, metal, you would… absorbing the photon, you would emit an electron, then you would take that electron, and with an electric field, you would basically make that electron go faster, and you would effectively amplify the effect of that… of the photon, the original photon.

By, by, by amplifying the electrons, and you would end up with a cascade of more and more and more electrons, that, would then become a large electric current

that you could then convert back, using a phosphor or something, you could convert back to a display. That's how old-fashioned photomultiplier tubes worked.

Today, I'm pretty sure most night vision stuff

is… uses, charge-couple devices, CCDs, which are the kinds of things that are used for cameras in your typical smartphone today, is one of those. And that's a thing which is kind of the reverse of what I was talking about, about how LEDs work.

And how you promote electrons and make them lose their energy by emitting a photon, so the reverse of that

is that you're absorbing a photon and pushing an electron into a different state so that you can then move that electron around and detect that it was there, more or less. That's more or less how these cameras work.

And, I think that's probably the, by this point, the most sensitive way of detecting the presence of a photon. Each photon can lead to a single electron doing something, and then you just have to capture the effect of that single electron in the semiconductor device.

So, let's see…

Brady asks, why infrared and ultraviolet on opposite poles when red is a component of violet?

Well… Yeah, that's a messy question.

So, if you look at a rainbow.

It will go from, rainbows, well, like prisms, rainbows, they're all things where you take white light.
And because your… the material, water, glass, whatever, bends the red light more than it bends the blue light, you're separating the white light into components.
Well, if you look at what you actually get, you'll get sort of a pure red going to something that more or less is pure blue at the other end.
Now, the thing we perceive as purple happens to be a mixture of red and blue. The fact that there is also sort of a purpley-blue at the very end of blue going into ultraviolet that we can't see,
That's… Why is that? That's… that's a tricky thing, because… okay, let me explain another complicated issue.
So… What do we mean by red, green, and blue?
Well…
One thing we could mean is, say, a red photon is a photon with 530 nanometers of wavelength, for example, a very… a single frequency of photon, a single energy of photon.
And same with green and blue.
we would successfully perceive a laser, for example, that produces, like, a helium neon laser, produces red light at a particular frequency, I think it's 532 nanometers. The,
And… And we perceive that as red.
But we would perceive other things as red as well. Other frequencies of photons will be sort of nearby reds.
But what we actually perceive is
Our so-called red cone cells don't just accept one frequency of light. They kind of are sensitive to a whole range of frequencies. They have a peak
at some particular red, but they also sense other kinds of red. So, when we say it's this amount of red, this amount of blue, this amount of green, what we're saying is the range of frequencies that our red cone cells detect overlap in this way with a range of frequencies
From, from that, in that particular light.
So… Okay, so what's the point here? Well, if you have a display, like a…
red, green, blue… so let's say you have a standard computer display. If you look at it under a magnifying glass, you'll see it has little bars of red, green, and blue. Those are little LEDs, red, green, and blue LEDs, that are producing, in a first approximation, though it isn't exactly this way, single frequency red light, green light, blue light.
Okay. If it was, well, actually, any…
Yeah, this is tricky.
It isn't single frequency, but it's sort of close to single frequency.
Okay, the range of colors that humans can perceive can be, can be represented by the so-called color triangle.
And the color triangle is telling you, different points in the triangle tell you… it's usually in so-called XYZ,
chromaticity diagram, it's… we're kind of classifying, instead of saying it's red, green, and blue, we say it's the X, Y, and Z, kind of cone cells, and you're basically saying how much
does a particular color excite the red cone… the quotes red cone cells, quotes blue, quotes green cone cells?
And you're representing that by these… by a position in this… in this…

