frontiers FOR YOUNG MINDS

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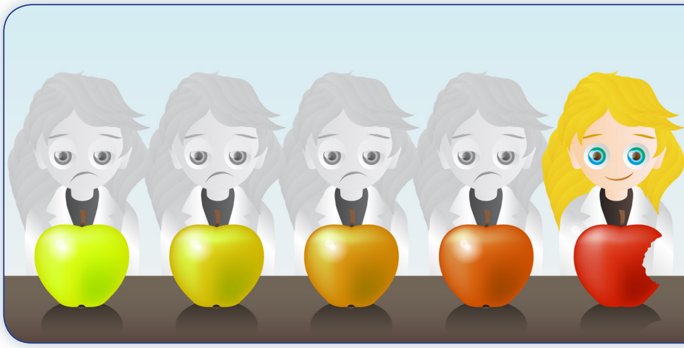

How do we see color?

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Reviewed by:

Sacha
14 years old

A time bomb: the heroine of the movie is leaning over a ticking bomb. Under the bright white lights of the mayor's office, the timer is racing down to zero and she has only one chance to defuse it. As she opens the cover from the control panel, a spaghetti jumble of multi-colored wires springs out, but she remains calm. "Just cut the red one" she thinks to herself as she carefully picks through them. "Not green, not blue – Yes. there!" With only seconds to spare, she picks out the correct wire and snips through it. The LED countdown stops at one second to detonation and City Hall is saved.

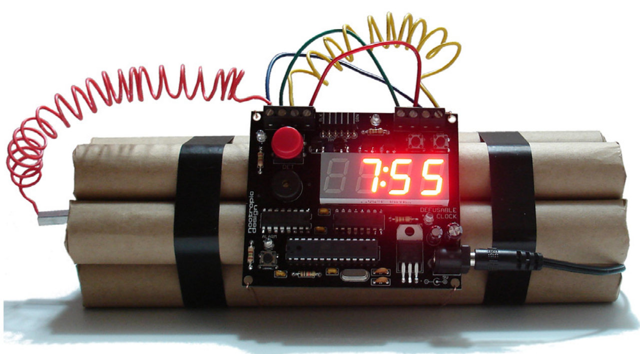

FIGURE 1 - When defusing a bomb, you must be able to see the color of the wires before deciding which to cut. Alarm clock made by http://nootropicdesign.com. Permission to use with CC attribution obtained.

WHAT IS COLOR GOOD FOR?

Although our distant ancestors probably first used color vision to find fruit in trees, it is still useful to us. Even though most of us will never have to defuse a bomb (Figure 1), colors are used to send all sorts of important messages in the modern world. Traffic lights turn from green to red to tell us to stop (Figure 2), warning lights turn orange on the car dashboard and the LED on my phone charger flashes green to let me know I can play Angry Birds again. Color is also beautiful – think how much time we spend admiring the hues in sunsets, art, and landscapes, and how much less-impressive firework displays would look in black and white. So how exactly is the sensation of color produced?

The science of color is full of surprises and the first is that seeing color is something that happens in your brain. The signals that lead to color vision come from your eyes but it is your *brain* that makes sense of them – allowing you to see a strawberry as red and the sky as blue. Your eyes *create* the code for color, as we will find out below, but those coded signals only make sense after your "visual cortex" (the part of your brain at the back of your head that deals with seeing)

