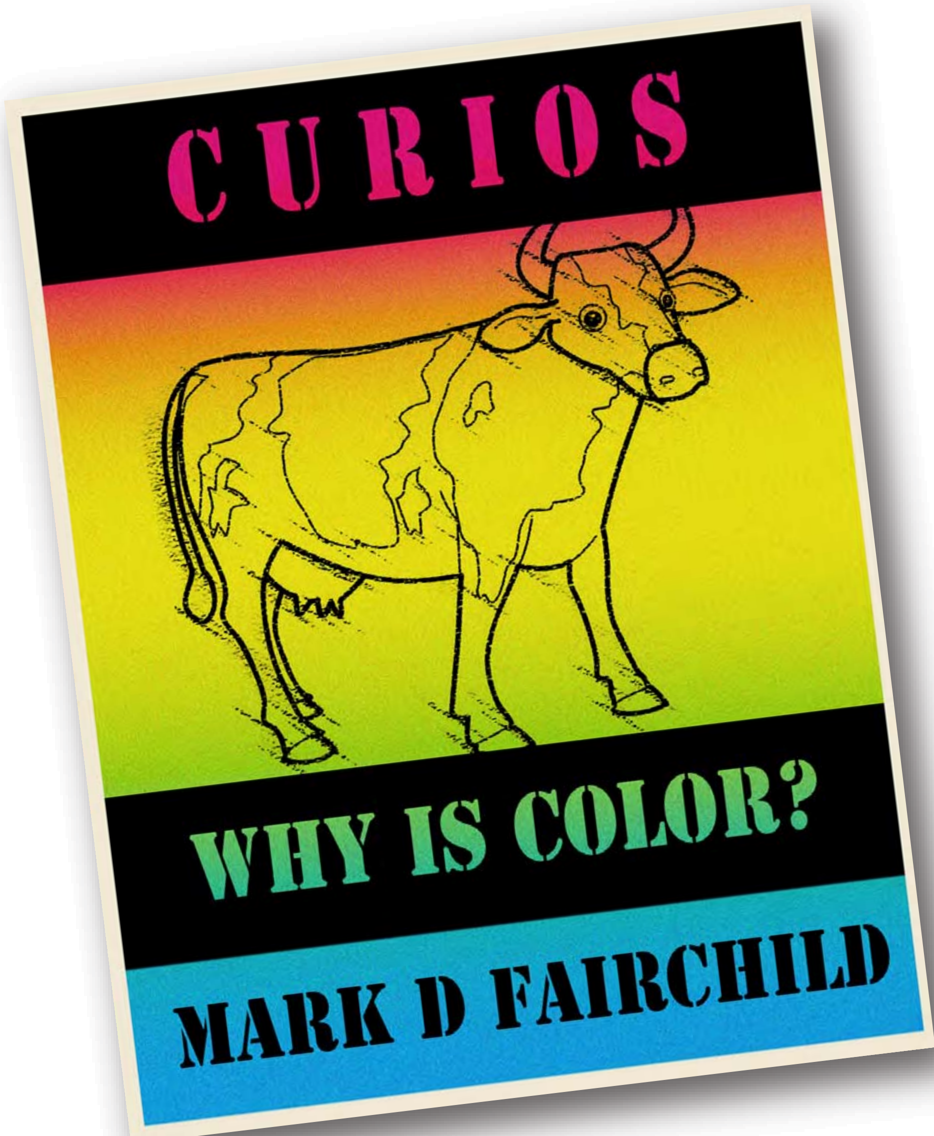
WHY IS COLOR?

www.whyiscolor.org

THE COLOR CURIOSITY SHOP



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Preface

The Color Curiosity Shop was born of out of a desire to do something different, to contribute to science in a way that I hadn't previously, and to create a fun and interesting project for a planned sabbatical leave from my normal professorial duties. Unfortunately I was not able to obtain sufficient funding for that sabbatical leave and this project took me significantly longer to complete (in my "spare" time) than initially expected. Instead of my initial goal of finishing the project in the 2006-07 academic year, I finally completed the online resource in the summer of 2010 and this book form in summer 2011. Better late than never!

My goal was simple in concept, but difficult to bring into reality. I simply wanted to do something to help inspire and motivate students of all ages to consider further education and careers in the sciences. As a color scientist, I had technical expertise on a topic that is of significant interest to most, our perception of color. My hypothesis was that I could use that innate curiosity about color to create an online resource that answered real student questions about color while secretly introducing them to classical disciplines of science. For many years prior, I had been running a very popular *Ask-A-Color-Scientist* section of our laboratory's website, so I knew there were many questions out there to be answered and a lot of innate interest and curiosity in the topic. So I did it and the <*whyiscolor.org*> website and this review book for students and teachers is my result. I have no idea how far the reach will be, but I have already heard feedback from students who appreciated what they learned on the website and are now further exploring careers in science. To me, even just one such story is a success!

As Henry David Thoreau wrote in his final manuscript:

> *Though I do not believe that a plant will spring up where no seed has been, I have great faith in a seed. Convince me that you have a seed there, and I am prepared to expect wonders.*

Finally, I express my deepest gratitude to those that have sponsored and assisted with this project including the Rochester Institute of Technology, RIT's College of Science, the Munsell Color Science Laboratory, the Chester F. Carlson Center for Imaging Science, the National Science Foundation, Apple Inc., Bruce MacEvoy / handprint.com, the Rochester Museum and Science Center, the SDC Colour Museum, the Inter-Society Color Council, and the many K-12 teachers and students who helped create questions and provide feedback. And I sincerely apologize if I have left anyone out.

Enjoy! Explore!

-MDF, Honeoye Falls, June 2011



Dedication

This book is dedicated with love and respect to my two wonderful daughters, Acadia and Ellie, who have given me first-hand experience in the work of educating a whole person from start to never finished! And I also thank them for all their help in creating questions, images, and answers for this project (and for their infinite font of questions).

I also dedicate this work to Chris Bond who was my high school earth science and physics teacher, soccer coach, class advisor, and a great inspiration to me in many ways. He was one of the teachers who helped at the beginning of this project, but sadly died of cancer before he could see the final product.

Table of Contents

Introduction

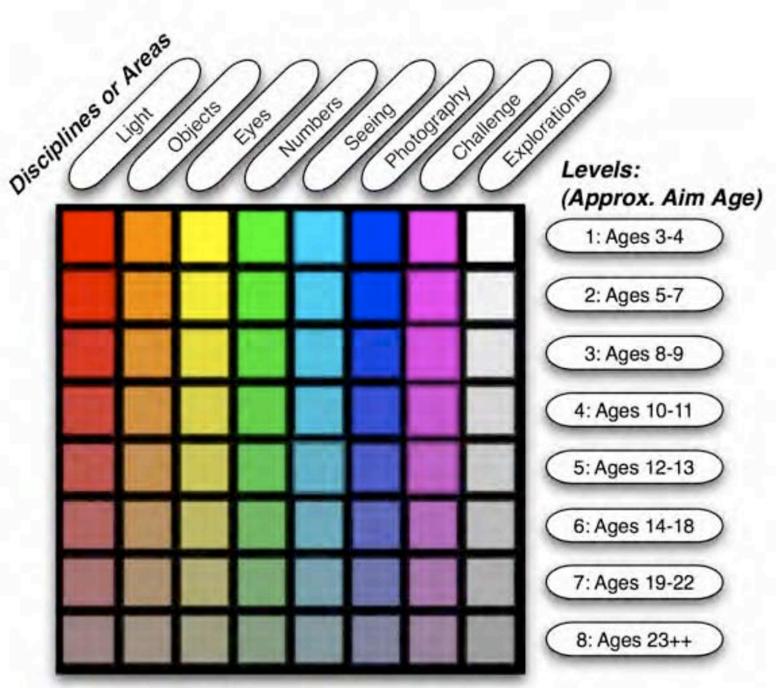
Welcome to *The Color Curiosity Shop*, a multilevel, multidisciplinary introduction to science through exploration of student questions about color.

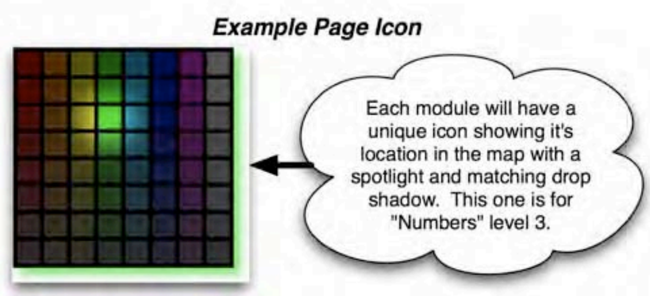
Overview: The Color Curiosity Shop is an interactive, multiple-medium, resource illuminating the relationships between scientific endeavors and everyday experiences. The theme is color — a topic of near-universal experience and fascination. Descriptions of color in scientific terms are made in a way that eliminates the potential intimidation of scientific and technical discourse. Once viewers work through an exploration series on color topics, they will discover they were learning about science without having to overcome any science anxiety. Innate curiosity is the driving force behind this mode of learning. Viewers greatly increase their knowledge about color, gain an appreciation of how science enriches everyday life, and perhaps be motivated to engage in additional exploration and education. This resource was developed from the longstanding tradition of color science education and research at the Munsell Color Science Laboratory (MCSL, *mcsl.rit.edu*), part of the Rochester Institute of Technology's (RIT, *www.rit.edu*) Chester F. Carlson Center for Imaging Science (CIS, *cis.rit.edu*).

The main resource is a public website with 64 modules addressing student questions about color at eight levels spanning eight traditional disciplines. As viewers navigate the modules they discover that science is ultimately about satisfying our natural curiosity. Further dissemination is through this downloadable, navigable, electronic book, a free printable book, and potential development of a museum or science-center exhibits.

The website is populated with common questions about color, their answers, and explanatory photographic illustrations. The modules are arranged in a color-coded, two-dimensional array where one dimension is increasing level (pre-school to post-graduate) and the other is scientific discipline (mathematics to psychology). Eight disciplines, each represented at eight levels, produce 64 modules, each addressing a different question. Viewers can optionally navigate at a constant level while exploring different disciplines, within a given discipline while increasing level, or through random topical selections. This book allows the same navigation strategies. Design is simple and uncluttered allowing exploration without distraction. Topics were derived from surveys of schools and students to assure that the questions are interesting and placed at appropriate levels. Disciplines are designated with common terms (*e.g.*, light instead of physics, objects instead of chemistry, numbers instead of mathematics) until viewers reach the highest level where the scientific disciplines are revealed with resources for ongoing exploration. Likewise, levels are notated simply, not defined by age or grade level.

Objectives: A major goal is to allay some fears of science. The problem addressed is one of motivation and interest. Science is widely held as one of the most respected career areas and the drive to understand the world is fundamental to our basic human needs. Scientists are also among the most satisfied with their personal careers. However, students at all levels can become discouraged from pursuing science because it is perceived to be difficult, boring, or impractical for their daily lives. The end result is that, for example, the United States has an unparalleled system of scientific research and education at the university level, but a lack of interested and motivated students to take advantage of those opportunities. This project aims to help bridge that disparity by encouraging a life-long interest in science among students of all ages from throughout the world by satisfying some of their natural curiosity about the world, specifically their color perceptions, through sound scientific explanations of phenomena illustrated with interesting and pleasing photographs and illustrations. The burdensome overhead of science classes and textbooks is absent. Only after viewers enjoy themselves and satisfy their curiosity might they discover that they have been learning some science and perhaps retain that connection.





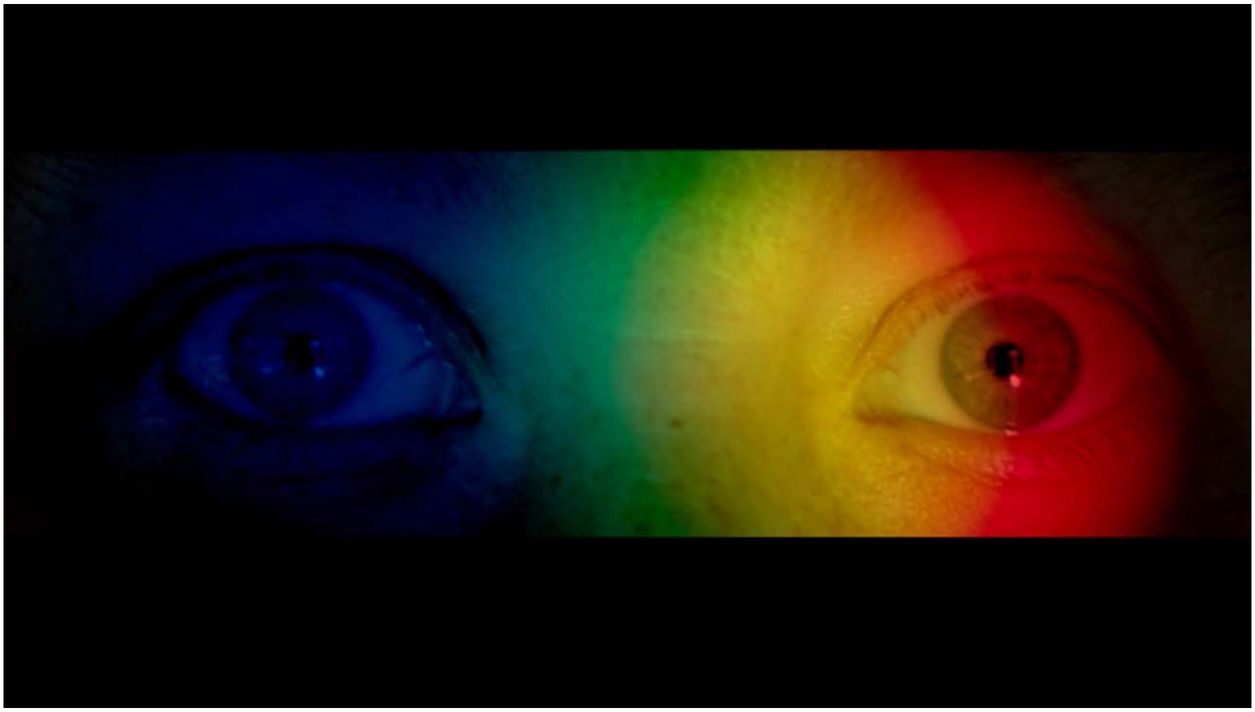
Online Resource: The best way to interact with *The Color Curiosity Shop* is online at <*whyiscolor.org*>. The purpose of this book form of the online material was to allow it to be used in places without internet access and to allow rapid human interaction with the entire resource (also known as flipping through the pages of a book!).

Book Layout: The book is laid out in three main sections. The first goes through each level of material one at a time covering each of the topical areas (in other words it moves through the map row by row). The second section repeats the same material but it is presented topic-by-topic while covering all eight levels before moving onto the next topic (in other words it moves through the map column by column). The map/icon on the lower right side of each odd-numbered page indicates the location within the resource. As a special treat, flipping quickly through the pages of the book while viewing the lower-right corner animates the map/icon.

A Note About Links: Some of the written material includes links to other websites. If you are viewing the PDF version of this book the links are active. If, however, you are reading the hardcopy the links are referred to but not written out explicitly. In such cases it is best to refer back to the main website when you are online to find the links. Or do some exploring to track them down!

Answers to Challenge Questions: Level 1: (C); Level 2: (B); Level 3: (D); Level 4: (B); Level 5: (C); Level 6: (C); Level 7: (A); Level 8: (B).

Q: What is Color?



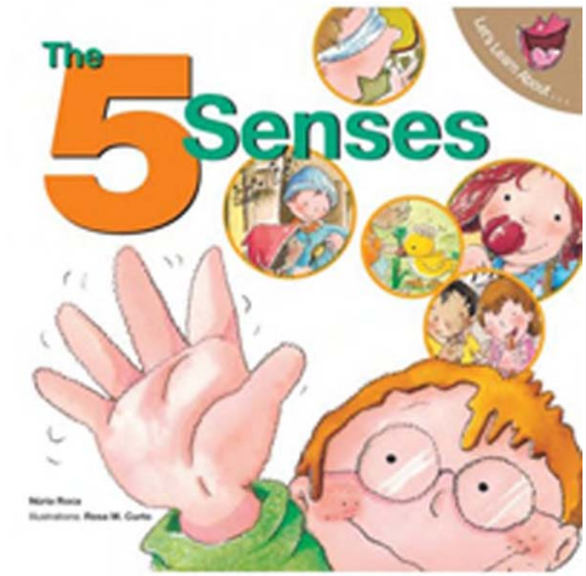
Our eyes sense the light from the world around us and start the process of seeing color. You might think the light on these eyes is colored, but really it is your very own eyes and brain that are creating that color from the light coming from this picture.

A:

Color is a human perception.

We see color because our eyes and brains respond to light present in the world around us. That light comes from light sources such as the sun, light bulbs, or even televisions. Sometimes that light interacts with objects before reaching our eyes and the objects allow more or less of the different types of light to reach our eyes. This makes different things look different colors.

Color is part of our sense of vision. It is similar to how we respond to other aspects of the world with our other senses such as taste, hearing, touch, and smell.



Our eyes provide just one of our five senses. They all help us to live in the world around us. It's fun to learn about all the senses.

Q: Why are Leaves Green?

Leaves look the way they do because of the stuff they are made of. When leaves, like this one from a sugar maple, change in the fall we can see different stuff in them and the green is replaced by bright yellows, oranges, and reds.

A:

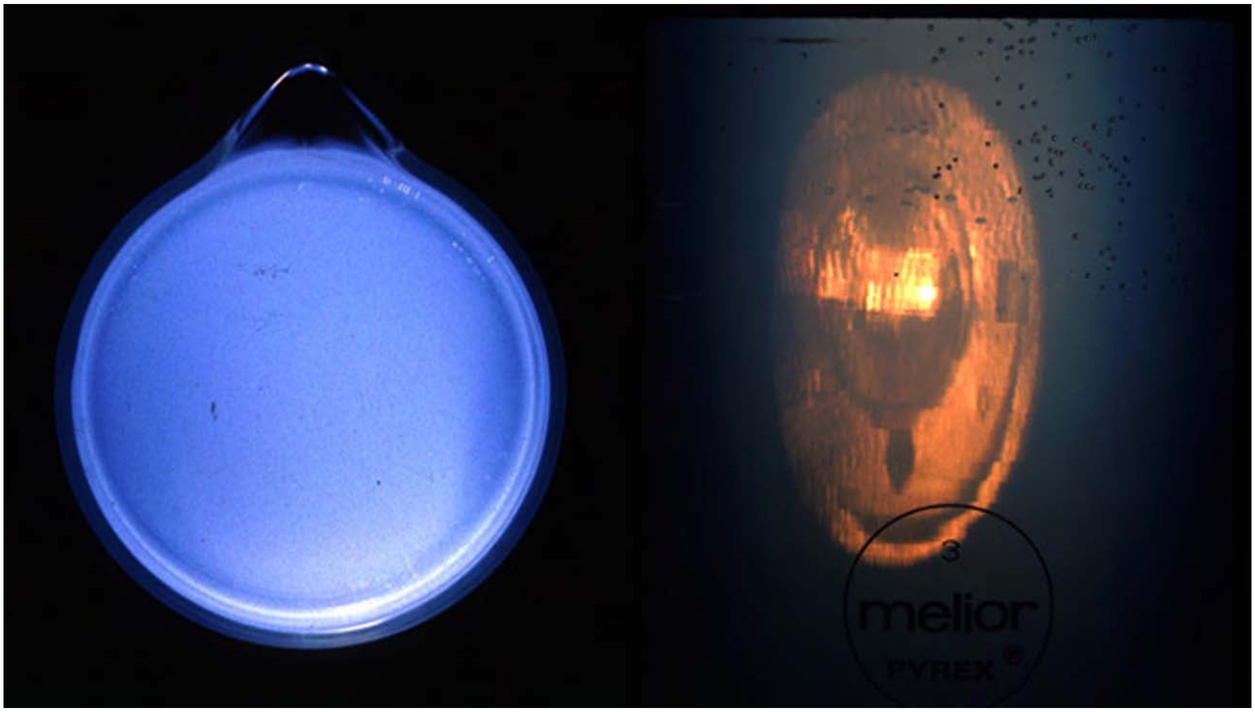
Since color is a perception, leaves are green simply because that's the way we see them!

But why do we see them that way? That's because of the stuff leaves are made of and how it plays with the light from the sun. One sort of stuff in the leaves is called chlorophyll. Chlorophyll is the main part of the leaf that makes them so good for nature. The chlorophyll takes carbon dioxide (CO_2) from the air and uses water and energy from sunlight to create sugar. That sugar is food for the tree and for animals (like us) that eat the leaves or make yummy things like maple syrup from the tree sap.

The light energy that the chlorophyll uses is mainly the types that would look red or blue to us. That leaves the green energy to bounce off (or pass through) the leaves and reach our eyes. And when that light reaches our eyes we see the leaves as green.

Sometimes leaves look very, very green. This can happen when leaves are near other leaves and the light we see bounces off many green leaves before it reaches our eyes.

Q: Why are Eyes Different Colors?



The colors of many things come from scattered light. Milk is white because it scatters almost all the light that hits it. This picture shows a glass beaker full of water with just a little bit of milk in it. The beaker was lit from the side. On the left the camera was above the milk and water and the light scattered sideways was blue. On the right side, the camera was across from the light on the side of the beaker and we can see the red light that passes through without being scattered to the side. This shows why the sky is blue (light scattered to the side) and a sunset is red (the light that goes straight through the sky).

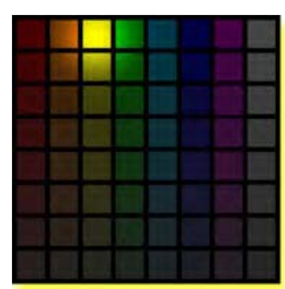
A:

Our skin, hair, and eyes come in many different colors. Amazingly all those different colors are made from exactly the same stuff! That stuff is a pigment, or colored material, called melanin.

The color of our hair and skin is mainly caused by the amount of melanin there (and the underlying blood and body tissue for our skin color). The more melanin present, the darker our hair or skin. Black hair has lots of melanin. Blonde hair has a little bit. And gray hair has none at all.

Eyes come in many colors. Here are the blue eye of a young child, a fairly rare gray eye, and a hazel eye, which is made up of several colors. Interestingly, some people wear colored contact lenses to change their eye color.

The same is true for eyes. The amount of melanin in our irises (the colored part of the eye) helps determine its color. But since melanin itself is black or very dark brown, how can we get blue eyes? Eye colors like blue and green are produced by small amounts of melanin in our eyes in the form of very small particles that scatter light, just like small particles in the sky scatter light to make it look blue (or the milk in water shown in the picture above). It is also interesting to note that the pattern in our iris (the colored part of the eye) is considered absolutely unique. The chances of finding a person with an identical iris are so low, that you would have to check far more people than are currently living on Earth to find one!



Numbers (Level 1)

Q: How Many Different Color Crayons are There?

If you were to go shopping for crayons you would be faced with very many choices. Crayola makes hundreds of different crayon, marker, pencil, and other fun coloring things. When you add in the choices from other companies, the numbers start to boggle the mind. Some way or another you can make pretty much any color you want.

A:

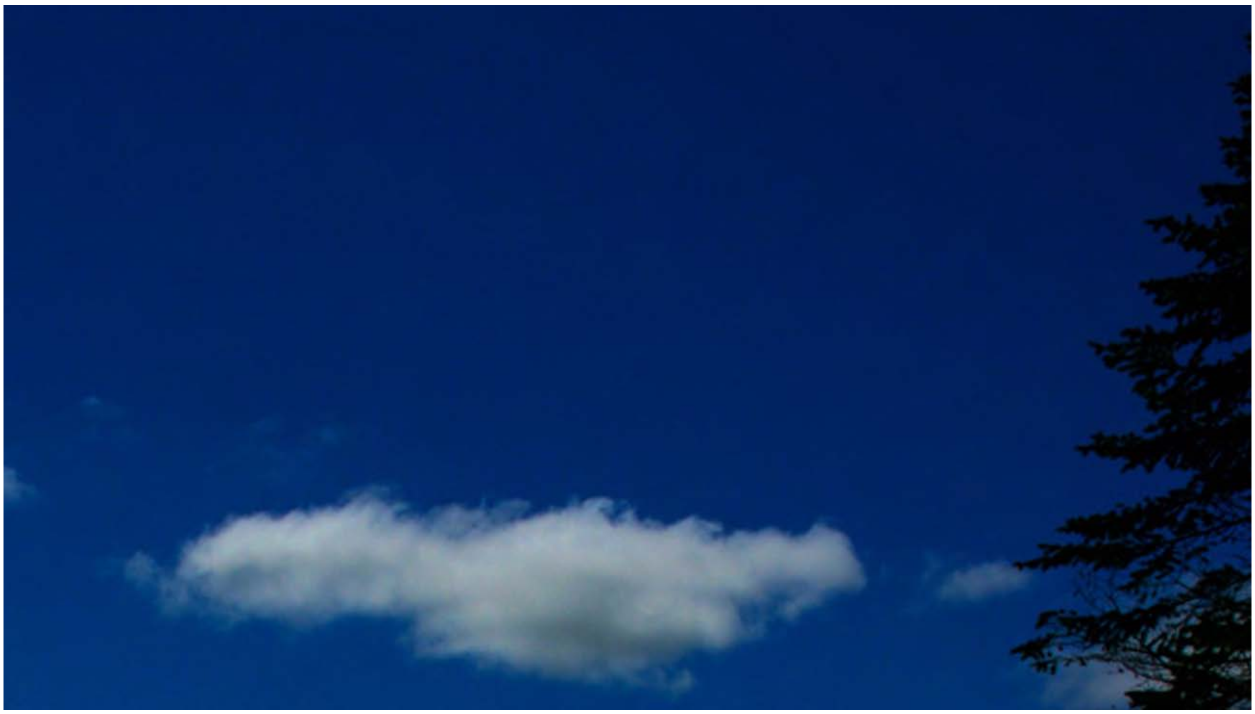
According to Crayola there are currently 120 colors of their crayons. Amazingly, in over 100 years that Crayola has been making crayons, they have created more than 400 different colors! You can read some more about their colors on the Crayola website. There are also other fun activities and facts about crayons there.

Right now, the biggest box of crayons that Crayola sells has 120 crayons of different colors. Not too long ago you could get a Telescoping Crayon Tower with 150 different crayons. I bought one a couple of years ago and it might still be possible to find some.

You can make your own crayons by melting old ones and mixing them together. Here I melted cyan, magenta and yellow crayons together on my stovetop (don't do this without a parent!) and you can see other colors in melted wax where it mixed together.

Crayola is just one of many brands of crayons. There are at least 25 different companies that make crayons sold with more than 100 different brand names. Of course some of those companies make crayon colors that are the same as one available from Crayola, but I'm sure there are some other colors out there. It's probably safe to guess that there are at least 200 different crayon colors out there in the world, and maybe even more.

Q: What's My Favorite Color?



Blue! When lots of people are asked to name their favorite color, the most popular choice by far is blue. Nobody knows why. Do you have any ideas? Maybe because the sky is blue, or because clean sea water is blue. What is your favorite color?

A:

Blue? If I had to guess your favorite color, my first guess would always be blue. Why? Well, for some reason that is the most popular color when people are asked what is their favorite. Of course your favorite color is a personal choice and it can be any color you like. And even though some people might try to tell you otherwise, your choice of a favorite color really doesn't say anything about you or your personality. My favorite color is red.

Do you have a favorite toy, stuffed animal, or food? I would guess that you do. We all have favorite things and each of our favorites is a personal decision. Nobody else can change your mind about that, unless you let them.

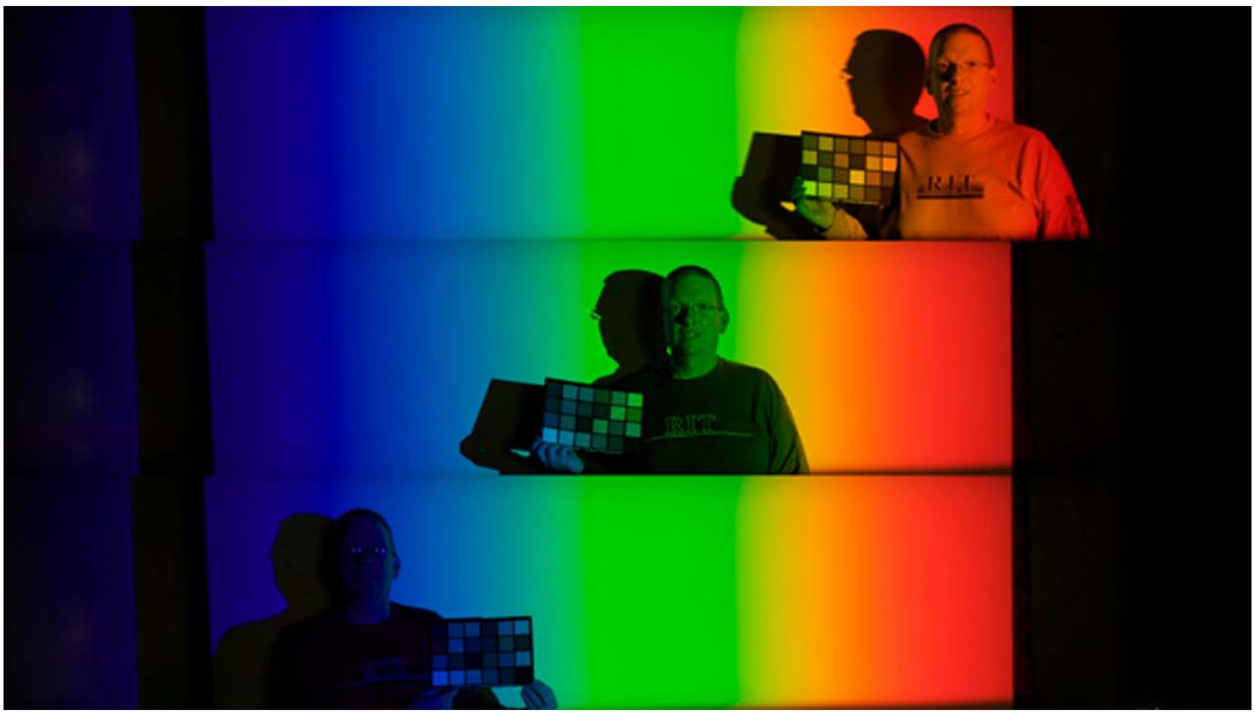
Crayola has done a survey on America's favorite crayon colors and their number one choice is blue, followed by cerulean blue, with several other shades of blue in the top choices. When I ask my students to name their favorites, blue always comes out on top.

Your favorite color also can change throughout your life. When I was young, my favorite color was green. When I went to college it was orange. A little later on it became red and that has been my favorite for some time now.

I found an interesting internet survey on favorite colors here. It shows more about the popularity of favorites for a bunch of different people. He also found that blue was most popular!

Photography (Level 1)

Q: How Do Colors Mix to Make Other Colors?



Funny things happen when differently colored objects are put under different colors of light. In this set of three pictures, look at how the color of my orange RIT t-shirt and my face change as I move from red, to green, to blue light in the spectrum. Why does my orange shirt look dark gray when lit with green light? Think about it and explore a bit more to learn the answers.

A:

Well really colors don't mix together at all! Light, or other stuff like paint, mix together to create a new thing for us to look at and that new thing might have a color that is different from any of the stuff mixed together. Remember, color is our perception of the stuff out there in the world.

When lights are mixed together, like on our television screens, all of the light from each part of the mixture is still there. However, our eyes are not able to see the different parts of the mixed light, so we just see a single color. The mixing happens in our eyes! You might want to play with this online demo from Boston University to see how red, green, and blue light mix together.

When you mix other stuff together, like paints, printer ink, or crayon wax, you get different colors than when you mix lights. This is because the stuff changes the light that falls on it in a certain way and when you mix different stuff together, the way the mixture changes light can be very complicated. You can play with a simple form of this mixing in another online demo from Boston University. It shows how different colors of ink or dye might mix together to form new colors.

The colors you see when you mix stuff of other colors is sometimes very surprising. The best way to learn is to play with lots of colors and observe what happens. Albert Einstein once said "play is the highest form of research"!

Sometimes surprises happen when two things are mixed together. Most people are surprised the first time they see green paint appear when blue and yellow paint are mixed together. It is a surprise because our eyes are much more complicated than we sometimes think. In this picture I found a surprise mixture while hiking in Algonquin Provincial Park. There are two different kinds of trees (a pine and a birch) growing as a mixture out of one set of old roots (the rotting stump)! Can you imagine how that happened?

Challenge (Level 1)

Q: Quiz Time: What is Color?

The road around Otter Point in Acadia National Park ... leading to new explorations.

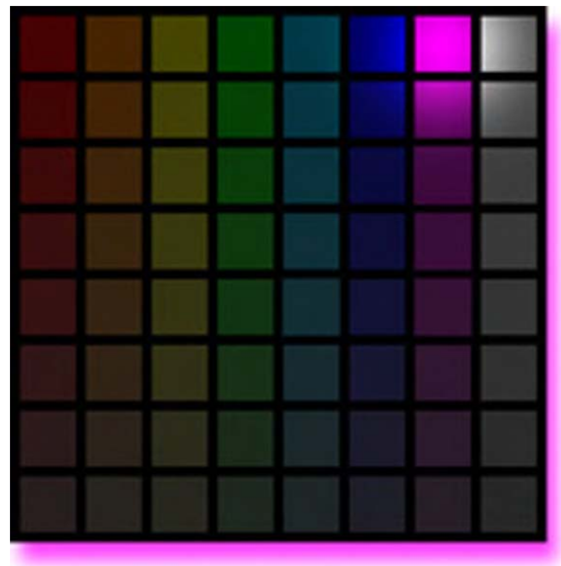
A:

(A) Something About what Light is Made of

(B) Something About what Objects are Made of

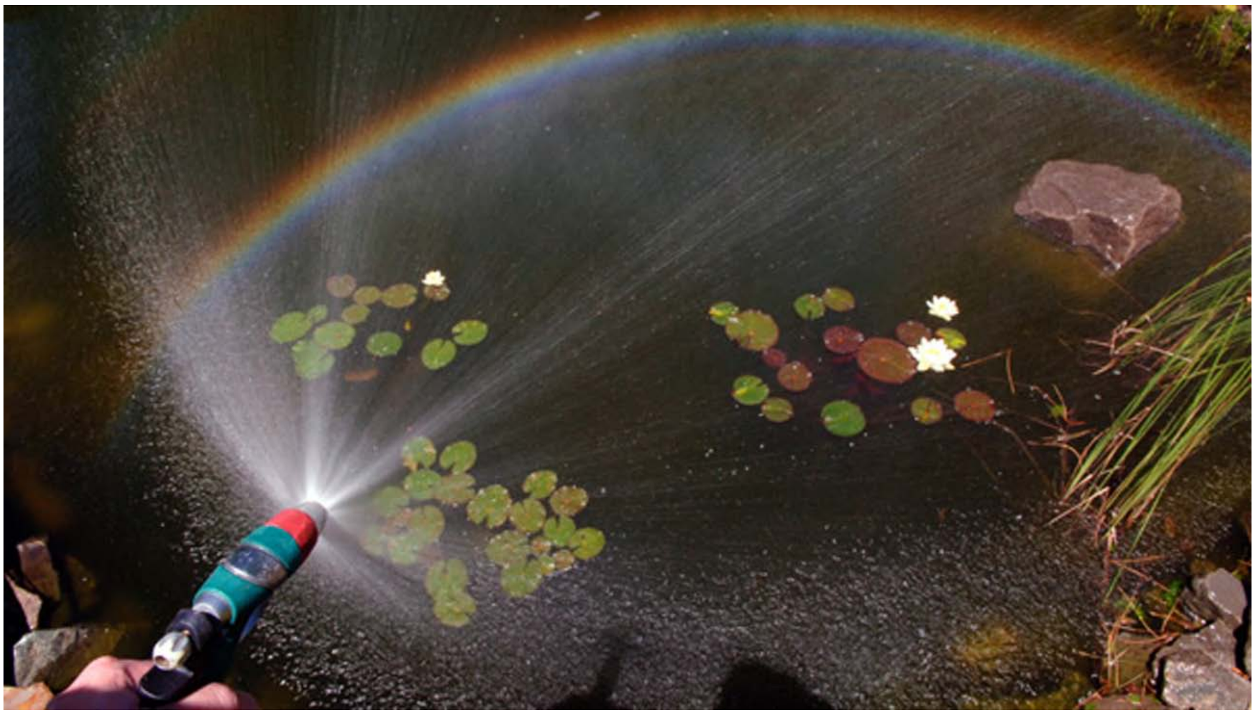
(C) Something We See

(D) A Dream!



Have you noticed the pattern in these icons yet?

Q: Why is a Rainbow?



It's easy to make your own rainbow. On a sunny day, look away from the sun and find the shadow of your head. Then spray some misty water (small droplets) in that direction. The rainbow will always be at an angle of 41 degrees (in a direction about half way between your nose and ear off to the side) away from the shadow of your head. If you could put water there (and see it), the rainbow would make a full circle around the shadow of your head! This is true for all rainbows. If you want to find one in nature, look for water in the sky (rain) at about that same angle when you are looking away from the sun. If there is a rainbow, that's where it will be. You can see the shadow of my water sprayer and my head at the very bottom of this picture and notice how the rainbow makes a curve around it.

A:

The beautiful colors of a rainbow are perceptions, like all colors. However, the process that creates the light we see as a rainbow is actually based on some fairly simple math.

That math is what we call geometry. The light from the sun is reflected by the surface of raindrops in the sky (just like it reflects off a window or surface of a lake) and its direction also changes when it enters and leaves the raindrop. The combination of all those changes in direction means that most of the light coming out of the raindrops is at an angle of about 41-42 degrees away from the shadow of our head (or in the direction half way between your nose and your ear when you look directly away from the sun). That alone would make a bright white circle in the sky. The reason the rainbow has its colors, is that the different wavelengths of light, producing different color perceptions, are reflected back to our eyes at slightly different angles. This makes the white light of the sun smear across the sky with different colors produce as the light is smeared and then we have a beautiful rainbow to see.

Here's a rainbow in nature. The sun is behind the camera to the left side and is also lighting up the cloud to the left in a very pretty way. You can also tell by the shape of the rainbow that the sun is about to set.

You might also see that the sky inside the curve of a rainbow is always brighter than the sky outside. This is also because of the way light reflects through the raindrops. You can even see that in the rainbow I made with my garden hose.

You can find a more detailed explanation of rainbows at this website from Dartmouth. And remember that rainbows are rarely seen since you need to have rain drops in the sky off in the distance in front of you and the sun low in the sky behind you; all at the same time!.

Q: Why do Colors of Stained Glass Windows Look so Beautiful and Different from Other Objects?

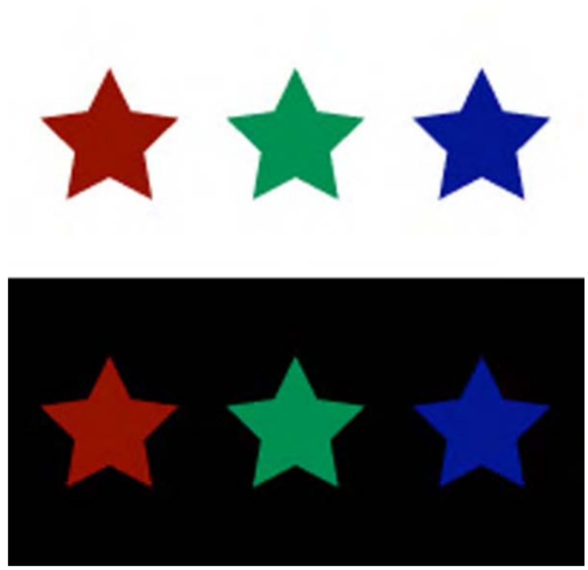
Stained glass is beautiful to look at. We see it as sparkling when we are inside a building because the colors are usually the brightest things we see. This picture shows a stained glass window with the sun right behind it. It took a special kind of photography to make this picture. Most cameras would make the glass look less colorful and less bright.

A:

They look beautiful because they are beautiful! And it is our own preferences that determine what is beautiful.

Even though beauty is a personal choice, most people agree that the colors we see when looking at stained glass windows from inside a dark building are very beautiful. The same is true when we see the windows from outside at night and the lights are on inside the building. The special colors we see in the windows are caused by the way our eyes and brains perceive color. We are always judging colors in relation to other colors that are nearby. This lets us see that a black cat and a white piece of paper always look black and white, even when the amount of light falling on them changes.

Stained glass windows take those comparisons to an extreme. The windows are often much brighter than their surroundings and that makes them appear to glow, much like the bright lights we see on Christmas trees or in fireworks displays. When colors are much brighter than their surroundings, they also look much more colorful to us. So, once again, it is how our eyes and brain work that makes the colors look so special.



This pictures helps to show why stained glass looks different than normal things. The three stars on the white background are identical to the stars on the black background. You can see that the change in background makes the colors look different. Are they a little brighter and more colorful like stained glass inside a dark building?

Q: Why Does Our Pupil Change Size?

The amount of light we encounter in the world varies over a tremendous range and our eyes are able to adapt and see well. This picture shows the range of light in a single scene and how difficult it is to photograph that range (since cameras are not as good at adapting to the range of light as we are). Each portion of this image is the same scene photographed with a factor of two change in exposure (recorded light level) compared to the preceding frame. In the first image, the sunlight on the mountain is visible but the forest is dark. In the last image, the darkest areas of the forest are visible but the sky and mountain are too bright for the camera. Our eyes can view both parts of this scene at the same time!

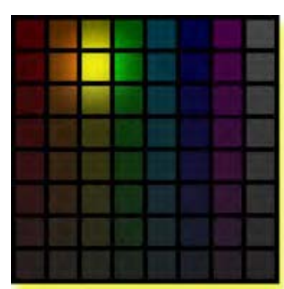
A:

As shown in the picture above, there is an amazing range of brightness in the world and our eyes are able to see well in both moonlight and bright sunlight. The pupil is one part of our vision system that helps make this possible.

The iris (the colored part of our eyes) is a muscle that controls the size of our pupil (the hole in the iris that allows light to enter the eye). The muscles of the iris respond reflexively to the amount of light we are seeing. When we look at a very bright scene, the pupils get smaller (contracts) to allow less light into the eye. This is a good thing since we don't need to allow so much of the light in to see well when the scene is bright. When we look at a very dark scene, the pupil gets larger (dilates) to allow more light into our eye. This is necessary to see well since there is little light in the scene and we have to capture as much of it as possible.

Different animals have very different pupils adapted to their environment and habits. Can you guess what animals each of these pupils belong to? I'll give you some hints. One belongs to a goat, one is my daughter's, one is my cat's, and the last one belongs to a lizard.

The pupil is just one of the features of our eyes that help us to see well almost all the time. It is part of our adaptation to the visual environment. Interestingly, the size of our pupils decrease as we get older. This probably helps compensate for other changes in our eyes as we age to keep vision as good as possible. Other methods of adaptation are described in different modules. Explore!

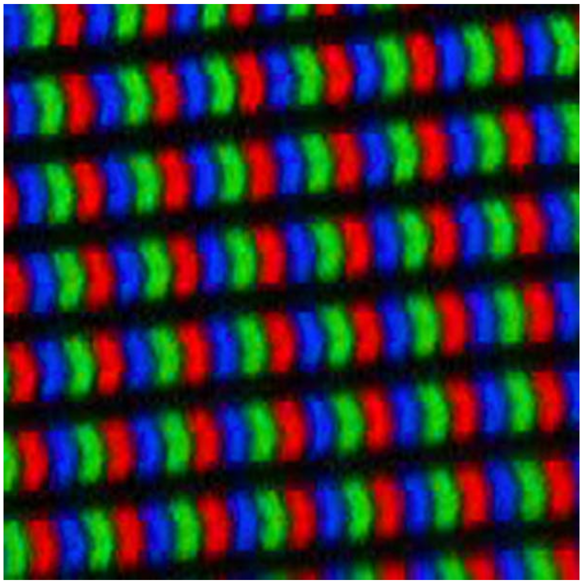


Q: What are the Primary Colors?

Almost any color can be a primary color depending on how it is used and what other colors it is used with. Notice how I was able to make gray paint out of two different sets of primaries, the more traditional red, yellow, and blue set and the very untraditional set of green, purple, and orange!

A:

Red, yellow, and blue, of course! Sorry, not so fast. Even though many of us are taught that red, yellow, and blue are the primary colors in our school art classes, we have actually been misled a little bit. Red, yellow, and blue are one common set of primary colors that are often used in painting pictures. However, they are not the only set of primary colors. In television and computer displays, red, green, and blue are the primary colors. In photography, red, green and blue are the primary colors for capturing the image, but cyan, magenta, and yellow are the primaries for printing the image. In printing, cyan, magenta, and yellow are common primary colors. And when colors are made for other purposes, like house paint, plastics, and textiles, very different sets of primary colors are often used. Why are there so many different sets of primary colors?



This is a very closeup image of the primaries used in a liquid-crystal display (LCD) that you might see on your computer, laptop, or television. All of the colors you see on those displays are made up of different amounts of the red, green, and blue primaries shown here.

Technically speaking, primary colors are defined as any set of three (or more) colors for which no one of the colors can be made by mixing any of the others from the set. With this definition, the best sets of primary colors depend on what you are doing with them. That is why we end up with the most common sets being red, yellow, and blue for artists' paints, red, green, and blue for televisions, and cyan, magenta, and yellow for printing.

There is another common use of the term "primary colors". Sometimes people will talk about something being decorated in primary colors. In that case, they are usually talking about very bright, saturated colors of any of the most basic hues. These would include red, orange, yellow, green, blue, and purple.

Q: Why Do Colors Fade in the Evening?

I took this photograph of a bright sunny autumn day in the Adirondacks. Then I changed the right side of the image to simulate what the same scene would look like when illuminated by dim moonlight. Most of the color would fade away, red areas would be darker than blue areas (called the Purkinje Effect), the scene would not be as sharply focused, and the perceived contrast (difference between light and dark areas) would be reduced. Some artists create night scenes as very bluish in color since blue areas tend to look brighter. Look at a very dark night scene and decide for yourself if it is more blue or gray.

A:

Our eyes have an amazing ability to see well over very large ranges of brightness from starlight to bright sunlight. The change in size of our pupils helps us to see well in both bright and dim light, but there are other features of our eyes at work as well. In fact, we really have two visual systems in each eye. One is best when there is plenty of light, can see fine details (like reading a book), and can see color. The other cannot see color at all, but is much more sensitive to light so it works well when there is little light available. That system also cannot see fine detail well at all. That's why we can't read books in the dark!

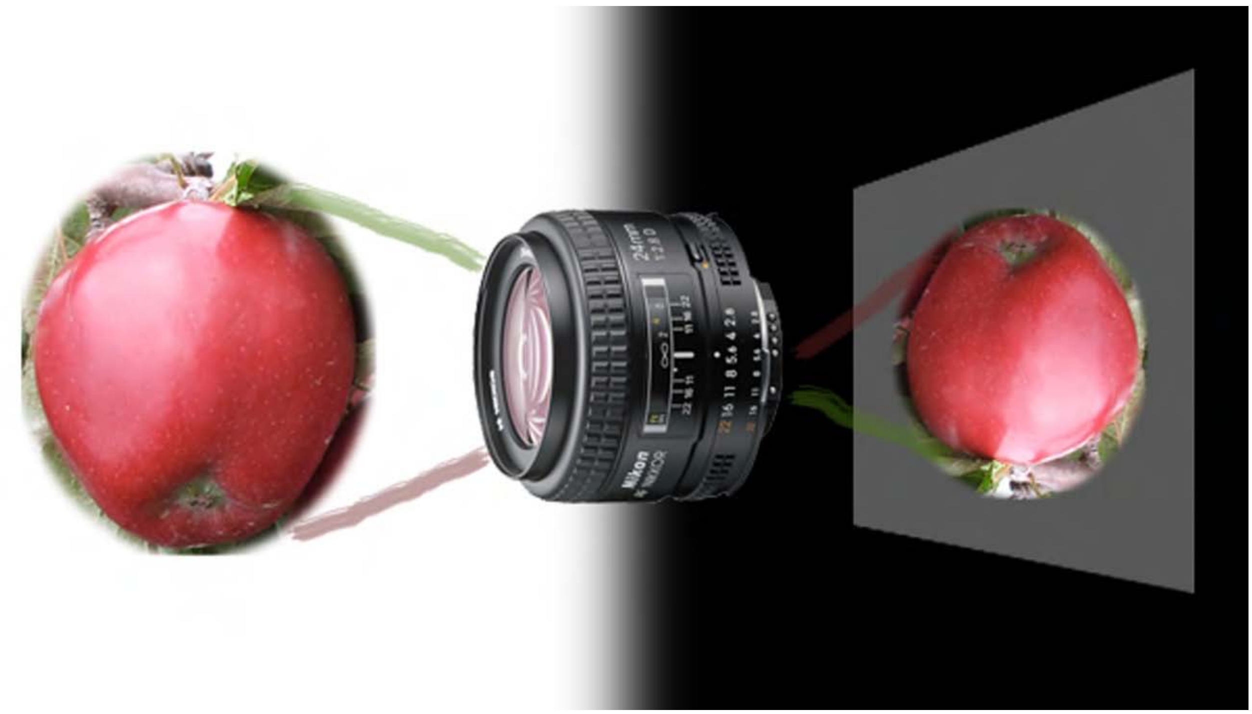
This star trail image was made by my daughter using a digital camera with a 30-minute exposure time. In that long time, there was enough light for the camera to respond and the stars moved in the image since the earth was rotating. Note that the stars have different colors that we normally cannot see since they are so dim. The yellow sky is due to light pollution from a nearby town.