color space, triangle, if you put things in triangular coordinates, it has the feature that the sum of all these perpendicular distances is constant. So it's like, you're fixing the intensity of light, and now you're just seeing the components in the XYZ roughly red, green, blue, components.
Okay.
The color triangle isn't a triangle. The color triangle is a sort of bulging thing that has, kind of, Has kind of edges that bow out.
Those edges correspond to, when you work out what these, the official name is the convolution of, this sort of acceptance function for the red cone cells with actual, light.
you find that you can, you can represent that by this sort of bulging color triangle. Okay. When you have particular light sources, like 3 particular light sources, a particular red one, green one, blue one.
Those are points in the color triangle. Each of those colors is a point in the color triangle. When you have
If you have a display that basically has 3 different color components in it.
then, those correspond to points in the color triangle, and the only colors that you can make on that display are ones that are in the actual triangle, whose corners are those points in the color triangle. So when you have a display, the display will make all kinds of colors.
But there are colors in the color triangle that there can be colors of flowers or paints or whatever else, that are colors that are outside of whatever you can make by just having 3 colors
of sort of three light sources in these little components and LEDs in the screen. So it will always be the case that when you have these pieces, that there will be colors that, in principle, can exist and that we can perceive that are not generatable by the display.
And, and, the, it's the same kind of thing
Well, with color printing, where instead of red, green, and blue, it's cyan, magenta, and yellow, the complementary colors, are the dots of ink that you get. If you really want to have some other color, you can have a special ink
that's separately printed, a so-called spot color, that's separately printed on your piece of paper that isn't part of the so-called four-color process that is the cyan, magenta, yellow, and also black that's used there. So, in any case, I suspect what happens with,
I suspect that this business about the fact that Violet
is, both on the end of the spectrum and sort of what we get by combining red and blue. I haven't really thought about this before, but I'm guessing that that has something to do with what's in the color triangle versus what you can get.
By combining, sort of, fixed, ways of representing color, my guess, at least.
Let's see, there's a question…
Reebok is claiming that cats have a sort of mirror in the back that reflects lost photons. That's why the eyes glow in the dark. I… I…
That's interesting. I thought it was just a retina that has, their retina with,
It's an interesting claim. I would think that having random photons bouncing around in one's eyes wouldn't be such a hot idea.
Because, really, you care about having photons that get directed specifically into the right spot on your retina, to see at a place that's the right place. I mean, if you're an insect or a trilobite, you have a compound… you have a,
an omitidium, which is just a little… a little sector of a sphere, and sort of all… you're not… you're seeing the world in a limited number of pixels, and it's just a question of, do you illuminate that pixel or not? And then, if you can… whatever you can do to those photons, even

if they're bouncing around crazily inside that little cone that is that sort of pixel that you're seeing, it'll be a win.

But my… my guess is, for eyes like ours, you don't want reflections. I mean, I think,

In, I don't think there are lots of internal reflections in,

in our eyes. I don't know effects that are the result of that.

Let's see… Pathf is saying, are we basically doing Fourier transforms in our brains to recognize colors? No.

In the case of sound, when…

Okay, different pictures of sound, different frequencies… correspond to different frequencies, we detect those in a certain way in our ears.

when we're detecting different frequencies of light in our eyes, it's a much more direct thing.

That is, there is a type of cone cell that is a particular protein where a red photon, a photon of that energy, will cause that protein to produce an electron.

And another protein senses green, and we're… we're selecting those.

So we're really, instead of saying, let's look at the whole spectrum, and let's be sensitive to the whole spectrum, instead we're just cutting out three different parts of that spectrum, although we do it in a kind of a smooth way, but we're just saying, how much red, how much green, how much blue?

By just the sort of very direct process of saying, we have red thing, red cone cells that absorb things mostly in the red, et cetera, et cetera, et cetera. So we're not sort of dissecting that frequency spectrum. In the case of sound, it's a little different.

In the case of sound, inside our cochlea, in our inner ears, there's a kind of spiral-shaped thing. If you… inside that, it's a kind of a cone shape, it's bigger at one end than the other. In a pretty complicated set of processes.

There's this fluid inside the inner ear, and sound goes into the inner ear, and sound waves, which are these compression-decompression waves, inside the cochlea, it will be the case that those sound waves, they're little hairs inside the cochlea that are literally being wiggled by the sound wave. And the way the cochlea works.

Is different parts of the cochlea detect

different frequencies of sound. So the tip, I think, detects the highest frequencies of sound, and, that's, and you're… you have the little tiny hair cells there and so on, and you're detecting lower frequencies of sound in other parts, and you're…

Is that right?

I think… I think that's right. I think it segregates the sounds, different parts of the cochlea. But for sure, you're detecting, kind of, the… the actual wavelength of sound gets laid out in the actual… this hair cell is going in that direction, that hair cell is going in that direction, inside the cochlea.

Let's see… a bunch of questions here, so…

Memes is asking, what energy levels are required to achieve a blackbody spectrum?

So… what happens… Is, in an atom.

And an atom that's… that's staying still.

The electrons in that atom have a quantized set of energy levels. If there's an electron, for example, in hydrogen, where there's a single proton, single electron.