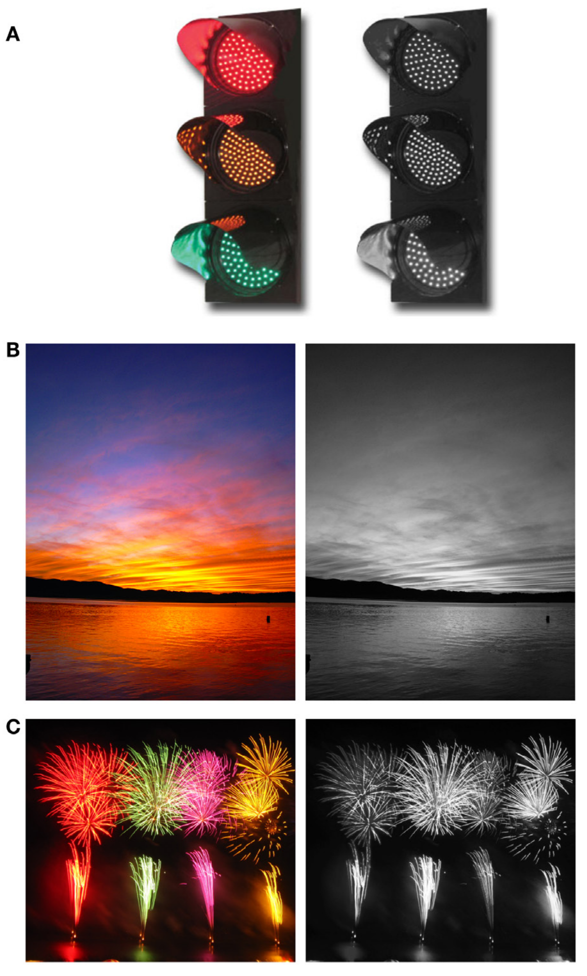

FIGURE 2 - Colored objects.
A. Traffic lights.
B. Evening twilight in Knysna, South Africa. Displaying the separation of orange colors in the direction from the Sun below the Horizon to the observer; and the blue components scattered from the surrounding sky.
C. Fireworks from the 352nd Chikugo River Fireworks Festival, Japan.
A. Available at: http://en.wikipedia.org/wiki/File:LED_Traffic_Light.jpg PD-icon.svg. This work has been released into the public domain by its author, Syafiqshahalam at the English Wikipedia project. B. Available at: http://en.wikipedia.org/wiki/File:Knysnasunset.jpg Image by Gerald Browne. This file is licensed under the Creative Commons Attribution-Share Alike 3.0 Unported license. C. Available at: http://en.wikipedia.org/wiki/File:ColorfulFireworks.png Image by 久留米市民 (Kurume-Shimin).

decodes them. Lots of different parts of visual vortex must work together for you to see color properly, and they will be the subject of a whole other paper.

But perhaps the most surprising thing about color is this: although you can see millions of different colors (all the colors of the rainbow, plus every possible mixture of those colors), you have only three types of color detectors in your eyes. These detectors are special types of cells called "cones" (because they look like little cones under a microscope) and each type of cone has a preference for a particular type of light. So how can just these three types of cells tell you about all the colors that you see around? To answer this question, we must first understand a bit of the science behind light.

SCIENCE OF LIGHT

The light you can see is just a small part of something bigger called the electromagnetic spectrum (Figure 3), which includes *X-rays* (used to see broken bones in hospitals), *gamma rays* (used to turn Bruce Banner into the Incredible Hulk), *microwaves* (used to heat up popcorn), *radio waves* (which allow us to make cell phone calls), and *ultraviolet radiation* (which will give you a burn if you do not cover up on sunny days).

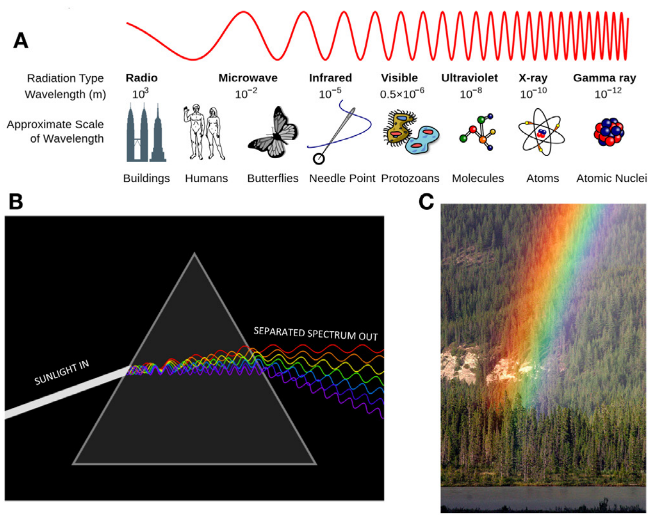

FIGURE 3 - A. The electromagnetic spectrum. We have different names for wavelengths of different sizes but they are really all the same type of energy.
B. A prism separating white light into different wavelengths.
C. A rainbow is made when raindrops split light into separate wavelengths.
A. Available at: http://en.wikipedia.org/wiki/Electromagnetic_spectrum (Modified). B. Available at: http://en.wikipedia.org/wiki/File:Light_dispersion_conceptual_waves.gif C. Available at: http://en.wikipedia.org/wiki/File:WhereRainbowRises.jpg

All parts of the electromagnetic spectrum can be thought of as sets of waves moving through space. The distance between two waves that follow each other is called a *wavelength*. Radio waves have a wavelength of about the length of a football field and microwaves have a wavelength about the size of an ant, which is why an ant can sometimes survive inside a microwave oven (but please do not try this at home!). Visible light waves are even smaller than the size of bacteria.