There are two types of cells in our eyes (technically, two types of photoreceptors in our retinas) that create these two systems. One type are called cones. The cones produce color vision, work in bright light, and resolve fine details. The other type are called rods. Rods cannot see different colors, only light and dark, but are very sensitive to light. To get this added light sensitivity, rods have to capture light across large areas of the eye and that means they cannot see fine details.

As night approaches and the amount of light in a scene drops, our vision system automatically switches from using the cones to using the rods ... and our perception of colors fades away.

Photography (Level 2)

Q: What is a Camera?



The lens of a camera gathers light from a scene (shown as an apple above) and projects it onto a light-sensitive surface (shown as the backwards and upside-down apple on the screen above). In the original cameras, the image was projected onto a piece of paper or canvas and traced by an artist. Later on photographic film was used in cameras to capture images of the world. Nowadays, the light sensitive surface is normally a digital detector array made of silicon. Our eyes can also be thought of as cameras. What is our light-sensitive surface?

A:

Original man-made cameras were called a *camera obscura* in Latin. Literally translated, that means *dark chamber*. The *camera obscura* was a dark room, or chamber, with a hole in one side (perhaps with a lens mounted in the hole to collect more light). Observers, or artists, would enter the camera obscura and see an image of the world projected (upside down) on a white surface on the other side of the room. They could trace, or paint, this image if they wanted to reproduce the scene.

My dog, Mystic, has two cameras in her head. Her eyes are darkened chambers. The light passes through her pupils, is focused by her cornea and lens, and is detected by her retina. Here she is using her camera to look at me and my camera along with my daughter getting her attention with a treat (you can see us reflected in her eye).

Today, cameras are still *dark chambers*. Normally there is a lens at the front of the camera to gather light. Modern lenses are actually made up of combinations of many individual lenses to improve the quality of the image. This light is then projected onto a surface at the back of a small (sometimes incredibly small as in cell-phone cameras) *dark chamber*. A light sensor is placed at the back of the chamber to capture an image of the light from the scene and allow us to process and view it. Our eyes are also built in the same basic form as a camera and can also be thought of as dark chambers.

So that's it ... a camera is a *dark chamber*.

Challenge (Level 2)

Q: Quiz Time: Can Different People See the Same Rainbow?

Ever wonder what is at the end of a rainbow, or why you can never find it?

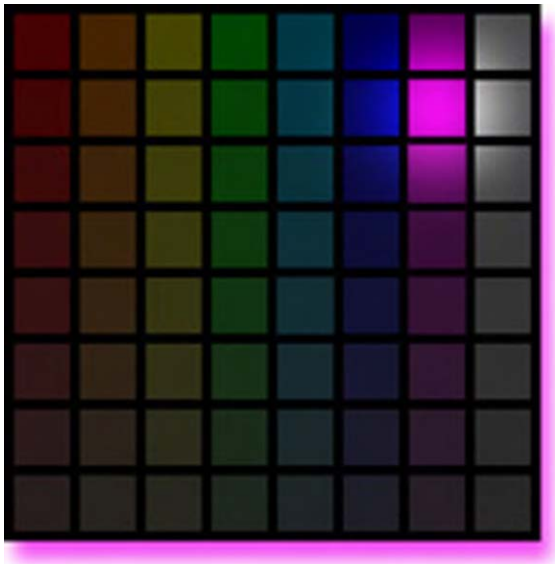
A:

(A) What Else Would They Be Seeing

(B) No, Not Really

(C) Yes, There is Only One Rainbow at Any Given Time

(D) Who Cares



Have you noticed the pattern in these icons yet?

Q: What is the Best Color for Sunglasses?

These pictures show how color changes when light goes through different colors of sunglasses. The upper-left picture is the original scene as viewed with the naked eye. The upper-right picture shows how the scene is not so bright, but all the colors are correct, when looking through gray sunglasses. The lower-left picture shows what happens with yellow sunglasses (notice how much the sky color changed). And the lower-right shows the world as viewed through rose-colored glasses. Those are pink and they make the sky a sort of purple color and green leaves look darker.

A:

The answer to this one depends on what you are trying to do with the sunglasses. Usually, the answer is gray. But sometimes it is yellow and other times it might be some other color. I'll explain why gray and yellow might be good choices.

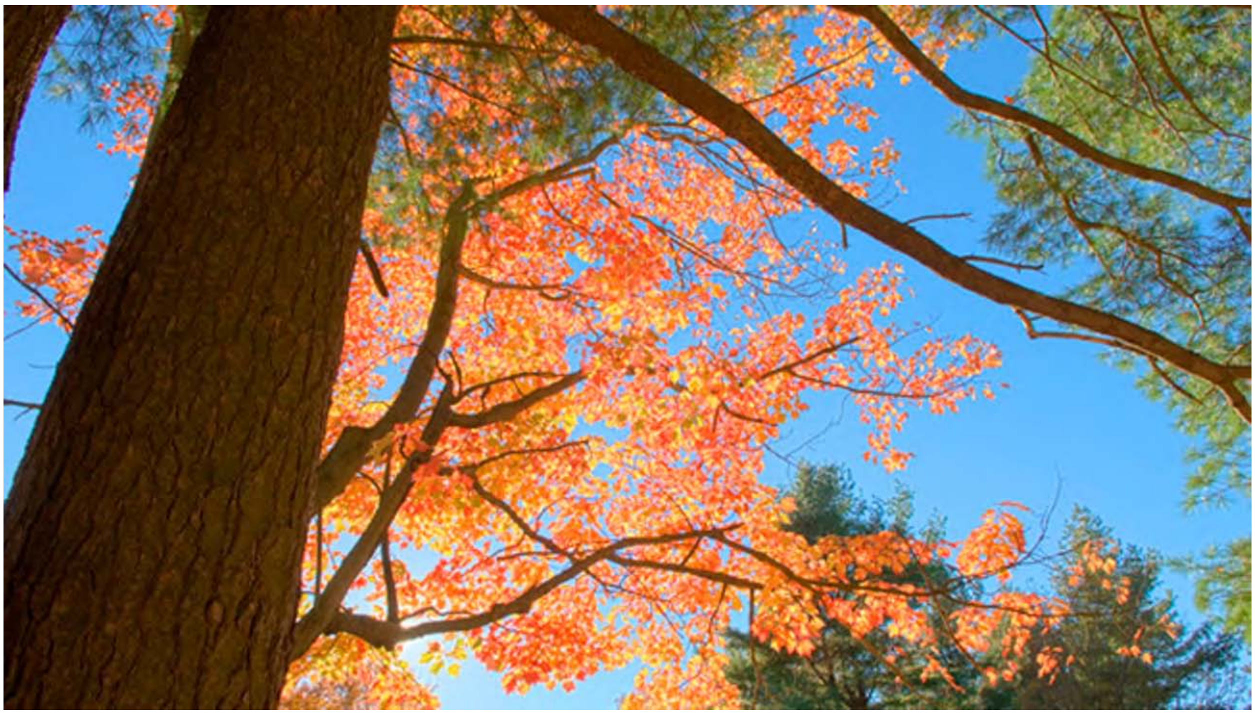
Gray is the best choice if you want to see the colors of things in the most natural and accurate way. All gray sunglasses do is remove some of the light of all wavelengths (colors) in equal amounts. It is exactly like just making the light on things a bit less bright. That helps us to see better on very bright sunny days when there is actually a bit too much light for our eyes. It will also make the contrast that we see less. Contrast is the difference we see between bright and dark places in a scene. That is one reason it is not a good idea to wear sunglasses when it is dark. Our eyes are already working hard and the contrast we see is low; adding sunglasses then only makes it harder to see anything at all.

Even when we look through colored glasses, we don't notice too much change because we adapt. Notice how yellowish the picture of the flowers looks. Then stare at the black dot on the yellow background without moving your eyes for about 30 seconds. Then look back at the center of the picture and you will see how your eyes adjusted to the yellow color and the green leaves look more like normal.

You can see in the pictures at left that gray sunglasses make the scene less bright and keep the colors looking nice. So why would anyone choose yellow sunglasses? It turns out that yellow glasses can actually help us to see more contrast and detail in a scene. They do this by removing the blue light. Blue light is the most difficult for our eyes to focus and that makes blue things look a bit blurry. Blue light is also scattered a lot by the air and water in the atmosphere and that reduces contrast, or our ability to see things. Thus, if we remove the blue light with yellow glasses, we are removing the light that is scattered around a lot in the world and the light that is focussed the most poorly by our eyes. The result is a sharper and more contrasty image. That is often helpful for athletes trying to perform well in bright light. Also, the increase in contrast actually gives us the perception that things are brighter, even though the glasses have actually removed some light.

Objects (Level 3)

Q: Why do Leaves Change in the Autumn?



Sugar maple trees are native to the northeastern United States and southeastern Canada. They produce beautiful brilliant orange colors in the autumn (like this one found in the Adirondack Mountains of New York). They also produce a sugary sap that is harvested in the spring and made into Maple Syrup. This photograph contrasts the orange hues of light passing through the maple leaves with the green colors of nearby evergreen trees (that don't change color or shed their leaves in the fall).

A:

There are actually several reasons leaves change color and function in the autumn. One that is sometimes overlooked is that it is very difficult for trees in northern climates that have snowy winters to bear the weight of snow on their leaves. Losing their leaves in the winter means less snow stays on the trees and they don't need to be so strong to survive until the warm weather in spring.

More often, people focus on the beautiful color changes in leaves that take place in the autumn in many places around the world. Why do those color changes happen? And how?

As the days grow shorter and colder, there is no longer enough light and water for the leaves to use (along with carbon dioxide from the air) to produce the food plants need for survival. The plants switch to stored food and when they shut down their food production by chlorophyll and photosynthesis, the green-colored chlorophyll begins to disappear from the leaves. We often are left to see the colors that are left behind. Many times these colors are simply dull browns and tans. However, some types of trees leave behind bright yellow and orange colors that we can see in the autumn. And some other plants actually start to produce other colors, like purples and reds, in the fall when the chlorophyll goes away. Eventually even these colors fade away as the leaves quit working and sever their connections to the trees. Then some wind or rain comes along and they "fall" off the trees to make room for new leaves in the spring.

You can read a little more detail on this explanation at this website.

Leaves are beautiful all year long. One interest fact is that they transmit a lot of light and don't just reflect it back to our eyes. This photograph was made of an early autumn sugar maple leaf with only light being transmitted, or passed through the leaf (note all the green, yellow, orange, and red colors in this leaf). One reason, leaves let so much light pass through is so that the energy in sunlight can be absorbed by all the leaves on a tree, not just those on the outer surface.

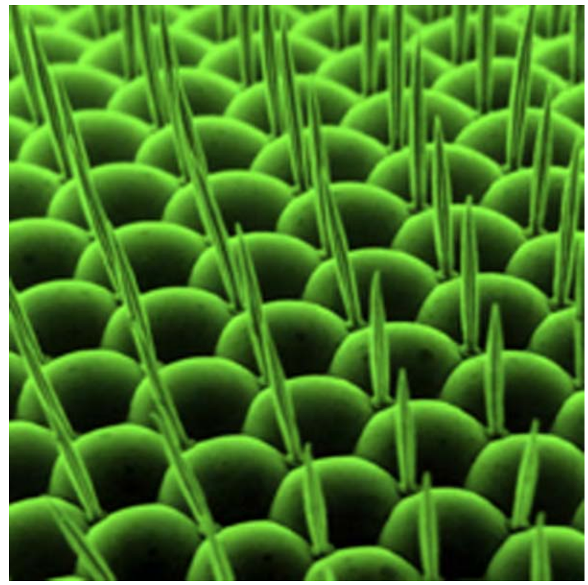
Q: How are Animal Eyes Different from Human Eyes?

One way to see how eyes are important to different types of animals is to look at their skulls. The main picture shows some cow skulls. One thing to notice is that cows have their eyes on the sides of their heads. That means that they can see things all around them, but there are almost no places that the cow can see with both eyes. As humans (skull in lower right inset), we have both eyes in the front of our heads. That means we can't see behind us, but it allows us to see depth (and 3D movies) much better. Animals that hunt usually have eyes in the front of their heads (like humans) and animals that are hunted usually have eyes to the sides of their heads so they can watch of hunters sneaking up on them. The lower left inset shows the skull of an eagle. Eagles, as hunters (predators) also have their eyes in the front of their heads and you can also see how large their eyes are with respect to the size of their heads (and brains!). That shows how important vision is to them to find their food. (Note: Eagle eyes are about as large as our own!) Eagles can see very well.

A:

There are many ways that the eyes of various animals are different from human eyes. They are different in size, shape, construction, light and color sensitivity, purpose and function. Just a few examples of these differences are mentioned here.

Color: We have color vision that is best described by the number three. Colors we se can be bright or dark, of different hues (e.g., red, yellow, green, blue, purple, etc.), and of different vividness (how much of the hue, or how different from neutral colors like white, black, or gray). Very few other animals have similar color vision. In fact only a few types of monkeys and fish seem to see color like we do. Some birds, insects, and shrimp can actually see more types of color variation than we can. Most animals cannot see color nearly as well as us. They see shades of gray and maybe on other type of change in hue; much like someone with color-blindness would. Cats, dogs, and other mammals fall into this category. But even though some of them can't see color well, they can see much better than us at night.

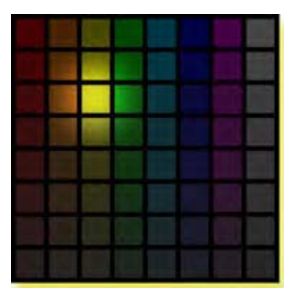


Insects have compound eyes. This is a picture of part of the eye of a fruit fly viewed with a very powerful microscope. Each section of the compound eye is sort of like an individual eye that looks at a small part of the world. In between the individual "eyes" you can see hairs that help protect the insect eye.

Purpose: Some animals, like cats, are nocturnal and their eyes are designed to be much more sensitive to light than ours. That helps them see when it is too dark for us to see much at all. Our color vision lets us do things like identify good food and find it to feed ourselves. Other animals need to see behind them in case a predator is trying to sneak up on them eat them. Others have overlapping vision in the two eyes to better be able to locate objects in the world. That's very important for animals that move quickly, or fly through the world.

Construction: Our eyes are made much like a camera with a lens, a pupil, and light-sensing cells in the back. Those eyes are great for land mammals and fish, but they are too large and complicated for other creatures, like insects, that have compound eyes. Compound eyes have a whole bunch of individual lenses focussed on different parts of the world. Each of those segments has a few light receptors, so they also don't get as much information about the world. Even stranger, some creatures, like lobsters, don't have lenses at all, but have mirrors to collect the light underwater.

Animal vision is endlessly fascinating and there is much more to learn about each of your favorite animals.



Numbers (Level 3)

Q: Why is Three an Important Number in Color?

If we try to sort colors, like these crayons, in a meaningful way, we need three types of descriptions. The first is whether they are colorful (those on the outside) or not (the white, black and gray in the middle), the second is by hue, or color name, such as red, orange, yellow, green, blue, and purple around the circle. And the third is by how light or dark the colors are. With those three types of describing words, we can accurately describe any colored object we can see.

A:

We see color the way we do because there are three types of light sensitive cells (called photoreceptors) in our eyes that produce our perceptions of light in the daytime (there is a fourth type that works at night when there is very little light to see). These cells are called cones because some of the scientists who first saw them thought they had shapes very much like the shape of an ice cream cone. The three types of cones each respond to different types of light and can be thought of as roughly sensitive to red, green, and blue light. Different colors have different amounts of red, green, and blue light coming from them and our three types of cones can help us figure out how much of each and therefore see beautiful colors. It is the fact that there are three types of cones that makes the number three so important in color.

Three colors (sometimes called primaries) can be mixed together to make other colors. This picture shows a colorful sun mask from New Mexico (yellow with other bright colors painted on it) with overlapping circles of red, green, and blue light falling on it. Can you figure out where the different colors of light are falling and why different parts of the mask look the way they do?

Those three cones result in color perceptions that can be described with three types of descriptions. These are called lightness (how light or dark a color is), chroma (how different a color is from white, gray, or black) and hue (the color names we give objects like red, green, yellow, and blue). A bright red sports car might have a medium lightness, a very high chroma, and a red hue.

Also because of the three types of cones, we can mix colored lights or materials together to make many other colors. It just takes three distinct colors (or primaries) in the mixtures to make a very wide variety of colors. As you can see, three is an important number in color for many reasons.

Q: Why Do Flowers Have Different Colors?

These are gorse bushes in full bloom along the coast of Oregon. They are also well-known for their presence on the seaside golf courses of Scotland. The bright yellow blossoms colorfully paint the often gray seaside dunes for several weeks each year. The large numbers of blossoms help the gorse to reproduce strongly and quickly grow over large areas. This is so effective for the gorse, that some consider this beautiful plant a weed. If you've read Winnie the Pooh, you might remember that once he found himself falling painfully into the sharp thorns of a gorse bush (those thorns serve to protect the bush from potential predators, furthering its ability to reproduce and spread).

A:

Simply put, flowers are colorful for one main purpose, survival. Flowers are the reproductive systems of plants and are therefore responsible for assuring that the plants can survive from one generation to another. Their bright and varied colors help make reproduction and survival possible in several ways. One way is by attracting insects that carry pollen from one flower to another allowing the reproduction process to continue through the creation of fruits and fertile seeds. The distribution of these seeds also might require the help of other animals and that is helped along by making the fruit so delicious and nutritious. Animals eat the fruit and then distribute the seed, and fertilize it, through their manure. Bees provide one example of an insect that benefits from colorful flowers and, in turn, benefit the plants through their work.

Flowers don't look the same to all creatures. The left side of this picture shows the colors of a black-eyed susan flower as we see them. The right side shows the patterns in the flower when viewed with ultraviolet (UV) energy. Bees can see this UV and the patterns are thought to attract them to the flower's nectar (food for the bees) and pollen (survival for the plants).

The bright colors of flowers (and patterns in the reflected UV, or ultraviolet, energy) attract bees to flowers and even to specific areas on the flowers. The bees like the flowers as a source of sweet nectar, which they process into honey for their food. The flowers like to attract the bees so that pollen from their flowers can attach itself to the bees for free ride to another flower. This transfer of pollen from one plant to another is required for the plant to reproduce and survive (or in some cases for it to produce delicious fruit). Thus, the colors of flowers can be directly responsible for the plant's survival and those plants with flowers that best attract the bees have the best chance for surviving and evolving. More about the ultraviolet and infrared appearance of flowers can be found at this interesting website where there are example pictures of many varieties of flowers.

It has been suggested, and is likely true, that some flowers have evolved simply to please people with their beauty. These beautiful flowers are assured of survival because humans will see to it that they can reproduce and survive through careful cultivation and gardening. Michael Pollan describes this co-evolution of humans and plants in a fascinating book, *The Botany of Desire*.

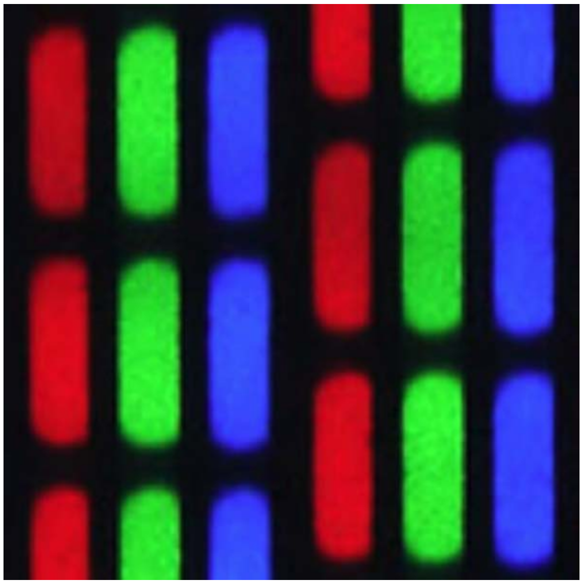
Photography (Level 3)

Q: How Does a Color Television Make Colors?

Televisions work by breaking a color picture into three color separation (or primary) pictures, one that shows how much red light is in the scene, one that shows how much green light, and a third that shows how much blue light. The picture above shows a full color scene on the left side and then patches of the red, green, and blue parts of the image on the right. Where all three colors overlap (like in a normal TV display) you can see the original image color (look at the center of the right panel). Where only two overlap, you can see some, but not all, colors. This is much like the colors that someone with color blindness might experience.

A:

The processes of color television that allow pictures of some scene to be captured and then transmitted to our homes for viewing (sometimes live while the captured events, such as s sporting event, are happening) are very complex. Focussing on the color aspect, color television relies on the number three that is so important in color. Since our visual systems can only respond three types of color using our three types of cone receptors, color television can recreate beautiful full-color pictures from just three black and white images. This is done by capturing three images that represent the red light, green light, and blue light in the original scene. After transmission to our home TV (or computer screen), that information is put back together by emitting roughly equivalent amounts of red, green, and blue light on the display. Since our eyes can only judge the relative amounts of the three types of light, we see a full color picture.



A closeup photograph of the colored phosphor dots on an old-fashioned cathode-ray tube (CRT) television display. Each area of a TV picture is made up of different amounts of red, green, and blue light mixed by our eyes to produce a wide variety of colors.

The process for making color described above is known as additive color mixing. Additive mixing happens when colored light is superimposed to make new colors. This can happen by projecting different color lights on top of one another, by flashing the lights so quickly we can't see the individual colors, or by making adjacent patches of the colors so small that they blur together in our eyes. It is this last technique (small dots of light) that is most often used in color television. However, some systems do use the other techniques.

There are other important parts of making color television work. These include breaking the picture up into small spots of light, called pixels, and mathematically encoding that information so that it can be processed in computers. The data is then compressed to make it easier to transmit to us through satellites, cable systems, or over-the-air radio transmission. Then the picture and sound information is transmitted and received and decoded by the tuners and processors in our TV (or set-top box). Finally the pictures are displayed for us to view.

Challenge (Level 3)

Q: Quiz Time: Can a Dog See Color as Well as You?

Do these look like ripe apples in a tree to you? If so, you are probably colorblind!

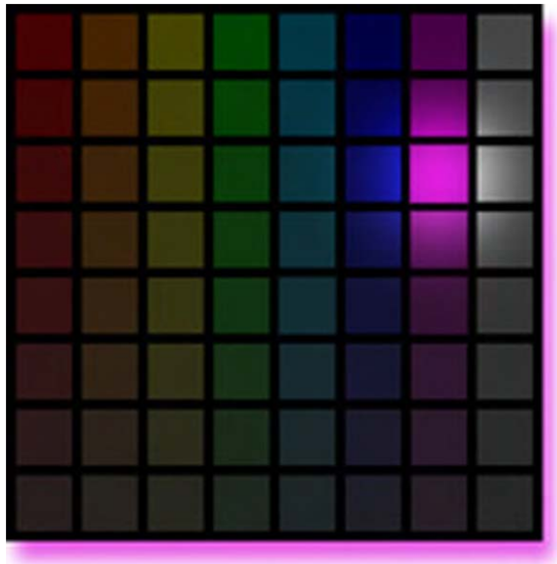
A:

(A) No, Dogs See No Color

(B) Absolutely!

(C) Dogs are Completely Blind; They Use Their Noses

(D) Maybe, If You Are Color Blind



Have you noticed the pattern in these icons yet?

Q: Why is the Sky Blue?

This image of a beautiful clear blue sky was taken on a cold autumn morning with the sun behind the camera. Red light from the sun keeps going straight away from the camera (you can see some bouncing back off the clouds) and the deep blue sky color is caused by the blue light that cannot pass straight through the sky and instead gets scattered back to the photographer's viewpoint. You can also see this clear blue color in the water. Most of that is caused by the surface reflection of the blue sky, but natural bodies of water often appear blue on their own. In such cases we see the blue color because red light is absorbed by the water and blue can pass through and reflect off objects in the water back to our eyes.

A:

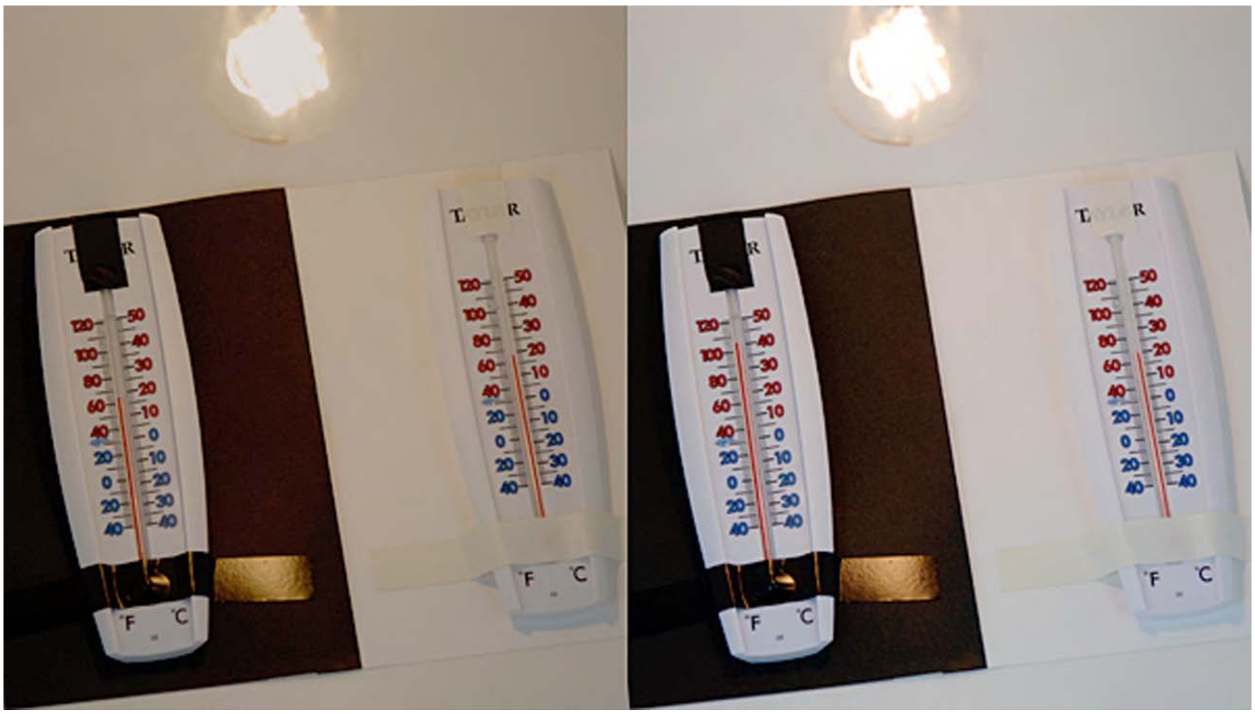
The direct answer is that the sky is blue because that is how we perceive it. Remember, color is a perception and not directly a property of objects. However, the way objects interact with light provide much of the information our visual systems use to determine what color we perceive. Thus, there is something about the sky that makes the light that reaches our eye appear blue in most circumstances.

That something is the fact that the light we see in the sky has not come to us directly from the sun, but it has been scattered by gasses and particles in the Earth's atmosphere. (Consider that in space the "sky" is black because there are no gasses or particles to scatter light and astronauts can only see light directly from the sun and objects that reflect the sun's light.) The kind of scattering that produces the blue sky is called Rayleigh scattering. That is named after a British scientist, Lord Rayleigh (his actual name was John William Strutt), who is considered the first scientist to describe this type of light scattering.

A sunset also helps us understand why the sky is normally blue. At sunset, we are seeing the red light passing straight through the sky while the blue light is scattered away. That's the blue light we normally see in the sky away from the sun.

Rayleigh scattering has the property that, for particles of the size typically found in the clear sky, blue light will scatter much more than red light. When we look at the sky away from the sun, we can only see scattered light (light that has bounced around the atmosphere and not passed straight through) and since Lord Rayleigh figured out and explained that blue light will be scattered the most in the atmosphere, it is blue that we see when we look at the sky. It is for this same reason that sunsets appear red. In the case of sunsets, we are seeing the light that passes straight through the atmosphere and not the scattered blue light. Clouds look white (or gray when little light passes through them) because the condensed water or ice particles in clouds are much larger than the wavelength of light and therefore they scatter all colors equally.

Q: Would a Dark Color M&M Melt Faster than a Light One?



One of the most common questions I receive about color is about the relationship between the colors of objects and how fast, or how much, they heat up in the sun. An alternative involves which color of a popsicle or ice cream melts the fastest in the sun. (Chocolate will melt faster than vanilla due to the color. Chocolate with almonds will melt faster still due to the salt on the almonds, which lowers the freezing point of water.) I took the image above of two identical thermometers mounted on white and black cardboard with white and black tape. After being stored in a cool dark place, both thermometers read the same temperature of about 20 deg. C (left) when the light was first turned on (shown in the dimmer image). However, after the light was on for a while you can see that the thermometer on the black background reads a significantly higher temperature of about 40 deg. C (right). This is because the black background absorbs a lot of light energy (that's why it looks black) and converts that energy into heat. The white background reflects most of the light and doesn't heat up as much.

A:

First of all, for those of you reading outside the USA, M&Ms are small candies that are chocolate covered with a hard and colorful shell. Some places in Europe have a similar candy called "Smarties", or "Lacasitos", *etc.* M&Ms are designed to let you eat chocolate without fear of making a mess since the hard candy shell isn't supposed to melt in your hands. However, like anything it will melt if it gets hot enough, or if it gets wet enough (they melt in your mouth!).

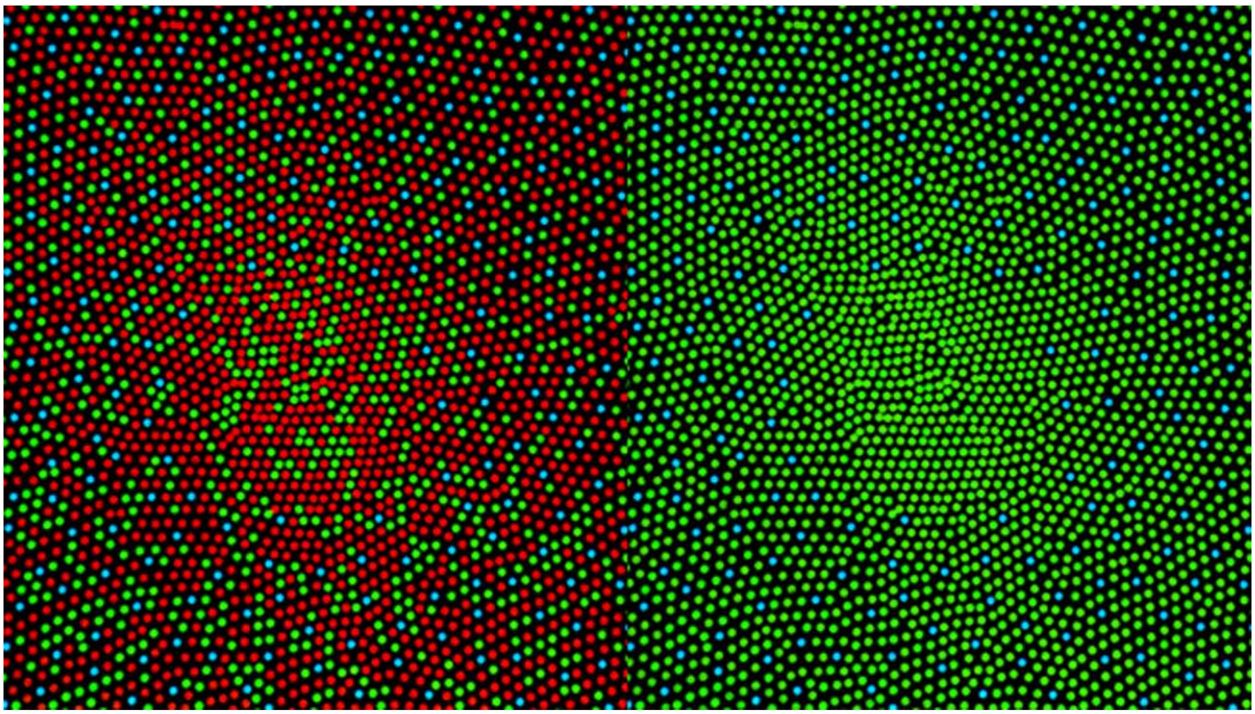
This question is about how the color of the M&M relates to how quickly the candy will melt. If we assume that the colorants (chemicals giving a material its color) in the various M&Ms have no significant impact on its properties (see the image at right for a case where this assumption fails), then in a darkened room followed by a darkened mouth, all M&M colors will melt at an equal rate.

A grade school student once sent me an email asking why blue M&Ms lose there color in water more slowly than other colors. I had no idea why (still don't) or even if it was true. So I tried an experiment and this image illustrates the results. What do you think?

The difference comes when the M&Ms are exposed to light like the thermometers in the image above. The dark colored M&Ms look dark because they are absorbing a lot of light. This light is energy and that energy has to go somewhere. For most materials that somewhere is a conversion into heat; the absorbed light makes the object hotter. This is the same reason we feel hotter in the direct sunlight than we do in the shade and people prefer to wear light colors on hot days and dark colors on cold days. So those M&Ms in the light will all heat up to different temperatures and the hotter ones will melt faster than the colder ones. It just turns out that the darker colors will also be the hotter M&Ms, so the bottom line is "yes" darker M&Ms will melt faster than light M&Ms if they have been exposed to enough light.

Eyes (Level 4)

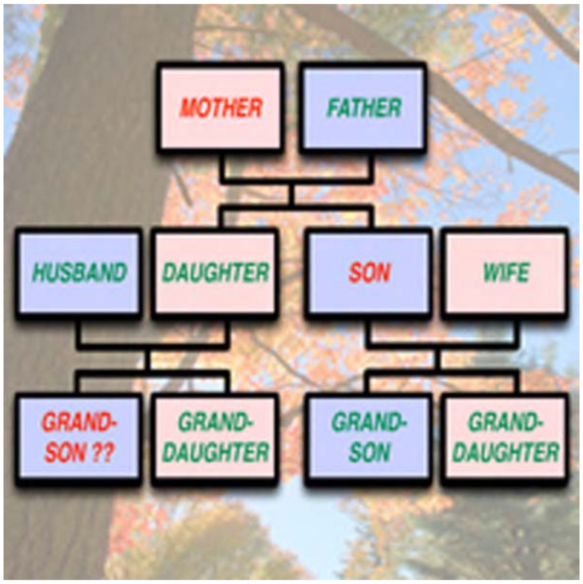
Q: Why are Some People Color Blind?



These images are a cartoon illustration of the mosaic of cones in the human retina. Each circle represents a cone photoreceptor. On the left, they are colored in red, green, and blue to represent the approximate wavelengths of light that each type of cone senses. The coloring also shows the relative populations of the various cone types. Most cones are red sensitive with about half as many being green sensitive and very few being blue sensitive. The right side of the image shows the same cone mosaic for a person with a certain type of color blindness known as protanopia. Here the protanopic observer has no red-sensitive cones. Instead all of those cones are green sensitive instead. This is one type of color vision deficiency. Another, called protanopia, would have all the green-sensitive cones replaced with red-sensitive cones. In other versions of color vision deficiency, one of the cone types is replaced with yet another type or has anomalous performance. For example, one might end up with blue-sensitive and two slightly different versions of green-sensitive cones.

A:

Genetics. We are all different in many ways due to genetics. Genetics is the study of how traits are inherited from our parents and earlier generations. For example, you might have red hair, blue eyes, or a hitch-hiker's thumb that you inherited from your parents. You might also notice that your brothers and sisters share certain traits with you that they inherited from your parents. Color blindness is one such trait. And just like we might be tall or short due to the genetic codes we inherited from our parents, we might end up with different sorts of color vision.



In most cases, color blindness is inherited and normally carried by females and expressed (present) in males. This family tree shows what might happen when a rare color blind grandmother has a daughter and son who each marry spouses with normal color vision (and who are not carriers). The son will be color blind, but his son most likely will not be. The daughter's son might be color blind (50-50 chance). Red text indicates expressed color blindness. Explore the genetics of color blindness to learn more.

While not everything about color vision and color blindness is fully understood, the inheritance of color blindness is fairly well documented. Most types of color blindness are considered a sex-linked genetic trait. Genetic means that it is inherited (not acquired from the environment) and sex-linked means that the genes that encode color vision are on the same chromosomes that determine our gender. These genes are on the X-chromosome. Females have two X-chromosomes (one from the mother and one from the father) while males have just one X-chromosome (from the mother) and a Y-chromosome (from the father). Since much information on color vision resides on the X-chromosome, women have two opportunities to inherit full, normal color vision (they must inherit two faulty X-chromosomes in order to become color blind). Males, on the other hand, only have one X-chromosome and therefore only one chance to inherit normal color vision. If they inherit an X-chromosome from their mother that encodes deficient color vision, then that's what they have.

The above explains why color blindness is so rare in females (less than 0.5% of the population) and far more common in males (about 8% of the population). Women can carry the deficiency without expressing the trait, while men that are carrying the deficiency also have the trait. As we like to remind our teenage daughter, life is not fair!

What happens when one inherits a color vision deficiency is that they do not get all three types of cone photoreceptors. Instead they only get two types. Protanopia refers to a lack of red-sensitive cones, deuteranopia to a lack of green-sensitive cones, and tritanopia to a lack of blue-sensitive cones. There are also anomalous observers who have a variant of one of the cone types instead of the normal type. Lastly, there are some rare individuals who are monochromats and can only see in shades of gray.

Q: How Many Colors Are There in the World?

Sun dogs on each side of the rising sun are caused by ice crystals in the sky on a very cold morning. Dispersion of light in the ice crystals also produces the rainbows. Since there are ice crystals in the air between the barn and the camera, the rainbow is also visible in front of the barn. There are many colors in this scene, produced in many different ways — lights, objects, and scattering volumes. You can also notice the different colors of the snow. It is yellow where the rising sun is falling on it and blue in the shadows where only the scattered blue light of the sky falls on it.

A:

The best answer is infinity!

Careful measurements of our visual system's best performance have been made by psycho-physicists (people who study human responses, like seeing color, to things in the world, like light). They have shown that we can see about 1000 levels of light-dark, 100 levels of red-green, and 100 levels of yellow-blue for a single, static viewing condition in a laboratory. This means that the total number of colors we can see might be about 1000 x 100 x 100 = 10,000,000 (10 million). A typical computer can display about 16.8 million colors to create full-color pictures, really far more than necessary for most situations.

There are just 24 crayons in this box, but imagine all the colors you can make with them, some creativity, and different objects to color on. Not only can you make an virtually infinite variety of colors, but other people might see them slightly differently as well!

However, the answer is not quite so simple. What color looks like is greatly affected by the viewing conditions. These conditions include the color of the lighting, the amount of lighting, and other colors in the scene. Colors also appear in different modes when they appear on different objects such as surfaces, light sources, or within volumes. Different people also have slight differences in the way they see color.

Since we can see as many as 10-million colors in a single viewing condition and the variety of viewing conditions and observers is endless, then the only truly correct answer is infinity. If we have 10-million colors, times 10-million lighting types, times 10-million lighting levels, times 10-million surrounding colors, times 6-billion people in the world, times 3 modes of viewing we get a really huge number. The result of that multiplication is 18 followed by 37 zeros (180,000,000,000,000,000,000,000,000,000,000,000,000), or 180 undecillion. That might not quite be infinity, but is close enough since all those estimated numbers are probably on the low side. And there is no way to exactly measure each of them. To learn more about the names of really big numbers, visit this site.

Q: What Does the World Look Like to Color Blind People?

This picture shows some nice ripe apples in an orchard. On the left is the view of a person with normal color vision. Note how the ripe fruit contrasts nicely with the green foliage. This makes it easy for humans to find (and eat) the ripe fruit. Identifying ripe fruit is thought to be one of the environmental situations favorable to the evolution of trichromatic human color vision. On the right is a simulation of what a deuteranope might see. A deuteranope has no green-sensitive cones and therefore loses the ability to discriminate red-green color differences such as the differences between ripe apples and leaves.

A:

This is a very difficult question because we can never truly know what someone else is perceiving and a color-blind person can't really describe colors in a way that is meaningful to those with normal color vision. We can, however, make some reasonable guesses and there is an interesting website, *vischeck.com*, that does just that. The image of the apples above was made using the software from that site.

We know that color-blind people are missing one of the cone types, so we can take a full-color image, transform the information to normal cone responses, delete one of those cone responses, and then transform the image back to RGB for display to see what they are missing. This does tell us which colors would be confused by the color-blind observer, but it doesn't really tell us what they look like since we are still viewing them with a normal color vision system. This technique also does not account for visual adaptation. The software at *vischeck.com*, does this first step, but it also approximates visual adaptation. It does that by assuming that equal cone responses produce neutral color perceptions (white, gray, black) in color-blind people, just like they do in others. This defines what looks neutral to the color blind-person and maps those colors to the grays that a person with normal vision sees. That gives us a better idea of what the color-blind person might be perceiving.

In very rare cases, people have monochromatic vision. That is, they see in black and white. Some of these people have only one type of cone while others, known as rod monochromats, have no cones at all. Rod monochromats have only rod photoreceptors and cannot see well in bright light. They see like everyone else in dim light.

However, we still can't be completely certain. All we can really do is ask a person with color-blindness if the original image and the processed image (left and right sections in image at left for a deuteranope) look alike. If they do, then we know we have removed the correct information, but we still can't say that we are seeing the same thing they are. And we never really will be able to. That alone is something to ponder!

Q: How Do Digital Cameras Detect Colors?

The array of colors on the left part of this image represents a Bayer filter array (named after a Kodak scientist who was one of the people to develop this particular arrangement of colors). This pattern of filters is placed on top of a black and white image sensor to make each element of the sensor respond to either red, green, or blue light. Notice that there are more green elements. This has to do with our eyes' better sensitivity to fine detail in the green region of the light spectrum. The middle panel shows a scene in Yosemite National Park and the rightmost panel shows how that scene would be sampled by a typical digital camera with the individual red, green, and blue pixels (or picture elements). A lot of computer processing takes place to convert these raw detected images into the pictures that you enjoy viewing.

A:

The "heart" of a digital camera (or perhaps more accurately, the "retina") is a sensor array made out of silicon. These sensors have small individual detectors (usually several million on a single sensor) that respond to light that falls upon them. What happens is the energy in the light causes a small electrical current in the detector at that particular location. That current is then measured electronically and converted to digital values that represent the amount of light detected. Those digital values, indexed to their location on the image, provide the information needed to draw an image on a computer monitor or printer. However, the sensor itself responds to the whole visible spectrum of light energy and some infrared energy as well. This overall response can only produce black and white images. To produce color images, multiple sensors are required to detect and discriminate the different color regions of the spectrum like our eyes do. The first step is to place an infrared filter in front of the sensor to get rid of that energy that we cannot see at all.

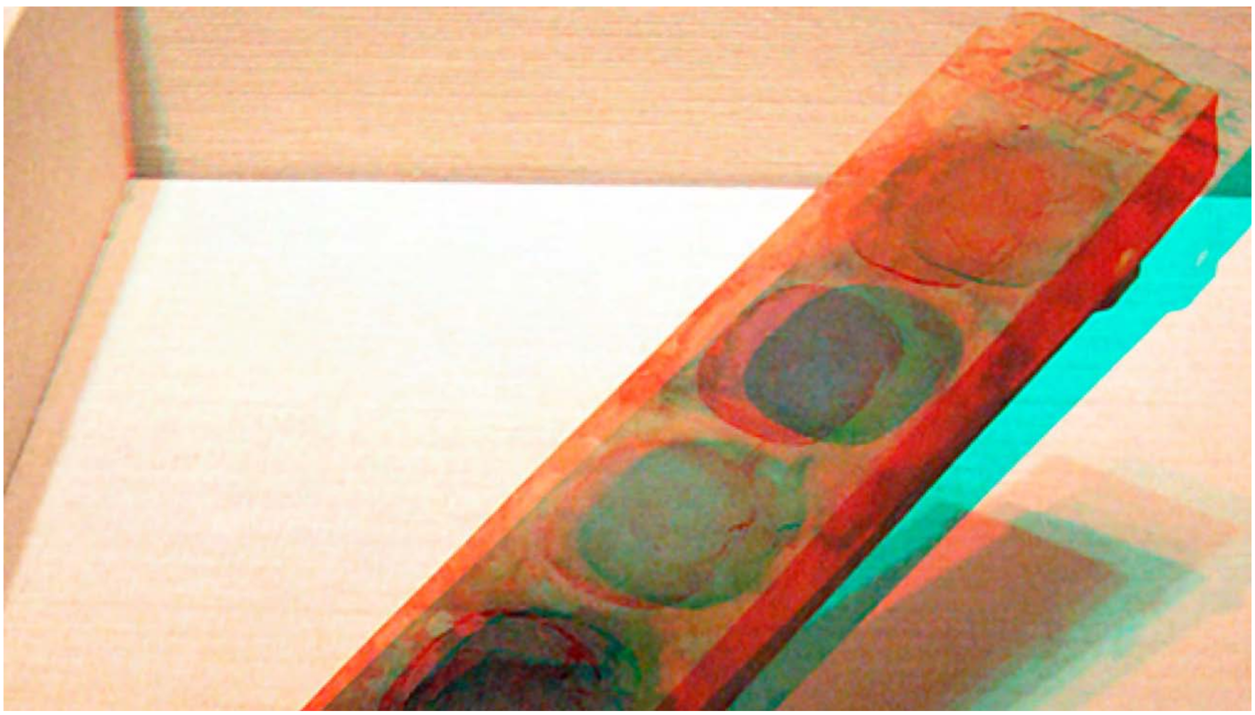
A photograph of the image sensor in a Nikon D3 digital single-lens reflex (SLR) camera. There are almost 13 million sensors (individual pixels) within the gray center area which fits easily inside the camera. The sensor area is about 1.0 x 1.5 inches (or 24 x 36 mm) so you cannot possibly see individual pixel sensors or the Bayer filter array in this picture.

The next step is to figure out how to separately detect red, green, and blue images in order to have all the information needed to create the different colors we can see. One way to do this is to use three image sensors and put red, green, and blue filters in front of each of the three respectively. This gives us the needed red, green, and blue images, but it also makes the cameras very bulky and expensive because three image sensors are required. Instead, most cameras use a filter array as illustrated in the above picture. The filter array results in a single image sensor that has some pixels that respond to each of the three red, green, blue, primary colors. Since we really want red, green, and blue information at every location in the image, fairly complicated computer processing is done to convert the detected image (with the filter array information superimposed) to a single full-color image. This process is known as demosaicking since the filter array can be considered a mosaic of colors. There is also a lot of other processing that goes on before we see the images to adjust the color, exposure, contrast, sharpness, noise levels, and other image attributes.

Finally, the combination of the image sensor, the color filter array, and the computer processing result in a set of three images. One represents the red information in the scene, one the green information, and the third the blue information. These can be combined on monitors or printers to give us the beautiful full-color images we are used to seeing when we simply push a button. This process is theoretically the same one that Scottish scientist James Clerk Maxwell developed in the 1800s when he is credited with inventing color photography (in reality he was trying to show that the human visual system detects colors by separating the information into just three images corresponding roughly to red, green, and blue information).

Challenge (Level 4)

Q: Quiz Time: Given 50 Women and 50 Men, About How Many will be Color Blind?



Did you know that there are also people who are stereo blind? That means that they cannot see 3D images and movies. In fact 3D movies can give them severe headaches. There are probably more stereo blind people in the world than color blind people (I'm one of them!). Some estimates are as high as 30% of the population with some deficiency in stereo vision. This is a picture of Egyptian red, green, and blue paint from about 1420 BCE that is still intact and colorful (now in the Cleveland Museum of Art).

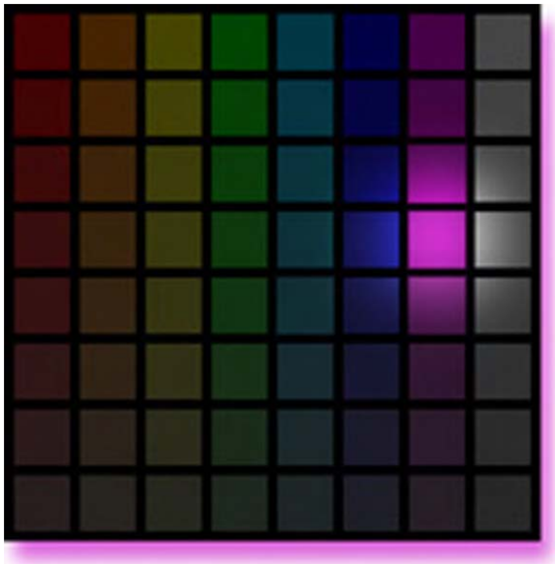
A:

(A) 0 Men and 8 Women

(B) 4 Men and 0 Women

(C) 4 Men and 4 Women

(D) All of Them!