There is a series of

of, energy levels for the electron, they actually go like, the main ones go like 1 over n squared. The nth level is sort of the…

the maximum value minus 1 over n squared. And so, they're each… they're a discrete set of levels, of energy levels, that an electron can have in a hydrogen atom.
And the way light is emitted by a hydrogen atom is because the electron has been promoted into one of those higher levels, and as it
there's a quantum mechanical process that causes it to decay. It's a quantum field theory process that causes it to decay from that higher energy state to the lower energy state. When it does that, where does the energy go? Well, it goes in a photon that's emitted by the electron.
I mean, one picture of what leads to that decay is that the vacuum, this is some kind of quantum fluctuations in the vacuum, are sort of constantly kicking the electron, and eventually it says, okay, I give up, I'm going to emit a photon and decay to this lower level.
But they're a discrete set of possible levels, possible energies that can be generated because you have this
sequence of energy levels, and the only… the photons that are emitted have to correspond to the energy differences between those discrete levels. So, for example, the lowest level in hydrogen from the first excited state, the so-called 2S or 1P excited state, down to the 1S level.
That transition is the thing called the Lyman Alpha Line. It's a fixed frequency of light that is actually in the ultraviolet.
And it's a thing used a lot in astrophysics, is to look for the emission, neutral hydrogen emission of that ultraviolet transition. So you can kind of tell different atoms, every different atom has these different specific energy levels and specific kind of frequencies of light that it produces. And, in a fluorescent light, those are the frequencies you're dealing with.
In…
What's happening in… when you have a black body is that in a first approximation, you've just got so… now, let's see how to think about this.
I think you just have so many of those energy levels involved that what matters is not the individual energy levels, but rather, sort of how
how the energy is distributed between different levels. So there's a fixed way that energy at a particular temperature, the so-called Planck spectrum or black body spectrum, it's a particular function, it's 1 over e to the, basically, frequency divided by temperature minus 1.
That that object, that mathematical formula, is the formula that tells you, in the case where you just have, sort of,
lots of possible energy levels, many, many energy levels, then that's the limit of sort of a… each energy level is discrete, but there are an infinite number of them.
that's the distribution of how energy… how energy is distributed across those energy levels. So I think the answer is, if you're dealing with… with,
Things where… you are… Let's think about this for a second.
I mean, there's another effect which I don't think is so important, which is the Doppler shift associated with the light that's emitted. So when the atom is moving around, the frequency of light that it emits will be changed.
But… and the amount it's changed is basically proportional to the fraction of the speed of light that the atom is moving at.
I don't think that's a significant effect, because atoms in materials are moving at something closer to the speed of sound, not the speed of light, so it's a tiny fraction of the speed of light.
It's, it's… so I think… I think the point is.

So the question is, at what point do you have enough, kind of, heat that's wiggling atoms around and pushing electrons into higher energy levels that it doesn't matter that there are specific discrete energy levels?
And, I think it's…
just the case that you've got, sort of, enough energy in these atoms that you're constantly having electrons in much higher energy levels, and you're not seeing the specific, oh, it's just in the particular, sort of, one excited level that's going to produce a specific spectral… a specific frequency of photon as output. You're just spraying it into lots of different energy levels.
I think that's… that's what's going on there.
Let's see… Okay, there's a question here.
Actually, this question from Lejepe.
Is there a way to train AI to assemble structures at the nanoscale so that light reflects off the item as a whole and have it show visual effects realistically, like fire, gems, etc? The answer to that will be yes. That's kind of what happens in a hologram.
A hologram is something where okay, the…
Well, let me explain a few different things.
So… Our eyes, when… Okay, one way of viewing light is it's a stream of photons.
Another way of viewing light is it's a sequence of electromagnetic waves.
Those are complementary views. Kind of a photon is like a wave packet, where there's a big intensity of the wave, and it's wiggling around a bit inside the photon, and it dies down, and you can kind of be really concentrating on the wiggling stuff, but you can be really concentrating on the packet of energy that is the photon.
Those are sort of complementary views. But when it comes to the wiggling part, there's a question of how are those wiggles aligned? What's the phase of those wiggles? Is it the case that the… if… and that can matter. So, for example, with sound.
It's, again, there's sound waves, and there's wiggles, and the sound waves are going compression, decomp, compression, decompression in the air, and they're traveling at the speed of sound, so as they go past your ears or into your ears, you'll be getting compression, decompression, compression, decompression, thousands of times a second.
If you have a source of sound, that source of sound is producing this compression, decompression, et cetera, et cetera, et cetera. If, if the sound is coming to one ear.
from a particular source that's fairly nearby, it will… there'll be a certain distance from that source to one ear, your other ear is in a different place, there's a different distance to that other ear.
And so if you say, well, which precise compression-decompression, thing did we get at left ear versus right ear, it'll be different, because the, by the time the sound got to your left ear, it will be a different compression-decompression cycle from when it got to your right ear.
And that leads to a phase difference, a difference in what level of compression versus decompression in this wave you are perceiving with each ear. And the brain uses that phase difference as one of its mechanisms to figure out the direction that a sound is coming from.
Okay, so in the case of light, also, there is this idea of phase of light.
And that, when you have the, sort of, the full, sort of, description of the light, it includes both the intensity of the light and the phase of the light.
In the case of a hologram.