Most light sources around you give off a variety of waves with lot of different wavelengths. A good example is sunlight, which is made up from a mixture of pretty much all the wavelengths that you can see. We call this mixture a "spectrum" and if you pass a spectrum through a special piece of glass called a prism, it will split into the different wavelengths, which you can project onto a piece of paper. If you do this, you will see that each part of the spectrum appears to have its own color and the entire collection looks like a rainbow. Short wavelengths appear bluish, long wavelengths appear reddish. Real rainbows in the sky are formed in the same way, except that nature uses water droplets to do the splitting, instead of a glass prism.

Okay – back to color vision and a real-life example. Imagine you are outside in an apple orchard at noon on a hot, bright day. How do you know if the fruit you are about to pick is ripe?

The light from the sun is bouncing off an apple and then after the bounce, it enters your eye. Ripe apples contain a special chemical in their skin, and during the bounce, that chemical absorbs some of the sunlight spectrum. It does not absorb all the wavelengths equally though – the short wavelengths are blocked but most of the long-wavelength light is reflected straight back out toward you. In other words, the bounce causes the spectrum of the sunlight to change and now it has much less short wavelength light in it.

The riper an apple is, the more of this color absorbing chemical it has in its skin, and the more short wavelength light it absorbs. By reflecting only a part of the sunlight spectrum to us, the apple is sending us a coded message: "I am delicious and ready to eat."[1]

CODE FOR COLOR

To understand this message, we do not have to know exactly what the spectrum of reflected light looks like. We just have to know that it has lots of long wavelength light in it, and not so much short wavelength light. This is where our cone cells come in.

The cone cells sit inside the back of the eye, and light gets to them through that black hole in the middle of your eye that is called a "pupil." You did know it was a hole, right? Each of the three cone types gets excited by a different part of the light spectrum – in other words by a different set of wavelengths. Because vision scientists have no imagination, we call the cones that prefer long wavelengths "*L cones*," the ones that prefer short wavelength "*S cones*" and the ones in the middle that prefer medium wavelengths are called, yes you guessed it, "*M cones*." When the light waves from the apple hit the back of your eye, the L cones will be very excited because the spectrum contains lots of long wavelengths. The M cones will be slightly excited because there are some medium wavelengths, but the S cones will be silent because the spectrum contains almost no short wavelengths – the apple skin absorbed them all. Each cone will then send a message to your brain telling it exactly how excited it is.

So when that big group of millions of different light waves bouncing off the apple goes into your eye and hits the millions of cone cells at the back, it generates just three signals: high, medium, and low at every location. For the apple, we might give scores to these signals as 90% (L), 70% (M), and 5% (S), and these

[1] You might think that we are cruelly taking advantage of apples by breeding them to go red when they are ripe so that we can eat them more easily. But in fact apples want to be eaten! This is how wild apple trees spread their seeds. So really, the apples are controlling us with their color instead. Think about that the next time you eat a packed lunch!

three numbers tell us something very important about the fruit: that it is reflecting lots of long, but not much short wavelength light, and so, it is ripe.

And this is how color works for pretty much everything we see. Each object reflects light into our eyes, and that reflected light creates responses in our L, M, and S cones. There are thousands and thousands of L, M, and S cones in your eye, each sending a coded message to your brain telling it how much long-, medium-, and short-wavelength light is bouncing off all the different things that you can see. These three types of signals tell you about what stuff each object is made of – and this three-number code is what we call *color*.

Light is a special case because we see its spectrum without it bouncing off anything, but the same ideas apply and its color is still due to the different amounts of signal that it generates in three cones.

You might have noticed that we tried not to mention the word color until the very end of this explanation. Lots of explanations of light, even in textbooks, contain statements like "long wavelengths are red." This is not quite true. As Isaac Newton, the famous British scientist (the same person who invented gravity and apples) once said, "The rays are not colored."[2] Instead, color is the *code* that your eye generates when a spectrum of light hits it. The idea that color is only in your head might seem strange at first, but think of it as being a bit like pain. A brick does not have "pain" – it only makes pain when it hits your toe. In the same way, light does not have "color" but it can make color when it hits your eye (Figure 4).