I'm sure you figured something out by now!

Light (Level 5)

Q: How Do Fireworks Make Light and Color?

You might wonder what neon signs like these have to do with fireworks. Neon lights produce their color by having gases in the tubes excited by electrical energy. Once the gas atoms or molecules are excited, they release that energy as very specific colors of light. Pure neon produces glowing orange or red signs. Other gases such as argon, helium, krypton, and xenon can be used alone, in combination with each other, or in combination with other gases to produce differently colored "neon" signs. Some tubes are also coated with phosphors that absorb energy of one type and emit different colors; this is also how fluorescent lights work. Fireworks also produce various colors by using the incandescent energy from the explosion (the fire part of the fireworks) to excite various atoms or molecules that, in turn, emit various colors when they release that energy.

A:

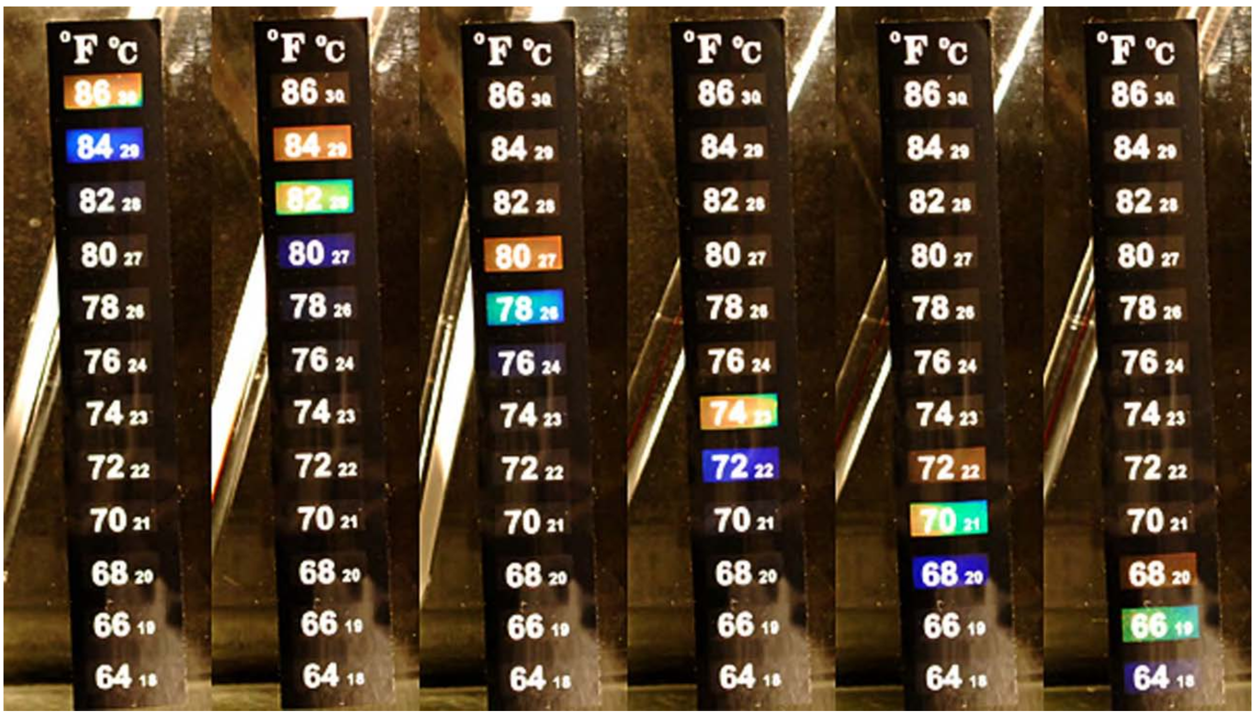
First of all, light and color are not two separate things. All light has some color and color is produced by our perception of light. So light and color in fireworks are made exactly the same way. There are two sources of light in fireworks. The first is simple incandescence, or light and color that is produced just because material is heated to very high temperatures. This can be considered the "fire" in fireworks. Just like a campfire emits light with yellow, orange, and red colors simply due to the high temperature of the material being burned, fireworks can produce similar colors due to the very hot explosion and burning of the explosive charge. These reds, oranges, yellows, and whites due to incandescence are the dominant colors in most fireworks even though they are often the colors we pay least attention to.

The "fire" in fireworks can only makes shades of red, orange, yellow, and white like any fire, or incandescent source of light. Incandescent light bulbs do this by using electricity to heat up a small tungsten wire (or filament), which then glows like a fire. These particular fireworks are showing the incandescent part of the explosion. The colors on the castle come either from incandescent lights with filters to absorb different colors or, more recently, from light-emitting diodes (LEDs).

The second method by which light and color is produced in fireworks is atomic and/or molecular excitation followed by emission of light. This is the same process that produces the interesting colors we see in neon signs as shown in the image above. Different elements and molecules will emit their own specific colors of light after they are excited by high levels of electrical energy (as in the neon signs) or heat energy (as in the fireworks). For example, sodium is a very strong emitter of yellow light. This can sometimes be seen by putting ordinary table salt (sodium chloride) into a candle flame. Sodium emission due to electrical excitation is also what produces the saturated yellow colors seen in some street lights and parking lot lights in large cities.

A variety of atoms and molecules are used to produce colors in fireworks. Some examples include sodium for yellow, calcium chloride for orange, strontium chloride for red, barium chloride for green, and copper chloride for blue. Think about all these atoms and molecules being heated up by incandescent explosions and then emitting their beautiful colors next time you see a fireworks display!

Q: How Does a Mood Ring Work? What do the Colors Mean?



This aquarium thermometers is made from thermochromic liquid crystals. Thermochromism is the term used to describe changes in color due to changes in temperature at temperatures for which the object is not burning (that is incandescence!). In the case of these thermometers, the color changes are correlated with the temperature of the liquid crystal to create a useful, inexpensive, and compact thermometer. The liquid crystals in the thermometer strip change their physical properties with temperature and this results in a change in the colors of light they reflect. In general, as a liquid crystal is heated, the reflected light progresses through the spectrum from red, through orange, yellow, green, and cyan, to blue. These color changes, in combination with optical filters or temperature calibration, can be used to construct a thermometer. Alternatively, a thermometer can be created by using slightly different liquid crystals to indicate each specific temperature. I made this sequence of pictures by putting the thermometer on a vase of hot water and gradually adding ice cubes to lower the temperature as I took pictures.

A:

If by "work" you are wondering how they tell your mood, then they simply do not work at all! They are fun and they do change colors. However, they are simply liquid crystal thermometers that you wear on your finger. So they do indicate a change in your body, but that change is actually the surface temperature of your finger. Mood rings are filled with a liquid crystal just like the aquarium thermometers described above.

Specifically, these materials are known as thermotropic liquid crystals and they change with temperature in ways very similar to how the liquid crystals in your LCD computer display or television change when an electrical current is applied to them. For mood rings, the system of glass and liquid crystal material that makes up the ring is calibrated to be a green for an average surface body temperature of about 82° F (28° C). As the ring-wearer's skin temperature increases, the liquid crystal changes toward blue and, as the temperature decreases, the ring changes toward black.

The standard interpretations of the colors of mood rings are:

- Dark Blue: Happy, Romantic, or Passionate
- Blue: Calm, Relaxed
- Blue-Green: Somewhat Relaxed
- Green: Normal
- Amber: Nervous, Anxious
- Gray: Very Nervous
- Black: Stressed, Tense

You can see that these moods might correlate somewhat with your body temperature, but not always. It is entirely possible that a person could be very happy and very cold and then the mood ring would be completely incorrect. So really the colors mean nothing about your mood, but do tell you something about your finger's temperature.

I found this nail polish for my daughters in a store in Albuquerque, New Mexico. It changes color when exposed to the ultraviolet (UV) energy in sunlight. The top section was exposed to UV energy while the bottom was kept in the dark. It is quite fun to have nail polish that is one color inside and a different color outside in the sun. This is caused by photochromism, which is a change in color of a material due to exposure to light or other optical energy. Can you think of any other materials that are photochromic?

Q: Why Can't I See Colors at Night?

The stimulus for color hasn't disappeared at night. The problem is that there simply isn't enough light for us to perceive colors. I took this picture of Yosemite Falls at night (about 11:00PM) on an early spring evening with a nearly-full moon. I set my camera exposure time to about two minutes in order to capture enough light to make the image. You can see that it was taken at night by looking at the stars in the sky and seeing that they actually moved a little bit (well actually the earth rotated a little) during the long exposure time. This full-color night-time image shows that all the colors are still there under moonlight, but we just can't see them. The sky is blue, the water white, trees green and brown, rocks gray and brown, etc. When I was in the original location, I could only see a black and white version of the scene with my naked eyes. That is because there was only enough light for my rods to function and not my cones.

A:

You can't see colors at night because our visual systems are not designed to see colors when there isn't very much light in a scene. We actually have two visual systems that work in parallel to help us survive in the world. When there is plenty of light, we use our cone photoreceptors. There are three types of cones roughly sensitive to red, green, and blue light and we can compare the images captured with these three systems to perceive the colors in the scene. We can also see fine detail with our cones.

However, the ability to see colors and detail with our cone system means that the cones cannot be very sensitive to light. As the light levels decrease at night, we reach a point where our cones can no longer respond because there simply is not enough light for them to produce a response. In this situation, our visual system automatically switches to a second set of photoreceptors known as rods. There is only one type of rod receptor, so that means we can only see in shades of gray when our rods are working and our cones are not. The rods also gang up together to capture light over relatively large areas. This helps them to be very sensitive to the small amounts of light available at night, but it means that they cannot possibly allow us to resolve fine details.

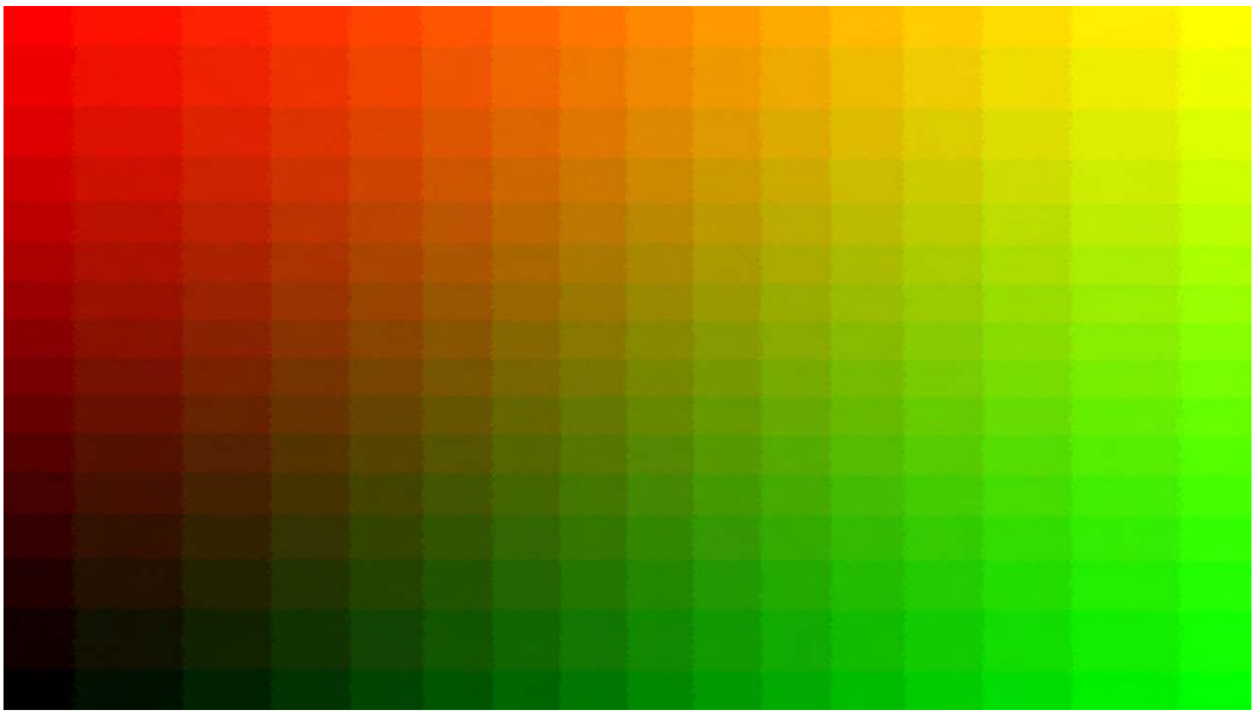
Thus, it is our switch from the color-sensitive, but light-insensitive, cone system to the color-insensitive, but very light-sensitive, rod system that causes us to loose our color vision at night. Or as it was once written by the rock band, The Moody Blues:

Cold hearted orb that rules the night
Removes the colours from our sight
Red is gray and yellow, white
But we decide which is right
And which is an illusion

This image shows about what the scene photographed above looked like to my eyes. The contrast was low, it was less sharp, and the world appeared only in shades of gray. And all of that is due to the limits of our visual system, not due to the lack of color or detail in the actual scene.

Numbers (Level 5)

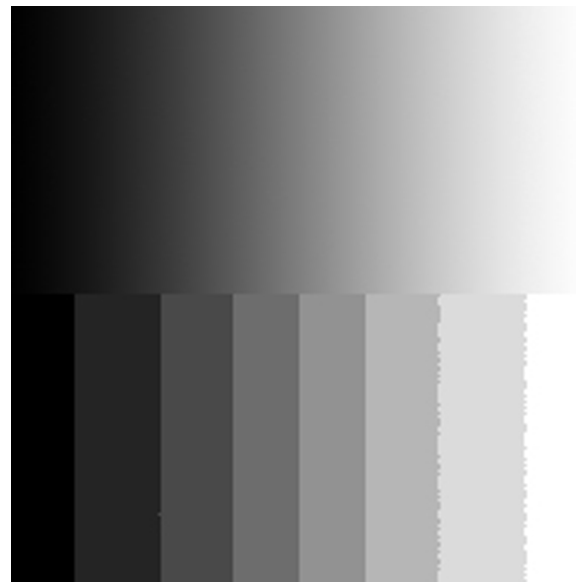
Q: How Does a Computer Represent Colors as Numbers?



In this image, only sixteen numbers are used to represent various amounts of red (R) or green (G) and all their possible combinations. The lower left (black) rectangle shows R=0 and G=0. The upper right (bright yellow) shows R=15 and G = 15. The upper left is all red (R=15) with no green (G=0) and the lower right is all green (G=15) with no red (R=0). The rest of the rectangles show all possible combinations of 16 levels of red and 16 levels of green. You can think of this picture as a graph of color with the green value increasing along the horizontal (X) axis and red value increasing along the vertical (Y) axis. Instead of showing the numbers on this graph, we are seeing the colors produced on your display by those numbers. Throughout this image, blue is set to zero.

A:

Computers represent everything as numbers. In fact, they represent everything using only two numbers, zero and one. Expressing numbers as zeroes and ones is known as using binary numbers. In computers the numbers are represented by electronic switches. An open switch represents a zero and a closed switch represents a one. With enough switches, virtually anything can be represented as numbers. Another name for these switches is "bits". These bits are stored in our computers' memories. Eight bits together makes what we call a "byte" of data. You've probably heard of how many megabytes (approximately millions of bytes) or gigabytes (approximately trillions of bytes) your computer can store. Ultimately the amount of memory in your computer determines how many numbers can be represented. Most commonly, colors are represented in computers using 8-bit numbers. This means that a set of eight zeroes and ones is used to represent a given color component. Every possible combination of eight zeroes and ones gives us 256 possible levels of color we can represent. For example the decimal integer 0 is represented in 8-bit binary digits as 00000000, while the decimal integer 255 is represented as 11111111.

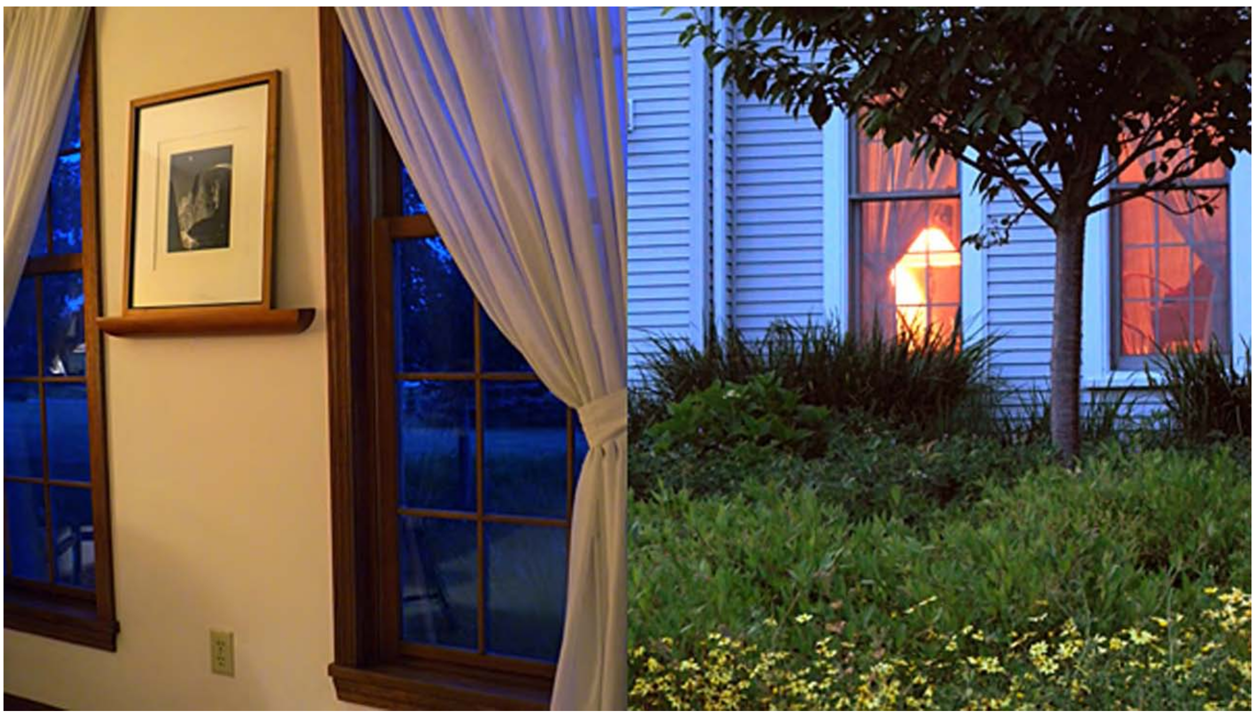


This picture shows what happens when different amounts of numbers are used to represent colors. In the top section there are 256 levels of gray (8-bits) while in the bottom section there are only 8 levels (3-bits) of gray. Most digital photographs are represented with 256 levels each of red, green, and blue.

There are many ways to represent colors with numbers. The most common method in computers is to represent the amount of red, green, and blue primary lights required to mix together to create the desired colors. This is the tradition because most computer displays work by adding together amounts of RGB primaries and the numbers can be used to directly display colors. If 8-bit numbers are used, then we can have values ranging from 0 - 255 for each of the RGB primaries of the color. In that case, black would be represented by (R=0,G=0,B=0) and white by (255,255,255). The red, green, and blue primaries would be represented by (255,0,0), (0,255,0), and (0,0,255) respectively. Similarly the cyan, magenta, and yellow secondaries would be represented by (0,255,255), (255,0,255), and (255,255,0). Intermediate colors are represented with intermediate numbers. For example a middle gray might be (128,128,128) and a pale yellow color (200,180,120).

As mentioned above, computers represent these numbers as binary numbers instead of decimal integers. Some computer programs represent colors in hexadecimal numbers. Hexadecimal doesn't have ten numerals like decimal (0123456789), but rather has 16 numerals represented by our normal decimal numerals and the first 6 letters of the alphabet (0123456789ABCDEF). Ultimately it is the display or decoding of the numbers that determines the color that you see. (200,180,120) does not turn out to be exactly the same color on all computer displays or printers. This complexity is what makes accurate color reproduction a serious technical and scientific challenge.

Q: Why Can I See Well Outside When My Mom (Who's Inside) Thinks It's Too Dark to be Out?



Here are two views of the same place at the same time. It was dusk and in the first view, I was inside looking out through the windows. My room inside was illuminated with yellowish incandescent lights, but it looked fairly neutral to me because of adaptation. Looking out through the window, outside appeared quite dark and bluish like in the left side of this image. However when I went outside, things looked fairly normal since my visual system could adapt to the low light level and bluish color of the sky light (the sun had set). In that case, when I looked inside the house, the illumination looked very bright and yellowish. When we are adapted to the bright and yellowish light inside, then outside looks dark and bluish. When we are outside and adapted to the dark and bluish light, then inside looks much brighter and yellowish. The only thing that changes is the way our visual system adapts to the scene (and I made my camera mimic that behavior!).

A:

Adaptation! It all comes down to how our visual systems adapt to their environment. We are normally interested in identifying objects in our environment and less interested in identifying the color and level of illumination. Imagine a white piece of paper. When we view it on a bright sunny day, it looks white. When we view it at dusk after the sun has set, it looks white. When we view it under the very yellowish illumination produced by incandescent light bulbs (or the even more yellow illumination of a candle), it still appears white. This is because our visual system has adapted to the prevailing levels and colors of illumination in order to be able to better judge the relative colors of objects in our world.

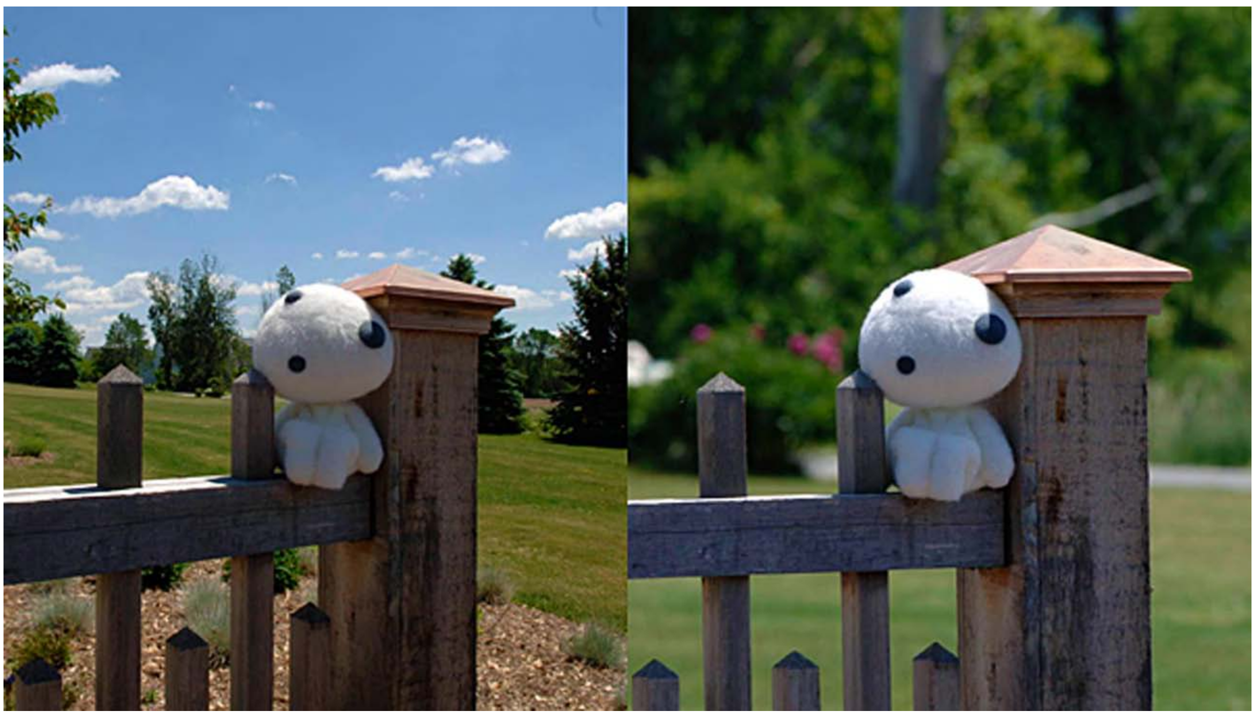
We don't completely adapt to all changes in illumination. When it gets very dark, our vision transitions from cones (seeing color) to rods (only seeing black and white) much like this image illustrates the same flowers in daylight and how they would look at night. Since our rods don't respond to yellow light, the bright flowers look dark at night.

When your mother is inside at dusk, she has probably turned on some lights and gradually adapted to that level of illumination. As it gets darker outside, she does not adapt to that change and when she glances out she notices that it appears very dark outside and calls her children in. The children, on the other hand, have been outside the entire time and adapted to the gradual change in the color and amount of light. The world outside still looks completely normal to them and they can still see fine when their mother seems to arbitrarily decide that it is too dark to be out. This change in appearance due to adaptation is illustrated in the images above.

Adaptation is a very powerful property of our visual system (and other perceptual systems) that allows us to easily detect changes in the world around us. For example, if you eat some sugar you will adapt to sweetness and when you taste some plain water it might seem bitter or sour. When you are very hot, a cool glass of water might feel very cold, but if you just came inside on a cold winter's day, that same glass of water might feel warm. If you spend time in a room full of tobacco smoke, you will gradually adjust to the smell and it won't seem as bad is it would if you walked into the same room from the fresh air outside. If you are in a room full of loud noises, then you can't hear a quite voice while if you are in a perfectly silent room, you can hear almost anything. These are all examples of adaptation and our visual system is very capable of adapting to changes in color and light level as well.

Photography (Level 5)

Q: Why Does the Moon Look Large on the Horizon, But This Doesn't Show Up in Photographs?

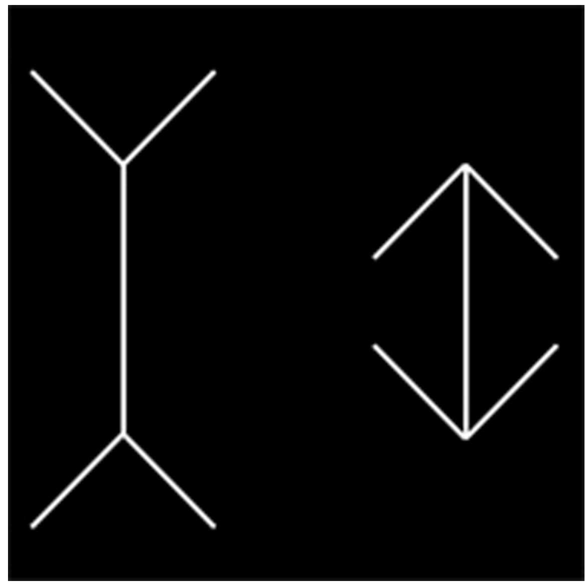


Here are two picture of my stuffed Kodama (a Japanese tree spirit) sitting on a fence. In the picture on the right, my Kodama is about the same size as the flower bush in the background. In the picture on the left, that flower bush is so small you almost cannot see it (it's just a little bit larger than the Kodama's little round mouth). However, the Kodama is about the same size in both pictures. How can this be? It turns out the relative sizes of objects in a scene depends on the lens used to capture the image. The image on the left was captured with a wide angle lens that tends to make things in the background look very far away. The image on the right was captured with a telephoto lens that tends to make far-away background objects look much closer and larger. It is all a matter of perspective and the field of view of the two lenses. Note that I had to be much farther away from the Kodama when I took the picture with the telephoto lens in order to get him (her?) to come out the same size.

A:

The answer to this question is still debated by scientists. It is known as the Moon Illusion. The moon is always almost exactly the same size when visible in the sky. Vision scientists like to measure size using angles and the angle subtended by the moon is about 0.5 degree. (Coincidentally, the angle of the sun is also almost exactly 0.5 degree at the Earth's surface. That's why both lunar and solar eclipses can happen the way they do!). When the moon is on the horizon, it is 0.5-degree wide (and high) and when it is straight up overhead, it is 0.5-deg. wide (and high). A camera simply records that physical geometry of the moon and the pictures make the moon look the same size (which it is) regardless of whether it is on the horizon or overhead.

Since there is no problem with the photographs, then the "error" must be in our perception of the moon. Indeed that is the case. That moon looks larger on the horizon to us even thought it really isn't and that is precisely the definition of the Moon Illusion. There are many theories about why the moon illusion occurs. My favorite has to do with perceived distance and another visual phenomenon called size constancy. Size constancy refers to the perception that the sizes of objects appear the same whether they are nearby or far away. For example, if you are right next to me, you will see me as a human about 6-feet (or 2-meters) tall. If you see me from 100-yards (or 100-meters) away across a football field, I will still look like a human that is about 6-feet (or 2-meters) tall even though I would only take up a very small portion of what you can see. In other words, even though the image of me on your retina decreases in size when I am farther away, your perceptual system takes into account your perception of how far away I am and I appear to remain the same size (size constancy).



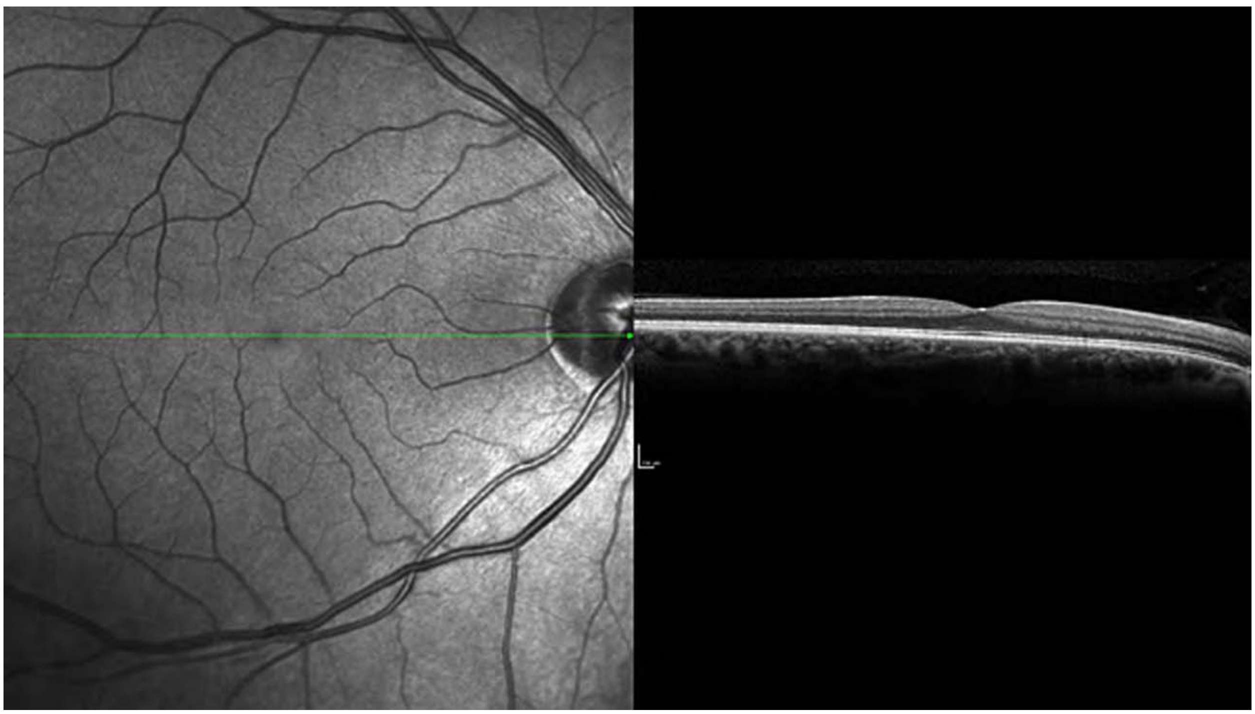
The two vertical lines in this image are exactly the same length. They appear different due to a perceptual effect known as the Müller-Lyer Illusion. Some say that this illusion is also related to perceptual distance as we see the two lines as either inside corners or outside corners.

This could create the moon illusion because people seem to perceive the "distance to the imaginary surface of the sky" where the moon is to be much larger at the horizon than overhead. Thus if the moon is always the same size on our retinas (it is), then our perception of the moon will be that it is larger at the horizon because we mistakenly perceive it to be farther away (it isn't). There are other possible explanations for the Moon Illusion, so you should do some more reading on those.

If you still don't believe me then check for yourself. Next time you see the moon, hold your thumb out at arm's length and compare the size of the moon to your thumbnail. The moon will be about half as wide as your thumbnail (yes, it really will!). Now repeat this experiment when you see the moon at different heights in the sky with different apparent sizes and you will notice that it is always about half the width of your thumbnail.

Challenge (Level 5)

Q: Quiz Time: What Is the Functional Difference Between Rods and Cones?



These are images of my retina (the back surface of my right eye). In the left panel you can see the blood vessels, the beginning of the optic nerve (right edge of image) and my fovea (near the center with no blood vessels). The right panel is a cross section of the area marked with the green line. You can see a slice through my fovea (the pit where the nerve fibers are pulled away to allow better vision) and the various layers of cells in my retina. The rod and cone inner segments are the dark gray area near the middle of the cross section.

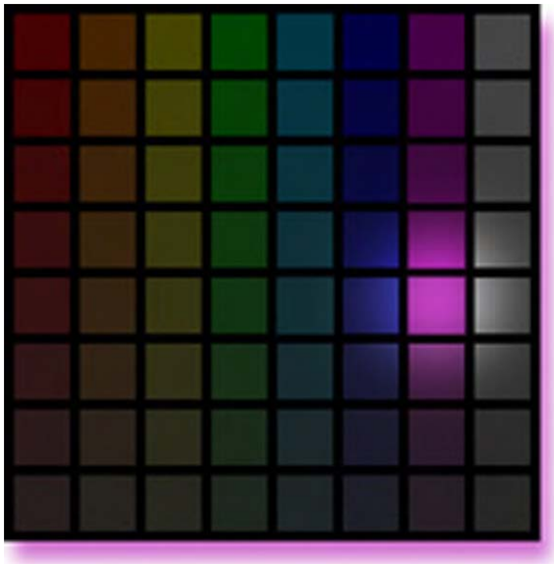
A:

(A) Nothing; They Are Exactly the Same

(B) Cones Hold More Ice Cream

(C) Cones Are Capable of Detecting Color; Rods Are Not

(D) Cones Respond to Light; Rods Respond to Dark



I'm sure you figured something out by now!

Q: How Does the Light Affect How Bright a Color Appears?

These pictures illustrate how brightness and colorfulness change with the amount of light. On the left the scene is shown as it would appear on a rather dim (perhaps hazy) day. Some might even call that a dull day. On the right is the same scene as it might appear on a bright sunny day. Notice that the colors are both brighter and more colorful when there is more illumination. Also, the scene appears to be of greater contrast and sharpness when there is more light. Pay close attention to how things look throughout the day from early morning, through noon sunlight, to dusk and you will witness these sorts of changes in color appearance.

A:

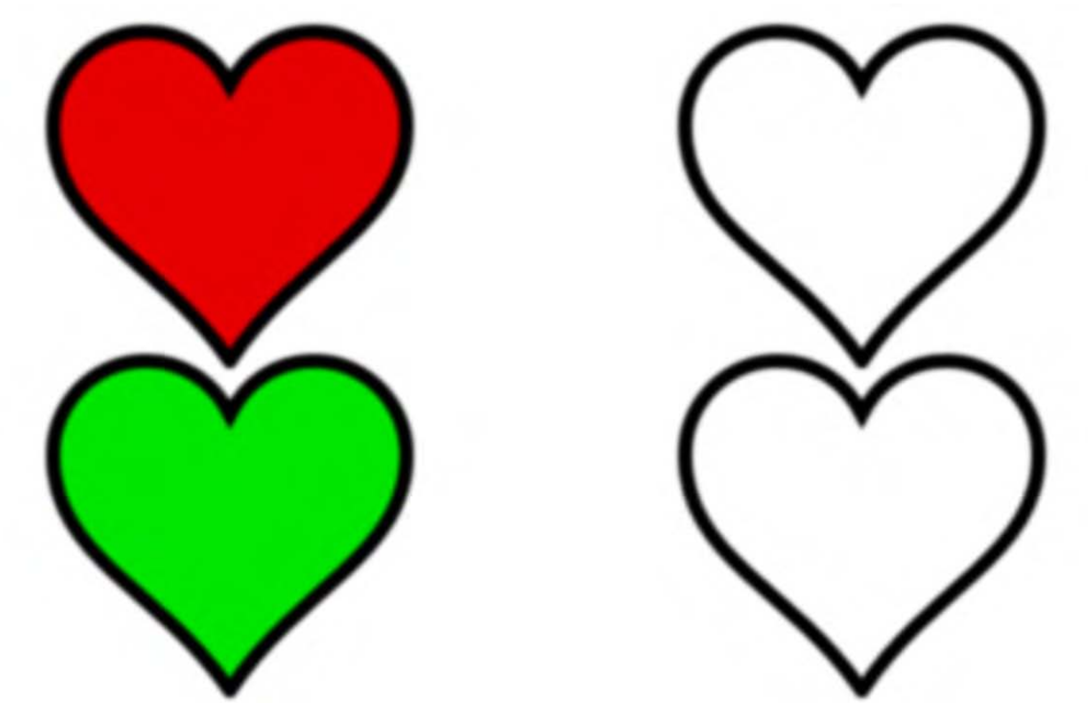
There are two general ways that lighting influences the apparent colors of objects. These are due to changes in the color of the light and changes in the amount of light. Color changes can have very strange effects. For example, if you were to illuminate a scene with red light, then red objects in the scene would appear brighter while blue or green objects might appear darker, or even black. In general, when the color of the illumination changes, objects of color similar to the illumination color become brighter.

More commonly we observe changes due to the amount of light. Think about how a room in your home appears in bright daylight, at dusk, and with lights on at night. If it didn't change in appearance we wouldn't be able to figure out what time of day it was without looking at a clock! In general, when there is more light falling on a scene it appears brighter, more colorful, more contrasty (the differences between colors show up more), sharper (more in focus), and less noisy (or grainy). You can observe all of these changes if you look closely.

Parts of these changes are due to the transition between rod vision and cone vision. Rod vision serves us in very low light levels. In order to gain that sensitivity to light, the rods collect light over larger areas and this results in less sharpness. Things also look more noisy, or grainy, because detecting such low amounts of light is difficult for the rod photoreceptors. When we are using our cones, we collect light over smaller areas so everything is sharper. It is also less noisy because there is plenty of light to capture. Rods can only produce black-and-white vision, so as the light increases and we transition to cone vision, the world starts to appear more colorful. As the light level increases further, the differences between colors become much easier to discriminate and everything looks more contrasty (bright and colorful). Also our pupils can close down when there is more light and that can help make the world appear more in focus.

Paul Bunyan and his blue ox Babe are characters from American folklore. These statues stand in Bemidji, Minnesota. Babe's blue body is all the same material, but the apparent color depends on the illumination. In the shadows, Babe doesn't look as colorful as in the direct sunlight. Color scientists would say that the image of Babe has the same saturation everywhere even though the colorfulness changes.

Q: Why Is Green Often Used for Surgeons' Scrubs?



OK, look at the very bottom point of the red heart and stare at that point for about 30 seconds. Then look over at the same point on the upper white heart. What do you see? If you've done the experiment carefully, you will see a faint greenish heart on top and a faint reddish heart on the bottom. The colors have switched positions! These faint colors are known as afterimages and they are caused by adaptation (or fatigue) of the cone receptors in your eyes. When you stare at the red heart, your visual system becomes less sensitive to red light in that area. When you then look at the white area, you respond less to the red light there and see a bluish-green color. The same thing happens with the green heart. Except in this case your visual system becomes tired of seeing green and when you look at the white heart, you respond more strongly to the reddish-blue light that is not green. Studying afterimages has allowed scientists to learn a lot about how vision works.

A:

Believe it or not, this is another case of adaptation! Surgeons spend a lot of time looking at the reddish colors of organs, muscles, and blood inside their patients and their eyes can easily tire of these red hues. When the surgeons look away from their work to rest and refresh their eyes, they would see eerie greenish afterimages of the objects they had been working on. This can be both disconcerting and distracting, two things that aren't desirable for surgeons in the middle of surgery. Instead, green, or greenish-blue, scrubs became more popular than the more traditional white (for cleanliness) scrubs because they were felt to be easier on the eyes. In this case, "easier on the eyes" means that the disconcerting afterimages are broken up and made less perceptible by glancing at the scrubs of the same color. This makes it easier for the surgeons to normalize their visual adaptation and then go back to work with the best sensitivity to subtle differences in red hues that they might be looking for.

Legend has it that bullfighters use red capes to enrage the bulls and make them charge. In reality, bulls are red-green colorblind and it is not the color that enrages the bulls, but instead the taunting with the flowing cape (and the fact that they have already been stabbed several times!). Also, magenta capes like the one shown (called "capote" are often used early in the bull fight while a smaller red one (called "muleta") is used only at the end.

Another interesting interaction between colors and objects is the Stroop effect. Look at the words in the list below and say they color of the text out loud. Then try again saying the word instead of the color of the letters in the word. You should notice that it is much easier to say the word than it is to correctly say the color of the letters. This is due to the interactions in our brain when we recognize things. The words themselves take precedence over the colors of the letters. Color is not so important for us in recognizing objects as form, or shape is.

RED
GREEN
YELLOW
BLUE
PURPLE
ORANGE
BROWN
BLACK
PINK

There are many interesting ways that color interacts with other perceptions and these interactions can be explored endlessly.

Q: Why Do People Get Red-Eye in Photographs?

Here is an example of two pictures taken of the same person with the same camera only a few minutes apart. In both cases the camera's flash was used. The image on the left was made under the worst possible conditions for red-eye. The subject was in a completely dark room so that her pupils opened wide and the photographer was far away so that the lens and flash were very close to each other. The subject also looked right into the camera lens (and flash). The picture on the right was done outside in sunlight. This closed down the subject's pupils. Also she looked slightly away from the camera and the photographer was closer (making the distance between flash and lens a little larger). In this case the flash only served to fill some light in the shadows on the face and there is also no red-eye at all.

A:

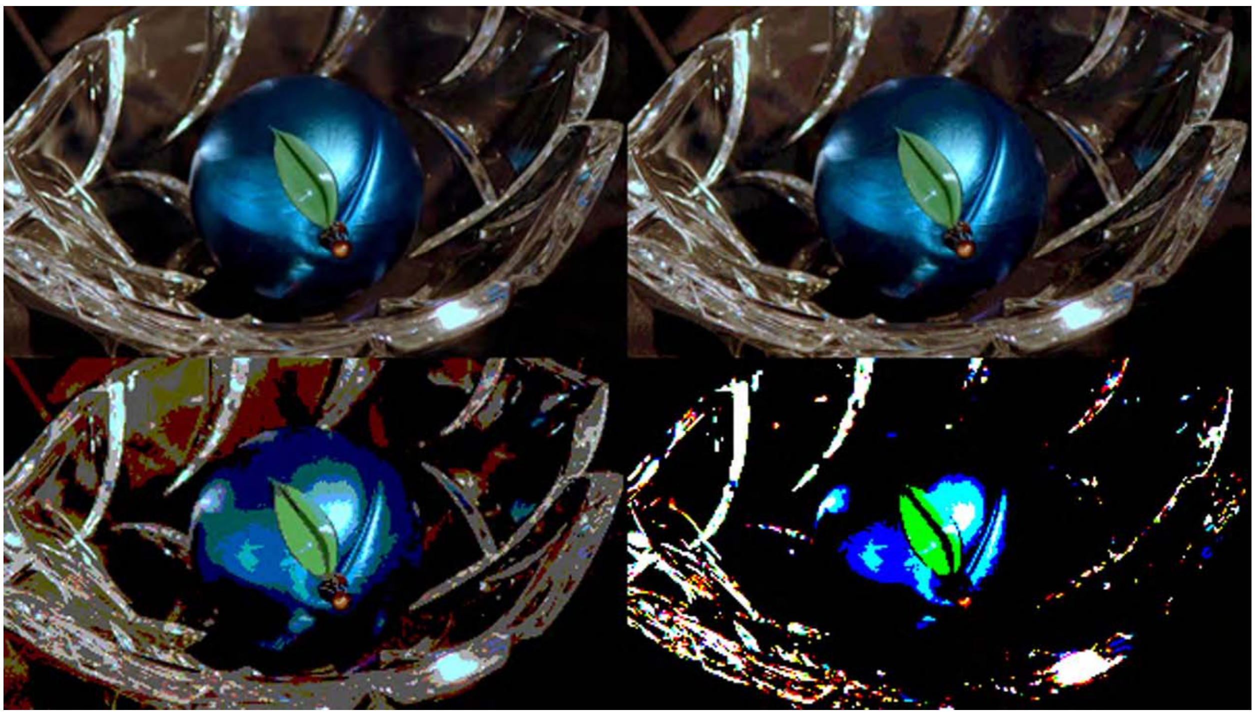
One reason is that they are looking at the camera! What this does is make an image of the camera in focus on the person's retina (back of the eye). That also means that the back of the eye is in focus at the camera and all the light from the back of the eyes goes right into the camera lens to make a bright (and blurred) image of the person's retina.

Since the retina is covered with blood vessels, the most dominant reflected color is red. It is the brightly reflected image of these blood vessels that we see as red-eye in the photograph. While such an image is always there, it becomes much more apparent under certain circumstances. These are when the flash is near the camera lens (which happens with most small cameras) and the person's pupils are wide open (which happens when it is dark and flashes are most commonly used). The combination of the flash and the wide open pupils makes for a particularly bright red-eye image.

The red-eye effect can be minimized by having some other light on the subject so that their pupils close down (some cameras do this with an extra flash before the photograph is taken), by having them look slightly away from the camera, by separating the flash from the camera lens, and by moving a little closer to effectively make the distance between lens and flash a bit larger.

Cats get yellow-eye or green-eye instead of red-eye in flash photographs. This is because nocturnal animals have a reflective layer at the back of their eyes to give them a second chance to detect the light as it bounces back and therefore make them better able to see at night. This reflection dominates any reflection of blood vessels in photographs of nocturnal animals.

Q: Can My Computer Really Display "Millions" of Colors?



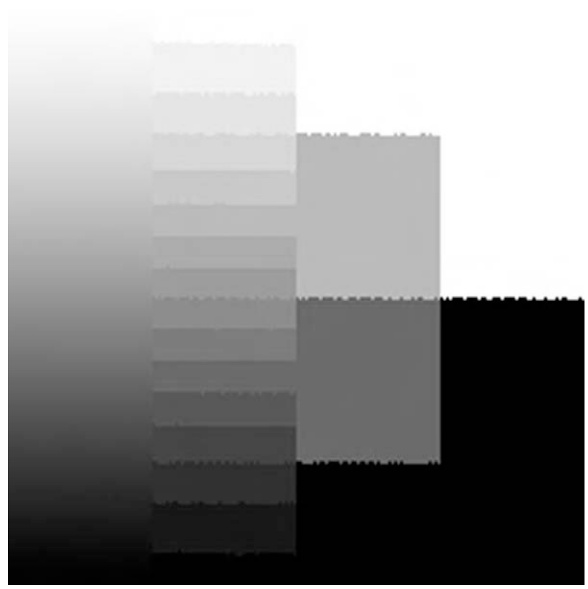
These image illustrates a color photograph quantized (or encoded) with different numbers of levels for each of the red, green, and blue primary channels. The upper left panel is encoded with 24 bits, or 8-bits each of red, green, and blue. This produces 256 levels of R, G, and B for a total of over 16.7 million possible color combinations. The upper-right panel is encoded with 12 bits (4 bits, or 16 levels for each RGB channel) for a total of 4096 possible color combinations. The lower-left panel is encoded with 6 bits (2 bits, or 4 levels for each RGB channel) for a total of 64 possible color combinations. Finally, the lower-right panel is encoded with 3 bits (1 bit, or 2 levels for each RGB channel) for a total of 8 possible color combinations. Incidentally, this is an image of a glass plum with a blue aurene finish. Blue aurene is an application of gold on the surface of the glass (or crystal) to produce an iridescent blue finish. This finish was made famous by Steuben Glass in the early 1900s.

A:

Not really. In theory most computers can produce about 16.777 million different color combinations for display on the monitor. This number comes from the fact that each of the red, green, and blue primary channels used to control the computer display is controlled with an 8-bit number. An 8-bit number can have 256 possible levels ranging from 0 to 255. Zero is used to represent the color channel being fully turned off while 255 represents fully turned on. Thus a black color is encoded with 0,0,0 for R,G,B while white is encoded with 255,255,255. Since there are 255 possible levels of red, green, and blue and each is independent of the other, then there are 255 x 255 x 255 different color combinations that the computer can theoretically display. 255 x 255 x 255 = 16.777 million and that is where the term "millions of colors" used for computer displays came from.

However, theory and practice are different. First of all, no computer displays have 16.777 million pixels, so it is not possible to display all of those color combinations at the same time. More typical displays have about one or two million pixels and therefore it impossible to display more than that many colors, even theoretically. Secondly, many of those color code combinations do not produce distinct colors. For example many of the color codes that are close to zero would all look black to us, so it is not correct to suggest that they are all separate colors when we cannot possibly tell them apart. (And remember, color is a perception.)