made with lasers, its holograms sort of contain the phase information as well as the intensity information. And that phase information allows you to sort of reconstruct the complete sort of pattern of light as it will reach your eyes.

If you just have intensity, you can know what direction the light is coming from when it reaches your eye, but you can't… if you kind of… there'll be this whole kind of,

sort of structure of light that's getting towards your eye, and if you move your head around, you'll see a different part of that structure. If you're just seeing a static picture based on intensity, it will, you know, you'll just see a different part of that picture. But if you can sense this whole kind of structure in space of the wave fronts of light and so on, then you can sort of see it in 3D. And that's… that's what happens in Hologram. In Hologram, you are using, well.

Laser light. Okay, ordinary light.

from an LED or an incandescent light bulb, the phase is sort of random, it's all over the place. From a laser, laser light is always… the phase is always the same. It's, at any given moment, a laser… a beam of laser light has a fixed phase.

And, and so that's why, when you have a hologram, you can produce a hologram, illuminate it with a laser, the phase is determined that that's consistent, the hologram has… is, is kind of changing the phase differently in different parts of the hologram.

And that's causing the kind of the wavefronts of light to be in different places, that's causing one to perceive the scene with all its whole 3D, kind of configuration.

Okay, so…

you can absolutely make… so, holograms can be made by, sort of, photographic-type processes. The thing that is still to come is to be able to make a hologram in real time.

So, you can have, devices like MEMS, microelectronic.

manipulators. MEMs are little tiny pieces of semiconductor that move around in response to… actually not… it's pizza electric, it's not a semiconductor. It's a… what is it? It's a ferroelectric, I think.

It's a slightly different kind of material. But in any case, the main point is that in, in, in MEMS, you are, an electric

voltage will physically move a piece of material. And so you can have a mirror that's a sort of a MEMS mirror, it's the way a lot of projectors are made, or at least used to be made, is that you would have a mirror that's kind of an active mirror, where every component

There are lots of pixels in the mirror, and what's happening is you're putting voltages on those little tiny mirrorlets, the little tiny, tiny pixel mirrors, and you're physically moving this thing so that you either reflect light right back, or you reflect light in a slightly different direction.

So, that's something which can be done at the level of lots of pixels across an image, and you can make a high-resolution projector that way.

If you could get those things down at the wavelength of light,

Which is, so, like, a few hundred,

nanometers, a few hundred billionths of a… of a meter. If you could get

those little, sort of manipulable mirrors down at that scale, you could make a hologram in real time.

You could actually have a thing where, as a display, you have a thing that is producing light with all its phase information intact, and projecting, you know.

Star Wars-like thing, you know, just projecting into… into free space, an image that will be a 3D image.

They're a… That's not quite possible yet.