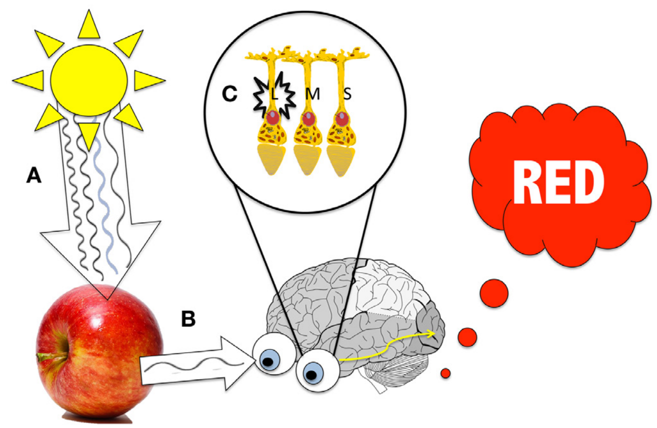

FIGURE 4 - Seeing red.
A. Light from the sun hits the apple. Some wavelengths are blocked by the chemicals in the apple's skin.
B. Reflected wavelengths pass through the pupil and excite the cone cells at the back of the eye.
C. The cones send a coded message to the brain about the wavelengths entering the eye. In this example, the L-cones are very excited, the M-cones are a little bit excited and the S cones are hardly excited at all. The brain translates this code into a sensation of "red".

COLOR, VIDEO GAMES, AND PHONES

Now you might have spotted a problem with this system. We would like to use color to tell things apart, but the only thing that you really know about the color of an object is the three-number code that it generates in your cones. It means that *any* two sets of light rays that make your cones respond the same way will look identical, even if they contain quite different wavelengths. In theory, this is correct, and there are some occasions when you will mistake two different objects that seem to have the same color. Luckily, this happens less than you might think – it is not a big problem. Even better, being able to mimic the color of one thing in real life using a different set of wavelengths turns out to be fantastically useful.

Imagine you have measured the exact spectrum of an apple, and you want to show a picture of that apple on a TV screen. TV screens are made of lots of little lights, arranged into a pattern that repeats over and over again. If you take a magnifying glass and look at your TV screen, or in fact pretty much any screen that you can find (like the one that is probably in front of you right now), you can see them. But before you do that, guess how many different *types* of light you need to reproduce the color of a juicy ripe apple *exactly*?

[2] Naturally he used the British spelling.

A MAGIC NUMBER

The answer is three, because all you have to do is *trick* the L, M, and S cones in your eye, into responding the same way that they would if they were seeing a real apple. Remember, nothing else matters to your brain except the three-number code from the L, M, and S cones. Now, go and look at your screen through a magnifying glass (or, more conveniently, look at Figure 5A) and you will see that there are only three types of light in any color video screen: one that looks red, one that looks green, and one that looks blue.

So having just three cone types in your eye is very efficient. First, it means that you do not need a complicated system for transmitting color information to your brain (just three signals from each location will do the trick). Second, it means that you only need three lights at every point on a video display to reproduce any color in the world. This is still a difficult problem – cramming three little lights into every point on a TV screen is difficult, and it took engineers a long time to make color TV sets after they invented black and white devices but they are now so good at it that colors on TV look pretty realistic and you never even think about the little dots that make up each point. If you had many more types of cones in your eye (like some birds and shrimp do), it would be practically impossible to get a good TV picture, and your mobile phone or hand-held game console would be annoyingly large.