Realistically, for most images and typical viewing conditions, an encoding with 5- or 6-bits per channel is indistinguishable from one with 8-bits per channel. That means that an image with around 33 thousand color combinations is usually indistinguishable from one with all 16.777 million possible color combinations. Therefore it is more realistic to say that the computer can really display only thousands of colors, not millions.



This image shows the same quantization as the color image above. From left to right are 256 gray levels (8-bits), 16 gray levels (4 bits), 4 gray levels (2 bits) and 2 gray levels (1 bit). In the color image, these numbers of levels (or bits) are used to encode each of the red, green, and blue primaries.

Seeing (Level 6)

Q: What is the meaning of different colors?

A red stop sign is widely recognized in many cultures. So much so that the shape and color alone are often enough to signal the intent. As such, we have learned to associate the color red with the action of stopping or the presence of danger. But is there anything intrinsic about red to create that association. Probably not as we could have all learned to associate any consistent color with stop signs, but red does have some natural correlates with danger through the color of blood and fire. Of course there are also favorable red stimuli in nature (e.g., ripe fruit, mating signals). The white wedding dress also represents another fairly common, but not universal, association of a meaning with a color. While the white wedding dress is often considered a representation of purity, the origin is actually from gowns worn by women making religious vows in the Catholic church. (Blue was historically used to represent purity). In some cultures, red is worn for wedding dresses as a color that represents good luck. Clearly, the colors themselves do not have any intrinsic meaning, but the cultural traditions relating to colors create certain interpretations.

A:

Colors in and of themselves have no intrinsic psychological meaning. Instead it is the association of colors with certain events or cultural traditions that can result in the colors seeming to have meaning all on their own. Even with such strong cultural traditions and relationships, it is easy to illustrate that the colors have no meaning on their own with simple counterexamples. While red might signify danger to you, it might evoke happiness and good luck in me. It is not the color red that has meaning, but instead our learned relationships that might seem to create such meaning.

The colors of signal lights have come to have specific meanings, sometimes transferred to other contexts, because of their familiar and common use. We use red for warnings/stop, yellow for caution, and green for safety/go in many situations. Can you figure out how I got all three lights on in a single photograph?

Despite the clear lack of any scientific evidence to link colors with specific psychological meanings or influences, there are many publications that claim to describe exactly what those relationships are and how to decorate a room, dress yourself, or create product packaging in order to produce the intended response in your unwary "victim". It is fun to read about these interpretations, but read such descriptions with a critical eye and think for yourself whether they make sense. For a balanced and critical examination of these topics, I suggest the books by Faber Birren (*Color and Human Response*) and Jean Bourges (*Color Bytes: Blending the Art and Science of Color*) that are referenced in topic 8 of The Color Curiosity Shop.

A related topic is the *Lüscher Color Test*. The Lüscher test has a subject rank order a series of color stimuli, usually eight, by preference. The theory is that the ranking one selects indicates deep-seated psychological tendencies that are not necessarily consciously understood. More recent research has tended to discredit the test by showing that the results do not correlated with more thorough and accepted personality assessments. You might be able to understand this if you read the results of a Lüscher test with a critical eye. The stated results tend to be very generic statements that could apply to anyone, much like horoscopes. Regardless of the scientific validity, the exam and results can be amusing.

Q: Why Aren't My Photographs the Same Colors as the Original Scenes?

Here are four pictures of the Ben & Jerry's Ice Cream factory in Vermont. They were all created from a high-dynamic-range image capture that almost perfectly recorded all of the color information in the scene. The upper left image shows a fairly accurate rendering of the appearance of the scene. The upper right image might be the result of a single exposure from a typical point-and-shoot digital camera. The lower left image represents a more film- or video-like rendering of the scene and the lower-right image is a black and white rendering. The point of these images is to illustrate that the very same scene information can be rendered in many different ways by different camera systems. And it is very rare that the aim of these systems is to actually reproduce the colors that you saw in the original scene.

A:

The most direct answer is simply that cameras are not the same as people and do not respond to color in the same way. More specifically the red, green, and blue detector sensitivities in a digital camera are not the same as, or even simply related to, the long-, middle-, and short-wavelength sensitivities of the human visual system. If they were, then computational procedures could be completed to make perfectly accurate color images from the camera data. Even if such perfect color data were recorded by a digital camera, there might still be differences due to variations in the displays and printers that we use to render our images. Lastly, even if all the above systems were perfectly accurate, we might not like the result and prefer to see a different image; perhaps one with colors that look better than the original scene (*e.g.*, bluer sky, greener grass, nicely tanned skintones).

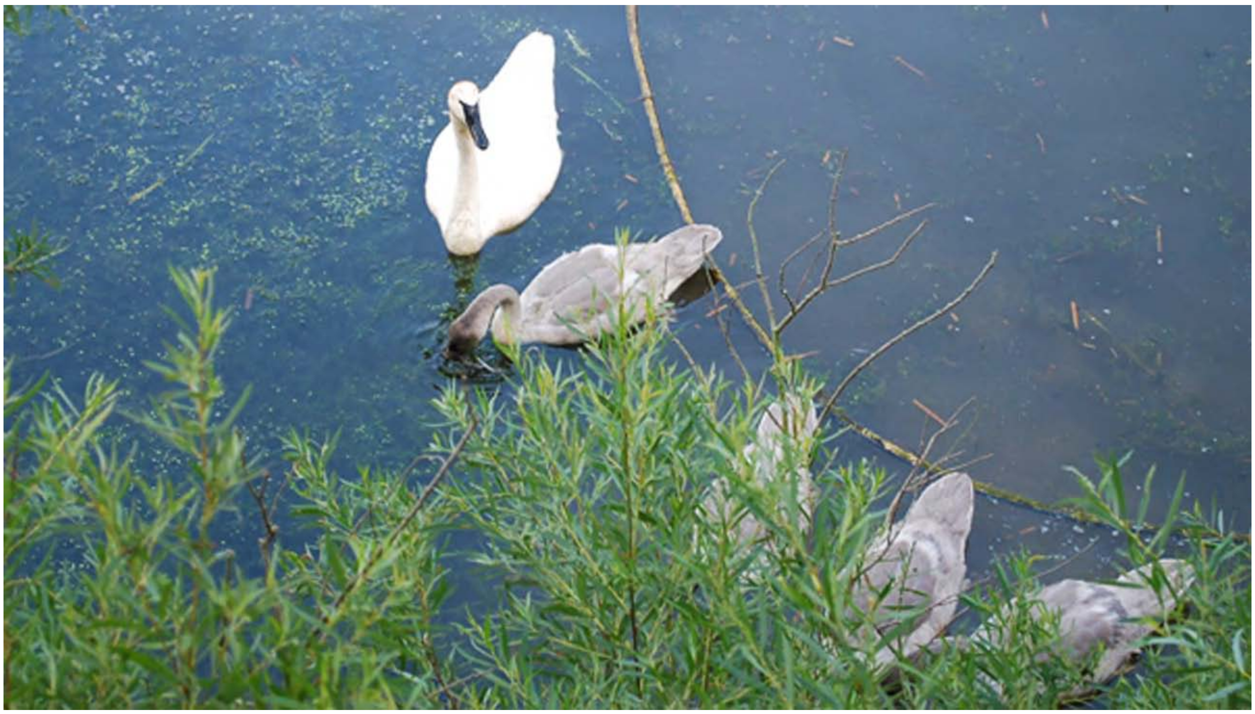
Meet MetaCow! These images are part of a larger MetaCow image that was created to evaluate the quality of imaging systems. The two cows on the left appear as they would to a human observer. On the right, the same two cows are shown as they would be "seen" by a typical digital camera. The front and back halves of the cows look different to the camera because it does not respond to color like a human.

Image rendering, or conversion of the captured image data to displayed colors, is a step in the digital photography process that also introduces a range of possible outcomes (see images at left). The data are processed in many ways to correct for properties of the image sensor, to reduce noise, to sharpen the details, to adjust for changes in illumination color and exposure, to compensate for assumed display properties, and finally to adjust to make images that the camera manufacturer feels will be more preferred. This objective of reproducing preferred colors has driven the photography industry since the beginning and is one of the main reasons that most imaging systems aren't designed to accurately reproduce the colors we see in the world; the cameras are designed to give us something we like better. Do you think they succeed all the time?

Color preferences are difficult to quantify and specify, but in general people prefer color reproductions that are accurate in hue, slightly more saturated than the original scene, and higher in contrast (the rate of change from dark to light). Pay attention to photographs that you get from your camera and print services and you will probably notice these sorts of changes. Do some experiments by taking pictures of objects you can later compare with the resulting photographs.

Challenge (Level 6)

Q: Quiz Time: What Is Adaptation?



Another kind of adaptation is how animals adapt to the environment in which they live. This is not the same as perceptual adaptation, but like perceptual adaptation it is an adjustment made to the prevailing environmental conditions. However, animal adaptations don't occur within a single organism like perceptual adaptation, they occur over evolutionary periods. These swans have at least two adaptations, webbed feet to help them swim and flattened bills to help them dig for food.

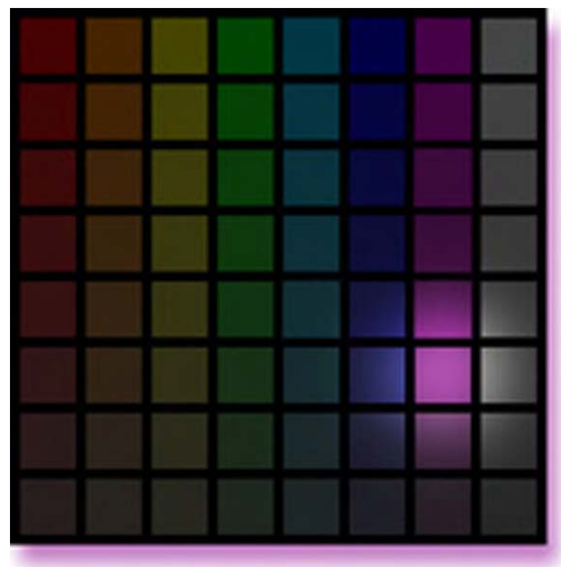
A:

(A) Your Ability to Ignore Your Parents

(B) When a Family Brings Home a New Pet

(C) The Ability of the Visual System (All Sensory Systems) to Adjust to Prevailing Conditions

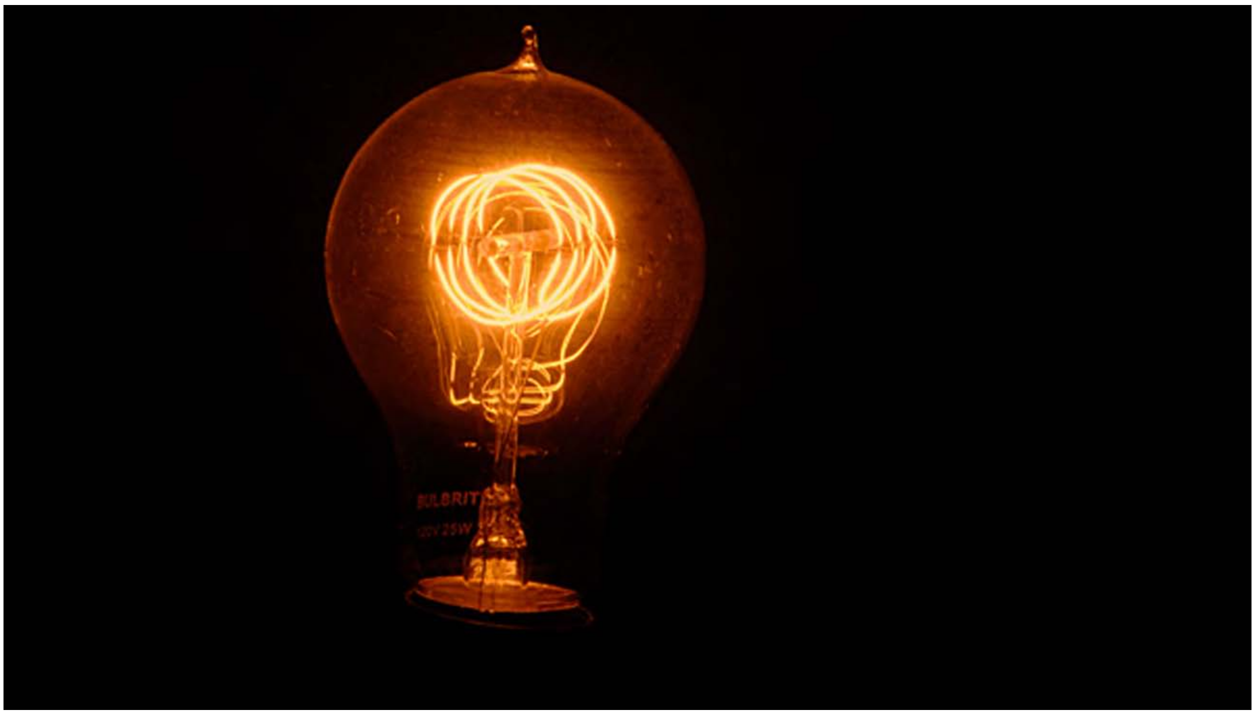
(D) Falling Asleep During Boring Class Lectures



I'm sure you figured something out by now!

Light (Level 7)

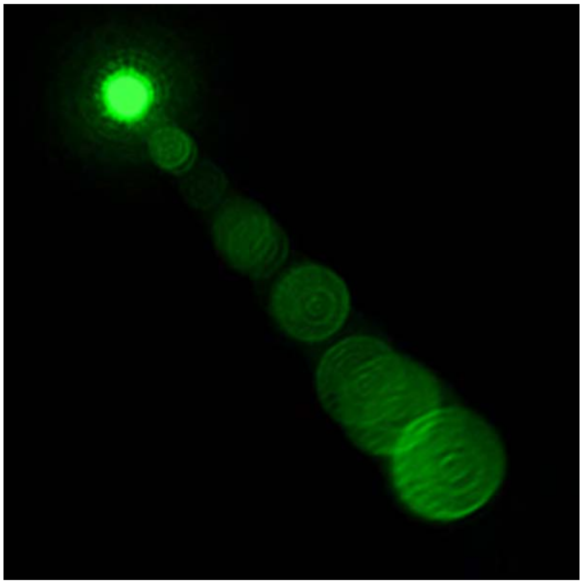
Q: What Is Light?



Common light bulbs for much of the previous century were incandescent lamps. Incandescence refers to the emission of light due to an increase in temperature. Incandescent light bulbs work by passing an electric current through a thin wire, normally made of tungsten. The electrical current heats up the wire (a phenomenon studied by the physicist James Prescott Joule in the 1840's) and when it becomes hot enough it glows. The filament will be a deep red at first and then become more whitish and brighter as the amount of electrical current, and therefore the filament temperature, is increased. Incandescent light bulbs are not very energy efficient. Less than 5% of the energy used by the light bulb is converted into light. The rest produces heat. That is why incandescent bulbs are quickly being replaced by compact fluorescent and LED sources that are far more energy efficient. (By the way, if you are worried about mercury exposure from broken compact fluorescent lamps, you should know that you are exposed to far more mercury by eating a single can of tuna than from cleaning up a broken lamp!)

A:

The technical definition of light from the Commission Internationale de L'Eclairage (CIE, the group that defines such things) is "Any radiation capable of causing a visual sensation directly". Loosely translated, light is electromagnetic radiation that we can see. Ultraviolet and infrared energy are also electromagnetic radiation, but we cannot see them so it is incorrect to call them "light". There is no such thing as "ultraviolet light" or "infrared light". Even though those terms are used colloquially (and sometimes by optical scientists), the more proper terms are "ultraviolet radiation" and "infrared radiation". Unfortunately people often don't like to use the word "radiation" because they associate it with radioactivity and nuclear radiation. Historically, it was recognized that light was some form of energy, but there were competing theories of its nature. Some considered light to be made up of particles, while others thought light was made up of waves.



The view looking nearly toward a green laser pointer in a darkened room. (Never look directly toward a laser to avoid possible eye damage.) The bright spot is the source of light and the path is illuminated by scattering off dust particles in the air between the laser and camera. Lasers are special light sources with highly directional, coherent, and monochromatic energy. They allow large amounts of energy to illuminate small spots.

The idea that light is made up of particles gained favor in the 1600s with the support of Sir Isaac Newton. He used the properties of light reflection and the fact that light travels in straight lines (in homogeneous isotropic media) to support his theory of light particles, or corpuscles. He however had difficulty explaining light diffraction (light bending around objects) with a particle theory and that turned out to be one of the reasons the wave theory of light became more popular later on. Interestingly, Albert Einstein brought back particle theory to some extent with his observation and explanation of the photoelectric effect (light striking a metal surface can produce an electrical current). This helped more recent researchers to figure out that light behaves as both a particle and a wave.

Sound energy travels through the air in waves that our ears can sense and we can observe waves on the surface of water as energy we can feel. Light also shares some of these properties. For example light diffracts, or bends, around surfaces in the same way that water waves can be observed to do. Thomas Young observed this and also observed the interference of light waves (again like the interference of water waves) and was one of the proponents of wave theory. Later on James Clerk Maxwell and others were able to explain light in terms of electromagnetic theory that still serves us well in modern technology. Thus, light was shown to be a form of electromagnetic energy just like radio waves, X-rays, infrared energy, and ultraviolet energy.

Ultimately, all these observations resulted in the concept of wave-particle duality, the idea that light sometimes behaves like waves (electromagnetic theory) and sometimes behaves like particles that define discrete units of energy (known as photons). This duality allows us to describe light well enough to utilize and control it in modern technology like television systems, digital cameras, and computer displays.

Q: What Color is the Moon?

I created this composite image of the earth and moon as they would look to us when seen together from space. When both are viewed simultaneously under the same illumination, it becomes apparent that the reflectance (sometimes called albedo) of the moon is similar to that of land on earth and significantly lower than the reflectance of clouds. If we could hold a piece of the moon in our hands here on earth it would appear dark gray, or nearly black. So why does it look so bright and nearly white in the sky?

A:

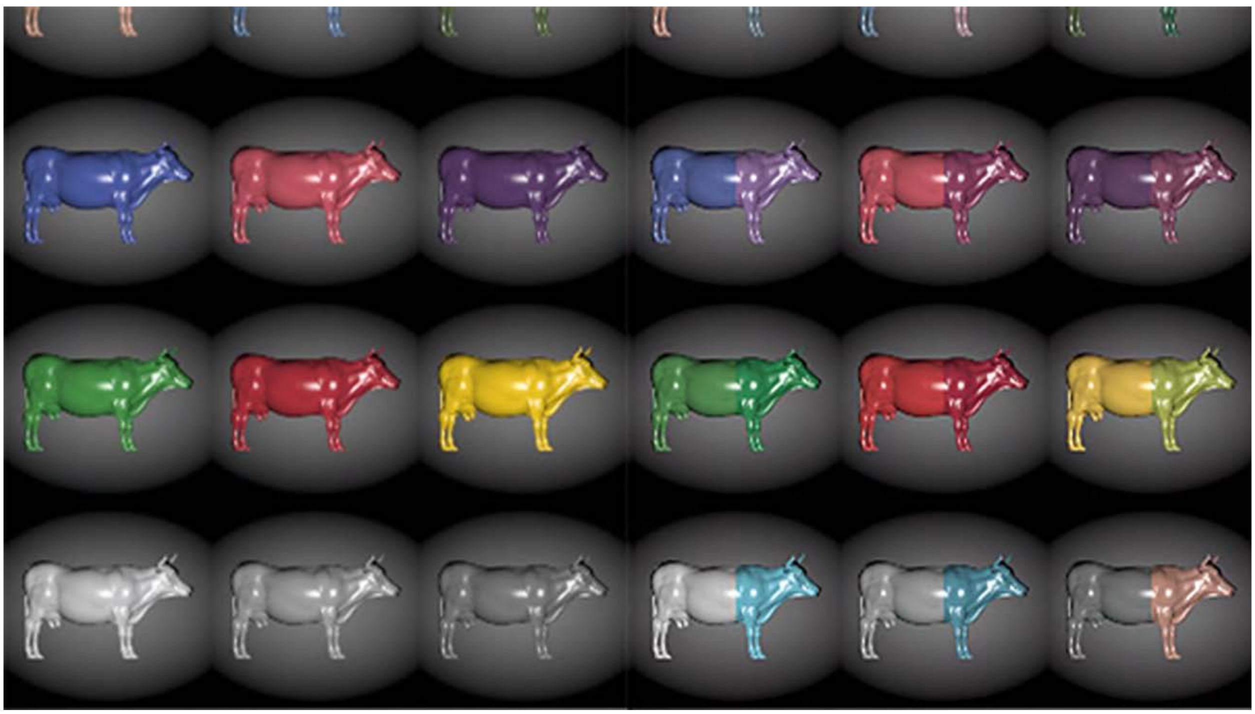
Like any other object, the color of the moon depends on how you look at it. Normally we see the moon as one of the brightest objects in the sky (or at least in its area of the sky) and our visual systems see such unrelated stimuli as either white (like a light bulb) or as a bright color (like signal lights). The facts that the moon reflects all wavelengths of light nearly equally and that we see the moon all by itself and cannot compare it to other similarly illuminated objects means that we cannot see it as any other color than nearly white (sometimes with a little bit of a yellowish tinge).

However, if we were to take the moon and put it next to other objects under the same direct illumination from the sun, we would have a very different perception. The moon would no longer be the only stimulus and it would also not be the brightest stimulus. In fact the surface of the moon only reflects about 12% of the light incident upon it. If we were to compare the moon to a white piece of paper (or an astronaut's white space suit) we would quickly recognize the moon as a dark gray object. In such situations we are viewing the moon as what is known as a related color and we have a more stable perception that is less dependent on the levels and type of illumination. This is illustrated in the composite image at left that I constructed based on the measured moon reflectance as well as the direct image taken by the NASA Galileo probe. You can also see it in pictures of astronauts on the moon's surface.

After creating the image above based on color science theory and reflectance measurements of the moon's surface, I found this view captured by NASA's Galileo probe. It shows directly how dark the moon is when viewed with the illuminated earth

Color perceptions such as gray and brown only exist as related colors (when we can compare them to other similarly illuminated objects). If we see these same stimuli as completely unrelated colors (isolated in a dark environment) then we will instead see white and orange. That is why we can't go to a store and purchase gray, or brown, light bulbs. Another interesting bit of trivia about the color of the moon is that moon dust is retroreflective. That means that, like a road sign, the moon tends to reflect light back in the direction it came from. That explains why the full moon appears fairly uniform in brightness from edge to edge instead of being shaded like a ball would be when illuminated from a single direction (*i.e.*, it looks like a disk, not a sphere).

Q: Why Can't We See All the Colors (Wavelengths) Within One Color?



This is a portion of the MetaCow test image. The left panel of 9 cows shows the appearance to an average human observer under fixed viewing conditions. Each cow is made up of two distinct spectral power distributions (amounts of the different wavelengths) that happen to be indistinguishable to the human eye. The right panel shows the same 9 cows as they appear when captured by a typical digital still camera. Now the front and back halves of the cows are distinguishable because the differences in wavelengths that were invisible to the human show up clearly to the camera. This is because the camera does not have the same sensitivities to different wavelengths that we do. The front and back halves of each cow are considered metameric matches for humans (stimuli that look the same color but have different spectral power distributions).

A:

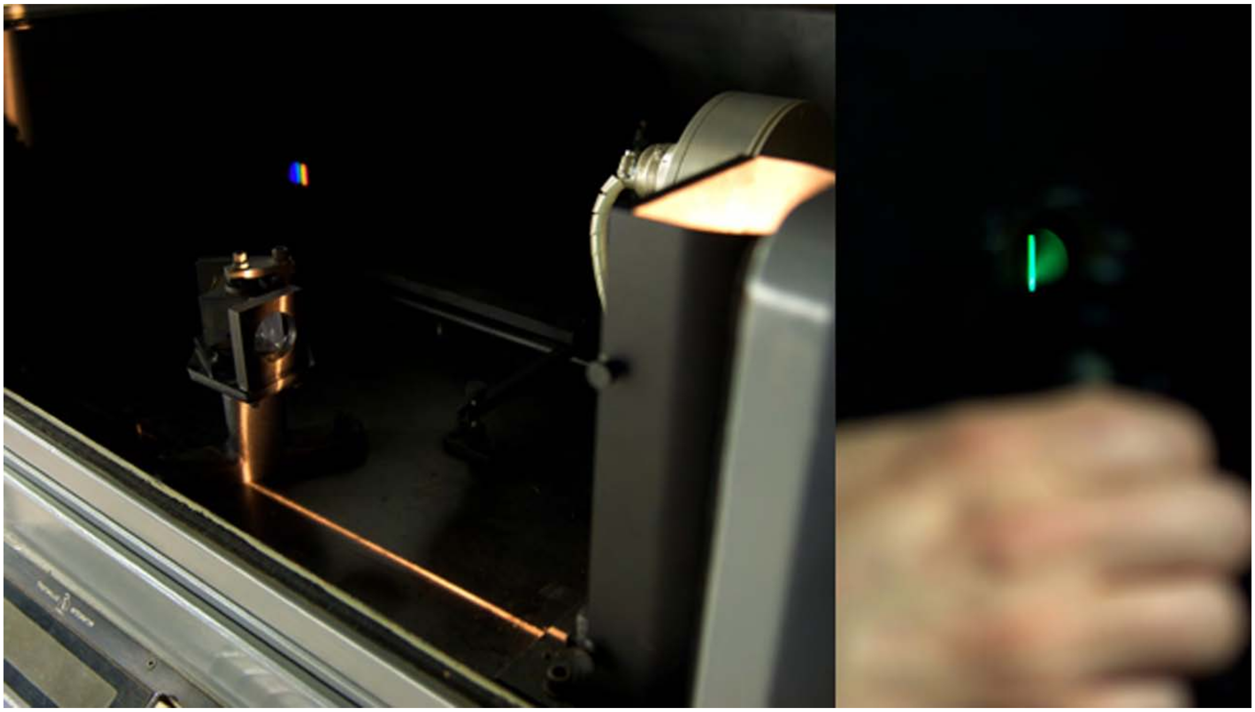
It's all because of two properties of the human vision system, trichromacy and univariance. Trichromacy refers to the fact that we have three types of cone photoreceptors, each sensitive to a different range of wavelengths. Vision scientists call them long-, middle-, and short-wavelength sensitive cones (LMS as shorthand), but they are sometimes referred to as red-, green-, and blue-sensitive (RGB). Univariance refers to the fact that there are no mechanisms within a single cone type to distinguish between different wavelengths of light. L cones, for example, respond to a range of wavelengths but the reaction produced by absorbing a photon of light is exactly the same regardless of wavelength. It is just the probability of that absorption that defines the cone's response.

A glass of candies as they normally appear (left) and as they would appear if we only had long-wavelength sensitive cones (right). Note the relative brightness of the various colors. If we only had one cone type, we would see the world in shades of gray since a single cone type can't distinguish what wavelength it absorbed to produce a response.

The practical result of univariance is that there are many different ways to produce the same response within a cone. We perceive color by comparing the responses of the three cone types and since there are multiple, essentially infinite, spectral energy distributions that can produce the same response within a single cone type, there are also multiple spectral energy distributions that can produce the same combination of cone signals and therefore the same color perceptions. This is known as metamerism; stimuli with different spectral power distributions can produce the same integrated color responses.

This property of metamerism is what allows us to develop fairly simple methods for measuring and producing colors. For example, it is what allows us to have color televisions with only three primaries, red, green, and blue.

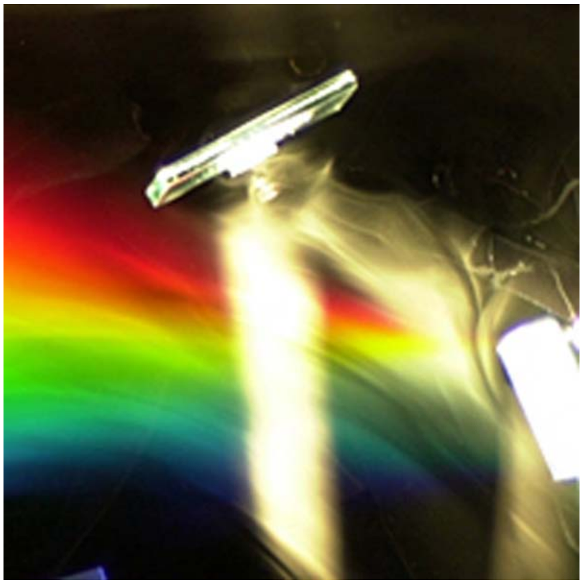
Q: How Are Colors Measured?



The first photo-electric recording spectrophotometer was invented by Arthur Hardy and marketed by General Electric. Prior to this instrument, measurements of material spectral reflectance were made using visual comparisons in a very tedious and time-consuming task. This instrument is built on a cast-iron base and requires four strong individuals to lift and move it (one on each corner!). Modern spectrophotometers can be held in one hand and carried from place to place in a backpack. The left panel of this image shows the light source of the instrument casting a beam onto one of its two prism and then a mirror/knife-edge combination selecting a green wavelength for measurement (you can see blue, yellow, and red light in the image, but green has passed through to be measured. The right panel shows my hand opening the sample holder and that green wavelength illuminating the point the sample would be placed for measurement. The instrument would then measure the ratio of the amount of light reflected from the test sample to the amount reflected from a white reference to determine spectral reflectance at that wavelength. The process is repeated (automatically) at all the other visible wavelengths to obtain a spectral reflectance curve.

A:

There is an entire scientific field called colorimetry, which means color measurement. The process of colorimetry mimics the process of human vision. Assuming we want to measure the color of a material that reflects light (like paint ... similar procedures are followed for measuring light sources or transmitting materials), the first step is to measure the object's spectral reflectance. This is the percentage of light of each wavelength that is reflected by the object and it is measured with an instrument called a spectrophotometer. We must then decide what light source to illuminate the object with for the measurements. This is done mathematically by selecting a standard spectral power distribution for the desired type of illumination (*e.g.*, daylight, incandescent, fluorescent, *etc.*) and multiplying the energy in the light source by the percent of that energy reflected by the object wavelength by wavelength. This defines the stimulus energy that reaches our eyes. We then use standard visual response functions, known as color matching functions to figure out how much of that energy is absorbed by each of the three cone types. These numbers are called tristimulus values and define color matches. One standard set of tristimulus values are known as CIE XYZ.



I have built a spectrum projector to show students in my classes how a spectrophotometer works. This shows a small part of it where light comes from a source below the image, strikes a mirror at the top and is then reflected from a diffraction grating (at right) that splits the light into the different wavelengths at different angles. The light in this image was made visible by fog from dry ice dropped in warm water.

XYZ tristimulus values define color matches, but they don't tell us what a color stimulus looks like. To do that, we need to account for adaptation to the viewing environment and the fact that the visual system responds nonlinearly to amounts of light (*e.g.*, a light with twice as much energy as another does not appear twice as bright). Another set of mathematical equations define a color space known as CIELAB with dimensions that roughly correspond to perception. These dimensions are L* for lightness, a* for redness-greenness, and b* for yellowness-blueness. Alternatively, the CIELAB color space can be expressed in cylindrical coordinates with L* still for lightness, C* for chroma (related to colorfulness), and H for hue angle (red, yellow, green, blue, *etc.*)

The CIELAB color space is widely used around the world to define color materials and set tolerances for commerce. Most colored products that you can buy were evaluated in the CIELAB space to make sure they were produced in the proper color. However, some situations call for even more complicated mathematical models. For example sometimes the absolute amount of energy in a scene or the properties of the visual environment are important. In these cases, a type of model known as a color appearance model is used. CIECAM02 is one example of a recent, and widely adopted, color appearance model. In addition to predicting apparent lightness, chroma, and hue, it also has predictors of brightness, colorfulness, and saturation.

Seeing (Level 7)

Q: If No Light Falls On an Object Does It still Have a Color?

"If a tree falls in a forest and no one is around to hear it, does it make a sound?" This is an interesting philosophical riddle that probably dates to the mid 1800s in its modern English-language form. Certainly similar riddles date back many centuries in other cultures, probably as long as recorded history. To me, the answer is simple. Since sound is a perception and no one was around to hear it, the tree did not make a sound. (That answer also assumes there were no other animals capable of perceiving sound around, which is highly unlikely.) Color is also a perception, so I like to ask students if the tree has a color. The answer is still "no". This image is of a fallen giant sequoia tree in California's Sequoia National Park. Giant sequoias are the world's largest trees in terms of total volume and grow to typical heights of 165-280 ft. (50-85 m). They are thought to essentially live forever with the oldest measured specimen being over 3500 years old. Their wood is very resistant to decay and fire and it is thought that the only way a sequoia dies is that it is knocked over. Since their wood and bark is brittle, they tend to shatter when they fall, as shown in the picture. Imagine the sound!

A:

Like the philosophical question about the sound of a tree falling in a forest, this is a question of perception. Since color is a visual perception and light is the stimulus that produces visual perception of objects, then with no light there is also no color. At least there is no color that belongs to that object. We might still perceive color due to the dark noise in our visual system. For example, when we are in a completely darkened room for a long period of time (so that we completely adapt), the perception is not one of black (which only exists as a related color), but one of a noisy (or grainy) dark gray.

"In clapping both hands, a sound is heard. What is the sound of one hand?" This is a famous Zen koan (or philosophical riddle) that Zen Masters use to help guide their students. It is in many ways similar to the question posed on this page. Note: This koan is often paraphrased as "what is the sound of one hand clapping", which is clearly a different question. One story of a correct answer is that the student simply thrust one hand forward to strike the teacher!

It is, of course, possible to perceive color without visual stimulation, but such colors would not be associated with specific objects in our environment since we couldn't see them. Dreams are one example. We can have clear color perceptions of imagined objects when we are dreaming. And, yes, people do perceive dreams in color. Although for some people it is difficult to recall dreams and some people do claim that their dreams are only in black and white. Another non-visual color perception comes from pressure on the eye. If you press gently at the corner of your eye you will see some bright flashes due to this pressure. These are known as pressure phosphenes. It is not very good for your eyes to press on them, so I don't recommend doing this experiment more than once and even then be very gentle. One could also consider afterimages as non-visual color perceptions since they result from the removal of the light stimulus rather than its presence. However, they are really still produced by visual stimulation.

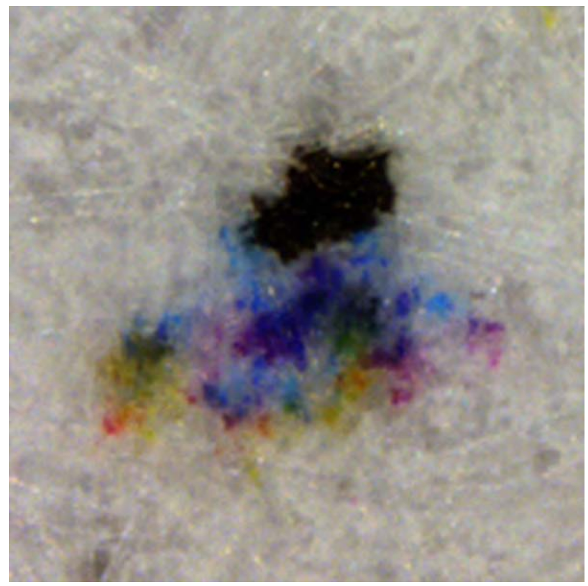
These types of questions can never be answered definitively. That's what makes them philosophical in nature. It is fun to ponder them and discuss the possible answers with others. Such thoughts and discussions can lead us into greater insights about ourselves and the world around us. Another one to ponder from *The Gateless Gate* ... "The wind is flapping a temple flag, and two monks were having an argument about it. One said, 'The flag is moving.' The other said, 'The wind is moving.' They argued back and forth but could not reach the truth. The sixth patriarch said, 'It is not the wind that moves. It is not the flag that moves. It is your mind that moves.' The two monks were struck with awe."

Q: How Does an Ink-Jet Printer Produce Colors?

Here is an image of a tree and the cyan, magenta, yellow, and black (CMYK) separation images that make it up. The separation images show the amounts of each of the four ink colors, or primaries, required to be printed in order to reproduce the green tree against the blue sky. On the left side are the cyan (top) and magenta (bottom) separations. On the right side are the yellow (top) and black (bottom) separations. The separation images indicate the amount, or density of ink required (darker areas mean more ink). For example, the sky is dark in the cyan separation and light in the yellow separation because a lot of cyan ink and no yellow ink must be used to reproduce the blue sky (which is nearly the same color as the cyan ink!). Looking at the greenish leaves, you can see that a large amount of yellow ink is required along with a slightly lesser amount of cyan. The subtractive mixture of yellow and a little cyan produces a bright, yellowish-green. Black ink is only used in the dark shadow areas.

A:

In the simplest sense, an ink jet printer produces colors by placing small dots of ink on paper. Traditional printers use four colors of ink, cyan, magenta, yellow, and black. Newer printers often have additional inks, such as light cyan, light magenta, or gray, to help improve image quality by reducing the visibility of the dots. A dot of each ink type can be placed at each location on the paper. The printed color depends on the size of the dots, or the amount of each type of ink, placed at each location. For example, to produce white, no dots are made at all, allowing the white paper to show through. To make black, large dots of all four types of ink are often printed. To make a saturated red, large dots of magenta and yellow ink are printed. The magenta absorbs green light while the yellow absorbs blue light, leaving only red to be reflected. In similar ways, the amounts of each of the four inks required to make just about any desired color can be determined.



This is a micrograph of a single dot from an ink jet printer. The RGB color sent from the computer was a dark gray (R = G = B = 50). You can see that this dark gray is produced with a large amount of black ink and a little bit of each of the other three primaries. You can also see how the primaries overlap and mix to make a variety of colors. We don't normally see this in a gray area on a print because the dots are so small.

Ink-jet printers are often considered subtractive color mixing devices. Subtractive color mixing occurs when various amounts of different dyes or pigments are mixed and each absorbs (or subtracts) its characteristic colors and amounts of light. On the other hand, additive mixing is what happens on our computer monitors and televisions when tiny spots of light are overlapped (or added together) to make mixtures of light. As it turns out, most printers actually function using a combination of additive and subtractive color mixing. Subtractive mixing occurs where the ink colors overlap and absorb different colors of light. Then additive mixing occurs when our eyes blur all of those very tiny dots together and effectively add the light reflected from each of the different areas (imagine blurring the micrograph at the left, or viewing it from a very large distance). Since those dots are often on the order of thousandths of an inch in diameter.

So why is black ink used in printers? A very wide range of colors can be made with cyan, magenta, and yellow primaries. And, after all, there are only three degrees of color freedom in the visual system, so we shouldn't need to use more than three inks. In fact, some very successful printing technologies do only rely on three primaries. Photographic printing, with just cyan, magenta, and yellow dyes on paper, is one such example. Black ink is used in many printing technologies for two main reasons. It allows for much darker colors to be printed. It is difficult to select cyan, magenta, and yellow primary inks that produce a deep, dark black while also allowing for saturated colors. Also, black ink can be used instead of overlapping large amounts of cyan, magenta, and yellow inks to make neutral colors. Such colors can be made with one-third the amount of ink and at the same time black ink tends to be less expensive than colored ink. An added bonus of this is that it is easier to make prints with consistent color appearance when neutrals are printed with mostly black ink instead of variable combinations of three inks.

Challenge (Level 7)

Q: Quiz Time: How is Color Perception Different From Hearing?

Different animals also perceive the world differently. While my daughter and her horse both have eyes and ears that function in similar manners, they have different capabilities. My daughter can see colors and fine details better than her horse. He can probably see a little better in dim light than she can. Hearing wise, the horse is probably sensitive to different frequencies and tuned into different important sounds (like the buzzing of flies rather than the sound of her mother's voice).

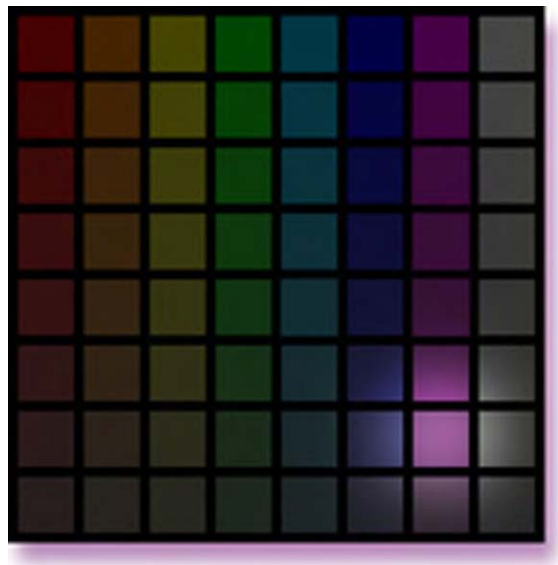
A:

(A) We Can't See Frequencies of Light (Wavelengths), Like We Can Hear Frequencies of Sound (Notes)

(B) We Can See Spectra, But Only Hear Certain Combinations of Notes (Chords)

(C) There Are Three Cone Types, But Only Two Types of Hearing Receptors

(D) We Can Localize Objects With Vision, But Not With Hearing



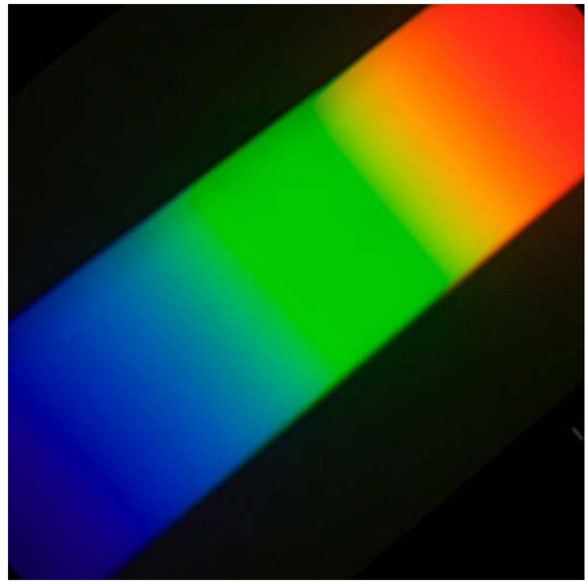
Both hue and chroma have a meaning.

Q: Why Can We Only See Visible Radiation?

While we can only directly perceive light with our visual systems, there are many other wavelengths of electromagnetic radiation (and other forms of energy) that can be used to sense the environment around us. The collected image data can then be rendered to displays that modulate light for us to perceive (like the images you are looking at right now). This image provides a collage of images collected at different wavelengths. In the center is a normal light image of a tree (below) with a reflected infrared image above. This infrared image was made with wavelengths just slightly longer than we can perceive. Notice how the sky is quite dark (not too much infrared scattered in the sky) while the leaves and grass are very bright (healthy foliage reflects a lot of infrared energy). The image of the house is a false-color representation of thermal infrared emission. This is even longer-wavelength energy that we sometimes consider as "heat". The red areas are where there is a larger amount of thermal infrared emission, or heat leaking through the rood of this house. On the right is a medical X-Ray of someone's repaired knee. X-Rays are very high energy (short wavelength) electromagnetic radiation that can pass through our soft tissue easily, but don't pass through bones so easily, and can't pass through the metal pins at all. This X-ray image is a negative and is darker where more energy passes through the subject. Finally, the upper-left image is an ultrasound image of my first daughter about 5 months before she was born. This image was made with very high frequency sound waves (vibrations of matter) that actually are not electromagnetic energy at all.

A:

In a way, the answer is simply a definition. Visible electromagnetic radiation, or light, is defined as the wavelengths that we can directly perceive with our visual systems. The greater question is why our visual systems evolved to respond to those particular wavelengths of electromagnetic radiation when there is such a vast range of wavelengths in the full spectrum. For example, why don't we see X-rays, or radio waves, or ultraviolet energy, or infrared wavelengths? Some insects actually do respond to ultraviolet energy, so clearly it is possible.

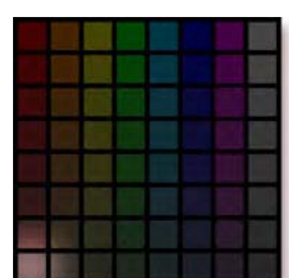


The visible spectrum, or light, is electromagnetic radiation that creates human visual sensations and perceptions. This is a photograph of an actual, linearly dispersed, spectrum. Does it differ in noticeable ways from artistic representations of the visible spectrum?

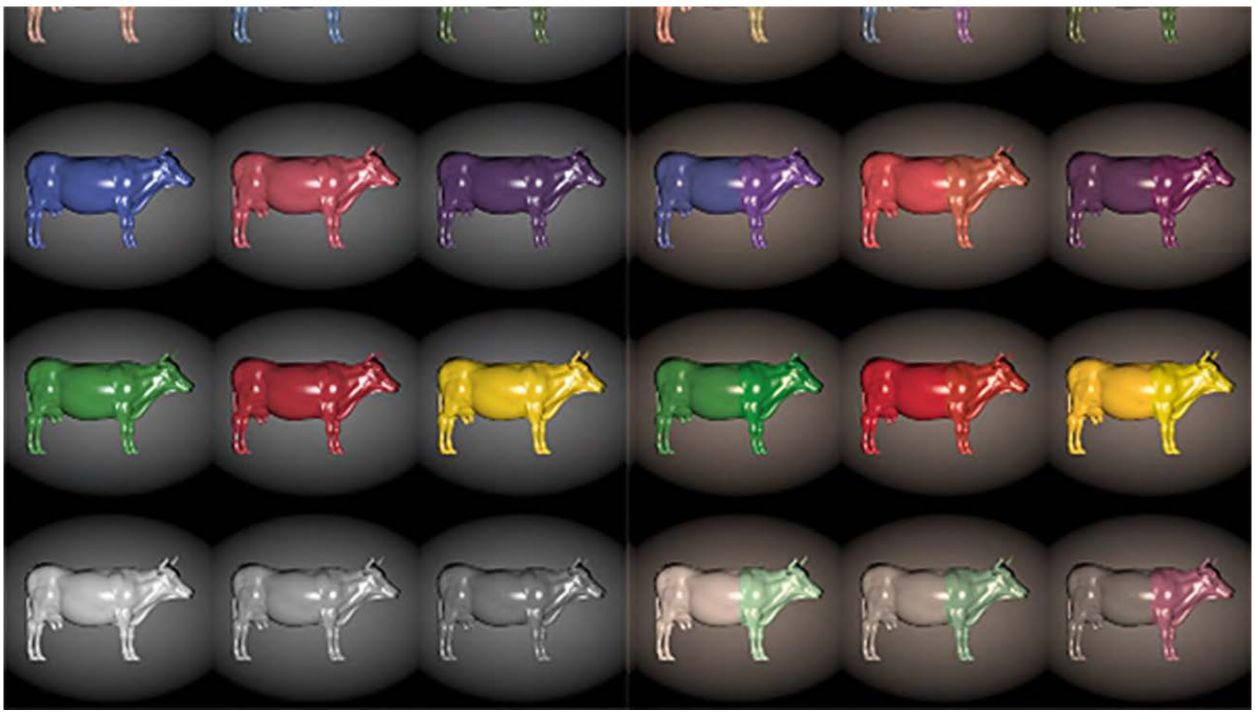
The true answer is that there are probably many reasons, functioning in combination, that resulted in our visual systems' functioning the way they do and responding to the range of wavelengths that they do. These include both physiological and ecological reasons. Physiologically, ultraviolet radiation (UV) is potentially very dangerous (and deadly) to biological tissue. Thus it would not serve us well to rely on detection of dangerous radiation to function in day-to-day living. Ultraviolet radiation is sometimes used to kill bacteria and other organisms. It would also damage our cells in a similar way. UV causes sunburn and also contributes to the development of cataracts (opacity) in the lenses of our eyes. Shorter wavelengths have even higher energy levels and can potentially cause more damage and/or pass right through us (like X-rays). So the UV end of the spectrum seems to be a reasonable limiting factor at the short-wavelength end of the visual spectrum. At the longer wavelengths, we have infrared radiation. It turns out that our body produces infrared energy simply because we are warm and that background radiation makes it difficult to detect infrared radiation from the environment (sensors in infrared cameras are cooled to very low temperatures for this reason). Thus visual noise might well be the limiting factor at the long-wavelength end of the spectrum. Even longer wavelengths, like radio-waves are so long that they pass right through (or perhaps more correctly around) us as well and we cannot detect them.

Ecologically, there are other reasons that narrow down the range of wavelengths we respond to visually. For one, the sun's peak energy output is very highly correlated with the wavelengths of light that we respond to. Thus we have a ready and plentiful source of energy to aid our visual perception. Additionally, many of the interesting interactions between electromagnetic energy and the elements and compounds we are made up of (as well as all the plants, animals, and objects we are interested in perceiving) happen in the visible wavelengths.

The bottom line is that we respond to the wavelengths we do because it is physiologically plausible for our visual systems to do so and because the information provided by such visual systems is tremendously useful to our survival.



Q: How Can Two Objects Match in One Lighting and Not Match in Another?