But that's something one might hope to be able to achieve with some kind of nanomaterial-type, type thing. To be able to make a hologram in, and once you can do that, once you can really control the phase of light.
And, sort of from everywhere. I think you can make anything, any configuration of light that we can sense, you can make.
So, that means that,
You know, that right now, we're very limited in that all we can produce is, with a display, is we can produce a particular configuration of intensities of light.
We can't deal with the phase information in the light, but that's what we need to truly be able to get it so that it is just… just like it was from whatever the thing was that was producing that light.
So, that's the thing that one's looking for, and we're not quite there yet, but I don't think there's anything physically impossible about making a nanomaterial that has those properties and being able to get to that point.
Tony is asking, why is depth perception affected when you lose sight in one eye? It's really simple. It's… you're using parallax information.
Using the fact that if you have a thing, you know, you hold up a thing, you can see… you hold a thing up a certain distance away from your face, you're seeing a slightly different side of that thing from one eye as from the other eye.
And so, what the brain does is it fuses together, you know, you get a different image. I mean, if you have a thing that's… that you're holding just in front of your nose, you will see, you know, the left-hand side from your left eye, the right-hand side from your right eye.
If the thing is further away, there's… there's less difference between the left eye and the right eye.
your brain is fusing together the left and right images. You know, if you mess around with your glasses or whatever, you can make it… or you have binoculars where you have a, you know, you're moving the binocular pieces apart and so on, you can get it so the two, the two things that you're seeing from your two eyes do not fuse together. You have to move them so that they do fuse together. But you can… your brain is fusing those images to give you just a single image, not these two different images. I mean, I often wonder, what would it be like to be a horse or something, or a… or something where you have eyes on the sides of your head.
Those images won't fuse together. Those images are different from the left eye and the right eye. But for us, we've got forward-facing eyes, and so we see just a little bit of a, you know, a leftward part of the image from the left eye, rightward part from the right eye.
And that's… and we use the depth cue that we have is, if we see something that's almost exactly the same from our left eye and our right eye, we know it's a long way away. There's very little difference between left eye's perspective and the right eye's perspective.
In general, it's actually a fairly easy algorithm to do, kind of, the optic flow algorithm, where you're trying to figure out, you know, are you coming close to an object? Because there's kind of all the different things that you see are moving apart, and so on.
I have to go in a moment here, but,
Let me try and address maybe one more.
Question from Tony. Why do optical illusions fool our brain?
So… Our brains…

do a lot of processing on the images we get. So, the first level of our brains is sensing things like edges and stripes, up and down stripes, and it's blobs and things like that. And when we say, that's a picture of a cat.

That's coming from sort of a higher level in our brains. In artificial neural nets, you can see these layers very explicitly. You end up with early layers that are detecting sort of general features of images, like blobs and lines and things like this, and then those are sort of combined together to say, that's a picture of a cat.

Okay, so most optical illusions are the result of kind of confusing the way those different layers work.

Just to give you a very generic optical illusion, in our eyes, each…

each one of our eyes, there's a place where there are just no photoreceptors on our retina, because that's the place in the really bad design of our eyes, where the optic nerve is taking the cross connection, the data from the cross connections that are in front of our photoreceptors on our retina, taking those cross connections, which is where the signals go, and

Putting them into the back of our brain, another piece of weird design, that the visual cortex is at the back of our brain, even though our eyes are at the front of our heads.

But in any case, the optic nerve kind of makes a hole in our retinas. So if you cover one eye, you put a big blob on a page, and you move to exactly the right distance, that blob will be, sort of… the place on your retina that would see that blob is right where your optic nerve is, and there's no retina there, there's no photoreceptors there, so you don't see the blob.

If you put graph paper, if you make a bunch of graph paper, you put the blob on the graph paper, you'll… your eye, you know, your brain will fill in graph paper where the blob was, even though, when you look from a different distance, you can see there's a blob on that piece of paper.

When that blob lines up with where your retina doesn't see it, your brain will just fill in these lines across the blob.

And the brain does lots of those kinds of things, just sort of extrapolating from what's there.

And most optical illusions are some form of extrapolation from what's there, and some confusion about how that extrapolation is working. Something where you have some sort of negative space where you've got something filling in, and you think that your brain will sort of fill in something in the middle, even though there's nothing actually there. I mean, there are some other optical illusions, like, for example, if you spin a black and white disc.

At a certain rate.

you'll see colors in that black and white disc. I was very curious about that when I was a kid.

And I had a theory, which I think is more or less the right theory, that it has to do with the fact that the red, green, and blue color receptors in our brains

have, slightly different, rates at which they, replenish themselves, and so when you're spinning this black and white disc.

When it's black-white, black-white at a certain frequency, you'll tend to get sort of more red and more blue. I think you get blue and yellow, typically, more than red in that situation. And that's because those things get, replenished either more quickly or more slowly. I'd have to work that out as the disc spins.

So, a few thoughts about that.

Alright, well… Today was… was,

Lighten Eyes Day, I suppose.

more questions I see saved up for another time.

Well, thanks for joining me, and

Look forward to seeing you another time.
Bye for now.