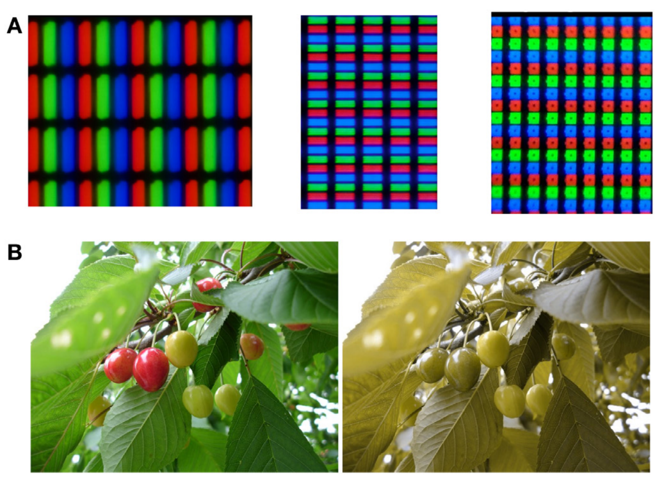

FIGURE 5 - A. LCD arrays and B. color blindness simulation.
A. Magnified views of different types of video screens (LCD monitor, iPhone screen, and Nintendo DS screen). Each screen is made up of hundreds of thousands of long, medium, and short wavelength emitting dots.
B. Cherries turn red when they are ripe, just like apples. For someone with normal color vision, it is easy to see the ripe cherries in a tree. Color blind people do not see the difference between red and green very well and so they find fruit picking much harder. We can now use computers to simulate different types of color blindness and even change images so that they are more visible to color blind people. Picture by Julie Kertesz, color blindness simulation. Available at: www.vischeck.com

BIRDS, BEES, AND SHRIMPS

Most people (and some monkeys) have three types of cone cells as we have described above. But quite a lot of people only have *two* cones and this means that their color vision is a little different. Having only two cone types does not mean you only see in black and white – usually, it just means that you have trouble in differentiating red from green, which can make some tasks more difficult (like picking fruit, decorating your living room, or defusing bombs). Even though people with only two cones (who are almost always male) can still see lots of colors, we call this condition "color blindness."

In the same way, cats and dogs may also be color blind – they have only two cones in their eyes and so they also have trouble in differentiating red from green. Figure 5B shows what the world would look like if you had only two cones. Of course if you are actually color blind, then the two pictures in Figure 5B will look very similar.

You may be feeling pretty smug at this point, knowing your color vision is better than that of a dog. But, it has recently been discovered that some very rare people have *four* types of cones. These people (who are all women – sorry boys!) are called *tetrachromats* and we think that they can see a whole extra set of colors that most people cannot. This is a difficult thing for most of us to imagine – it is like a color blind person trying to imagine the difference between red and green. It is interesting to try to think what the world might look like to these people but although we can study their vision scientifically, we can never really experience it.

And these women are not the only ones better at seeing color than you! Some birds also have four cones, and the amazing mantis shrimp (see Figure 6) is thought to see the world in more colors than any other animal: some species of mantis shrimp have over 8 different photoreceptors (cones) and can even see different regions of the electromagnetic spectrum such as infrared and ultraviolet. The color vision of these animals is not fully understood yet, and scientists are unsure whether they use all these different photoreceptors in the same way that humans do, but if they look that colorful to those of us with only three cones, imagine what they look like to each other!

INTO THE ABYSS

Finally, back to bombs. As color vision scientists, one of our favorite movie moments is a scene from "The Abyss" where the hero has to defuse a nuclear bomb at the bottom of the sea by cutting a blue striped wire and avoiding a black wire. He dives down and reaches the bomb but with time running out he discovers that the light he has brought with him makes both wires look the same (see Figure 7). We would not spoil the end of the movie for you but the science here is correct: the diver's light source is a yellow glow stick and the spectrum it gives off only has medium wavelengths in it. To our brains, the only difference between a black and a blue wire is the amount of short-wavelength light that each one reflects – and hence the amount of S-cone activity that each one creates. If the glow stick is not sending out any short wavelengths in the first place, then there would be nothing to reflect and both types of wire would look the same[3]. The moral of the story is if you *have* to defuse a bomb two miles under the sea, try to bring a flashlight.

[3] Yes, we really do think about this sort of thing when we are at the movies. Then we nudge our friends and tell them in case they missed it. This makes us very popular.

FIGURE 6 - A Mantis shrimp.
The brightly colored mantis shrimp. Available at: http://en.wikipedia.org/wiki/File:OdontodactylusScyllarus.jpg Image by Silke Baron

FIGURE 7 - A tense scene from "The Abyss".
Make sure you cut the blue and white wire, not the black and white wire!
Image from the Web. Twentieth Century Fox Film Corporation – Fair use.

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REVIEWED BY:

Sacha, 14 years old

When I was just a few weeks old, we moved to Bennekom, a small town close to Arnhem ("a bridge too far"). I am now 14 years old and follow the bilingual stream in secondary school, receiving lessons in English and Dutch. I hope to do the International Bacquelaurate before I leave school. In my spare time, I like to play football and hang out with my mates. Editing interested me for three reasons: I really wanted to understand more about my dad's work; I like the idea of this journal that helps us understand what our parents do; and I also like the idea of being an editor!

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