This is another example from the MetaCow test image. The front half of each cow is a metameric match to the back half when viewed by an average human with normal color vision under typical daylight illumination. This is illustrated in the left half of the image. Metameric matches are two stimuli that match in color, but are different in their spectral power distributions (or in this case their spectral reflectances). When those same cows are viewed by the same human observer under incandescent light (right half of image), then the matches break down. The differences in spectral reflectances that were invisible under daylight become readily apparent under incandescent light. In other words, the metameric matches no longer hold under incandescent illumination.

A:

Metamerism. A simple, one-word answer. Metamerism describes the phenomenon of metameric color matches. Isomeric (or identical) color matches occur when two stimuli have identical spectral power distributions (identical emission or reflection of light at every visible wavelength). However, since we only have three types of cone photoreceptors, it is possible for two stimuli to match in color without having identical spectral power distributions. As long as the integrated responses of the three cone types are equal, then the stimuli will match in color. Basically, a little less energy at one wavelength can be compensated for at other wavelengths. When color matches happen despite differences in spectral power distributions (or spectral reflectance of objects), they are called metameric color matches and they exhibit the property of metamerism.

Toy secret codes that only show up when viewed through a certain color filter take advantage of the spectral properties of materials. This image has a message that only shows up with a blue filter (or under blue light). The blue filter or light makes the hidden yellow text dark, while leaving the white background and cyan masking pattern relatively light.

Isomeric color matches hold for any observer and any viewing conditions. The two objects are physically identical and we cannot perceive a difference between them as long as they are viewed together under the same conditions. However, metameric color matches (sometimes called conditional matches) depend on both the illumination and the observer. Changes in the illumination can highlight, or diminish, certain differences in spectral reflectance properties and make them more or less pronounced. Likewise different observers have slightly different visual sensitivities and a nice metameric match for me might look like a significant mismatch for you. On top of that, our visual systems change as we age, so a match for me today might not have looked like a match to me 30 years ago.

Metamerism is one of the most fundamental concepts of color science and presents us with many opportunities (such as trichromatic color reproduction systems) and many challenges (such as materials that change appearance with changes in lighting or observer). It is an endlessly fascinating topic and it is interesting to ponder how important it would be in the natural world. Or is it just an artifact of man-made color systems?

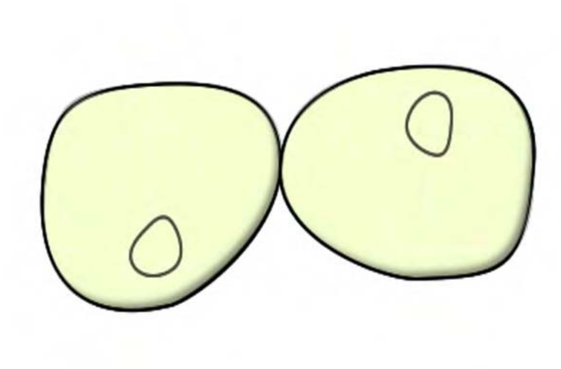
Q: Do You Attribute the Incredibly Complex Workings of the Eye to Evolution or Creation?

These two Burmese Pythons live in the Rochester (NY) zoo. One is normal with the normal brown markings on its skin. The other is what is known as an amelanistic python. Amelanistic means without melanin. Recall that melanin is the dark pigment that gives our skin, hair, and eyes their color. It is also responsible for the coloration of many animals such as the normal python. The yellow coloration is due to the presence of other pigments, called carotenoids, which are present in both snakes. Amelanistic animals are sometimes called "albinos". This abnormality can affect a wide variety of animals including fish, amphibians, birds, reptiles, and mammals. If there were an advantage for survival or mating to having no melanin pigment, then the trait could well end up dominating the species and the new amelanistic animals would be considered normal and have evolved from the original pigmented species. Unfortunately for the amelanistic animals, the trait is probably not beneficial as they would be more visible to predators and prey and perhaps not as attractive to potential mates.

A:

This question is one of the most intriguing, and perhaps most important, questions I have received amongst the thousands that have been submitted by students to this project and others. For me, there is no question that the preponderance of the scientific evidence points to evolution as the source of our species and our visual system. I say that with full sensitivity that some religious traditions teach, and believe, otherwise. That is their right and privilege, but it is not science. Science and religion should not be confused and they both have a place in society and education.
This website is about science.

Scientists use a well-established and self-regulated procedure to observe the natural world and attempt to figure out how it works for a variety of reasons (e.g., developing technology to help our lives). The process involves first making careful observations of the world and its behavior. The scientist then makes a hypothesis about how the observed phenomena might work. Then careful experiments are designed and performed to test the hypothesis through more careful observations and objective measurements. This process is then iterated upon to refine the original hypothesis and perform more tests. Once consistent, and repeatable, results are obtained, scientists then form a theory that might gain support through consensus of the scientific community. Theories are continually tested and expanded upon through the scientific process and almost all are subject to improvement. Occasionally theories are so well established and agreed upon that they are called scientific laws (like the law of conservation of energy).



Bacteria, and other organisms, reproduce asexually through processes such as the binary fission (splitting) shown in this image. This sort of reproduction allows for very rapid evolution as a mutation in a single cell replicates itself by a factor of two in each reproduction and, if the mutated version is more adapted to the environment it can wipe out the original version very quickly.

Every step in the scientific process has uncertainty associated with it and good scientists do not hesitate to report the degree of uncertainty. Unfortunately, some with political or business agendas see these statements of uncertainty and use them for their personal gain. This has led to baseless attacks on science in recent times. For example there are some who claim that there has been no warming of the climate in recent decades even though the data are unequivocal. They then take small uncertainties in the results and say that those minute possibilities prove there is no climate change and that, even if there was, it is not caused by human impact on the environment. Well, they are correct about only one point; there is uncertainty. However the uncertainty is so tiny, and the scientific consensus so strong, that I have no doubt that both the climate is warming and it is due to human activities. I encourage everyone to study for themselves, look at original results and analysis, and draw your own conclusions. Simultaneously investigate the motivations (and funding sources) of those writing what you read, including this site.

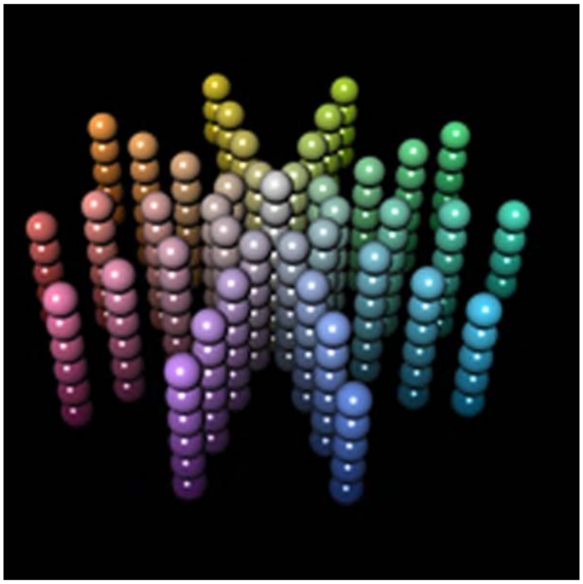
Unfortunately, the same sort of attacks have happened in the field of evolution science. There is little scientific doubt that evolution (both micro and macro) has taken place on earth. and these conclusions are backed by countless theories and observations.

Q: How Many Dimensions Are Required to Describe Color Appearance?

This image of the RIT Tiger provides all the information needed to answer the question. The image itself is represented with three dimensions of information (RGB digital values) and that might suggest that only three dimensions are needed. However, examination of the image also shows there are at least two environments represented in the picture, direct sunlight illumination and shadow areas. In fact, some objects are visible in both the sunlight and shadow. Thus it takes more than three dimensions to describe their appearance (RGB values in sunlight and RGB values in the shadow). Due to perceptual, and physical, correlation between the object in sunlight and shadow, all six dimensions are not required. Instead, five are adequate. These are the lightness, chroma, and hue that describe the object properties and the brightness and colorfulness that also describe the illumination environment.

A:

Most would answer this question with the number three. After all, even this website can be quoted as saying that three is the most important number in color science. The visual system has three types of cone photoreceptors, we can describe objects with three appearance attributes (lightness, chroma, and hue), and we can make metameric matches to objects with just three primary colors (as in color television). There are also a plethora of three-dimensional color spaces used in various aspects of color science and technology. So how could the answer be anything other than three? It is, the correct answer is that it takes more than three dimensions to full describe color appearance and the most probable number is five.



This is a computer graphics rendering of the Munsell Book of Color. The Munsell system divides color into three perceptual dimension of lightness, chroma, and hue. That works for object colors (relative appearance), but it does not address brightness and colorfulness.

There are actually six distinct terms that are used to describe color appearance. These are brightness, lightness, colorfulness, chroma, saturation, and hue. So if all six of these dimensions are independent, then it would take six dimensions to describe color appearance. In reality, colorfulness, chroma, and saturation are inter-related in such a way that only two of those three are required for a full description of appearance. Thus, the final answer that five dimensions are required to describe color appearance. There are a class of color spaces, known as color appearance models, that include all six of these dimensions. While there might be alternative viable theories of color perception, it is clear that the overall description does require more than three dimensions and that is due to our ability to perceive attributes about the illumination environment in addition to the relative color attributes of objects. The definitions of the perceptual dimensions are given below.

All of the dimensions are attributes of visual perception (recall that color is a perception, not a physical quantity). Brightness is our perception of the amount of light coming from a stimulus. Lightness is the brightness of a stimulus relative to something that looks white under the same illumination (lightness is relative brightness). Colorfulness is our perception of how much hue content (difference from neutral gray, black, or white) is present in the stimulus. Saturation is colorfulness relative to the brightness of the stimulus (like lightness is relative brightness, saturation is relative colorfulness). Next, chroma is colorfulness relative to the brightness of a similarly illuminated white (again, chroma is relative colorfulness, but in a sense different from saturation). Saturation and chroma describe similar dimensions of appearance, but in different ways. For the mathematically inclined, chroma can be thought of as the an expression of colorfulness in cylindrical coordinates while saturation expresses the same information in conical coordinates. Lastly, hue is the attribute of appearance that is often colloquially called "color". Hue is the similarity to red, green, yellow, or blue, which are all examples of hue names.

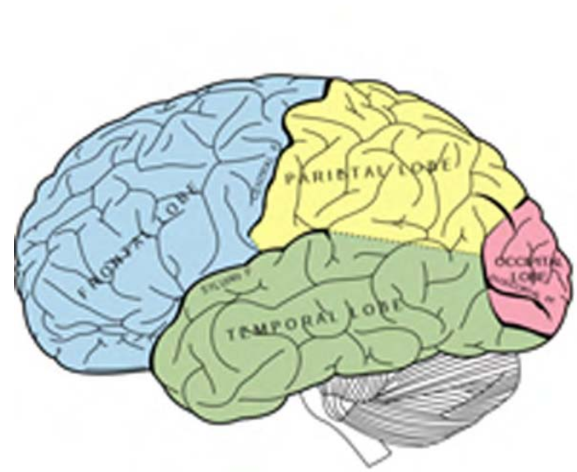
Seeing (Level 8)

Q: Why Is Color?

Color science can be described with a triangle and this same triangle is sometimes used to answer the question "What is Color?" The triangle is represented in this image by connecting the light source (the light bulb) to the object being observed (the color markers) and then to the observer's visual system (eyes and brain). The third side of the triangle connecting the observer with the light source is also important. Color perceptions are produced by light from the source interacting with the objects with the reflected light reaching the observers eyes, which in turn send signals to the brain that can be interpreted as color. The apparent color is also influenced by the observer's adaptation to the illumination (the third side of the triangle). In color science, physics is used to describe light sources, physics and chemistry to describe materials, and then anatomy, physiology, and psychology to describe the observers' responses.

A:

This seems like a strange question. However it is so important that it is actually the name of this website whyiscolor.org. More typically people ask (and answer) the question, "What is color?" That is simply to answer; color is a human perception! "Why is color?" is far more difficult to answer and that is the way we have come to prefer to ask the question in our laboratory (the Munsell Color Science Laboratory). In answering why, one can ponder the reasons we have the perception of color as well as how those perceptions are produced. The image above and its explanation describe how color perceptions are produced and they go a long way toward explaining why. After all, the "what" is a big part of the "why". For example, we could just say that we have color perceptions because our eyes have three cone photoreceptor types that respond to stimuli produced by the interactions of light sources and materials to produce neural signals that our brain can interpret as color.



The human brain is amazing in its function and complexity. It is entirely possible that science will never fully understand how the brain works. Yet it is in the brain that color ultimately resides. Color is a perception, not a property of objects.

Looking deeper into the "why" part of the question leads us somewhat out of the domains of the objective sciences of physics, chemistry, anatomy, physiology, psychology and the mathematical language used in all of them. We quickly end up in a more philosophical place. However we don't need to fixate solely on the philosophy. Perhaps the simple answer that color perception makes the world a more beautiful place for us (most of the time) is enough to satisfy the philosophical question. We can then fall back on some biological science to examine the question of why humans evolved to have color perceptions, or even more specifically why they are trichromatic.

The most widely accepted theories on the evolution of color vision are that it serves human survival in three ways. These are to help identify healthy (and willing) mates, to identify healthful and ripe food, and to warn us of potential dangers. Other creatures have evolved, and survive very well, with very different types of visual systems. Some have more than three receptor types (*e.g.*, some birds, fish, insects, and famously the mantis shrimp). Others survive quite well with dichromatic color vision (e.g., most mammals). So the answer is not the same for all species and that only makes sense. All species don't have wings, or gills, or stingers, or fangs either. Another important aspect of our color vision system is how well it matches our environment. For example our eyes respond to the wavelengths of energy most prevalent in our main light source, the sun. And statistical analyses have shown that three types of cone photoreceptors are adequate to describe the variability in the spectra of natural objects (having four wouldn't really help us, but three is significantly more helpful than two).

Why is color, indeed?

Q: Why is Digital TV Better than Analog TV? Is HDTV Really Better than SDTV?

This image compares the spatial resolution (ability to reproduce fine details) of a high-definition (HDTV) television system (left) with a standard-definition (SDTV) television system (right). The difference is obvious and this is identical to the difference you can observe on an HDTV display by switching from HD input to SD input for a given channel. This demonstration ignores any differences due to interlace (or the alternative called progressive scan). The butterfly is a Blue Morpho Butterfly. They produce their highly saturated and brilliant blue appearance through optical interference (rather than light absorption that happens in most materials). This allows them to be very bright while reflecting nearly a single wavelength of light (actually a small range of wavelengths).

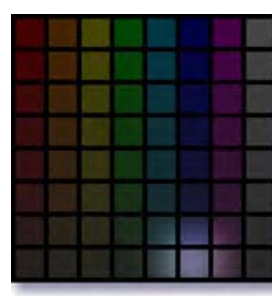
A:

Let's begin with the second question. The image quality of HDTV is clearly superior to that of SDTV. It should also be noted that either level of definition is possible in either analog or digital television systems. However in the USA, HDTV is strictly a digital system. The previous SDTV system was analog and is now obsolete. Currently SDTV signals are also digital. Whether or not HDTV is really better than SDTV is ultimately a personal opinion. If your TV displays shows little difference in your viewing environment, then it is difficult to say that HDTV is better. Also, the content is the same. There is nothing about HDTV that makes the content superior!

The first question can also be a matter of personal preference. In the USA, there no longer is an analog TV system, so the question is moot. It is still of technical interest to compare the systems. Digital TV transmission does not suffer from the artifacts and degradations that were often seen with analog transmission. With digital systems you generally either have a signal or you do not. In analog systems we had artifacts from interlace, from chromatic aliasing due to crosstalk between luminance and color dimensions, and noise from transmission and decoding. In digital systems, most of these artifacts are gone, but we do see blocking artifacts from data compression on occasion. Overall, however, in digital television systems we now have capabilities for HDTV (more spatial resolution), wider color gamuts, non-interlaced (or progressive) transmission and display, more accurate color, surround sound, and the transmission of metadata. It would seem that all of these improvements clearly make digital television systems better than our previous analog systems.

Interlace refers to a process in video whereby every other line of the image is transmitted first for the whole image, followed by the alternate lines for the whole image. It results in artifacts (breakup) for moving subjects as shown above. Interlace was necessary in early video systems to overcome limitations in display refresh speed and transmission bandwidth. Interlace is no longer required.

While the transition to digital and HDTV took a long time, it is now past the critical point where large-screen digital HDTV displays are very affordable commodities. In fact, I recently (August 2010), saw flat-panel HDTV sets simply sitting on a store shelf like a loaf of bread. Customers could put them in a cart to take to the checkout themselves. I think that is a sure sign that HDTV has finally arrived (in the USA, anyway).



Challenge (Level 8)

Q: Quiz Time: What is Metamerism?

Are there metameric matches in nature, or are they a man-made phenomenon? I have often wondered about this, but never had the time (and instrumentation available) to make a detailed search for natural metamers. One theory I have is that gray squirrel fur is metameric with tree bark. What do you think? Squirrels and trees do not have the same pigments. Squirrels do blend in well. Is it metamerism? Or is it just good camouflage with similar distributions of colors

A:

(A) A Process for Deciding Whether to Have White or Red Wine with Dinner

(B) Two Stimuli that Match in Color Despite Spectral Differences

(C) A Love of Information About Mermaids

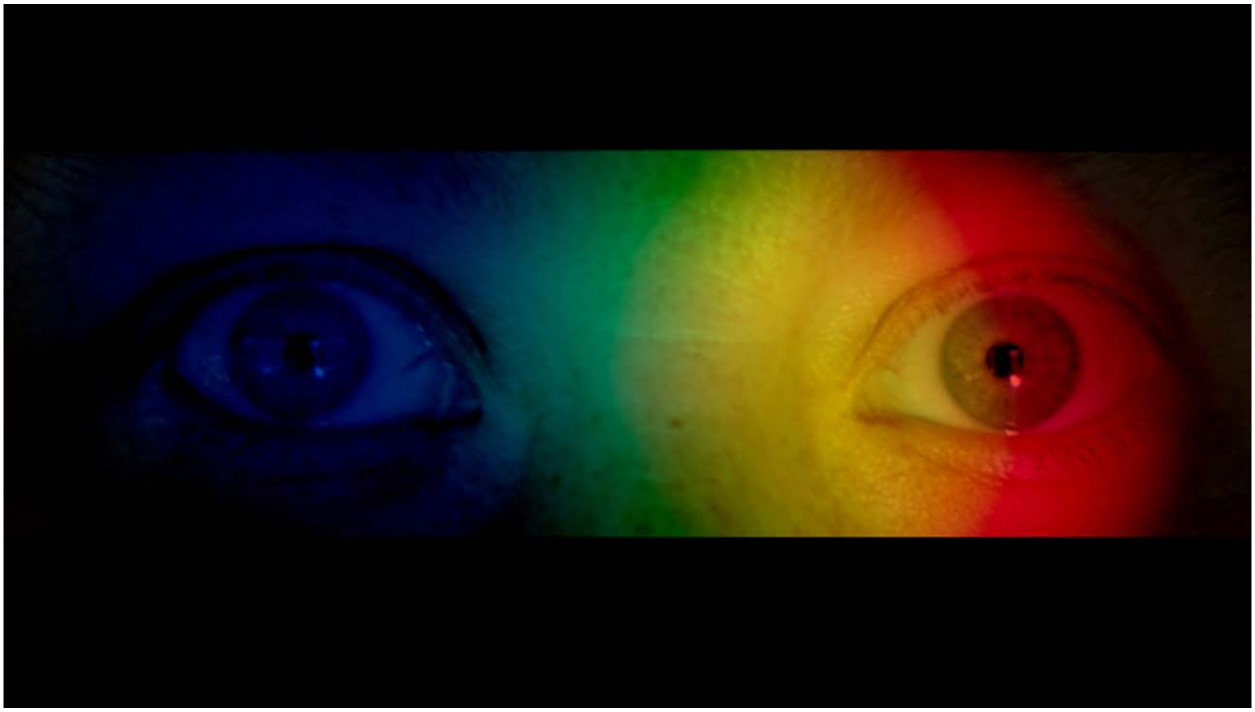
(D) The Combination of Light and Object that Matches a Stimulus

There are different hues for the different disciplines (topics) and different chroma levels for the different levels (decreasing chroma with increasing level).

Previous pages arranged by level.

Forthcoming pages arranged by topic.

Q: What is Color?



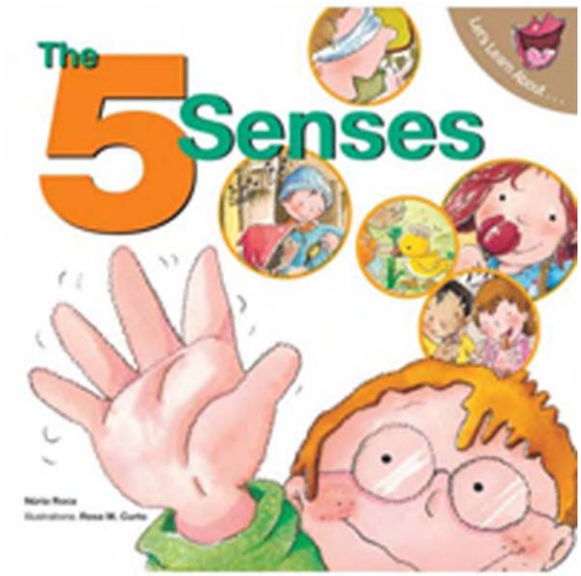
Our eyes sense the light from the world around us and start the process of seeing color. You might think the light on these eyes is colored, but really it is your very own eyes and brain that are creating that color from the light coming from this picture.

A:

Color is a human perception.

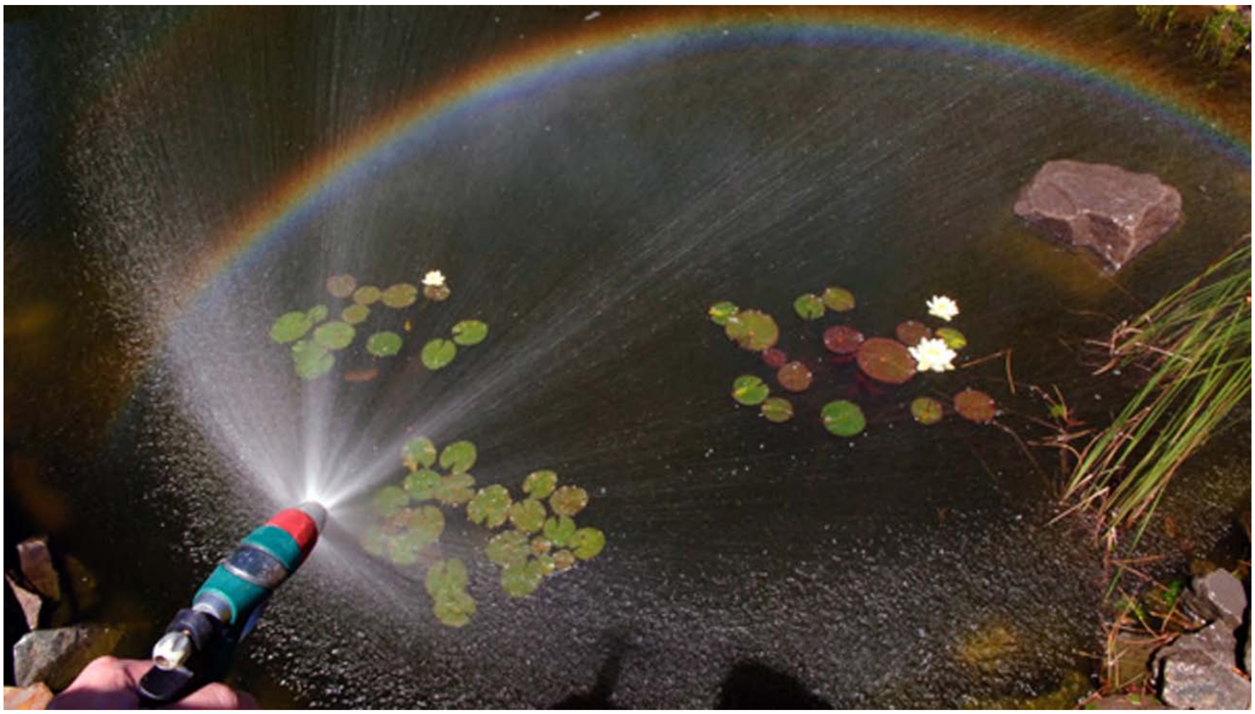
We see color because our eyes and brains respond to light present in the world around us. That light comes from light sources such as the sun, light bulbs, or even televisions. Sometimes that light interacts with objects before reaching our eyes and the objects allow more or less of the different types of light to reach our eyes. This makes different things look different colors.

Color is part of our sense of vision. It is similar to how we respond to other aspects of the world with our other senses such as taste, hearing, touch, and smell.



Our eyes provide just one of our five senses. They all help us to live in the world around us. It's fun to learn about all the senses.

Q: Why is a Rainbow?



It's easy to make your own rainbow. On a sunny day, look away from the sun and find the shadow of your head. Then spray some misty water (small droplets) in that direction. The rainbow will always be at an angle of 41 degrees (in a direction about half way between your nose and ear off to the side) away from the shadow of your head. If you could put water there (and see it), the rainbow would make a full circle around the shadow of your head! This is true for all rainbows. If you want to find one in nature, look for water in the sky (rain) at about that same angle when you are looking away from the sun. If there is a rainbow, that's where it will be. You can see the shadow of my water sprayer and my head at the very bottom of this picture and notice how the rainbow makes a curve around it.

A:

The beautiful colors of a rainbow are perceptions, like all colors. However, the process that creates the light we see as a rainbow is actually based on some fairly simple math.

That math is what we call geometry. The light from the sun is reflected by the surface of raindrops in the sky (just like it reflects off a window or surface of a lake) and its direction also changes when it enters and leaves the raindrop. The combination of all those changes in direction means that most of the light coming out of the raindrops is at an angle of about 41-42 degrees away from the shadow of our head (or in the direction half way between your nose and your ear when you look directly away from the sun). That alone would make a bright white circle in the sky. The reason the rainbow has its colors, is that the different wavelengths of light, producing different color perceptions, are reflected back to our eyes at slightly different angles. This makes the white light of the sun smear across the sky with different colors produce as the light is smeared and then we have a beautiful rainbow to see.

Here's a rainbow in nature. The sun is behind the camera to the left side and is also lighting up the cloud to the left in a very pretty way. You can also tell by the shape of the rainbow that the sun is about to set.

You might also see that the sky inside the curve of a rainbow is always brighter than the sky outside. This is also because of the way light reflects through the raindrops. You can even see that in the rainbow I made with my garden hose.

You can find a more detailed explanation of rainbows at this website from Dartmouth. And remember that rainbows are rarely seen since you need to have rain drops in the sky off in the distance in front of you and the sun low in the sky behind you; all at the same time!.

Q: What is the Best Color for Sunglasses?

These pictures show how color changes when light goes through different colors of sunglasses. The upper-left picture is the original scene as viewed with the naked eye. The upper-right picture shows how the scene is not so bright, but all the colors are correct, when looking through gray sunglasses. The lower-left picture shows what happens with yellow sunglasses (notice how much the sky color changed). And the lower-right shows the world as viewed through rose-colored glasses. Those are pink and they make the sky a sort of purple color and green leaves look darker.

A:

The answer to this one depends on what you are trying to do with the sunglasses. Usually, the answer is gray. But sometimes it is yellow and other times it might be some other color. I'll explain why gray and yellow might be good choices.

Gray is the best choice if you want to see the colors of things in the most natural and accurate way. All gray sunglasses do is remove some of the light of all wavelengths (colors) in equal amounts. It is exactly like just making the light on things a bit less bright. That helps us to see better on very bright sunny days when there is actually a bit too much light for our eyes. It will also make the contrast that we see less. Contrast is the difference we see between bright and dark places in a scene. That is one reason it is not a good idea to wear sunglasses when it is dark. Our eyes are already working hard and the contrast we see is low; adding sunglasses then only makes it harder to see anything at all.

Even when we look through colored glasses, we don't notice too much change because we adapt. Notice how yellowish the picture of the flowers looks. Then stare at the black dot on the yellow background without moving your eyes for about 30 seconds. Then look back at the center of the picture and you will see how your eyes adjusted to the yellow color and the green leaves look more like normal.

You can see in the pictures at left that gray sunglasses make the scene less bright and keep the colors looking nice. So why would anyone choose yellow sunglasses? It turns out that yellow glasses can actually help us to see more contrast and detail in a scene. They do this by removing the blue light. Blue light is the most difficult for our eyes to focus and that makes blue things look a bit blurry. Blue light is also scattered a lot by the air and water in the atmosphere and that reduces contrast, or our ability to see things. Thus, if we remove the blue light with yellow glasses, we are removing the light that is scattered around a lot in the world and the light that is focussed the most poorly by our eyes. The result is a sharper and more contrasty image. That is often helpful for athletes trying to perform well in bright light. Also, the increase in contrast actually gives us the perception that things are brighter, even though the glasses have actually removed some light.

Light (Level 4)

Q: Why is the Sky Blue?

This image of a beautiful clear blue sky was taken on a cold autumn morning with the sun behind the camera. Red light from the sun keeps going straight away from the camera (you can see some bouncing back off the clouds) and the deep blue sky color is caused by the blue light that cannot pass straight through the sky and instead gets scattered back to the photographer's viewpoint. You can also see this clear blue color in the water. Most of that is caused by the surface reflection of the blue sky, but natural bodies of water often appear blue on their own. In such cases we see the blue color because red light is absorbed by the water and blue can pass through and reflect off objects in the water back to our eyes.

A:

The direct answer is that the sky is blue because that is how we perceive it. Remember, color is a perception and not directly a property of objects. However, the way objects interact with light provide much of the information our visual systems use to determine what color we perceive. Thus, there is something about the sky that makes the light that reaches our eye appear blue in most circumstances.

That something is the fact that the light we see in the sky has not come to us directly from the sun, but it has been scattered by gasses and particles in the Earth's atmosphere. (Consider that in space the "sky" is black because there are no gasses or particles to scatter light and astronauts can only see light directly from the sun and objects that reflect the sun's light.) The kind of scattering that produces the blue sky is called Rayleigh scattering. That is named after a British scientist, Lord Rayleigh (his actual name was John William Strutt), who is considered the first scientist to describe this type of light scattering.

A sunset also helps us understand why the sky is normally blue. At sunset, we are seeing the red light passing straight through the sky while the blue light is scattered away. That's the blue light we normally see in the sky away from the sun.

Rayleigh scattering has the property that, for particles of the size typically found in the clear sky, blue light will scatter much more than red light. When we look at the sky away from the sun, we can only see scattered light (light that has bounced around the atmosphere and not passed straight through) and since Lord Rayleigh figured out and explained that blue light will be scattered the most in the atmosphere, it is blue that we see when we look at the sky. It is for this same reason that sunsets appear red. In the case of sunsets, we are seeing the light that passes straight through the atmosphere and not the scattered blue light. Clouds look white (or gray when little light passes through them) because the condensed water or ice particles in clouds are much larger than the wavelength of light and therefore they scatter all colors equally.

Q: How Do Fireworks Make Light and Color?

You might wonder what neon signs like these have to do with fireworks. Neon lights produce their color by having gases in the tubes excited by electrical energy. Once the gas atoms or molecules are excited, they release that energy as very specific colors of light. Pure neon produces glowing orange or red signs. Other gases such as argon, helium, krypton, and xenon can be used alone, in combination with each other, or in combination with other gases to produce differently colored "neon" signs. Some tubes are also coated with phosphors that absorb energy of one type and emit different colors; this is also how fluorescent lights work. Fireworks also produce various colors by using the incandescent energy from the explosion (the fire part of the fireworks) to excite various atoms or molecules that, in turn, emit various colors when they release that energy.

A:

First of all, light and color are not two separate things. All light has some color and color is produced by our perception of light. So light and color in fireworks are made exactly the same way. There are two sources of light in fireworks. The first is simple incandescence, or light and color that is produced just because material is heated to very high temperatures. This can be considered the "fire" in fireworks. Just like a campfire emits light with yellow, orange, and red colors simply due to the high temperature of the material being burned, fireworks can produce similar colors due to the very hot explosion and burning of the explosive charge. These reds, oranges, yellows, and whites due to incandescence are the dominant colors in most fireworks even though they are often the colors we pay least attention to.

The "fire" in fireworks can only makes shades of red, orange, yellow, and white like any fire, or incandescent source of light. Incandescent light bulbs do this by using electricity to heat up a small tungsten wire (or filament), which then glows like a fire. These particular fireworks are showing the incandescent part of the explosion. The colors on the castle come either from incandescent lights with filters to absorb different colors or, more recently, from light-emitting diodes (LEDs).

The second method by which light and color is produced in fireworks is atomic and/or molecular excitation followed by emission of light. This is the same process that produces the interesting colors we see in neon signs as shown in the image above. Different elements and molecules will emit their own specific colors of light after they are excited by high levels of electrical energy (as in the neon signs) or heat energy (as in the fireworks). For example, sodium is a very strong emitter of yellow light. This can sometimes be seen by putting ordinary table salt (sodium chloride) into a candle flame. Sodium emission due to electrical excitation is also what produces the saturated yellow colors seen in some street lights and parking lot lights in large cities.

A variety of atoms and molecules are used to produce colors in fireworks. Some examples include sodium for yellow, calcium chloride for orange, strontium chloride for red, barium chloride for green, and copper chloride for blue. Think about all these atoms and molecules being heated up by incandescent explosions and then emitting their beautiful colors next time you see a fireworks display!

Q: How Does the Light Affect How Bright a Color Appears?

These pictures illustrate how brightness and colorfulness change with the amount of light. On the left the scene is shown as it would appear on a rather dim (perhaps hazy) day. Some might even call that a dull day. On the right is the same scene as it might appear on a bright sunny day. Notice that the colors are both brighter and more colorful when there is more illumination. Also, the scene appears to be of greater contrast and sharpness when there is more light. Pay close attention to how things look throughout the day from early morning, through noon sunlight, to dusk and you will witness these sorts of changes in color appearance.

A:

There are two general ways that lighting influences the apparent colors of objects. These are due to changes in the color of the light and changes in the amount of light. Color changes can have very strange effects. For example, if you were to illuminate a scene with red light, then red objects in the scene would appear brighter while blue or green objects might appear darker, or even black. In general, when the color of the illumination changes, objects of color similar to the illumination color become brighter.

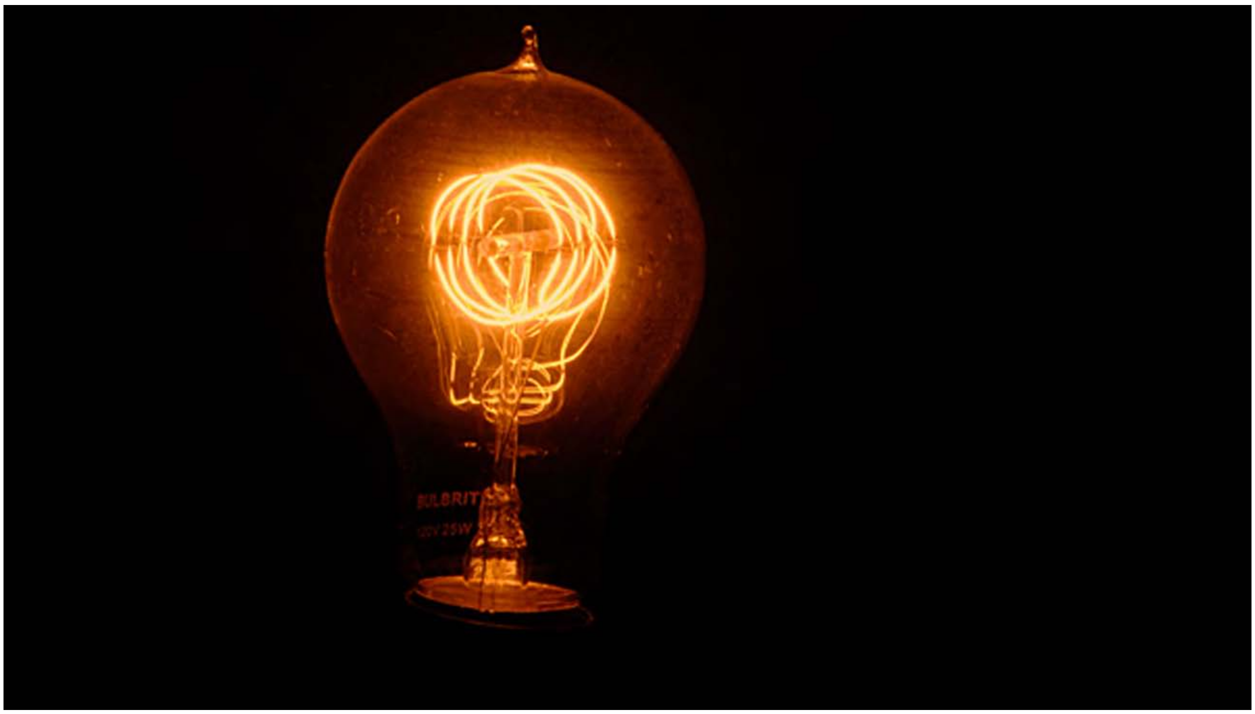
More commonly we observe changes due to the amount of light. Think about how a room in your home appears in bright daylight, at dusk, and with lights on at night. If it didn't change in appearance we wouldn't be able to figure out what time of day it was without looking at a clock! In general, when there is more light falling on a scene it appears brighter, more colorful, more contrasty (the differences between colors show up more), sharper (more in focus), and less noisy (or grainy). You can observe all of these changes if you look closely.

Parts of these changes are due to the transition between rod vision and cone vision. Rod vision serves us in very low light levels. In order to gain that sensitivity to light, the rods collect light over larger areas and this results in less sharpness. Things also look more noisy, or grainy, because detecting such low amounts of light is difficult for the rod photoreceptors. When we are using our cones, we collect light over smaller areas so everything is sharper. It is also less noisy because there is plenty of light to capture. Rods can only produce black-and-white vision, so as the light increases and we transition to cone vision, the world starts to appear more colorful. As the light level increases further, the differences between colors become much easier to discriminate and everything looks more contrasty (bright and colorful). Also our pupils can close down when there is more light and that can help make the world appear more in focus.

Paul Bunyan and his blue ox Babe are characters from American folklore. These statues stand in Bemidji, Minnesota. Babe's blue body is all the same material, but the apparent color depends on the illumination. In the shadows, Babe doesn't look as colorful as in the direct sunlight. Color scientists would say that the image of Babe has the same saturation everywhere even though the colorfulness changes.

Light (Level 7)

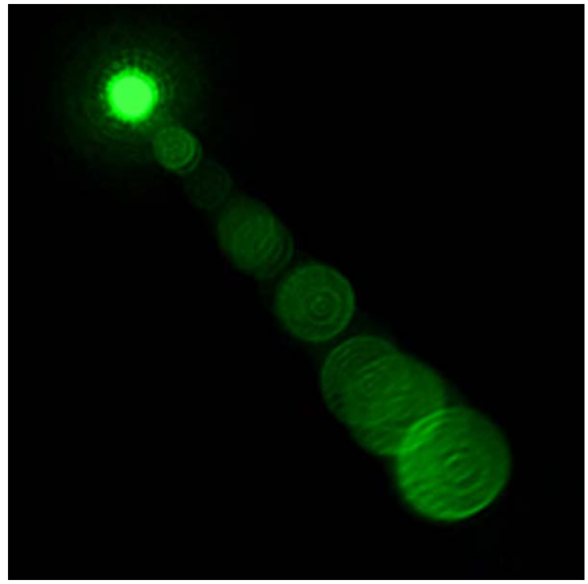
Q: What Is Light?



Common light bulbs for much of the previous century were incandescent lamps. Incandescence refers to the emission of light due to an increase in temperature. Incandescent light bulbs work by passing an electric current through a thin wire, normally made of tungsten. The electrical current heats up the wire (a phenomenon studied by the physicist James Prescott Joule in the 1840's) and when it becomes hot enough it glows. The filament will be a deep red at first and then become more whitish and brighter as the amount of electrical current, and therefore the filament temperature, is increased. Incandescent light bulbs are not very energy efficient. Less than 5% of the energy used by the light bulb is converted into light. The rest produces heat. That is why incandescent bulbs are quickly being replaced by compact fluorescent and LED sources that are far more energy efficient. (By the way, if you are worried about mercury exposure from broken compact fluorescent lamps, you should know that you are exposed to far more mercury by eating a single can of tuna than from cleaning up a broken lamp!)

A:

The technical definition of light from the Commission Internationale de L'Eclairage (CIE, the group that defines such things) is "Any radiation capable of causing a visual sensation directly". Loosely translated, light is electromagnetic radiation that we can see. Ultraviolet and infrared energy are also electromagnetic radiation, but we cannot see them so it is incorrect to call them "light". There is no such thing as "ultraviolet light" or "infrared light". Even though those terms are used colloquially (and sometimes by optical scientists), the more proper terms are "ultraviolet radiation" and "infrared radiation". Unfortunately people often don't like to use the word "radiation" because they associate it with radioactivity and nuclear radiation. Historically, it was recognized that light was some form of energy, but there were competing theories of its nature. Some considered light to be made up of particles, while others thought light was made up of waves.



The view looking nearly toward a green laser pointer in a darkened room. (Never look directly toward a laser to avoid possible eye damage.) The bright spot is the source of light and the path is illuminated by scattering off dust particles in the air between the laser and camera. Lasers are special light sources with highly directional, coherent, and monochromatic energy. They allow large amounts of energy to illuminate small spots.

The idea that light is made up of particles gained favor in the 1600s with the support of Sir Isaac Newton. He used the properties of light reflection and the fact that light travels in straight lines (in homogeneous isotropic media) to support his theory of light particles, or corpuscles. He however had difficulty explaining light diffraction (light bending around objects) with a particle theory and that turned out to be one of the reasons the wave theory of light became more popular later on. Interestingly, Albert Einstein brought back particle theory to some extent with his observation and explanation of the photoelectric effect (light striking a metal surface can produce an electrical current). This helped more recent researchers to figure out that light behaves as both a particle and a wave.

Sound energy travels through the air in waves that our ears can sense and we can observe waves on the surface of water as energy we can feel. Light also shares some of these properties. For example light diffracts, or bends, around surfaces in the same way that water waves can be observed to do. Thomas Young observed this and also observed the interference of light waves (again like the interference of water waves) and was one of the proponents of wave theory. Later on James Clerk Maxwell and others were able to explain light in terms of electromagnetic theory that still serves us well in modern technology. Thus, light was shown to be a form of electromagnetic energy just like radio waves, X-rays, infrared energy, and ultraviolet energy.

Ultimately, all these observations resulted in the concept of wave-particle duality, the idea that light sometimes behaves like waves (electromagnetic theory) and sometimes behaves like particles that define discrete units of energy (known as photons). This duality allows us to describe light well enough to utilize and control it in modern technology like television systems, digital cameras, and computer displays.

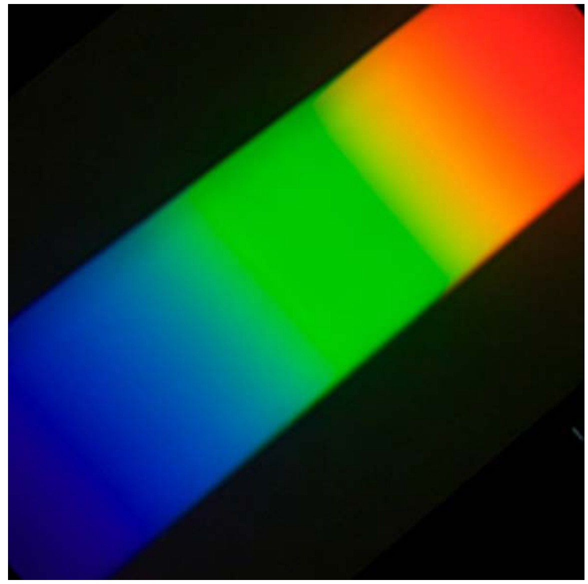
Q: Why Can We Only See Visible Radiation?

While we can only directly perceive light with our visual systems, there are many other wavelengths of electromagnetic radiation (and other forms of energy) that can be used to sense the environment around us. The collected image data can then be rendered to displays that modulate light for us to perceive (like the images you are looking at right now). This image provides a collage of images collected at different wavelengths. In the center is a normal light image of a tree (below) with a reflected infrared image above. This infrared image was made with wavelengths just slightly longer than we can perceive. Notice how the sky is quite dark (not too much infrared scattered in the sky) while the leaves and grass are very bright (healthy foliage reflects a lot of infrared energy). The image of the house is a false-color representation of thermal infrared emission. This is even longer-wavelength energy that we sometimes consider as "heat". The red areas are where there is a larger amount of thermal infrared emission, or heat leaking through the rood of this house. On the right is a medical X-Ray of someone's repaired knee. X-Rays are very high energy (short wavelength) electromagnetic radiation that can pass through our soft tissue easily, but don't pass through bones so easily, and can't pass through the metal pins at all. This X-ray image is a negative and is darker where more energy passes through the subject. Finally, the upper-left image is an ultrasound image of my first daughter about 5 months before she was born. This image was made with very high frequency sound waves (vibrations of matter) that actually are not electromagnetic energy at all.

A:

In a way, the answer is simply a definition. Visible electromagnetic radiation, or light, is defined as the wavelengths that we can directly perceive with our visual systems. The greater question is why our visual systems evolved to respond to those particular wavelengths of electromagnetic radiation when there is such a vast range of wavelengths in the full spectrum. For example, why don't we see X-rays, or radio waves, or ultraviolet energy, or infrared wavelengths? Some insects actually do respond to ultraviolet energy, so clearly it is possible.

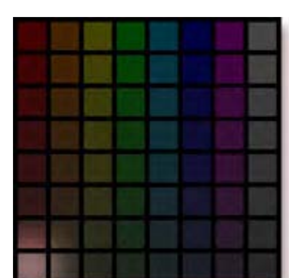
The true answer is that there are probably many reasons, functioning in combination, that resulted in our visual systems' functioning the way they do and responding to the range of wavelengths that they do. These include both physiological and ecological reasons. Physiologically, ultraviolet radiation (UV) is potentially very dangerous (and deadly) to biological tissue. Thus it would not serve us well to rely on detection of dangerous radiation to function in day-to-day living. Ultraviolet radiation is sometimes used to kill bacteria and other organisms. It would also damage our cells in a similar way. UV causes sunburn and also contributes to the development of cataracts (opacity) in the lenses of our eyes. Shorter wavelengths have even higher energy levels and can potentially cause more damage and/or pass right through us (like X-rays). So the UV end of the spectrum seems to be a reasonable limiting factor at the short-wavelength end of the visual spectrum. At the longer wavelengths, we have infrared radiation. It turns out that our body produces infrared energy simply because we are warm and that background radiation makes it difficult to detect infrared radiation from the environment (sensors in infrared cameras are cooled to very low temperatures for this reason). Thus visual noise might well be the limiting factor at the long-wavelength end of the spectrum. Even longer wavelengths, like radio-waves are so long that they pass right through (or perhaps more correctly around) us as well and we cannot detect them.



The visible spectrum, or light, is electromagnetic radiation that creates human visual sensations and perceptions. This is a photograph of an actual, linearly dispersed, spectrum. Does it differ in noticeable ways from artistic representations of the visible spectrum?

Ecologically, there are other reasons that narrow down the range of wavelengths we respond to visually. For one, the sun's peak energy output is very highly correlated with the wavelengths of light that we respond to. Thus we have a ready and plentiful source of energy to aid our visual perception. Additionally, many of the interesting interactions between electromagnetic energy and the elements and compounds we are made up of (as well as all the plants, animals, and objects we are interested in perceiving) happen in the visible wavelengths.

The bottom line is that we respond to the wavelengths we do because it is physiologically plausible for our visual systems to do so and because the information provided by such visual systems is tremendously useful to our survival.



Q: Why are Leaves Green?

Leaves look the way they do because of the stuff they are made of. When leaves, like this one from a sugar maple, change in the fall we can see different stuff in them and the green is replaced by bright yellows, oranges, and reds.

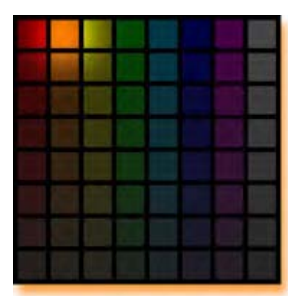
A:

Since color is a perception, leaves are green simply because that's the way we see them!

But why do we see them that way? That's because of the stuff leaves are made of and how it plays with the light from the sun. One sort of stuff in the leaves is called chlorophyll. Chlorophyll is the main part of the leaf that makes them so good for nature. The chlorophyll takes carbon dioxide (CO_2) from the air and uses water and energy from sunlight to create sugar. That sugar is food for the tree and for animals (like us) that eat the leaves or make yummy things like maple syrup from the tree sap.

The light energy that the chlorophyll uses is mainly the types that would look red or blue to us. That leaves the green energy to bounce off (or pass through) the leaves and reach our eyes. And when that light reaches our eyes we see the leaves as green.

Sometimes leaves look very, very green. This can happen when leaves are near other leaves and the light we see bounces off many green leaves before it reaches our eyes.



Q: Why do Colors of Stained Glass Windows Look so Beautiful and Different from Other Objects?

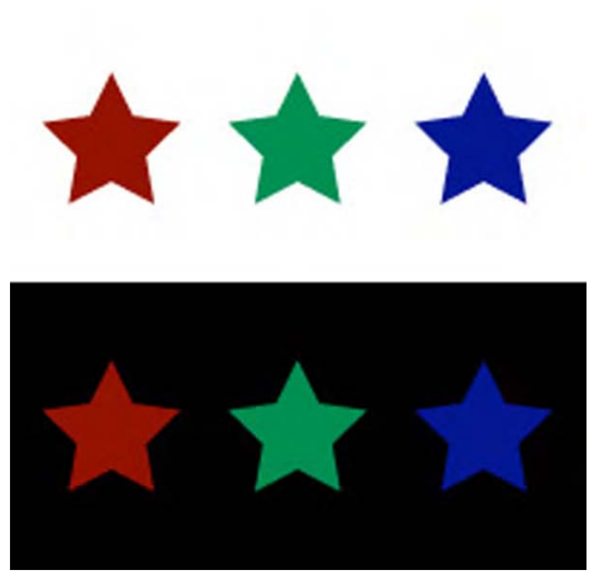
Stained glass is beautiful to look at. We see it as sparkling when we are inside a building because the colors are usually the brightest things we see. This picture shows a stained glass window with the sun right behind it. It took a special kind of photography to make this picture. Most cameras would make the glass look less colorful and less bright.

A:

They look beautiful because they are beautiful! And it is our own preferences that determine what is beautiful.

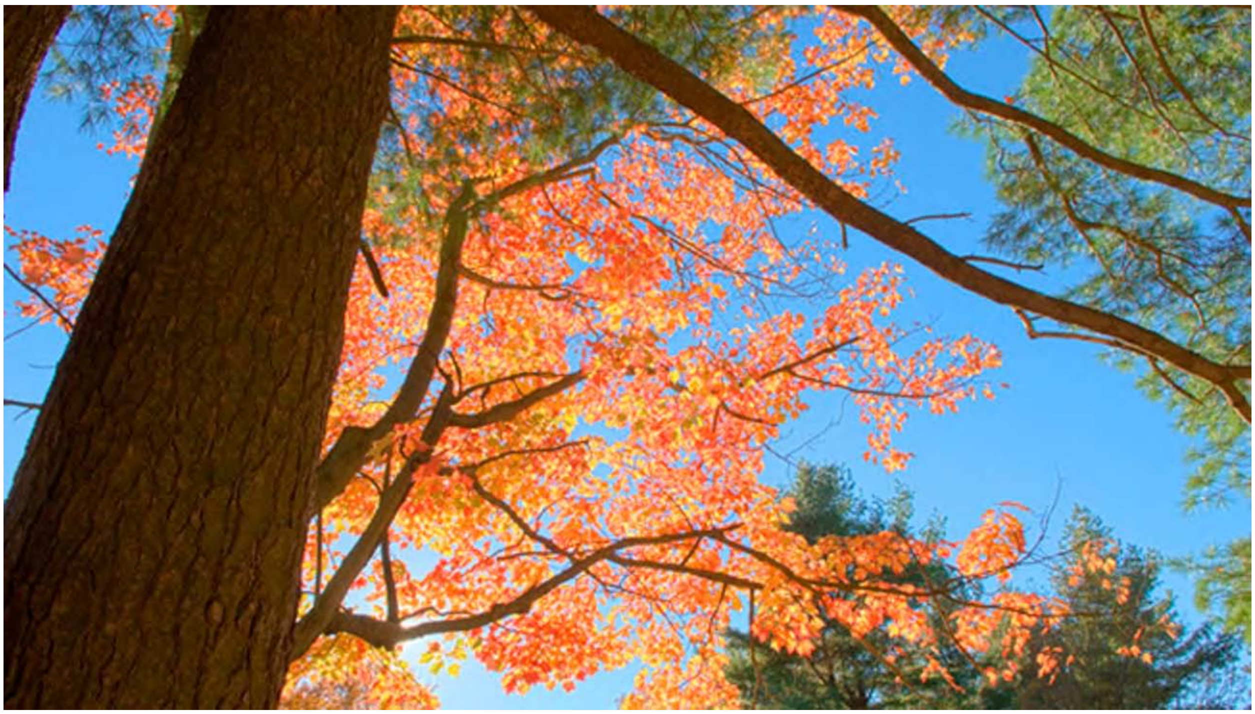
Even though beauty is a personal choice, most people agree that the colors we see when looking at stained glass windows from inside a dark building are very beautiful. The same is true when we see the windows from outside at night and the lights are on inside the building. The special colors we see in the windows are caused by the way our eyes and brains perceive color. We are always judging colors in relation to other colors that are nearby. This lets us see that a black cat and a white piece of paper always look black and white, even when the amount of light falling on them changes.

Stained glass windows take those comparisons to an extreme. The windows are often much brighter than their surroundings and that makes them appear to glow, much like the bright lights we see on Christmas trees or in fireworks displays. When colors are much brighter than their surroundings, they also look much more colorful to us. So, once again, it is how our eyes and brain work that makes the colors look so special.



This pictures helps to show why stained glass looks different than normal things. The three stars on the white background are identical to the stars on the black background. You can see that the change in background makes the colors look different. Are they a little brighter and more colorful like stained glass inside a dark building?

Q: Why do Leaves Change in the Autumn?



Sugar maple trees are native to the northeastern United States and southeastern Canada. They produce beautiful brilliant orange colors in the autumn (like this one found in the Adirondack Mountains of New York). They also produce a sugary sap that is harvested in the spring and made into Maple Syrup. This photograph contrasts the orange hues of light passing through the maple leaves with the green colors of nearby evergreen trees (that don't change color or shed their leaves in the fall).

A:

There are actually several reasons leaves change color and function in the autumn. One that is sometimes overlooked is that it is very difficult for trees in northern climates that have snowy winters to bear the weight of snow on their leaves. Losing their leaves in the winter means less snow stays on the trees and they don't need to be so strong to survive until the warm weather in spring.

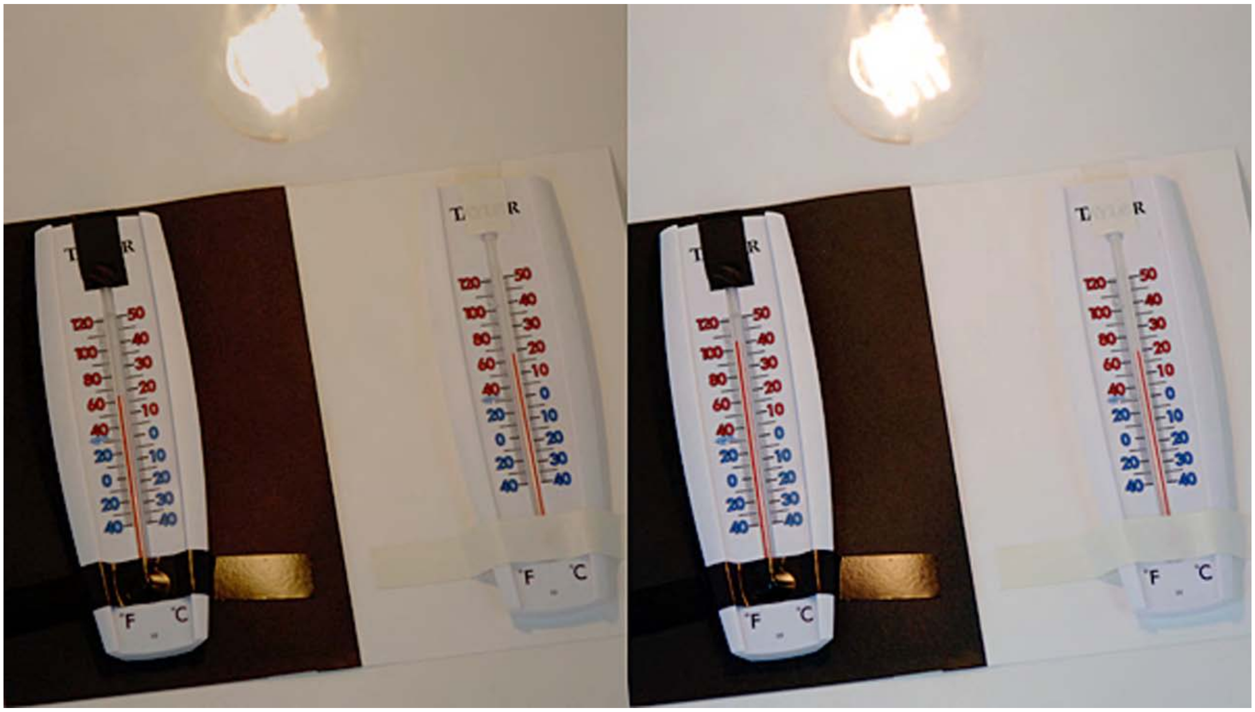
More often, people focus on the beautiful color changes in leaves that take place in the autumn in many places around the world. Why do those color changes happen? And how?

As the days grow shorter and colder, there is no longer enough light and water for the leaves to use (along with carbon dioxide from the air) to produce the food plants need for survival. The plants switch to stored food and when they shut down their food production by chlorophyll and photosynthesis, the green-colored chlorophyll begins to disappear from the leaves. We often are left to see the colors that are left behind. Many times these colors are simply dull browns and tans. However, some types of trees leave behind bright yellow and orange colors that we can see in the autumn. And some other plants actually start to produce other colors, like purples and reds, in the fall when the chlorophyll goes away. Eventually even these colors fade away as the leaves quit working and sever their connections to the trees. Then some wind or rain comes along and they "fall" off the trees to make room for new leaves in the spring.

You can read a little more detail on this explanation at this website.

Leaves are beautiful all year long. One interest fact is that they transmit a lot of light and don't just reflect it back to our eyes. This photograph was made of an early autumn sugar maple leaf with only light being transmitted, or passed through the leaf (note all the green, yellow, orange, and red colors in this leaf). One reason, leaves let so much light pass through is so that the energy in sunlight can be absorbed by all the leaves on a tree, not just those on the outer surface.

Q: Would a Dark Color M&M Melt Faster than a Light One?



One of the most common questions I receive about color is about the relationship between the colors of objects and how fast, or how much, they heat up in the sun. An alternative involves which color of a popsicle or ice cream melts the fastest in the sun. (Chocolate will melt faster than vanilla due to the color. Chocolate with almonds will melt faster still due to the salt on the almonds, which lowers the freezing point of water.) I took the image above of two identical thermometers mounted on white and black cardboard with white and black tape. After being stored in a cool dark place, both thermometers read the same temperature of about 20 deg. C (left) when the light was first turned on (shown in the dimmer image). However, after the light was on for a while you can see that the thermometer on the black background reads a significantly higher temperature of about 40 deg. C (right). This is because the black background absorbs a lot of light energy (that's why it looks black) and converts that energy into heat. The white background reflects most of the light and doesn't heat up as much.

A:

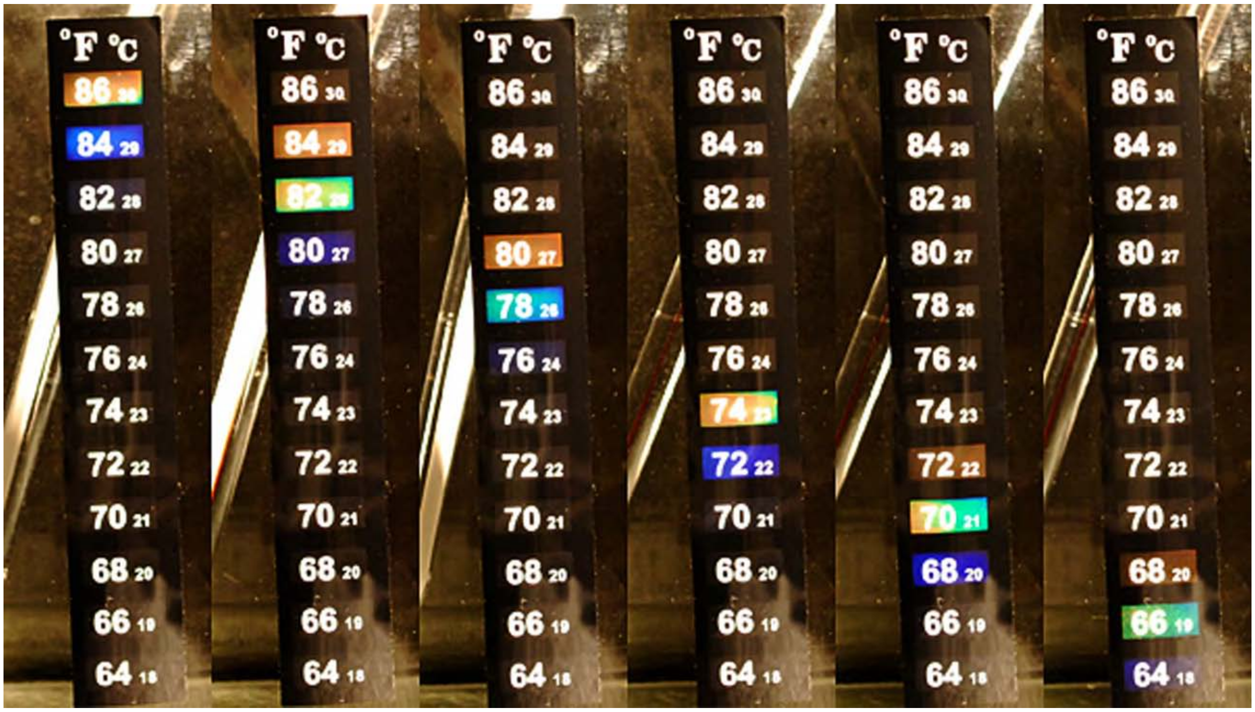
First of all, for those of you reading outside the USA, M&Ms are small candies that are chocolate covered with a hard and colorful shell. Some places in Europe have a similar candy called "Smarties", or "Lacasitos", *etc.* M&Ms are designed to let you eat chocolate without fear of making a mess since the hard candy shell isn't supposed to melt in your hands. However, like anything it will melt if it gets hot enough, or if it gets wet enough (they melt in your mouth!).

This question is about how the color of the M&M relates to how quickly the candy will melt. If we assume that the colorants (chemicals giving a material its color) in the various M&Ms have no significant impact on its properties (see the image at right for a case where this assumption fails), then in a darkened room followed by a darkened mouth, all M&M colors will melt at an equal rate.

A grade school student once sent me an email asking why blue M&Ms lose there color in water more slowly than other colors. I had no idea why (still don't) or even if it was true. So I tried an experiment and this image illustrates the results. What do you think?

The difference comes when the M&Ms are exposed to light like the thermometers in the image above. The dark colored M&Ms look dark because they are absorbing a lot of light. This light is energy and that energy has to go somewhere. For most materials that somewhere is a conversion into heat; the absorbed light makes the object hotter. This is the same reason we feel hotter in the direct sunlight than we do in the shade and people prefer to wear light colors on hot days and dark colors on cold days. So those M&Ms in the light will all heat up to different temperatures and the hotter ones will melt faster than the colder ones. It just turns out that the darker colors will also be the hotter M&Ms, so the bottom line is "yes" darker M&Ms will melt faster than light M&Ms if they have been exposed to enough light.

Q: How Does a Mood Ring Work? What do the Colors Mean?



This aquarium thermometers is made from thermochromic liquid crystals. Thermochromism is the term used to describe changes in color due to changes in temperature at temperatures for which the object is not burning (that is incandescence!). In the case of these thermometers, the color changes are correlated with the temperature of the liquid crystal to create a useful, inexpensive, and compact thermometer. The liquid crystals in the thermometer strip change their physical properties with temperature and this results in a change in the colors of light they reflect. In general, as a liquid crystal is heated, the reflected light progresses through the spectrum from red, through orange, yellow, green, and cyan, to blue. These color changes, in combination with optical filters or temperature calibration, can be used to construct a thermometer. Alternatively, a thermometer can be created by using slightly different liquid crystals to indicate each specific temperature. I made this sequence of pictures by putting the thermometer on a vase of hot water and gradually adding ice cubes to lower the temperature as I took pictures.

A:

If by "work" you are wondering how they tell your mood, then they simply do not work at all! They are fun and they do change colors. However, they are simply liquid crystal thermometers that you wear on your finger. So they do indicate a change in your body, but that change is actually the surface temperature of your finger. Mood rings are filled with a liquid crystal just like the aquarium thermometers described above.

Specifically, these materials are known as thermotropic liquid crystals and they change with temperature in ways very similar to how the liquid crystals in your LCD computer display or television change when an electrical current is applied to them. For mood rings, the system of glass and liquid crystal material that makes up the ring is calibrated to be a green for an average surface body temperature of about 82° F (28° C). As the ring-wearer's skin temperature increases, the liquid crystal changes toward blue and, as the temperature decreases, the ring changes toward black.

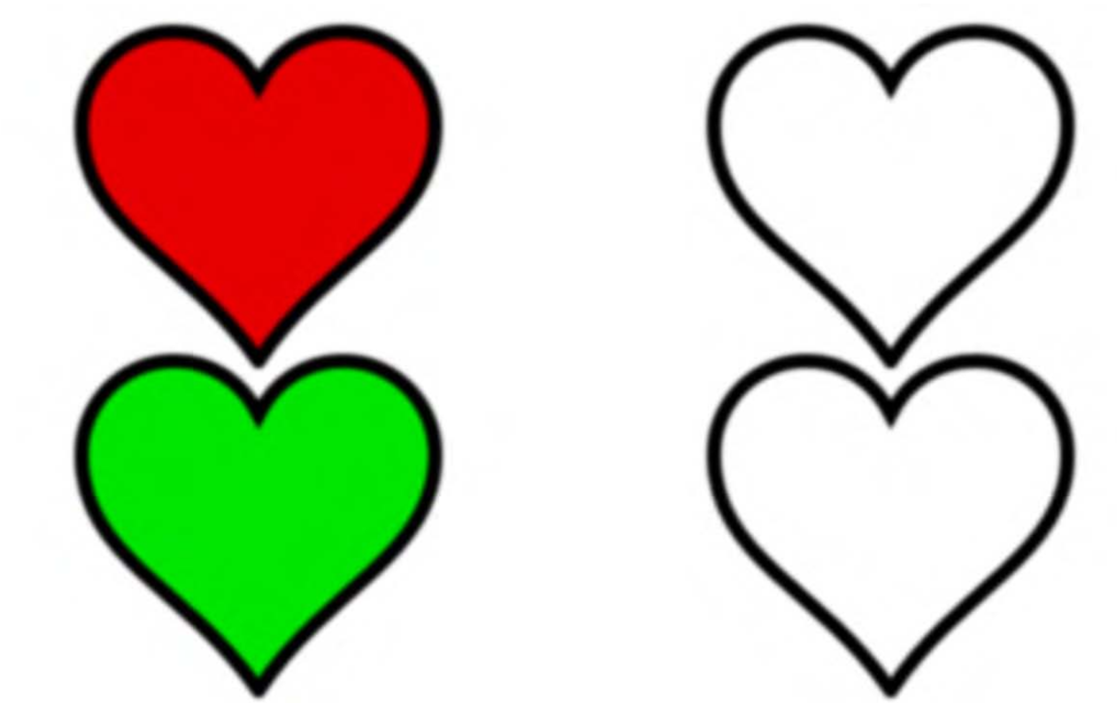
The standard interpretations of the colors of mood rings are:

- Dark Blue: Happy, Romantic, or Passionate
- Blue: Calm, Relaxed
- Blue-Green: Somewhat Relaxed
- Green: Normal
- Amber: Nervous, Anxious
- Gray: Very Nervous
- Black: Stressed, Tense

You can see that these moods might correlate somewhat with your body temperature, but not always. It is entirely possible that a person could be very happy and very cold and then the mood ring would be completely incorrect. So really the colors mean nothing about your mood, but do tell you something about your finger's temperature.

I found this nail polish for my daughters in a store in Albuquerque, New Mexico. It changes color when exposed to the ultraviolet (UV) energy in sunlight. The top section was exposed to UV energy while the bottom was kept in the dark. It is quite fun to have nail polish that is one color inside and a different color outside in the sun. This is caused by photochromism, which is a change in color of a material due to exposure to light or other optical energy. Can you think of any other materials that are photochromic?

Q: Why Is Green Often Used for Surgeons' Scrubs?



OK, look at the very bottom point of the red heart and stare at that point for about 30 seconds. Then look over at the same point on the upper white heart. What do you see? If you've done the experiment carefully, you will see a faint greenish heart on top and a faint reddish heart on the bottom. The colors have switched positions! These faint colors are known as afterimages and they are caused by adaptation (or fatigue) of the cone receptors in your eyes. When you stare at the red heart, your visual system becomes less sensitive to red light in that area. When you then look at the white area, you respond less to the red light there and see a bluish-green color. The same thing happens with the green heart. Except in this case your visual system becomes tired of seeing green and when you look at the white heart, you respond more strongly to the reddish-blue light that is not green. Studying afterimages has allowed scientists to learn a lot about how vision works.

A:

Believe it or not, this is another case of adaptation! Surgeons spend a lot of time looking at the reddish colors of organs, muscles, and blood inside their patients and their eyes can easily tire of these red hues. When the surgeons look away from their work to rest and refresh their eyes, they would see eerie greenish afterimages of the objects they had been working on. This can be both disconcerting and distracting, two things that aren't desirable for surgeons in the middle of surgery. Instead, green, or greenish-blue, scrubs became more popular than the more traditional white (for cleanliness) scrubs because they were felt to be easier on the eyes. In this case, "easier on the eyes" means that the disconcerting afterimages are broken up and made less perceptible by glancing at the scrubs of the same color. This makes it easier for the surgeons to normalize their visual adaptation and then go back to work with the best sensitivity to subtle differences in red hues that they might be looking for.

Legend has it that bullfighters use red capes to enrage the bulls and make them charge. In reality, bulls are red-green colorblind and it is not the color that enrages the bulls, but instead the taunting with the flowing cape (and the fact that they have already been stabbed several times!). Also, magenta capes like the one shown (called "capote" are often used early in the bull fight while a smaller red one (called "muleta") is used only at the end.

Another interesting interaction between colors and objects is the Stroop effect. Look at the words in the list below and say they color of the text out loud. Then try again saying the word instead of the color of the letters in the word. You should notice that it is much easier to say the word than it is to correctly say the color of the letters. This is due to the interactions in our brain when we recognize things. The words themselves take precedence over the colors of the letters. Color is not so important for us in recognizing objects as form, or shape is.

RED
GREEN
YELLOW
BLUE
PURPLE
ORANGE
BROWN
BLACK
PINK

There are many interesting ways that color interacts with other perceptions and these interactions can be explored endlessly.

Objects (Level 7)

Q: What Color is the Moon?

I created this composite image of the earth and moon as they would look to us when seen together from space. When both are viewed simultaneously under the same illumination, it becomes apparent that the reflectance (sometimes called albedo) of the moon is similar to that of land on earth and significantly lower than the reflectance of clouds. If we could hold a piece of the moon in our hands here on earth it would appear dark gray, or nearly black. So why does it look so bright and nearly white in the sky?

A:

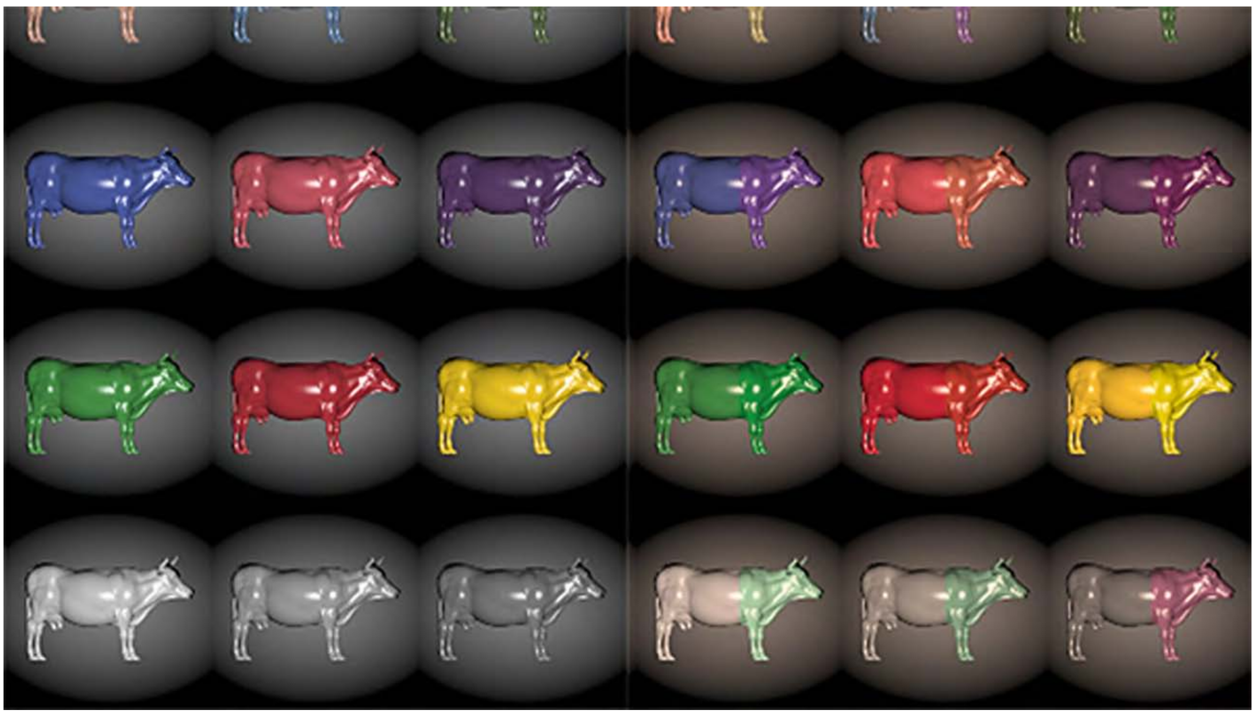
Like any other object, the color of the moon depends on how you look at it. Normally we see the moon as one of the brightest objects in the sky (or at least in its area of the sky) and our visual systems see such unrelated stimuli as either white (like a light bulb) or as a bright color (like signal lights). The facts that the moon reflects all wavelengths of light nearly equally and that we see the moon all by itself and cannot compare it to other similarly illuminated objects means that we cannot see it as any other color than nearly white (sometimes with a little bit of a yellowish tinge).

After creating the image above based on color science theory and reflectance measurements of the moon's surface, I found this view captured by NASA's Galileo probe. It shows directly how dark the moon is when viewed with the illuminated earth

However, if we were to take the moon and put it next to other objects under the same direct illumination from the sun, we would have a very different perception. The moon would no longer be the only stimulus and it would also not be the brightest stimulus. In fact the surface of the moon only reflects about 12% of the light incident upon it. If we were to compare the moon to a white piece of paper (or an astronaut's white space suit) we would quickly recognize the moon as a dark gray object. In such situations we are viewing the moon as what is known as a related color and we have a more stable perception that is less dependent on the levels and type of illumination. This is illustrated in the composite image at left that I constructed based on the measured moon reflectance as well as the direct image taken by the NASA Galileo probe. You can also see it in pictures of astronauts on the moon's surface.

Color perceptions such as gray and brown only exist as related colors (when we can compare them to other similarly illuminated objects). If we see these same stimuli as completely unrelated colors (isolated in a dark environment) then we will instead see white and orange. That is why we can't go to a store and purchase gray, or brown, light bulbs. Another interesting bit of trivia about the color of the moon is that moon dust is retroreflective. That means that, like a road sign, the moon tends to reflect light back in the direction it came from. That explains why the full moon appears fairly uniform in brightness from edge to edge instead of being shaded like a ball would be when illuminated from a single direction (*i.e.*, it looks like a disk, not a sphere).

Q: How Can Two Objects Match in One Lighting and Not Match in Another?



This is another example from the MetaCow test image. The front half of each cow is a metameric match to the back half when viewed by an average human with normal color vision under typical daylight illumination. This is illustrated in the left half of the image. Metameric matches are two stimuli that match in color, but are different in their spectral power distributions (or in this case their spectral reflectances). When those same cows are viewed by the same human observer under incandescent light (right half of image), then the matches break down. The differences in spectral reflectances that were invisible under daylight become readily apparent under incandescent light. In other words, the metameric matches no longer hold under incandescent illumination.

A:

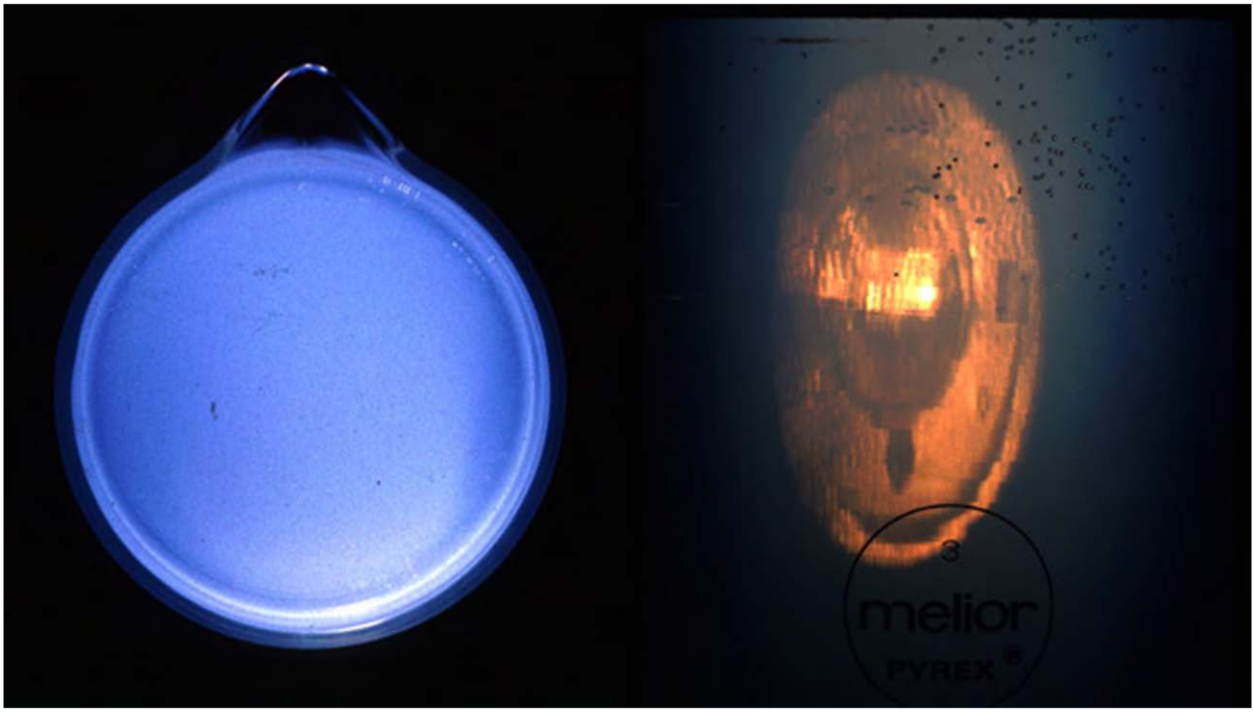
Metamerism. A simple, one-word answer. Metamerism describes the phenomenon of metameric color matches. Isomeric (or identical) color matches occur when two stimuli have identical spectral power distributions (identical emission or reflection of light at every visible wavelength). However, since we only have three types of cone photoreceptors, it is possible for two stimuli to match in color without having identical spectral power distributions. As long as the integrated responses of the three cone types are equal, then the stimuli will match in color. Basically, a little less energy at one wavelength can be compensated for at other wavelengths. When color matches happen despite differences in spectral power distributions (or spectral reflectance of objects), they are called metameric color matches and they exhibit the property of metamerism.

Toy secret codes that only show up when viewed through a certain color filter take advantage of the spectral properties of materials. This image has a message that only shows up with a blue filter (or under blue light). The blue filter or light makes the hidden yellow text dark, while leaving the white background and cyan masking pattern relatively light.

Isomeric color matches hold for any observer and any viewing conditions. The two objects are physically identical and we cannot perceive a difference between them as long as they are viewed together under the same conditions. However, metameric color matches (sometimes called conditional matches) depend on both the illumination and the observer. Changes in the illumination can highlight, or diminish, certain differences in spectral reflectance properties and make them more or less pronounced. Likewise different observers have slightly different visual sensitivities and a nice metameric match for me might look like a significant mismatch for you. On top of that, our visual systems change as we age, so a match for me today might not have looked like a match to me 30 years ago.

Metamerism is one of the most fundamental concepts of color science and presents us with many opportunities (such as trichromatic color reproduction systems) and many challenges (such as materials that change appearance with changes in lighting or observer). It is an endlessly fascinating topic and it is interesting to ponder how important it would be in the natural world. Or is it just an artifact of man-made color systems?

Q: Why are Eyes Different Colors?



The colors of many things come from scattered light. Milk is white because it scatters almost all the light that hits it. This picture shows a glass beaker full of water with just a little bit of milk in it. The beaker was lit from the side. On the left the camera was above the milk and water and the light scattered sideways was blue. On the right side, the camera was across from the light on the side of the beaker and we can see the red light that passes through without being scattered to the side. This shows why the sky is blue (light scattered to the side) and a sunset is red (the light that goes straight through the sky).

A:

Our skin, hair, and eyes come in many different colors. Amazingly all those different colors are made from exactly the same stuff! That stuff is a pigment, or colored material, called melanin.

The color of our hair and skin is mainly caused by the amount of melanin there (and the underlying blood and body tissue for our skin color). The more melanin present, the darker our hair or skin. Black hair has lots of melanin. Blonde hair has a little bit. And gray hair has none at all.

Eyes come in many colors. Here are the blue eye of a young child, a fairly rare gray eye, and a hazel eye, which is made up of several colors. Interestingly, some people wear colored contact lenses to change their eye color.

The same is true for eyes. The amount of melanin in our irises (the colored part of the eye) helps determine its color. But since melanin itself is black or very dark brown, how can we get blue eyes? Eye colors like blue and green are produced by small amounts of melanin in our eyes in the form of very small particles that scatter light, just like small particles in the sky scatter light to make it look blue (or the milk in water shown in the picture above). It is also interesting to note that the pattern in our iris (the colored part of the eye) is considered absolutely unique. The chances of finding a person with an identical iris are so low, that you would have to check far more people than are currently living on Earth to find one!

Q: Why Does Our Pupil Change Size?

The amount of light we encounter in the world varies over a tremendous range and our eyes are able to adapt and see well. This picture shows the range of light in a single scene and how difficult it is to photograph that range (since cameras are not as good at adapting to the range of light as we are). Each portion of this image is the same scene photographed with a factor of two change in exposure (recorded light level) compared to the preceding frame. In the first image, the sunlight on the mountain is visible but the forest is dark. In the last image, the darkest areas of the forest are visible but the sky and mountain are too bright for the camera. Our eyes can view both parts of this scene at the same time!

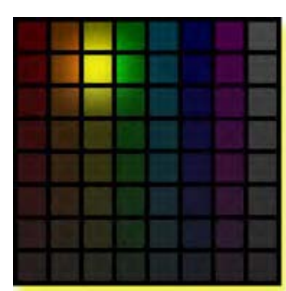
A:

As shown in the picture above, there is an amazing range of brightness in the world and our eyes are able to see well in both moonlight and bright sunlight. The pupil is one part of our vision system that helps make this possible.

The iris (the colored part of our eyes) is a muscle that controls the size of our pupil (the hole in the iris that allows light to enter the eye). The muscles of the iris respond reflexively to the amount of light we are seeing. When we look at a very bright scene, the pupils get smaller (contracts) to allow less light into the eye. This is a good thing since we don't need to allow so much of the light in to see well when the scene is bright. When we look at a very dark scene, the pupil gets larger (dilates) to allow more light into our eye. This is necessary to see well since there is little light in the scene and we have to capture as much of it as possible.

Different animals have very different pupils adapted to their environment and habits. Can you guess what animals each of these pupils belong to? I'll give you some hints. One belongs to a goat, one is my daughter's, one is my cat's, and the last one belongs to a lizard.

The pupil is just one of the features of our eyes that help us to see well almost all the time. It is part of our adaptation to the visual environment. Interestingly, the size of our pupils decrease as we get older. This probably helps compensate for other changes in our eyes as we age to keep vision as good as possible. Other methods of adaptation are described in different modules. Explore!



Eyes (Level 3)

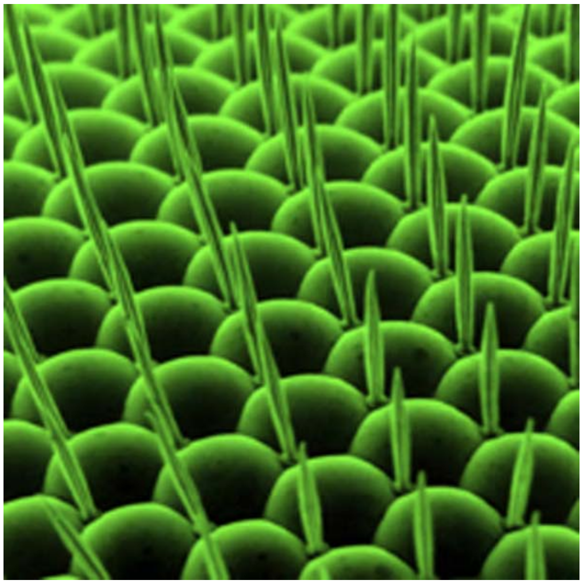
Q: How are Animal Eyes Different from Human Eyes?

One way to see how eyes are important to different types of animals is to look at their skulls. The main picture shows some cow skulls. One thing to notice is that cows have their eyes on the sides of their heads. That means that they can see things all around them, but there are almost no places that the cow can see with both eyes. As humans (skull in lower right inset), we have both eyes in the front of our heads. That means we can't see behind us, but it allows us to see depth (and 3D movies) much better. Animals that hunt usually have eyes in the front of their heads (like humans) and animals that are hunted usually have eyes to the sides of their heads so they can watch of hunters sneaking up on them. The lower left inset shows the skull of an eagle. Eagles, as hunters (predators) also have their eyes in the front of their heads and you can also see how large their eyes are with respect to the size of their heads (and brains!). That shows how important vision is to them to find their food. (Note: Eagle eyes are about as large as our own!) Eagles can see very well.

A:

There are many ways that the eyes of various animals are different from human eyes. They are different in size, shape, construction, light and color sensitivity, purpose and function. Just a few examples of these differences are mentioned here.

Color: We have color vision that is best described by the number three. Colors we se can be bright or dark, of different hues (e.g., red, yellow, green, blue, purple, etc.), and of different vividness (how much of the hue, or how different from neutral colors like white, black, or gray). Very few other animals have similar color vision. In fact only a few types of monkeys and fish seem to see color like we do. Some birds, insects, and shrimp can actually see more types of color variation than we can. Most animals cannot see color nearly as well as us. They see shades of gray and maybe on other type of change in hue; much like someone with color-blindness would. Cats, dogs, and other mammals fall into this category. But even though some of them can't see color well, they can see much better than us at night.



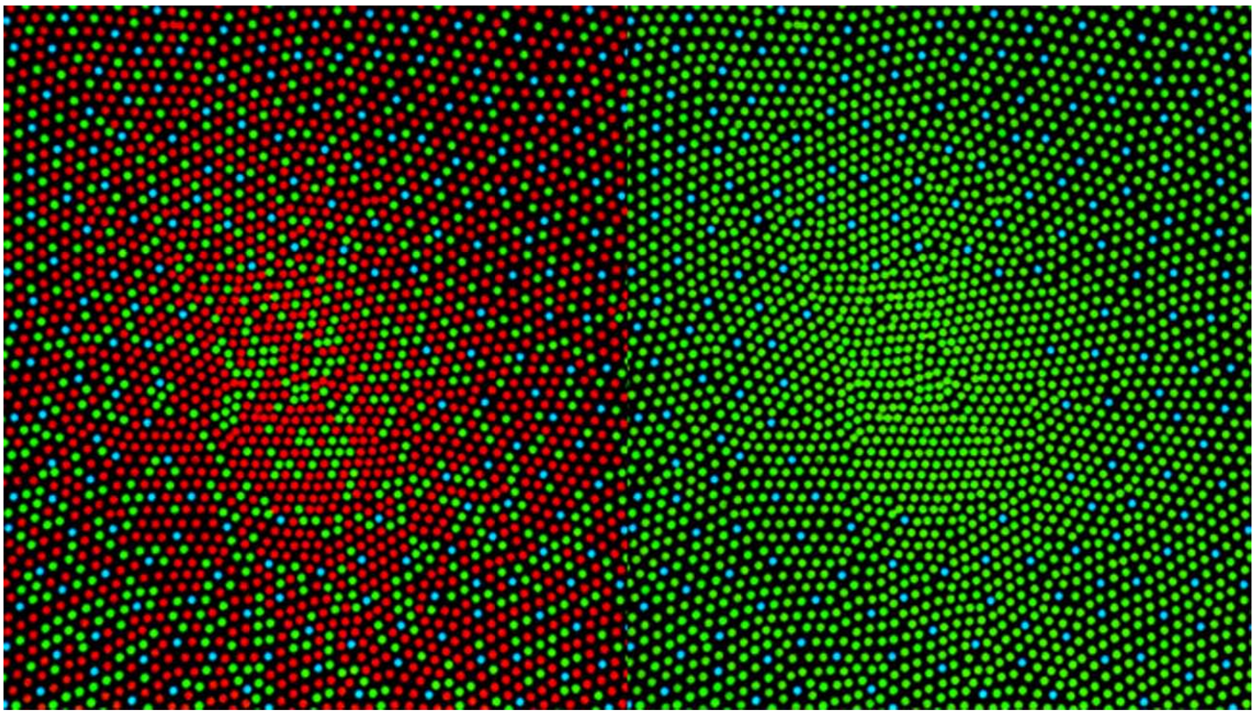
Insects have compound eyes. This is a picture of part of the eye of a fruit fly viewed with a very powerful microscope. Each section of the compound eye is sort of like an individual eye that looks at a small part of the world. In between the individual "eyes" you can see hairs that help protect the insect eye.

Purpose: Some animals, like cats, are nocturnal and their eyes are designed to be much more sensitive to light than ours. That helps them see when it is too dark for us to see much at all. Our color vision lets us do things like identify good food and find it to feed ourselves. Other animals need to see behind them in case a predator is trying to sneak up on them eat them. Others have overlapping vision in the two eyes to better be able to locate objects in the world. That's very important for animals that move quickly, or fly through the world.

Construction: Our eyes are made much like a camera with a lens, a pupil, and light-sensing cells in the back. Those eyes are great for land mammals and fish, but they are too large and complicated for other creatures, like insects, that have compound eyes. Compound eyes have a whole bunch of individual lenses focussed on different parts of the world. Each of those segments has a few light receptors, so they also don't get as much information about the world. Even stranger, some creatures, like lobsters, don't have lenses at all, but have mirrors to collect the light underwater.

Animal vision is endlessly fascinating and there is much more to learn about each of your favorite animals.

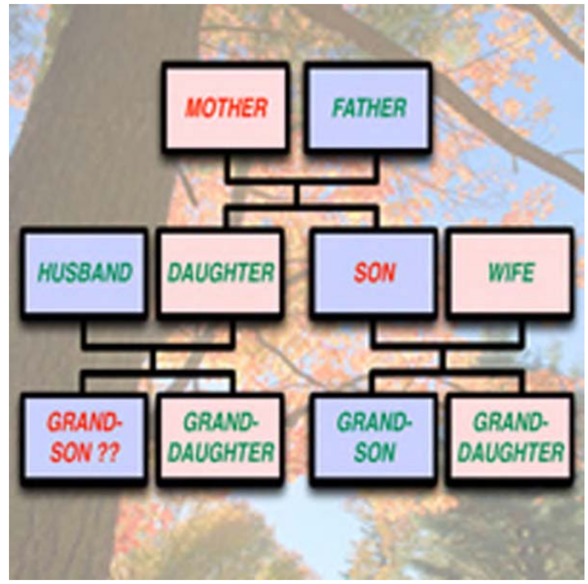
Q: Why are Some People Color Blind?



These images are a cartoon illustration of the mosaic of cones in the human retina. Each circle represents a cone photoreceptor. On the left, they are colored in red, green, and blue to represent the approximate wavelengths of light that each type of cone senses. The coloring also shows the relative populations of the various cone types. Most cones are red sensitive with about half as many being green sensitive and very few being blue sensitive. The right side of the image shows the same cone mosaic for a person with a certain type of color blindness known as protanopia. Here the protanopic observer has no red-sensitive cones. Instead all of those cones are green sensitive instead. This is one type of color vision deficiency. Another, called protanopia, would have all the green-sensitive cones replaced with red-sensitive cones. In other versions of color vision deficiency, one of the cone types is replaced with yet another type or has anomalous performance. For example, one might end up with blue-sensitive and two slightly different versions of green-sensitive cones.

A:

Genetics. We are all different in many ways due to genetics. Genetics is the study of how traits are inherited from our parents and earlier generations. For example, you might have red hair, blue eyes, or a hitch-hiker's thumb that you inherited from your parents. You might also notice that your brothers and sisters share certain traits with you that they inherited from your parents. Color blindness is one such trait. And just like we might be tall or short due to the genetic codes we inherited from our parents, we might end up with different sorts of color vision.



In most cases, color blindness is inherited and normally carried by females and expressed (present) in males. This family tree shows what might happen when a rare color blind grandmother has a daughter and son who each marry spouses with normal color vision (and who are not carriers). The son will be color blind, but his son most likely will not be. The daughter's son might be color blind (50-50 chance). Red text indicates expressed color blindness. Explore the genetics of color blindness to learn more.

While not everything about color vision and color blindness is fully understood, the inheritance of color blindness is fairly well documented. Most types of color blindness are considered a sex-linked genetic trait. Genetic means that it is inherited (not acquired from the environment) and sex-linked means that the genes that encode color vision are on the same chromosomes that determine our gender. These genes are on the X-chromosome. Females have two X-chromosomes (one from the mother and one from the father) while males have just one X-chromosome (from the mother) and a Y-chromosome (from the father). Since much information on color vision resides on the X-chromosome, women have two opportunities to inherit full, normal color vision (they must inherit two faulty X-chromosomes in order to become color blind). Males, on the other hand, only have one X-chromosome and therefore only one chance to inherit normal color vision. If they inherit an X-chromosome from their mother that encodes deficient color vision, then that's what they have.

The above explains why color blindness is so rare in females (less than 0.5% of the population) and far more common in males (about 8% of the population). Women can carry the deficiency without expressing the trait, while men that are carrying the deficiency also have the trait. As we like to remind our teenage daughter, life is not fair!

What happens when one inherits a color vision deficiency is that they do not get all three types of cone photoreceptors. Instead they only get two types. Protanopia refers to a lack of red-sensitive cones, deuteranopia to a lack of green-sensitive cones, and tritanopia to a lack of blue-sensitive cones. There are also anomalous observers who have a variant of one of the cone types instead of the normal type. Lastly, there are some rare individuals who are monochromats and can only see in shades of gray.

Q: Why Can't I See Colors at Night?

The stimulus for color hasn't disappeared at night. The problem is that there simply isn't enough light for us to perceive colors. I took this picture of Yosemite Falls at night (about 11:00PM) on an early spring evening with a nearly-full moon. I set my camera exposure time to about two minutes in order to capture enough light to make the image. You can see that it was taken at night by looking at the stars in the sky and seeing that they actually moved a little bit (well actually the earth rotated a little) during the long exposure time. This full-color night-time image shows that all the colors are still there under moonlight, but we just can't see them. The sky is blue, the water white, trees green and brown, rocks gray and brown, etc. When I was in the original location, I could only see a black and white version of the scene with my naked eyes. That is because there was only enough light for my rods to function and not my cones.

A:

You can't see colors at night because our visual systems are not designed to see colors when there isn't very much light in a scene. We actually have two visual systems that work in parallel to help us survive in the world. When there is plenty of light, we use our cone photoreceptors. There are three types of cones roughly sensitive to red, green, and blue light and we can compare the images captured with these three systems to perceive the colors in the scene. We can also see fine detail with our cones.

However, the ability to see colors and detail with our cone system means that the cones cannot be very sensitive to light. As the light levels decrease at night, we reach a point where our cones can no longer respond because there simply is not enough light for them to produce a response. In this situation, our visual system automatically switches to a second set of photoreceptors known as rods. There is only one type of rod receptor, so that means we can only see in shades of gray when our rods are working and our cones are not. The rods also gang up together to capture light over relatively large areas. This helps them to be very sensitive to the small amounts of light available at night, but it means that they cannot possibly allow us to resolve fine details.

Thus, it is our switch from the color-sensitive, but light-insensitive, cone system to the color-insensitive, but very light-sensitive, rod system that causes us to loose our color vision at night. Or as it was once written by the rock band, The Moody Blues:

Cold hearted orb that rules the night
Removes the colours from our sight
Red is gray and yellow, white
But we decide which is right
And which is an illusion

This image shows about what the scene photographed above looked like to my eyes. The contrast was low, it was less sharp, and the world appeared only in shades of gray. And all of that is due to the limits of our visual system, not due to the lack of color or detail in the actual scene.

Q: Why Do People Get Red-Eye in Photographs?

Here is an example of two pictures taken of the same person with the same camera only a few minutes apart. In both cases the camera's flash was used. The image on the left was made under the worst possible conditions for red-eye. The subject was in a completely dark room so that her pupils opened wide and the photographer was far away so that the lens and flash were very close to each other. The subject also looked right into the camera lens (and flash). The picture on the right was done outside in sunlight. This closed down the subject's pupils. Also she looked slightly away from the camera and the photographer was closer (making the distance between flash and lens a little larger). In this case the flash only served to fill some light in the shadows on the face and there is also no red-eye at all.

A:

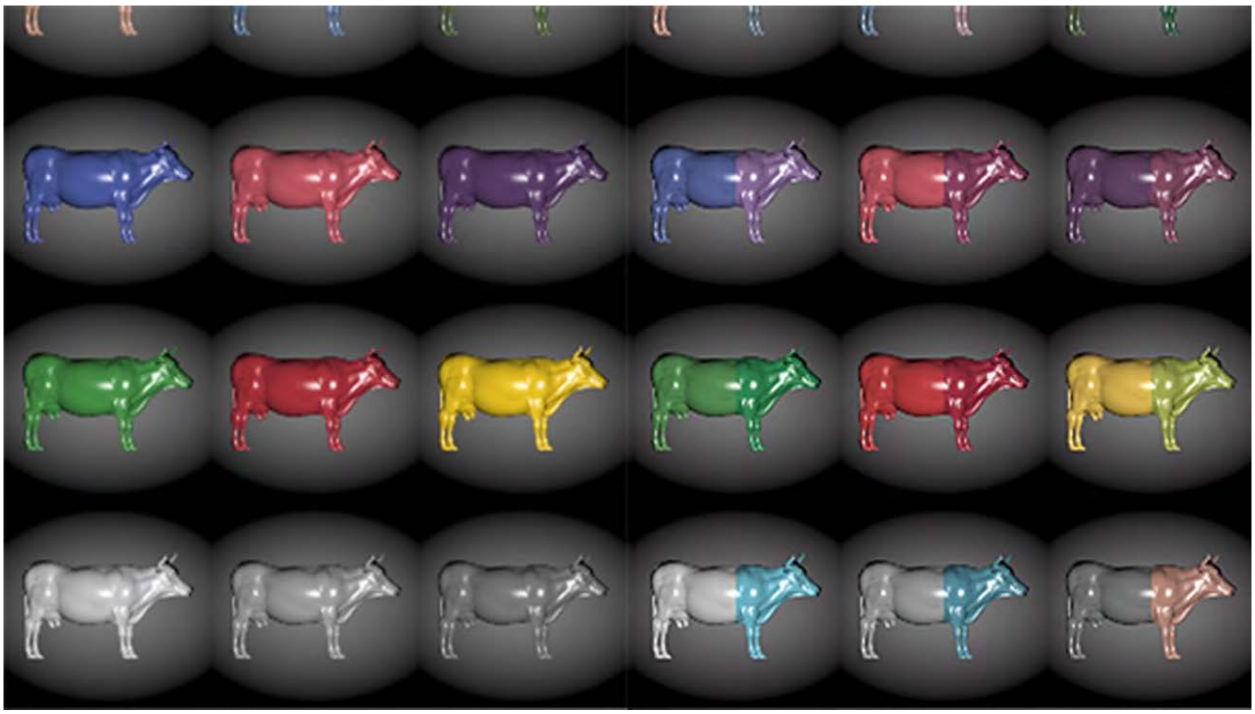
One reason is that they are looking at the camera! What this does is make an image of the camera in focus on the person's retina (back of the eye). That also means that the back of the eye is in focus at the camera and all the light from the back of the eyes goes right into the camera lens to make a bright (and blurred) image of the person's retina.

Since the retina is covered with blood vessels, the most dominant reflected color is red. It is the brightly reflected image of these blood vessels that we see as red-eye in the photograph. While such an image is always there, it becomes much more apparent under certain circumstances. These are when the flash is near the camera lens (which happens with most small cameras) and the person's pupils are wide open (which happens when it is dark and flashes are most commonly used). The combination of the flash and the wide open pupils makes for a particularly bright red-eye image.

The red-eye effect can be minimized by having some other light on the subject so that their pupils close down (some cameras do this with an extra flash before the photograph is taken), by having them look slightly away from the camera, by separating the flash from the camera lens, and by moving a little closer to effectively make the distance between lens and flash a bit larger.

Cats get yellow-eye or green-eye instead of red-eye in flash photographs. This is because nocturnal animals have a reflective layer at the back of their eyes to give them a second chance to detect the light as it bounces back and therefore make them better able to see at night. This reflection dominates any reflection of blood vessels in photographs of nocturnal animals.

Q: Why Can't We See All the Colors (Wavelengths) Within One Color?



This is a portion of the MetaCow test image. The left panel of 9 cows shows the appearance to an average human observer under fixed viewing conditions. Each cow is made up of two distinct spectral power distributions (amounts of the different wavelengths) that happen to be indistinguishable to the human eye. The right panel shows the same 9 cows as they appear when captured by a typical digital still camera. Now the front and back halves of the cows are distinguishable because the differences in wavelengths that were invisible to the human show up clearly to the camera. This is because the camera does not have the same sensitivities to different wavelengths that we do. The front and back halves of each cow are considered metameric matches for humans (stimuli that look the same color but have different spectral power distributions).

A:

It's all because of two properties of the human vision system, trichromacy and univariance. Trichromacy refers to the fact that we have three types of cone photoreceptors, each sensitive to a different range of wavelengths. Vision scientists call them long-, middle-, and short-wavelength sensitive cones (LMS as shorthand), but they are sometimes referred to as red-, green-, and blue-sensitive (RGB). Univariance refers to the fact that there are no mechanisms within a single cone type to distinguish between different wavelengths of light. L cones, for example, respond to a range of wavelengths but the reaction produced by absorbing a photon of light is exactly the same regardless of wavelength. It is just the probability of that absorption that defines the cone's response.

A glass of candies as they normally appear (left) and as they would appear if we only had long-wavelength sensitive cones (right). Note the relative brightness of the various colors. If we only had one cone type, we would see the world in shades of gray since a single cone type can't distinguish what wavelength it absorbed to produce a response.

The practical result of univariance is that there are many different ways to produce the same response within a cone. We perceive color by comparing the responses of the three cone types and since there are multiple, essentially infinite, spectral energy distributions that can produce the same response within a single cone type, there are also multiple spectral energy distributions that can produce the same combination of cone signals and therefore the same color perceptions. This is known as metamerism; stimuli with different spectral power distributions can produce the same integrated color responses.

This property of metamerism is what allows us to develop fairly simple methods for measuring and producing colors. For example, it is what allows us to have color televisions with only three primaries, red, green, and blue.

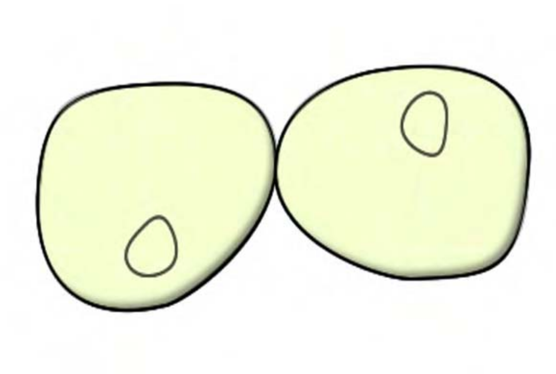
Q: Do You Attribute the Incredibly Complex Workings of the Eye to Evolution or Creation?

These two Burmese Pythons live in the Rochester (NY) zoo. One is normal with the normal brown markings on its skin. The other is what is known as an amelanistic python. Amelanistic means without melanin. Recall that melanin is the dark pigment that gives our skin, hair, and eyes their color. It is also responsible for the coloration of many animals such as the normal python. The yellow coloration is due to the presence of other pigments, called carotenoids, which are present in both snakes. Amelanistic animals are sometimes called "albinos". This abnormality can affect a wide variety of animals including fish, amphibians, birds, reptiles, and mammals. If there were an advantage for survival or mating to having no melanin pigment, then the trait could well end up dominating the species and the new amelanistic animals would be considered normal and have evolved from the original pigmented species. Unfortunately for the amelanistic animals, the trait is probably not beneficial as they would be more visible to predators and prey and perhaps not as attractive to potential mates.

A:

This question is one of the most intriguing, and perhaps most important, questions I have received amongst the thousands that have been submitted by students to this project and others. For me, there is no question that the preponderance of the scientific evidence points to evolution as the source of our species and our visual system. I say that with full sensitivity that some religious traditions teach, and believe, otherwise. That is their right and privilege, but it is not science. Science and religion should not be confused and they both have a place in society and education.
This website is about science.

Scientists use a well-established and self-regulated procedure to observe the natural world and attempt to figure out how it works for a variety of reasons (e.g., developing technology to help our lives). The process involves first making careful observations of the world and its behavior. The scientist then makes a hypothesis about how the observed phenomena might work. Then careful experiments are designed and performed to test the hypothesis through more careful observations and objective measurements. This process is then iterated upon to refine the original hypothesis and perform more tests. Once consistent, and repeatable, results are obtained, scientists then form a theory that might gain support through consensus of the scientific community. Theories are continually tested and expanded upon through the scientific process and almost all are subject to improvement. Occasionally theories are so well established and agreed upon that they are called scientific laws (like the law of conservation of energy).



Bacteria, and other organisms, reproduce asexually through processes such as the binary fission (splitting) shown in this image. This sort of reproduction allows for very rapid evolution as a mutation in a single cell replicates itself by a factor of two in each reproduction and, if the mutated version is more adapted to the environment it can wipe out the original version very quickly.

Every step in the scientific process has uncertainty associated with it and good scientists do not hesitate to report the degree of uncertainty. Unfortunately, some with political or business agendas see these statements of uncertainty and use them for their personal gain. This has led to baseless attacks on science in recent times. For example there are some who claim that there has been no warming of the climate in recent decades even though the data are unequivocal. They then take small uncertainties in the results and say that those minute possibilities prove there is no climate change and that, even if there was, it is not caused by human impact on the environment. Well, they are correct about only one point; there is uncertainty. However the uncertainty is so tiny, and the scientific consensus so strong, that I have no doubt that both the climate is warming and it is due to human activities. I encourage everyone to study for themselves, look at original results and analysis, and draw your own conclusions. Simultaneously investigate the motivations (and funding sources) of those writing what you read, including this site.

Unfortunately, the same sort of attacks have happened in the field of evolution science. There is little scientific doubt that evolution (both micro and macro) has taken place on earth. and these conclusions are backed by countless theories and observations.

Q: How Many Different Color Crayons are There?

If you were to go shopping for crayons you would be faced with very many choices. Crayola makes hundreds of different crayon, marker, pencil, and other fun coloring things. When you add in the choices from other companies, the numbers start to boggle the mind. Some way or another you can make pretty much any color you want.

A:

According to Crayola there are currently 120 colors of their crayons. Amazingly, in over 100 years that Crayola has been making crayons, they have created more than 400 different colors! You can read some more about their colors on the Crayola website. There are also other fun activities and facts about crayons there.

Right now, the biggest box of crayons that Crayola sells has 120 crayons of different colors. Not too long ago you could get a Telescoping Crayon Tower with 150 different crayons. I bought one a couple of years ago and it might still be possible to find some.

You can make your own crayons by melting old ones and mixing them together. Here I melted cyan, magenta and yellow crayons together on my stovetop (don't do this without a parent!) and you can see other colors in melted wax where it mixed together.

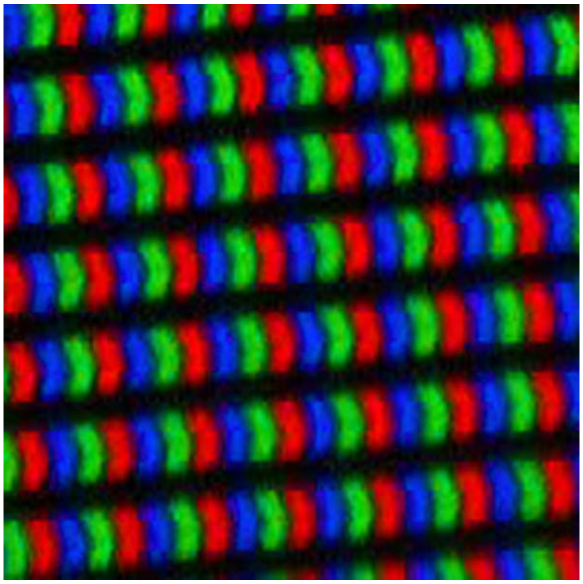
Crayola is just one of many brands of crayons. There are at least 25 different companies that make crayons sold with more than 100 different brand names. Of course some of those companies make crayon colors that are the same as one available from Crayola, but I'm sure there are some other colors out there. It's probably safe to guess that there are at least 200 different crayon colors out there in the world, and maybe even more.

Q: What are the Primary Colors?

Almost any color can be a primary color depending on how it is used and what other colors it is used with. Notice how I was able to make gray paint out of two different sets of primaries, the more traditional red, yellow, and blue set and the very untraditional set of green, purple, and orange!

A:

Red, yellow, and blue, of course! Sorry, not so fast. Even though many of us are taught that red, yellow, and blue are the primary colors in our school art classes, we have actually been misled a little bit. Red, yellow, and blue are one common set of primary colors that are often used in painting pictures. However, they are not the only set of primary colors. In television and computer displays, red, green, and blue are the primary colors. In photography, red, green and blue are the primary colors for capturing the image, but cyan, magenta, and yellow are the primaries for printing the image. In printing, cyan, magenta, and yellow are common primary colors. And when colors are made for other purposes, like house paint, plastics, and textiles, very different sets of primary colors are often used. Why are there so many different sets of primary colors?



This is a very closeup image of the primaries used in a liquid-crystal display (LCD) that you might see on your computer, laptop, or television. All of the colors you see on those displays are made up of different amounts of the red, green, and blue primaries shown here.

Technically speaking, primary colors are defined as any set of three (or more) colors for which no one of the colors can be made by mixing any of the others from the set. With this definition, the best sets of primary colors depend on what you are doing with them. That is why we end up with the most common sets being red, yellow, and blue for artists' paints, red, green, and blue for televisions, and cyan, magenta, and yellow for printing.

There is another common use of the term "primary colors". Sometimes people will talk about something being decorated in primary colors. In that case, they are usually talking about very bright, saturated colors of any of the most basic hues. These would include red, orange, yellow, green, blue, and purple.

Numbers (Level 3)

Q: Why is Three an Important Number in Color?

If we try to sort colors, like these crayons, in a meaningful way, we need three types of descriptions. The first is whether they are colorful (those on the outside) or not (the white, black and gray in the middle), the second is by hue, or color name, such as red, orange, yellow, green, blue, and purple around the circle. And the third is by how light or dark the colors are. With those three types of describing words, we can accurately describe any colored object we can see.

A:

We see color the way we do because there are three types of light sensitive cells (called photoreceptors) in our eyes that produce our perceptions of light in the daytime (there is a fourth type that works at night when there is very little light to see). These cells are called cones because some of the scientists who first saw them thought they had shapes very much like the shape of an ice cream cone. The three types of cones each respond to different types of light and can be thought of as roughly sensitive to red, green, and blue light. Different colors have different amounts of red, green, and blue light coming from them and our three types of cones can help us figure out how much of each and therefore see beautiful colors. It is the fact that there are three types of cones that makes the number three so important in color.

Those three cones result in color perceptions that can be described with three types of descriptions. These are called lightness (how light or dark a color is), chroma (how different a color is from white, gray, or black) and hue (the color names we give objects like red, green, yellow, and blue). A bright red sports car might have a medium lightness, a very high chroma, and a red hue.

Also because of the three types of cones, we can mix colored lights or materials together to make many other colors. It just takes three distinct colors (or primaries) in the mixtures to make a very wide variety of colors. As you can see, three is an important number in color for many reasons.

Three colors (sometimes called primaries) can be mixed together to make other colors. This picture shows a colorful sun mask from New Mexico (yellow with other bright colors painted on it) with overlapping circles of red, green, and blue light falling on it. Can you figure out where the different colors of light are falling and why different parts of the mask look the way they do?

Q: How Many Colors Are There in the World?

Sun dogs on each side of the rising sun are caused by ice crystals in the sky on a very cold morning. Dispersion of light in the ice crystals also produces the rainbows. Since there are ice crystals in the air between the barn and the camera, the rainbow is also visible in front of the barn. There are many colors in this scene, produced in many different ways — lights, objects, and scattering volumes. You can also notice the different colors of the snow. It is yellow where the rising sun is falling on it and blue in the shadows where only the scattered blue light of the sky falls on it.

A:

The best answer is infinity!

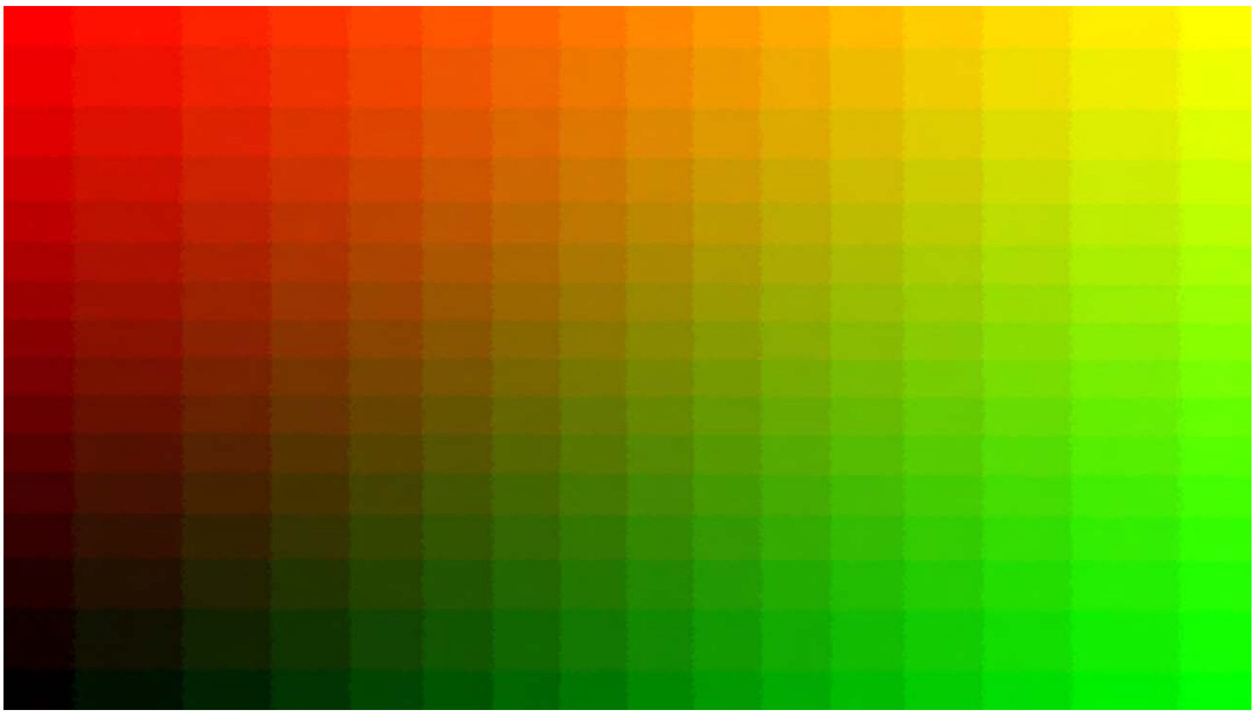
Careful measurements of our visual system's best performance have been made by psychophysicists (people who study human responses, like seeing color, to things in the world, like light). They have shown that we can see about 1000 levels of light-dark, 100 levels of red-green, and 100 levels of yellow-blue for a single, static viewing condition in a laboratory. This means that the total number of colors we can see might be about 1000 x 100 x 100 = 10,000,000 (10 million). A typical computer can display about 16.8 million colors to create full-color pictures, really far more than necessary for most situations.

There are just 24 crayons in this box, but imagine all the colors you can make with them, some creativity, and different objects to color on. Not only can you make an virtually infinite variety of colors, but other people might see them slightly differently as well!

However, the answer is not quite so simple. What color looks like is greatly affected by the viewing conditions. These conditions include the color of the lighting, the amount of lighting, and other colors in the scene. Colors also appear in different modes when they appear on different objects such as surfaces, light sources, or within volumes. Different people also have slight differences in the way they see color.

Since we can see as many as 10-million colors in a single viewing condition and the variety of viewing conditions and observers is endless, then the only truly correct answer is infinity. If we have 10-million colors, times 10-million lighting types, times 10-million lighting levels, times 10-million surrounding colors, times 6-billion people in the world, times 3 modes of viewing we get a really huge number. The result of that multiplication is 18 followed by 37 zeros (180,000,000,000,000,000,000,000,000,000,000,000,000), or 180 undecillion. That might not quite be infinity, but is close enough since all those estimated numbers are probably on the low side. And there is no way to exactly measure each of them. To learn more about the names of really big numbers, visit this site.

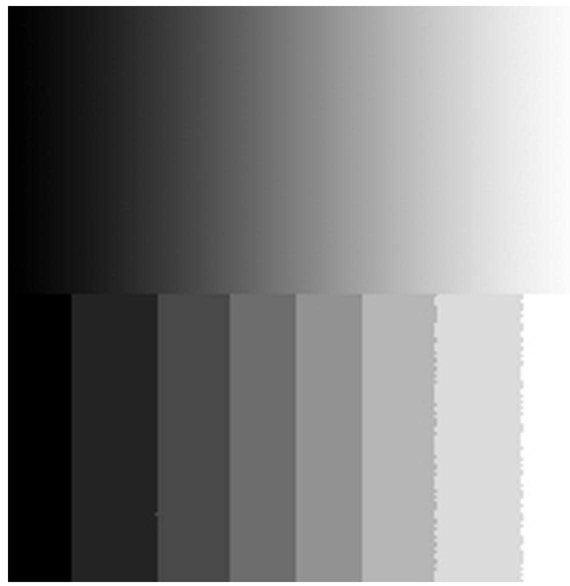
Q: How Does a Computer Represent Colors as Numbers?



In this image, only sixteen numbers are used to represent various amounts of red (R) or green (G) and all their possible combinations. The lower left (black) rectangle shows R=0 and G=0. The upper right (bright yellow) shows R=15 and G = 15. The upper left is all red (R=15) with no green (G=0) and the lower right is all green (G=15) with no red (R=0). The rest of the rectangles show all possible combinations of 16 levels of red and 16 levels of green. You can think of this picture as a graph of color with the green value increasing along the horizontal (X) axis and red value increasing along the vertical (Y) axis. Instead of showing the numbers on this graph, we are seeing the colors produced on your display by those numbers. Throughout this image, blue is set to zero.

A:

Computers represent everything as numbers. In fact, they represent everything using only two numbers, zero and one. Expressing numbers as zeroes and ones is known as using binary numbers. In computers the numbers are represented by electronic switches. An open switch represents a zero and a closed switch represents a one. With enough switches, virtually anything can be represented as numbers. Another name for these switches is "bits". These bits are stored in our computers' memories. Eight bits together makes what we call a "byte" of data. You've probably heard of how many megabytes (approximately millions of bytes) or gigabytes (approximately trillions of bytes) your computer can store. Ultimately the amount of memory in your computer determines how many numbers can be represented. Most commonly, colors are represented in computers using 8-bit numbers. This means that a set of eight zeroes and ones is used to represent a given color component. Every possible combination of eight zeroes and ones gives us 256 possible levels of color we can represent. For example the decimal integer 0 is represented in 8-bit binary digits as 00000000, while the decimal integer 255 is represented as 11111111.

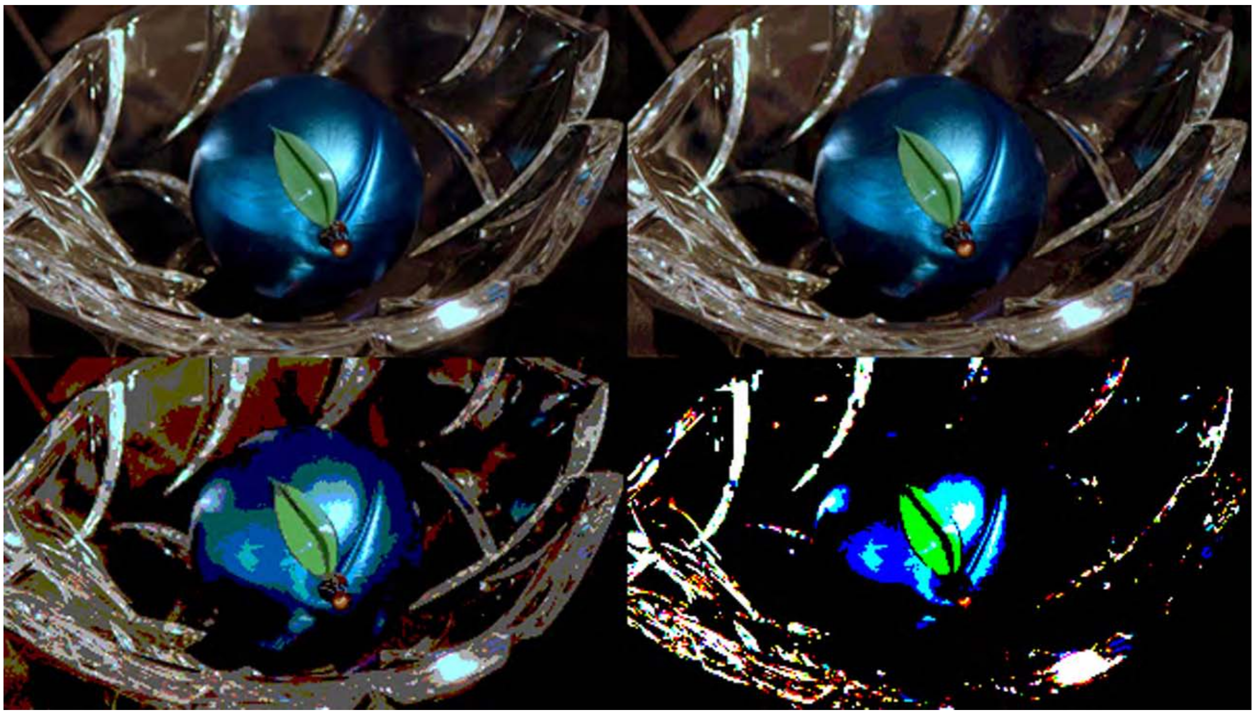


This picture shows what happens when different amounts of numbers are used to represent colors. In the top section there are 256 levels of gray (8-bits) while in the bottom section there are only 8 levels (3-bits) of gray. Most digital photographs are represented with 256 levels each of red, green, and blue.

There are many ways to represent colors with numbers. The most common method in computers is to represent the amount of red, green, and blue primary lights required to mix together to create the desired colors. This is the tradition because most computer displays work by adding together amounts of RGB primaries and the numbers can be used to directly display colors. If 8-bit numbers are used, then we can have values ranging from 0 - 255 for each of the RGB primaries of the color. In that case, black would be represented by (R=0,G=0,B=0) and white by (255,255,255). The red, green, and blue primaries would be represented by (255,0,0), (0,255,0), and (0,0,255) respectively. Similarly the cyan, magenta, and yellow secondaries would be represented by (0,255,255), (255,0,255), and (255,255,0). Intermediate colors are represented with intermediate numbers. For example a middle gray might be (128,128,128) and a pale yellow color (200,180,120).

As mentioned above, computers represent these numbers as binary numbers instead of decimal integers. Some computer programs represent colors in hexadecimal numbers. Hexadecimal doesn't have ten numerals like decimal (0123456789), but rather has 16 numerals represented by our normal decimal numerals and the first 6 letters of the alphabet (0123456789ABCDEF). Ultimately it is the display or decoding of the numbers that determines the color that you see. (200,180,120) does not turn out to be exactly the same color on all computer displays or printers. This complexity is what makes accurate color reproduction a serious technical and scientific challenge.

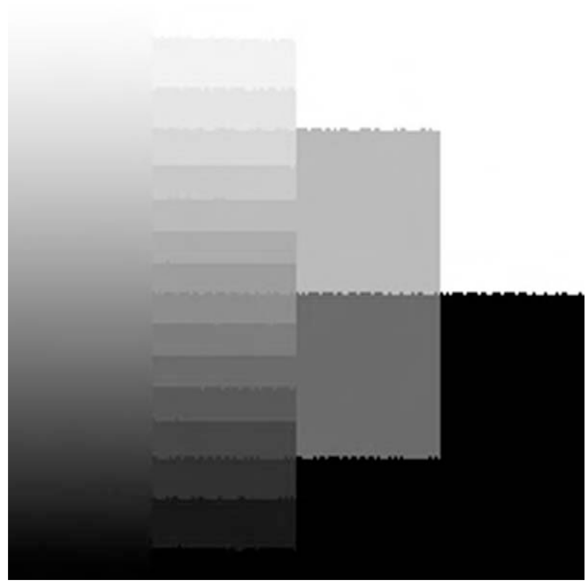
Q: Can My Computer Really Display "Millions" of Colors?



These image illustrates a color photograph quantized (or encoded) with different numbers of levels for each of the red, green, and blue primary channels. The upper left panel is encoded with 24 bits, or 8-bits each of red, green, and blue. This produces 256 levels of R, G, and B for a total of over 16.7 million possible color combinations. The upper-right panel is encoded with 12 bits (4 bits, or 16 levels for each RGB channel) for a total of 4096 possible color combinations. The lower-left panel is encoded with 6 bits (2 bits, or 4 levels for each RGB channel) for a total of 64 possible color combinations. Finally, the lower-right panel is encoded with 3 bits (1 bit, or 2 levels for each RGB channel) for a total of 8 possible color combinations. Incidentally, this is an image of a glass plum with a blue aurene finish. Blue aurene is an application of gold on the surface of the glass (or crystal) to produce an iridescent blue finish. This finish was made famous by Steuben Glass in the early 1900s.

A:

Not really. In theory most computers can produce about 16.777 million different color combinations for display on the monitor. This number comes from the fact that each of the red, green, and blue primary channels used to control the computer display is controlled with an 8-bit number. An 8-bit number can have 256 possible levels ranging from 0 to 255. Zero is used to represent the color channel being fully turned off while 255 represents fully turned on. Thus a black color is encoded with 0,0,0 for R,G,B while white is encoded with 255,255,255. Since there are 255 possible levels of red, green, and blue and each is independent of the other, then there are 255 x 255 x 255 different color combinations that the computer can theoretically display. 255 x 255 x 255 = 16.777 million and that is where the term "millions of colors" used for computer displays came from.

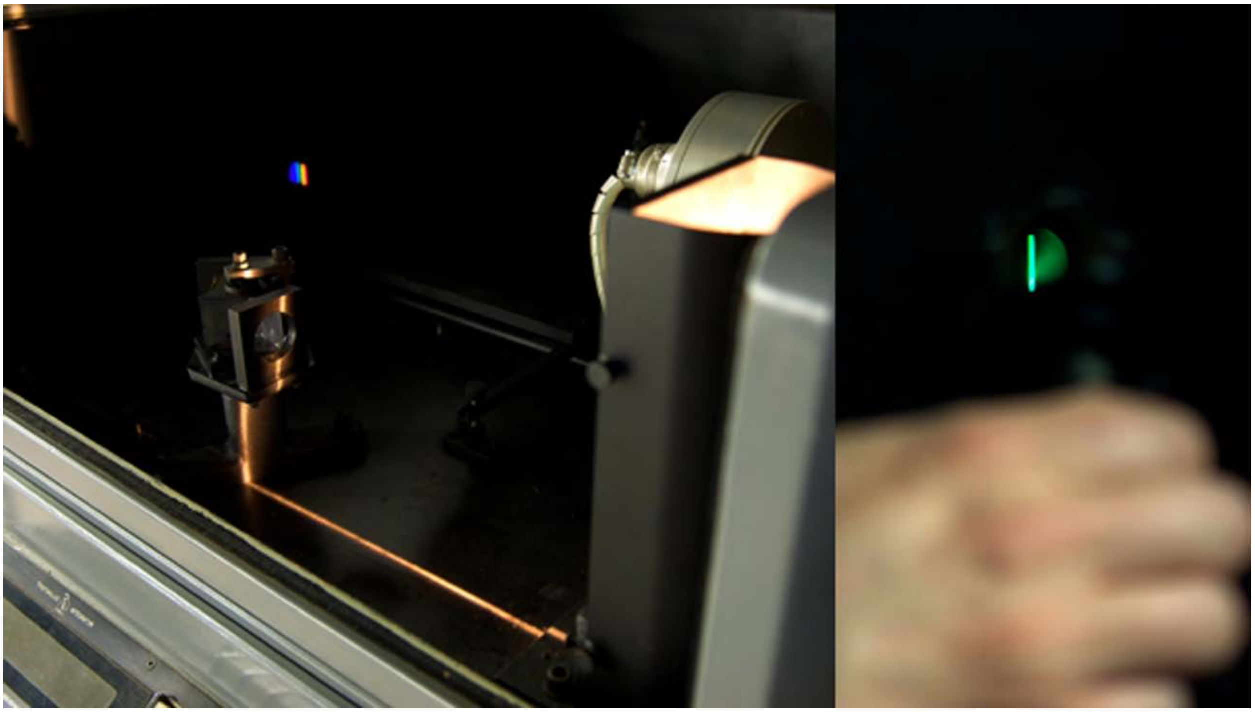


This image shows the same quantization as the color image above. From left to right are 256 gray levels (8-bits), 16 gray levels (4 bits), 4 gray levels (2 bits) and 2 gray levels (1 bit). In the color image, these numbers of levels (or bits) are used to encode each of the red, green, and blue primaries.

However, theory and practice are different. First of all, no computer displays have 16.777 million pixels, so it is not possible to display all of those color combinations at the same time. More typical displays have about one or two million pixels and therefore it impossible to display more than that many colors, even theoretically. Secondly, many of those color code combinations do not produce distinct colors. For example many of the color codes that are close to zero would all look black to us, so it is not correct to suggest that they are all separate colors when we cannot possibly tell them apart. (And remember, color is a perception.)

Realistically, for most images and typical viewing conditions, an encoding with 5- or 6-bits per channel is indistinguishable from one with 8-bits per channel. That means that an image with around 33 thousand color combinations is usually indistinguishable from one with all 16.777 million possible color combinations. Therefore it is more realistic to say that the computer can really display only thousands of colors, not millions.

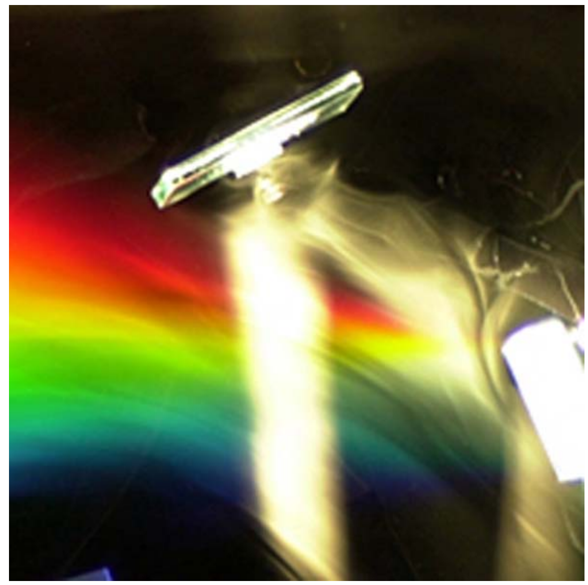
Q: How Are Colors Measured?



The first photo-electric recording spectrophotometer was invented by Arthur Hardy and marketed by General Electric. Prior to this instrument, measurements of material spectral reflectance were made using visual comparisons in a very tedious and time-consuming task. This instrument is built on a cast-iron base and requires four strong individuals to lift and move it (one on each corner!). Modern spectrophotometers can be held in one hand and carried from place to place in a backpack. The left panel of this image shows the light source of the instrument casting a beam onto one of its two prism and then a mirror/knife-edge combination selecting a green wavelength for measurement (you can see blue, yellow, and red light in the image, but green has passed through to be measured. The right panel shows my hand opening the sample holder and that green wavelength illuminating the point the sample would be placed for measurement. The instrument would then measure the ratio of the amount of light reflected from the test sample to the amount reflected from a white reference to determine spectral reflectance at that wavelength. The process is repeated (automatically) at all the other visible wavelengths to obtain a spectral reflectance curve.

A:

There is an entire scientific field called colorimetry, which means color measurement. The process of colorimetry mimics the process of human vision. Assuming we want to measure the color of a material that reflects light (like paint ... similar procedures are followed for measuring light sources or transmitting materials), the first step is to measure the object's spectral reflectance. This is the percentage of light of each wavelength that is reflected by the object and it is measured with an instrument called a spectrophotometer. We must then decide what light source to illuminate the object with for the measurements. This is done mathematically by selecting a standard spectral power distribution for the desired type of illumination (*e.g.*, daylight, incandescent, fluorescent, *etc.*) and multiplying the energy in the light source by the percent of that energy reflected by the object wavelength by wavelength. This defines the stimulus energy that reaches our eyes. We then use standard visual response functions, known as color matching functions to figure out how much of that energy is absorbed by each of the three cone types. These numbers are called tristimulus values and define color matches. One standard set of tristimulus values are known as CIE XYZ.



I have built a spectrum projector to show students in my classes how a spectrophotometer works. This shows a small part of it where light comes from a source below the image, strikes a mirror at the top and is then reflected from a diffraction grating (at right) that splits the light into the different wavelengths at different angles. The light in this image was made visible by fog from dry ice dropped in warm water.

XYZ tristimulus values define color matches, but they don't tell us what a color stimulus looks like. To do that, we need to account for adaptation to the viewing environment and the fact that the visual system responds nonlinearly to amounts of light (*e.g.*, a light with twice as much energy as another does not appear twice as bright). Another set of mathematical equations define a color space known as CIELAB with dimensions that roughly correspond to perception. These dimensions are L* for lightness, a* for redness-greenness, and b* for yellowness-blueness. Alternatively, the CIELAB color space can be expressed in cylindrical coordinates with L* still for lightness, C* for chroma (related to colorfulness), and H for hue angle (red, yellow, green, blue, *etc.*)

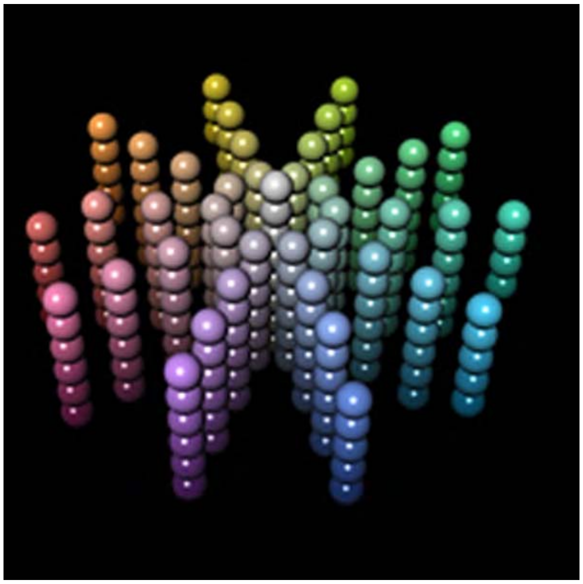
The CIELAB color space is widely used around the world to define color materials and set tolerances for commerce. Most colored products that you can buy were evaluated in the CIELAB space to make sure they were produced in the proper color. However, some situations call for even more complicated mathematical models. For example sometimes the absolute amount of energy in a scene or the properties of the visual environment are important. In these cases, a type of model known as a color appearance model is used. CIECAM02 is one example of a recent, and widely adopted, color appearance model. In addition to predicting apparent lightness, chroma, and hue, it also has predictors of brightness, colorfulness, and saturation.

Q: How Many Dimensions Are Required to Describe Color Appearance?

This image of the RIT Tiger provides all the information needed to answer the question. The image itself is represented with three dimensions of information (RGB digital values) and that might suggest that only three dimensions are needed. However, examination of the image also shows there are at least two environments represented in the picture, direct sunlight illumination and shadow areas. In fact, some objects are visible in both the sunlight and shadow. Thus it takes more than three dimensions to describe their appearance (RGB values in sunlight and RGB values in the shadow). Due to perceptual, and physical, correlation between the object in sunlight and shadow, all six dimensions are not required. Instead, five are adequate. These are the lightness, chroma, and hue that describe the object properties and the brightness and colorfulness that also describe the illumination environment.

A:

Most would answer this question with the number three. After all, even this website can be quoted as saying that three is the most important number in color science. The visual system has three types of cone photoreceptors, we can describe objects with three appearance attributes (lightness, chroma, and hue), and we can make metameric matches to objects with just three primary colors (as in color television). There are also a plethora of three-dimensional color spaces used in various aspects of color science and technology. So how could the answer be anything other than three? It is, the correct answer is that it takes more than three dimensions to full describe color appearance and the most probable number is five.

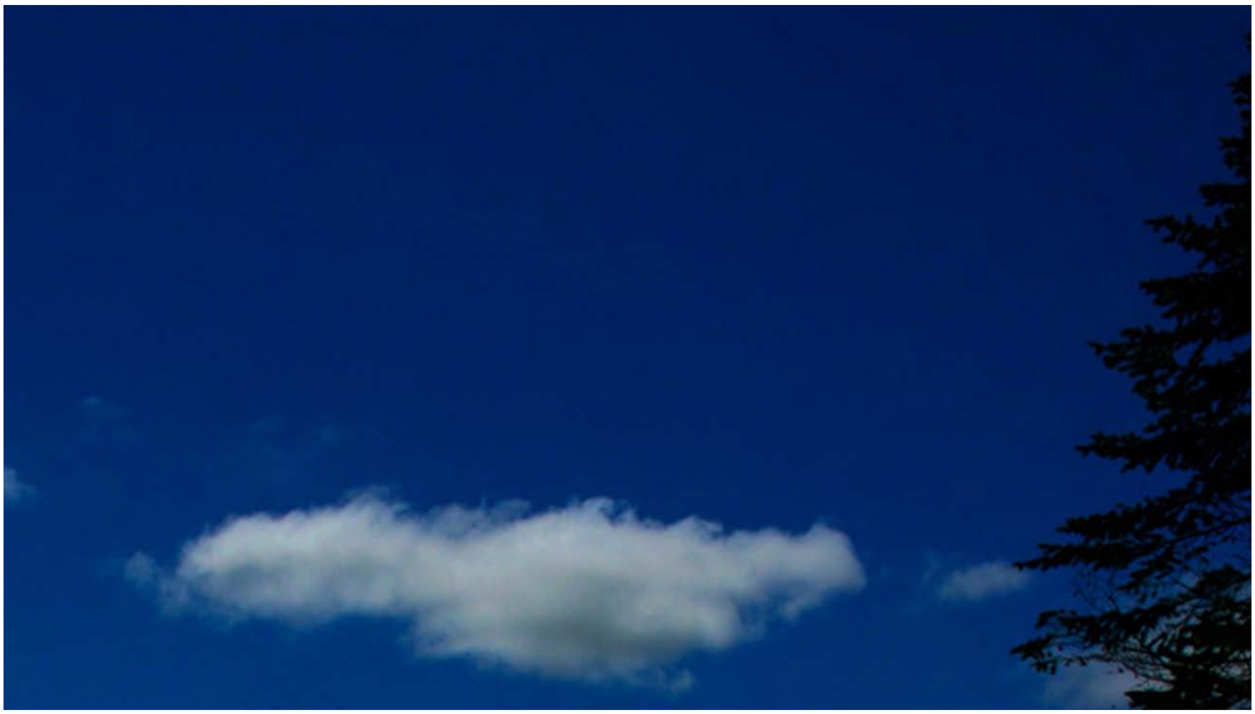


This is a computer graphics rendering of the Munsell Book of Color. The Munsell system divides color into three perceptual dimension of lightness, chroma, and hue. That works for object colors (relative appearance), but it does not address brightness and colorfulness.

There are actually six distinct terms that are used to describe color appearance. These are brightness, lightness, colorfulness, chroma, saturation, and hue. So if all six of these dimensions are independent, then it would take six dimensions to describe color appearance. In reality, colorfulness, chroma, and saturation are inter-related in such a way that only two of those three are required for a full description of appearance. Thus, the final answer that five dimensions are required to describe color appearance. There are a class of color spaces, known as color appearance models, that include all six of these dimensions. While there might be alternative viable theories of color perception, it is clear that the overall description does require more than three dimensions and that is due to our ability to perceive attributes about the illumination environment in addition to the relative color attributes of objects. The definitions of the perceptual dimensions are given below.

All of the dimensions are attributes of visual perception (recall that color is a perception, not a physical quantity). Brightness is our perception of the amount of light coming from a stimulus. Lightness is the brightness of a stimulus relative to something that looks white under the same illumination (lightness is relative brightness). Colorfulness is our perception of how much hue content (difference from neutral gray, black, or white) is present in the stimulus. Saturation is colorfulness relative to the brightness of the stimulus (like lightness is relative brightness, saturation is relative colorfulness). Next, chroma is colorfulness relative to the brightness of a similarly illuminated white (again, chroma is relative colorfulness, but in a sense different from saturation). Saturation and chroma describe similar dimensions of appearance, but in different ways. For the mathematically inclined, chroma can be thought of as the an expression of colorfulness in cylindrical coordinates while saturation expresses the same information in conical coordinates. Lastly, hue is the attribute of appearance that is often colloquially called "color". Hue is the similarity to red, green, yellow, or blue, which are all examples of hue names.

Q: What's My Favorite Color?



Blue! When lots of people are asked to name their favorite color, the most popular choice by far is blue. Nobody knows why. Do you have any ideas? Maybe because the sky is blue, or because clean sea water is blue. What is your favorite color?

A:

Blue? If I had to guess your favorite color, my first guess would always be blue. Why? Well, for some reason that is the most popular color when people are asked what is their favorite. Of course your favorite color is a personal choice and it can be any color you like. And even though some people might try to tell you otherwise, your choice of a favorite color really doesn't say anything about you or your personality. My favorite color is red.

Do you have a favorite toy, stuffed animal, or food? I would guess that you do. We all have favorite things and each of our favorites is a personal decision. Nobody else can change your mind about that, unless you let them.

Crayola has done a survey on America's favorite crayon colors and their number one choice is blue, followed by cerulean blue, with several other shades of blue in the top choices. When I ask my students to name their favorites, blue always comes out on top.

Your favorite color also can change throughout your life. When I was young, my favorite color was green. When I went to college it was orange. A little later on it became red and that has been my favorite for some time now.

I found an interesting internet survey on favorite colors here. It shows more about the popularity of favorites for a bunch of different people. He also found that blue was most popular!

Q: Why Do Colors Fade in the Evening?

I took this photograph of a bright sunny autumn day in the Adirondacks. Then I changed the right side of the image to simulate what the same scene would look like when illuminated by dim moonlight. Most of the color would fade away, red areas would be darker than blue areas (called the Purkinje Effect), the scene would not be as sharply focused, and the perceived contrast (difference between light and dark areas) would be reduced. Some artists create night scenes as very bluish in color since blue areas tend to look brighter. Look at a very dark night scene and decide for yourself if it is more blue or gray.

A:

Our eyes have an amazing ability to see well over very large ranges of brightness from starlight to bright sunlight. The change in size of our pupils helps us to see well in both bright and dim light, but there are other features of our eyes at work as well. In fact, we really have two visual systems in each eye. One is best when there is plenty of light, can see fine details (like reading a book), and can see color. The other cannot see color at all, but is much more sensitive to light so it works well when there is little light available. That system also cannot see fine detail well at all. That's why we can't read books in the dark!

This star trail image was made by my daughter using a digital camera with a 30-minute exposure time. In that long time, there was enough light for the camera to respond and the stars moved in the image since the earth was rotating. Note that the stars have different colors that we normally cannot see since they are so dim. The yellow sky is due to light pollution from a nearby town.

There are two types of cells in our eyes (technically, two types of photoreceptors in our retinas) that create these two systems. One type are called cones. The cones produce color vision, work in bright light, and resolve fine details. The other type are called rods. Rods cannot see different colors, only light and dark, but are very sensitive to light. To get this added light sensitivity, rods have to capture light across large areas of the eye and that means they cannot see fine details.

As night approaches and the amount of light in a scene drops, our vision system automatically switches from using the cones to using the rods ... and our perception of colors fades away.

Q: Why Do Flowers Have Different Colors?

These are gorse bushes in full bloom along the coast of Oregon. They are also well-known for their presence on the seaside golf courses of Scotland. The bright yellow blossoms colorfully paint the often gray seaside dunes for several weeks each year. The large numbers of blossoms help the gorse to reproduce strongly and quickly grow over large areas. This is so effective for the gorse, that some consider this beautiful plant a weed. If you've read Winnie the Pooh, you might remember that once he found himself falling painfully into the sharp thorns of a gorse bush (those thorns serve to protect the bush from potential predators, furthering its ability to reproduce and spread).

A:

Simply put, flowers are colorful for one main purpose, survival. Flowers are the reproductive systems of plants and are therefore responsible for assuring that the plants can survive from one generation to another. Their bright and varied colors help make reproduction and survival possible in several ways. One way is by attracting insects that carry pollen from one flower to another allowing the reproduction process to continue through the creation of fruits and fertile seeds. The distribution of these seeds also might require the help of other animals and that is helped along by making the fruit so delicious and nutritious. Animals eat the fruit and then distribute the seed, and fertilize it, through their manure. Bees provide one example of an insect that benefits from colorful flowers and, in turn, benefit the plants through their work.

Flowers don't look the same to all creatures. The left side of this picture shows the colors of a black-eyed susan flower as we see them. The right side shows the patterns in the flower when viewed with ultraviolet (UV) energy. Bees can see this UV and the patterns are thought to attract them to the flower's nectar (food for the bees) and pollen (survival for the plants).

The bright colors of flowers (and patterns in the reflected UV, or ultraviolet, energy) attract bees to flowers and even to specific areas on the flowers. The bees like the flowers as a source of sweet nectar, which they process into honey for their food. The flowers like to attract the bees so that pollen from their flowers can attach itself to the bees for free ride to another flower. This transfer of pollen from one plant to another is required for the plant to reproduce and survive (or in some cases for it to produce delicious fruit). Thus, the colors of flowers can be directly responsible for the plant's survival and those plants with flowers that best attract the bees have the best chance for surviving and evolving. More about the ultraviolet and infrared appearance of flowers can be found at this interesting website where there are example pictures of many varieties of flowers.

It has been suggested, and is likely true, that some flowers have evolved simply to please people with their beauty. These beautiful flowers are assured of survival because humans will see to it that they can reproduce and survive through careful cultivation and gardening. Michael Pollan describes this co-evolution of humans and plants in a fascinating book, *The Botany of Desire*.

Q: What Does the World Look Like to Color Blind People?

This picture shows some nice ripe apples in an orchard. On the left is the view of a person with normal color vision. Note how the ripe fruit contrasts nicely with the green foliage. This makes it easy for humans to find (and eat) the ripe fruit. Identifying ripe fruit is thought to be one of the environmental situations favorable to the evolution of trichromatic human color vision. On the right is a simulation of what a deuteranope might see. A deuteranope has no green-sensitive cones and therefore loses the ability to discriminate red-green color differences such as the differences between ripe apples and leaves.

A:

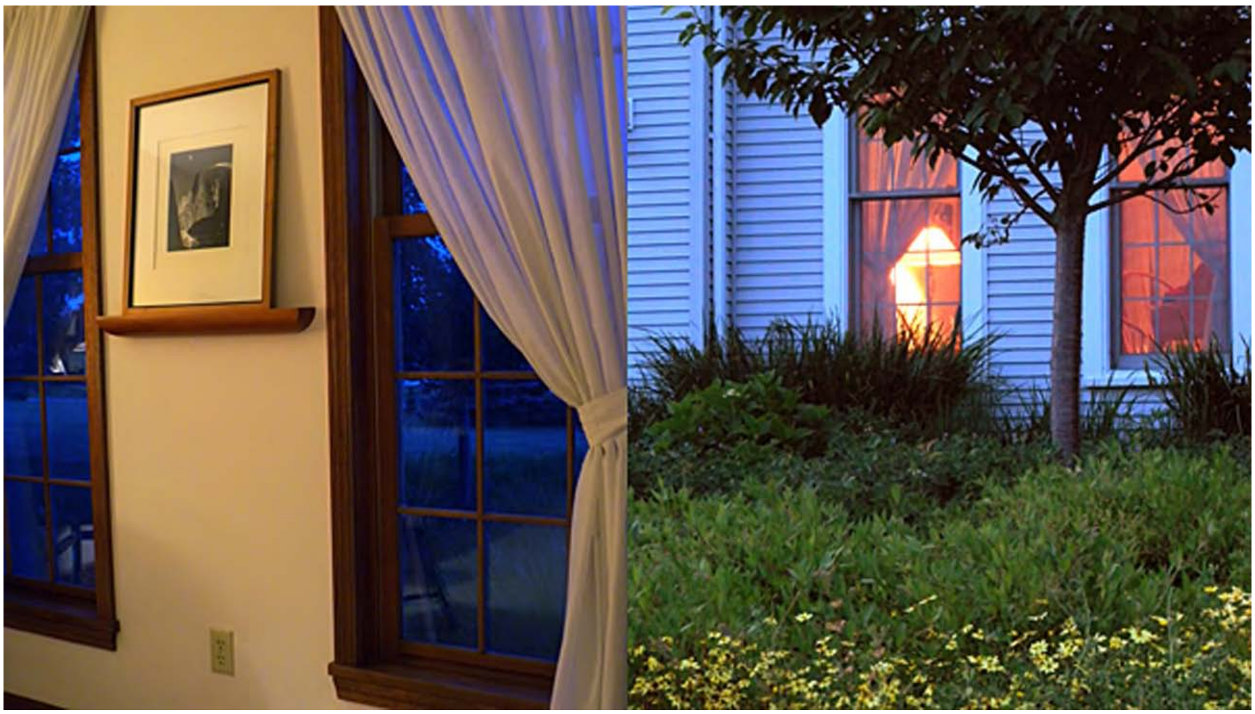
This is a very difficult question because we can never truly know what someone else is perceiving and a color-blind person can't really describe colors in a way that is meaningful to those with normal color vision. We can, however, make some reasonable guesses and there is an interesting website, *vischeck.com*, that does just that. The image of the apples above was made using the software from that site.

We know that color-blind people are missing one of the cone types, so we can take a full-color image, transform the information to normal cone responses, delete one of those cone responses, and then transform the image back to RGB for display to see what they are missing. This does tell us which colors would be confused by the color-blind observer, but it doesn't really tell us what they look like since we are still viewing them with a normal color vision system. This technique also does not account for visual adaptation. The software at *vischeck.com*, does this first step, but it also approximates visual adaptation. It does that by assuming that equal cone responses produce neutral color perceptions (white, gray, black) in color-blind people, just like they do in others. This defines what looks neutral to the color blind-person and maps those colors to the grays that a person with normal vision sees. That gives us a better idea of what the color-blind person might be perceiving.

In very rare cases, people have monochromatic vision. That is, they see in black and white. Some of these people have only one type of cone while others, known as rod monochromats, have no cones at all. Rod monochromats have only rod photoreceptors and cannot see well in bright light. They see like everyone else in dim light.

However, we still can't be completely certain. All we can really do is ask a person with color-blindness if the original image and the processed image (left and right sections in image at left for a deuteranope) look alike. If they do, then we know we have removed the correct information, but we still can't say that we are seeing the same thing they are. And we never really will be able to. That alone is something to ponder!

Q: Why Can I See Well Outside When My Mom (Who's Inside) Thinks It's Too Dark to be Out?



Here are two views of the same place at the same time. It was dusk and in the first view, I was inside looking out through the windows. My room inside was illuminated with yellowish incandescent lights, but it looked fairly neutral to me because of adaptation. Looking out through the window, outside appeared quite dark and bluish like in the left side of this image. However when I went outside, things looked fairly normal since my visual system could adapt to the low light level and bluish color of the sky light (the sun had set). In that case, when I looked inside the house, the illumination looked very bright and yellowish. When we are adapted to the bright and yellowish light inside, then outside looks dark and bluish. When we are outside and adapted to the dark and bluish light, then inside looks much brighter and yellowish. The only thing that changes is the way our visual system adapts to the scene (and I made my camera mimic that behavior!).

A:

Adaptation! It all comes down to how our visual systems adapt to their environment. We are normally interested in identifying objects in our environment and less interested in identifying the color and level of illumination. Imagine a white piece of paper. When we view it on a bright sunny day, it looks white. When we view it at dusk after the sun has set, it looks white. When we view it under the very yellowish illumination produced by incandescent light bulbs (or the even more yellow illumination of a candle), it still appears white. This is because our visual system has adapted to the prevailing levels and colors of illumination in order to be able to better judge the relative colors of objects in our world.

We don't completely adapt to all changes in illumination. When it gets very dark, our vision transitions from cones (seeing color) to rods (only seeing black and white) much like this image illustrates the same flowers in daylight and how they would look at night. Since our rods don't respond to yellow light, the bright flowers look dark at night.

When your mother is inside at dusk, she has probably turned on some lights and gradually adapted to that level of illumination. As it gets darker outside, she does not adapt to that change and when she glances out she notices that it appears very dark outside and calls her children in. The children, on the other hand, have been outside the entire time and adapted to the gradual change in the color and amount of light. The world outside still looks completely normal to them and they can still see fine when their mother seems to arbitrarily decide that it is too dark to be out. This change in appearance due to adaptation is illustrated in the images above.

Adaptation is a very powerful property of our visual system (and other perceptual systems) that allows us to easily detect changes in the world around us. For example, if you eat some sugar you will adapt to sweetness and when you taste some plain water it might seem bitter or sour. When you are very hot, a cool glass of water might feel very cold, but if you just came inside on a cold winter's day, that same glass of water might feel warm. If you spend time in a room full of tobacco smoke, you will gradually adjust to the smell and it won't seem as bad is it would if you walked into the same room from the fresh air outside. If you are in a room full of loud noises, then you can't hear a quite voice while if you are in a perfectly silent room, you can hear almost anything. These are all examples of adaptation and our visual system is very capable of adapting to changes in color and light level as well.

Q: What is the meaning of different colors?

A red stop sign is widely recognized in many cultures. So much so that the shape and color alone are often enough to signal the intent. As such, we have learned to associate the color red with the action of stopping or the presence of danger. But is there anything intrinsic about red to create that association. Probably not as we could have all learned to associate any consistent color with stop signs, but red does have some natural correlates with danger through the color of blood and fire. Of course there are also favorable red stimuli in nature (e.g., ripe fruit, mating signals). The white wedding dress also represents another fairly common, but not universal, association of a meaning with a color. While the white wedding dress is often considered a representation of purity, the origin is actually from gowns worn by women making religious vows in the Catholic church. (Blue was historically used to represent purity). In some cultures, red is worn for wedding dresses as a color that represents good luck. Clearly, the colors themselves do not have any intrinsic meaning, but the cultural traditions relating to colors create certain interpretations.

A:

Colors in and of themselves have no intrinsic psychological meaning. Instead it is the association of colors with certain events or cultural traditions that can result in the colors seeming to have meaning all on their own. Even with such strong cultural traditions and relationships, it is easy to illustrate that the colors have no meaning on their own with simple counterexamples. While red might signify danger to you, it might evoke happiness and good luck in me. It is not the color red that has meaning, but instead our learned relationships that might seem to create such meaning.

Despite the clear lack of any scientific evidence to link colors with specific psychological meanings or influences, there are many publications that claim to describe exactly what those relationships are and how to decorate a room, dress yourself, or create product packaging in order to produce the intended response in your unwary "victim". It is fun to read about these interpretations, but read such descriptions with a critical eye and think for yourself whether they make sense. For a balanced and critical examination of these topics, I suggest the books by Faber Birren (*Color and Human Response*) and Jean Bourges (*Color Bytes: Blending the Art and Science of Color*) that are referenced in topic 8 of The Color Curiosity Shop.

A related topic is the *Lüscher Color Test*. The Lüscher test has a subject rank order a series of color stimuli, usually eight, by preference. The theory is that the ranking one selects indicates deep-seated psychological tendencies that are not necessarily consciously understood. More recent research has tended to discredit the test by showing that the results do not correlated with more thorough and accepted personality assessments. You might be able to understand this if you read the results of a Lüscher test with a critical eye. The stated results tend to be very generic statements that could apply to anyone, much like horoscopes. Regardless of the scientific validity, the exam and results can be amusing.

The colors of signal lights have come to have specific meanings, sometimes transferred to other contexts, because of their familiar and common use. We use red for warnings/stop, yellow for caution, and green for safety/go in many situations. Can you figure out how I got all three lights on in a single photograph?

Q: If No Light Falls On an Object Does It still Have a Color?

"If a tree falls in a forest and no one is around to hear it, does it make a sound?" This is an interesting philosophical riddle that probably dates to the mid 1800s in its modern English-language form. Certainly similar riddles date back many centuries in other cultures, probably as long as recorded history. To me, the answer is simple. Since sound is a perception and no one was around to hear it, the tree did not make a sound. (That answer also assumes there were no other animals capable of perceiving sound around, which is highly unlikely.) Color is also a perception, so I like to ask students if the tree has a color. The answer is still "no". This image is of a fallen giant sequoia tree in California's Sequoia National Park. Giant sequoias are the world's largest trees in terms of total volume and grow to typical heights of 165-280 ft. (50-85 m). They are thought to essentially live forever with the oldest measured specimen being over 3500 years old. Their wood is very resistant to decay and fire and it is thought that the only way a sequoia dies is that it is knocked over. Since their wood and bark is brittle, they tend to shatter when they fall, as shown in the picture. Imagine the sound!

A:

Like the philosophical question about the sound of a tree falling in a forest, this is a question of perception. Since color is a visual perception and light is the stimulus that produces visual perception of objects, then with no light there is also no color. At least there is no color that belongs to that object. We might still perceive color due to the dark noise in our visual system. For example, when we are in a completely darkened room for a long period of time (so that we completely adapt), the perception is not one of black (which only exists as a related color), but one of a noisy (or grainy) dark gray.

"In clapping both hands, a sound is heard. What is the sound of one hand?" This is a famous Zen koan (or philosophical riddle) that Zen Masters use to help guide their students. It is in many ways similar to the question posed on this page. Note: This koan is often paraphrased as "what is the sound of one hand clapping", which is clearly a different question. One story of a correct answer is that the student simply thrust one hand forward to strike the teacher!

It is, of course, possible to perceive color without visual stimulation, but such colors would not be associated with specific objects in our environment since we couldn't see them. Dreams are one example. We can have clear color perceptions of imagined objects when we are dreaming. And, yes, people do perceive dreams in color. Although for some people it is difficult to recall dreams and some people do claim that their dreams are only in black and white. Another non-visual color perception comes from pressure on the eye. If you press gently at the corner of your eye you will see some bright flashes due to this pressure. These are known as pressure phosphenes. It is not very good for your eyes to press on them, so I don't recommend doing this experiment more than once and even then be very gentle. One could also consider afterimages as non-visual color perceptions since they result from the removal of the light stimulus rather than its presence. However, they are really still produced by visual stimulation.

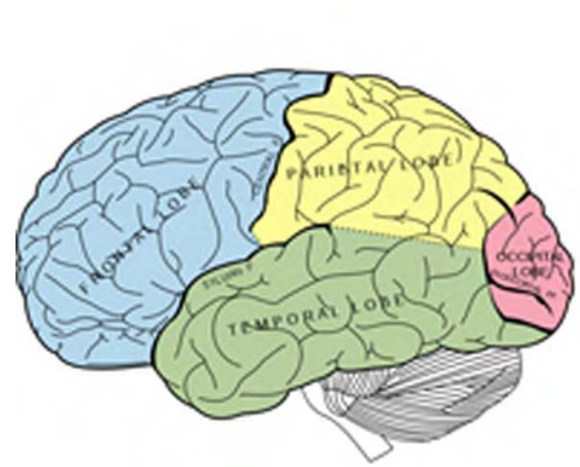
These types of questions can never be answered definitively. That's what makes them philosophical in nature. It is fun to ponder them and discuss the possible answers with others. Such thoughts and discussions can lead us into greater insights about ourselves and the world around us. Another one to ponder from *The Gateless Gate* ... "The wind is flapping a temple flag, and two monks were having an argument about it. One said, 'The flag is moving.' The other said, 'The wind is moving.' They argued back and forth but could not reach the truth. The sixth patriarch said, 'It is not the wind that moves. It is not the flag that moves. It is your mind that moves.' The two monks were struck with awe."

Q: Why Is Color?

Color science can be described with a triangle and this same triangle is sometimes used to answer the question "What is Color?" The triangle is represented in this image by connecting the light source (the light bulb) to the object being observed (the color markers) and then to the observer's visual system (eyes and brain). The third side of the triangle connecting the observer with the light source is also important. Color perceptions are produced by light from the source interacting with the objects with the reflected light reaching the observers eyes, which in turn send signals to the brain that can be interpreted as color. The apparent color is also influenced by the observer's adaptation to the illumination (the third side of the triangle). In color science, physics is used to describe light sources, physics and chemistry to describe materials, and then anatomy, physiology, and psychology to describe the observers' responses.

A:

This seems like a strange question. However it is so important that it is actually the name of this website whyiscolor.org. More typically people ask (and answer) the question, "What is color?" That is simply to answer; color is a human perception! "Why is color?" is far more difficult to answer and that is the way we have come to prefer to ask the question in our laboratory (the Munsell Color Science Laboratory). In answering why, one can ponder the reasons we have the perception of color as well as how those perceptions are produced. The image above and its explanation describe how color perceptions are produced and they go a long way toward explaining why. After all, the "what" is a big part of the "why". For example, we could just say that we have color perceptions because our eyes have three cone photoreceptor types that respond to stimuli produced by the interactions of light sources and materials to produce neural signals that our brain can interpret as color.



The human brain is amazing in its function and complexity. It is entirely possible that science will never fully understand how the brain works. Yet it is in the brain that color ultimately resides. Color is a perception, not a property of objects.

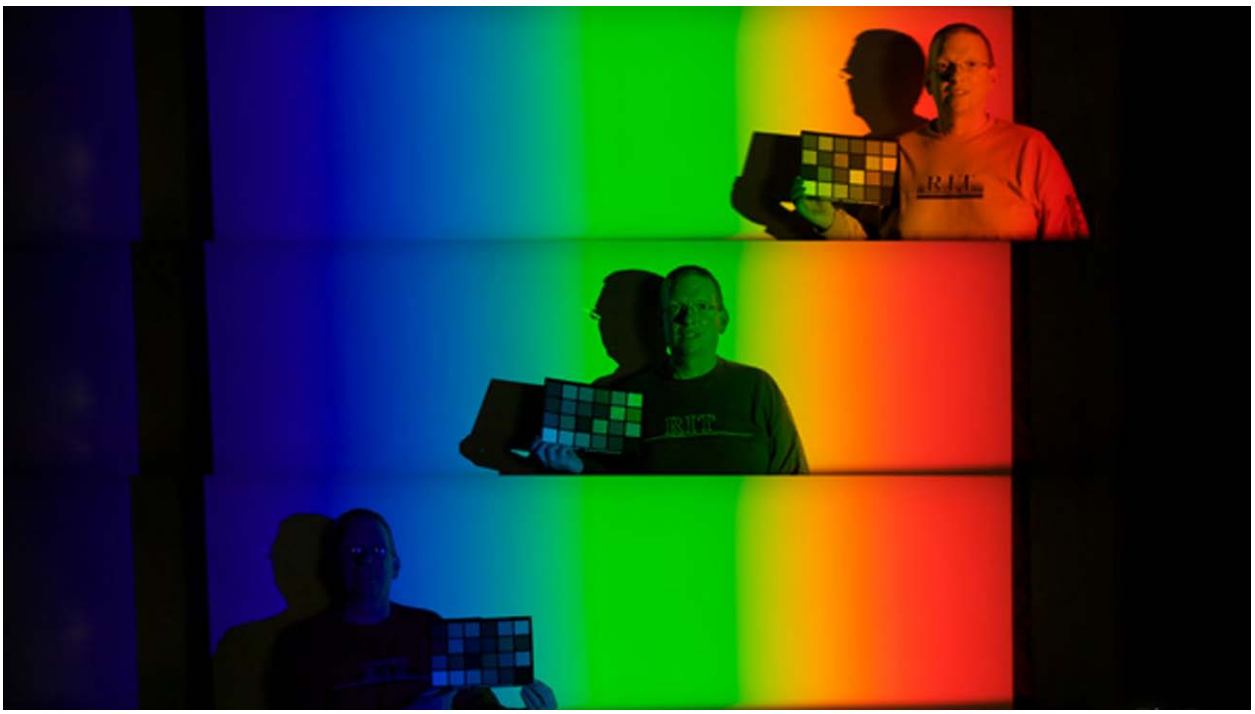
Looking deeper into the "why" part of the question leads us somewhat out of the domains of the objective sciences of physics, chemistry, anatomy, physiology, psychology and the mathematical language used in all of them. We quickly end up in a more philosophical place. However we don't need to fixate solely on the philosophy. Perhaps the simple answer that color perception makes the world a more beautiful place for us (most of the time) is enough to satisfy the philosophical question. We can then fall back on some biological science to examine the question of why humans evolved to have color perceptions, or even more specifically why they are trichromatic.

The most widely accepted theories on the evolution of color vision are that it serves human survival in three ways. These are to help identify healthy (and willing) mates, to identify healthful and ripe food, and to warn us of potential dangers. Other creatures have evolved, and survive very well, with very different types of visual systems. Some have more than three receptor types (*e.g.*, some birds, fish, insects, and famously the mantis shrimp). Others survive quite well with dichromatic color vision (e.g., most mammals). So the answer is not the same for all species and that only makes sense. All species don't have wings, or gills, or stingers, or fangs either. Another important aspect of our color vision system is how well it matches our environment. For example our eyes respond to the wavelengths of energy most prevalent in our main light source, the sun. And statistical analyses have shown that three types of cone photoreceptors are adequate to describe the variability in the spectra of natural objects (having four wouldn't really help us, but three is significantly more helpful than two).

Why is color, indeed?

Photography (Level 1)

Q: How Do Colors Mix to Make Other Colors?



Funny things happen when differently colored objects are put under different colors of light. In this set of three pictures, look at how the color of my orange RIT t-shirt and my face change as I move from red, to green, to blue light in the spectrum. Why does my orange shirt look dark gray when lit with green light? Think about it and explore a bit more to learn the answers.

A:

Well really colors don't mix together at all! Light, or other stuff like paint, mix together to create a new thing for us to look at and that new thing might have a color that is different from any of the stuff mixed together. Remember, color is our perception of the stuff out there in the world.

When lights are mixed together, like on our television screens, all of the light from each part of the mixture is still there. However, our eyes are not able to see the different parts of the mixed light, so we just see a single color. The mixing happens in our eyes! You might want to play with this online demo from Boston University to see how red, green, and blue light mix together.

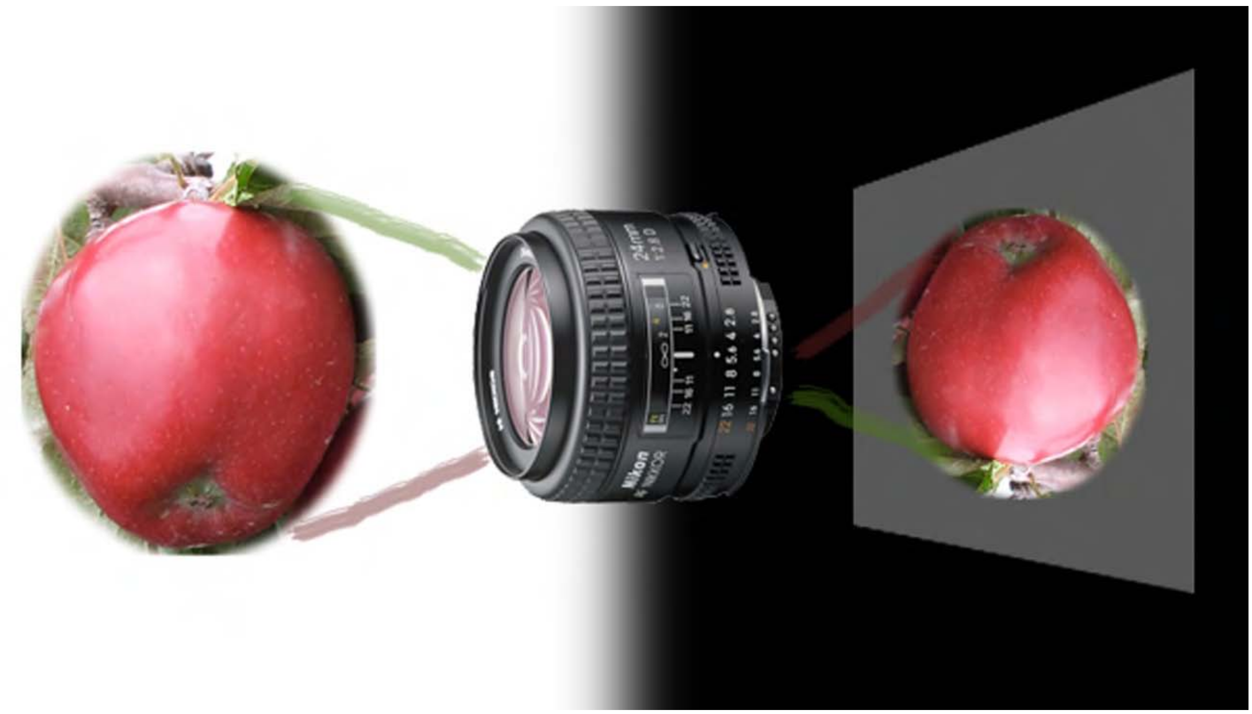
When you mix other stuff together, like paints, printer ink, or crayon wax, you get different colors than when you mix lights. This is because the stuff changes the light that falls on it in a certain way and when you mix different stuff together, the way the mixture changes light can be very complicated. You can play with a simple form of this mixing in another online demo from Boston University. It shows how different colors of ink or dye might mix together to form new colors.

The colors you see when you mix stuff of other colors is sometimes very surprising. The best way to learn is to play with lots of colors and observe what happens. Albert Einstein once said "play is the highest form of research"!

Sometimes surprises happen when two things are mixed together. Most people are surprised the first time they see green paint appear when blue and yellow paint are mixed together. It is a surprise because our eyes are much more complicated than we sometimes think. In this picture I found a surprise mixture while hiking in Algonquin Provincial Park. There are two different kinds of trees (a pine and a birch) growing as a mixture out of one set of old roots (the rotting stump)! Can you imagine how that happened?

Photography (Level 2)

Q: What is a Camera?



The lens of a camera gathers light from a scene (shown as an apple above) and projects it onto a light-sensitive surface (shown as the backwards and upside-down apple on the screen above). In the original cameras, the image was projected onto a piece of paper or canvas and traced by an artist. Later on photographic film was used in cameras to capture images of the world. Nowadays, the light sensitive surface is normally a digital detector array made of silicon. Our eyes can also be thought of as cameras. What is our light-sensitive surface?

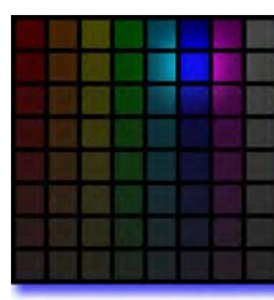
A:

Original man-made cameras were called a *camera obscura* in Latin. Literally translated, that means *dark chamber*. The *camera obscura* was a dark room, or chamber, with a hole in one side (perhaps with a lens mounted in the hole to collect more light). Observers, or artists, would enter the camera obscura and see an image of the world projected (upside down) on a white surface on the other side of the room. They could trace, or paint, this image if they wanted to reproduce the scene.

My dog, Mystic, has two cameras in her head. Her eyes are darkened chambers. The light passes through her pupils, is focused by her cornea and lens, and is detected by her retina. Here she is using her camera to look at me and my camera along with my daughter getting her attention with a treat (you can see us reflected in her eye).

Today, cameras are still *dark chambers*. Normally there is a lens at the front of the camera to gather light. Modern lenses are actually made up of combinations of many individual lenses to improve the quality of the image. This light is then projected onto a surface at the back of a small (sometimes incredibly small as in cell-phone cameras) *dark chamber*. A light sensor is placed at the back of the chamber to capture an image of the light from the scene and allow us to process and view it. Our eyes are also built in the same basic form as a camera and can also be thought of as dark chambers.

So that's it ... a camera is a *dark chamber*.

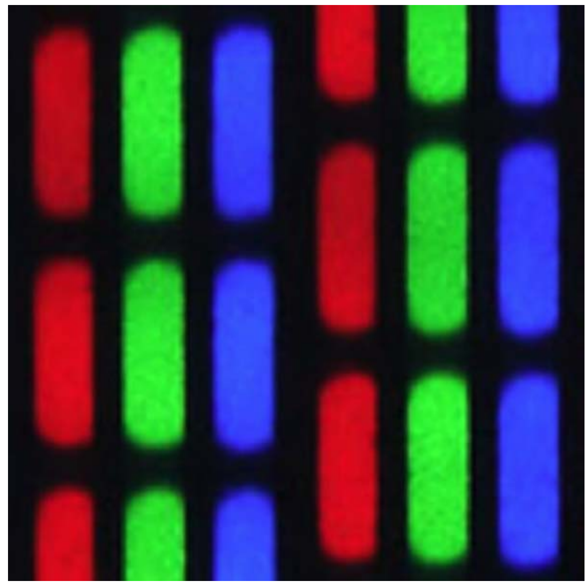


Q: How Does a Color Television Make Colors?

Televisions work by breaking a color picture into three color separation (or primary) pictures, one that shows how much red light is in the scene, one that shows how much green light, and a third that shows how much blue light. The picture above shows a full color scene on the left side and then patches of the red, green, and blue parts of the image on the right. Where all three colors overlap (like in a normal TV display) you can see the original image color (look at the center of the right panel). Where only two overlap, you can see some, but not all, colors. This is much like the colors that someone with color blindness might experience.

A:

The processes of color television that allow pictures of some scene to be captured and then transmitted to our homes for viewing (sometimes live while the captured events, such as s sporting event, are happening) are very complex. Focussing on the color aspect, color television relies on the number three that is so important in color. Since our visual systems can only respond three types of color using our three types of cone receptors, color television can recreate beautiful full-color pictures from just three black and white images. This is done by capturing three images that represent the red light, green light, and blue light in the original scene. After transmission to our home TV (or computer screen), that information is put back together by emitting roughly equivalent amounts of red, green, and blue light on the display. Since our eyes can only judge the relative amounts of the three types of light, we see a full color picture.



A closeup photograph of the colored phosphor dots on an old-fashioned cathode-ray tube (CRT) television display. Each area of a TV picture is made up of different amounts of red, green, and blue light mixed by our eyes to produce a wide variety of colors.

The process for making color described above is known as additive color mixing. Additive mixing happens when colored light is superimposed to make new colors. This can happen by projecting different color lights on top of one another, by flashing the lights so quickly we can't see the individual colors, or by making adjacent patches of the colors so small that they blur together in our eyes. It is this last technique (small dots of light) that is most often used in color television. However, some systems do use the other techniques.

There are other important parts of making color television work. These include breaking the picture up into small spots of light, called pixels, and mathematically encoding that information so that it can be processed in computers. The data is then compressed to make it easier to transmit to us through satellites, cable systems, or over-the-air radio transmission. Then the picture and sound information is transmitted and received and decoded by the tuners and processors in our TV (or set-top box). Finally the pictures are displayed for us to view.

Q: How Do Digital Cameras Detect Colors?

The array of colors on the left part of this image represents a Bayer filter array (named after a Kodak scientist who was one of the people to develop this particular arrangement of colors). This pattern of filters is placed on top of a black and white image sensor to make each element of the sensor respond to either red, green, or blue light. Notice that there are more green elements. This has to do with our eyes' better sensitivity to fine detail in the green region of the light spectrum. The middle panel shows a scene in Yosemite National Park and the rightmost panel shows how that scene would be sampled by a typical digital camera with the individual red, green, and blue pixels (or picture elements). A lot of computer processing takes place to convert these raw detected images into the pictures that you enjoy viewing.

A:

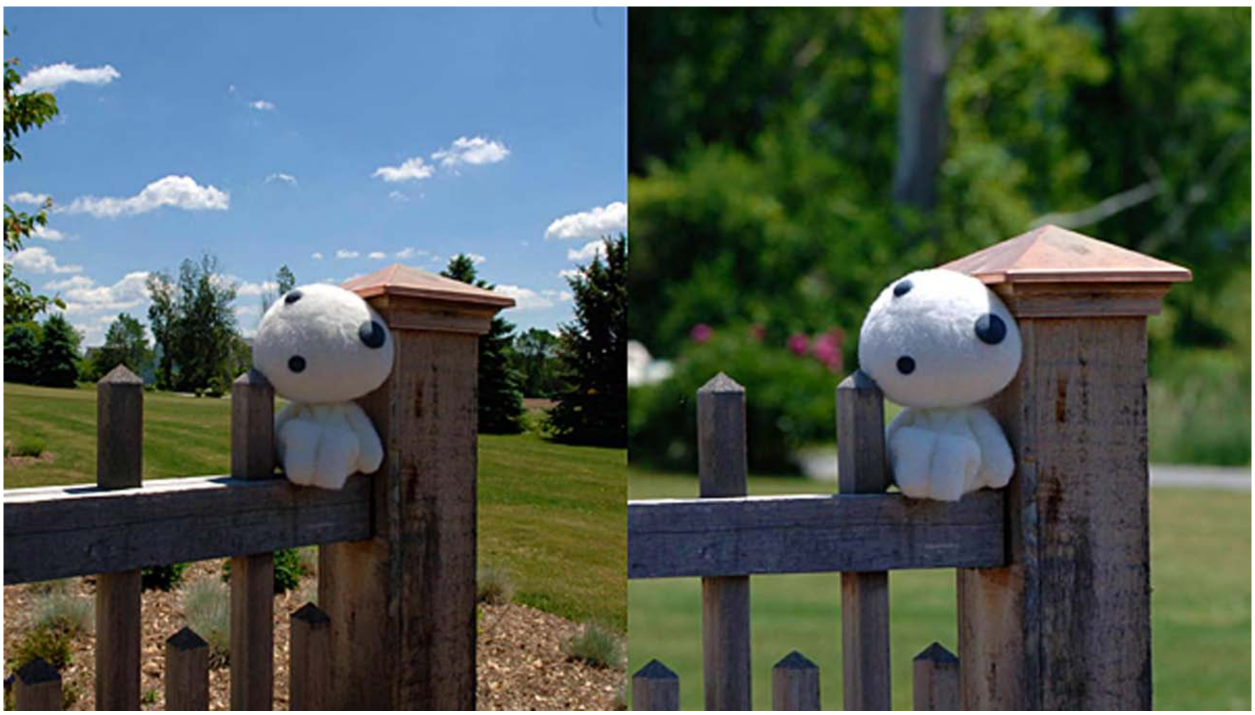
The "heart" of a digital camera (or perhaps more accurately, the "retina") is a sensor array made out of silicon. These sensors have small individual detectors (usually several million on a single sensor) that respond to light that falls upon them. What happens is the energy in the light causes a small electrical current in the detector at that particular location. That current is then measured electronically and converted to digital values that represent the amount of light detected. Those digital values, indexed to their location on the image, provide the information needed to draw an image on a computer monitor or printer. However, the sensor itself responds to the whole visible spectrum of light energy and some infrared energy as well. This overall response can only produce black and white images. To produce color images, multiple sensors are required to detect and discriminate the different color regions of the spectrum like our eyes do. The first step is to place an infrared filter in front of the sensor to get rid of that energy that we cannot see at all.

A photograph of the image sensor in a Nikon D3 digital single-lens reflex (SLR) camera. There are almost 13 million sensors (individual pixels) within the gray center area which fits easily inside the camera. The sensor area is about 1.0 x 1.5 inches (or 24 x 36 mm) so you cannot possibly see individual pixel sensors or the Bayer filter array in this picture.

The next step is to figure out how to separately detect red, green, and blue images in order to have all the information needed to create the different colors we can see. One way to do this is to use three image sensors and put red, green, and blue filters in front of each of the three respectively. This gives us the needed red, green, and blue images, but it also makes the cameras very bulky and expensive because three image sensors are required. Instead, most cameras use a filter array as illustrated in the above picture. The filter array results in a single image sensor that has some pixels that respond to each of the three red, green, blue, primary colors. Since we really want red, green, and blue information at every location in the image, fairly complicated computer processing is done to convert the detected image (with the filter array information superimposed) to a single full-color image. This process is known as demosaicking since the filter array can be considered a mosaic of colors. There is also a lot of other processing that goes on before we see the images to adjust the color, exposure, contrast, sharpness, noise levels, and other image attributes.

Finally, the combination of the image sensor, the color filter array, and the computer processing result in a set of three images. One represents the red information in the scene, one the green information, and the third the blue information. These can be combined on monitors or printers to give us the beautiful full-color images we are used to seeing when we simply push a button. This process is theoretically the same one that Scottish scientist James Clerk Maxwell developed in the 1800s when he is credited with inventing color photography (in reality he was trying to show that the human visual system detects colors by separating the information into just three images corresponding roughly to red, green, and blue information).

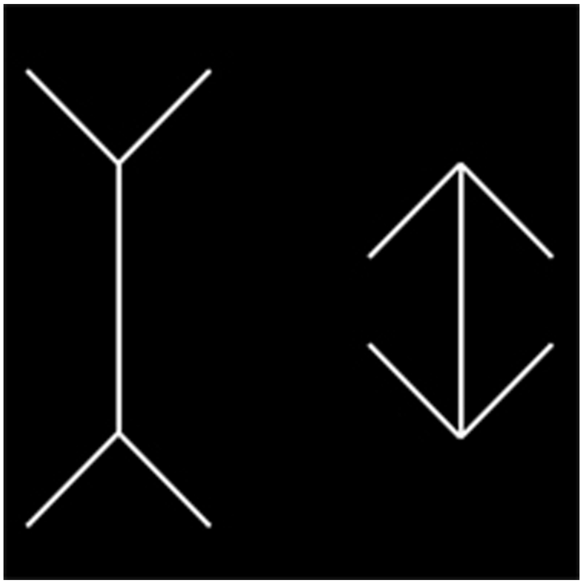
Q: Why Does the Moon Look Large on the Horizon, But This Doesn't Show Up in Photographs?



Here are two picture of my stuffed Kodama (a Japanese tree spirit) sitting on a fence. In the picture on the right, my Kodama is about the same size as the flower bush in the background. In the picture on the left, that flower bush is so small you almost cannot see it (it's just a little bit larger than the Kodama's little round mouth). However, the Kodama is about the same size in both pictures. How can this be? It turns out the relative sizes of objects in a scene depends on the lens used to capture the image. The image on the left was captured with a wide angle lens that tends to make things in the background look very far away. The image on the right was captured with a telephoto lens that tends to make far-away background objects look much closer and larger. It is all a matter of perspective and the field of view of the two lenses. Note that I had to be much farther away from the Kodama when I took the picture with the telephoto lens in order to get him (her?) to come out the same size.

A:

The answer to this question is still debated by scientists. It is known as the Moon Illusion. The moon is always almost exactly the same size when visible in the sky. Vision scientists like to measure size using angles and the angle subtended by the moon is about 0.5 degree. (Coincidentally, the angle of the sun is also almost exactly 0.5 degree at the Earth's surface. That's why both lunar and solar eclipses can happen the way they do!). When the moon is on the horizon, it is 0.5-degree wide (and high) and when it is straight up overhead, it is 0.5-deg. wide (and high). A camera simply records that physical geometry of the moon and the pictures make the moon look the same size (which it is) regardless of whether it is on the horizon or overhead.



The two vertical lines in this image are exactly the same length. They appear different due to a perceptual effect known as the Müller-Lyer Illusion. Some say that this illusion is also related to perceptual distance as we see the two lines as either inside corners or outside corners.

Since there is no problem with the photographs, then the "error" must be in our perception of the moon. Indeed that is the case. That moon looks larger on the horizon to us even thought it really isn't and that is precisely the definition of the Moon Illusion. There are many theories about why the moon illusion occurs. My favorite has to do with perceived distance and another visual phenomenon called size constancy. Size constancy refers to the perception that the sizes of objects appear the same whether they are nearby or far away. For example, if you are right next to me, you will see me as a human about 6-feet (or 2-meters) tall. If you see me from 100-yards (or 100-meters) away across a football field, I will still look like a human that is about 6-feet (or 2-meters) tall even though I would only take up a very small portion of what you can see. In other words, even though the image of me on your retina decreases in size when I am farther away, your perceptual system takes into account your perception of how far away I am and I appear to remain the same size (size constancy).

This could create the moon illusion because people seem to perceive the "distance to the imaginary surface of the sky" where the moon is to be much larger at the horizon than overhead. Thus if the moon is always the same size on our retinas (it is), then our perception of the moon will be that it is larger at the horizon because we mistakenly perceive it to be farther away (it isn't). There are other possible explanations for the Moon Illusion, so you should do some more reading on those.

If you still don't believe me then check for yourself. Next time you see the moon, hold your thumb out at arm's length and compare the size of the moon to your thumbnail. The moon will be about half as wide as your thumbnail (yes, it really will!). Now repeat this experiment when you see the moon at different heights in the sky with different apparent sizes and you will notice that it is always about half the width of your thumbnail.

Q: Why Aren't My Photographs the Same Colors as the Original Scenes?

Here are four pictures of the Ben & Jerry's Ice Cream factory in Vermont. They were all created from a high-dynamic-range image capture that almost perfectly recorded all of the color information in the scene. The upper left image shows a fairly accurate rendering of the appearance of the scene. The upper right image might be the result of a single exposure from a typical point-and-shoot digital camera. The lower left image represents a more film- or video-like rendering of the scene and the lower-right image is a black and white rendering. The point of these images is to illustrate that the very same scene information can be rendered in many different ways by different camera systems. And it is very rare that the aim of these systems is to actually reproduce the colors that you saw in the original scene.

A:

The most direct answer is simply that cameras are not the same as people and do not respond to color in the same way. More specifically the red, green, and blue detector sensitivities in a digital camera are not the same as, or even simply related to, the long-, middle-, and short-wavelength sensitivities of the human visual system. If they were, then computational procedures could be completed to make perfectly accurate color images from the camera data. Even if such perfect color data were recorded by a digital camera, there might still be differences due to variations in the displays and printers that we use to render our images. Lastly, even if all the above systems were perfectly accurate, we might not like the result and prefer to see a different image; perhaps one with colors that look better than the original scene (*e.g.*, bluer sky, greener grass, nicely tanned skin-tones).

Meet MetaCow! These images are part of a larger MetaCow image that was created to evaluate the quality of imaging systems. The two cows on the left appear as they would to a human observer. On the right, the same two cows are shown as they would be "seen" by a typical digital camera. The front and back halves of the cows look different to the camera because it does not respond to color like a human.

Image rendering, or conversion of the captured image data to displayed colors, is a step in the digital photography process that also introduces a range of possible outcomes (see images at left). The data are processed in many ways to correct for properties of the image sensor, to reduce noise, to sharpen the details, to adjust for changes in illumination color and exposure, to compensate for assumed display properties, and finally to adjust to make images that the camera manufacturer feels will be more preferred. This objective of reproducing preferred colors has driven the photography industry since the beginning and is one of the main reasons that most imaging systems aren't designed to accurately reproduce the colors we see in the world; the cameras are designed to give us something we like better. Do you think they succeed all the time?

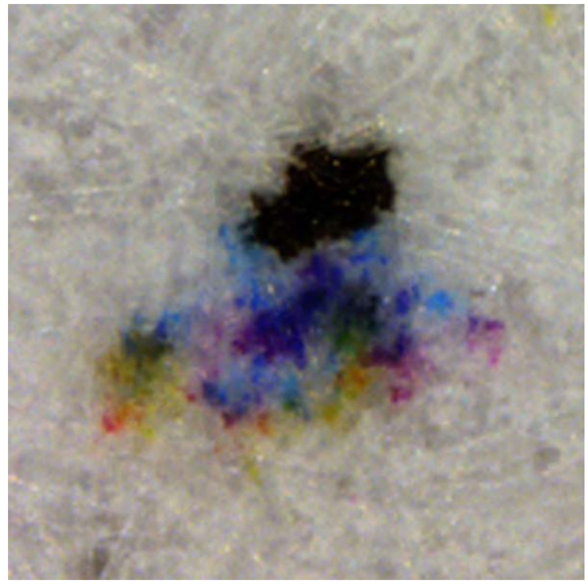
Color preferences are difficult to quantify and specify, but in general people prefer color reproductions that are accurate in hue, slightly more saturated than the original scene, and higher in contrast (the rate of change from dark to light). Pay attention to photographs that you get from your camera and print services and you will probably notice these sorts of changes. Do some experiments by taking pictures of objects you can later compare with the resulting photographs.

Q: How Does an Ink-Jet Printer Produce Colors?

Here is an image of a tree and the cyan, magenta, yellow, and black (CMYK) separation images that make it up. The separation images show the amounts of each of the four ink colors, or primaries, required to be printed in order to reproduce the green tree against the blue sky. On the left side are the cyan (top) and magenta (bottom) separations. On the right side are the yellow (top) and black (bottom) separations. The separation images indicate the amount, or density of ink required (darker areas mean more ink). For example, the sky is dark in the cyan separation and light in the yellow separation because a lot of cyan ink and no yellow ink must be used to reproduce the blue sky (which is nearly the same color as the cyan ink!). Looking at the greenish leaves, you can see that a large amount of yellow ink is required along with a slightly lesser amount of cyan. The subtractive mixture of yellow and a little cyan produces a bright, yellowish-green. Black ink is only used in the dark shadow areas.

A:

In the simplest sense, an ink jet printer produces colors by placing small dots of ink on paper. Traditional printers use four colors of ink, cyan, magenta, yellow, and black. Newer printers often have additional inks, such as light cyan, light magenta, or gray, to help improve image quality by reducing the visibility of the dots. A dot of each ink type can be placed at each location on the paper. The printed color depends on the size of the dots, or the amount of each type of ink, placed at each location. For example, to produce white, no dots are made at all, allowing the white paper to show through. To make black, large dots of all four types of ink are often printed. To make a saturated red, large dots of magenta and yellow ink are printed. The magenta absorbs green light while the yellow absorbs blue light, leaving only red to be reflected. In similar ways, the amounts of each of the four inks required to make just about any desired color can be determined.



This is a micrograph of a single dot from an ink jet printer. The RGB color sent from the computer was a dark gray (R = G = B = 50). You can see that this dark gray is produced with a large amount of black ink and a little bit of each of the other three primaries. You can also see how the primaries overlap and mix to make a variety of colors. We don't normally see this in a gray area on a print because the dots are so small.

Ink-jet printers are often considered subtractive color mixing devices. Subtractive color mixing occurs when various amounts of different dyes or pigments are mixed and each absorbs (or subtracts) its characteristic colors and amounts of light. On the other hand, additive mixing is what happens on our computer monitors and televisions when tiny spots of light are overlapped (or added together) to make mixtures of light. As it turns out, most printers actually function using a combination of additive and subtractive color mixing. Subtractive mixing occurs where the ink colors overlap and absorb different colors of light. Then additive mixing occurs when our eyes blur all of those very tiny dots together and effectively add the light reflected from each of the different areas (imagine blurring the micrograph at the left, or viewing it from a very large distance). Since those dots are often on the order of thousandths of an inch in diameter.

So why is black ink used in printers? A very wide range of colors can be made with cyan, magenta, and yellow primaries. And, after all, there are only three degrees of color freedom in the visual system, so we shouldn't need to use more than three inks. In fact, some very successful printing technologies do only rely on three primaries. Photographic printing, with just cyan, magenta, and yellow dyes on paper, is one such example. Black ink is used in many printing technologies for two main reasons. It allows for much darker colors to be printed. It is difficult to select cyan, magenta, and yellow primary inks that produce a deep, dark black while also allowing for saturated colors. Also, black ink can be used instead of overlapping large amounts of cyan, magenta, and yellow inks to make neutral colors. Such colors can be made with one-third the amount of ink and at the same time black ink tends to be less expensive than colored ink. An added bonus of this is that it is easier to make prints with consistent color appearance when neutrals are printed with mostly black ink instead of variable combinations of three inks.

Q: Why is Digital TV Better than Analog TV? Is HDTV Really Better than SDTV?

This image compares the spatial resolution (ability to reproduce fine details) of a high-definition (HDTV) television system (left) with a standard-definition (SDTV) television system (right). The difference is obvious and this is identical to the difference you can observe on an HDTV display by switching from HD input to SD input for a given channel. This demonstration ignores any differences due to interlace (or the alternative called progressive scan). The butterfly is a Blue Morpho Butterfly. They produce their highly saturated and brilliant blue appearance through optical interference (rather than light absorption that happens in most materials). This allows them to be very bright while reflecting nearly a single wavelength of light (actually a small range of wavelengths).

A:

Let's begin with the second question. The image quality of HDTV is clearly superior to that of SDTV. It should also be noted that either level of definition is possible in either analog or digital television systems. However in the USA, HDTV is strictly a digital system. The previous SDTV system was analog and is now obsolete. Currently SDTV signals are also digital. Whether or not HDTV is really better than SDTV is ultimately a personal opinion. If your TV displays shows little difference in your viewing environment, then it is difficult to say that HDTV is better. Also, the content is the same. There is nothing about HDTV that makes the content superior!

The first question can also be a matter of personal preference. In the USA, there no longer is an analog TV system, so the question is moot. It is still of technical interest to compare the systems. Digital TV transmission does not suffer from the artifacts and degradations that were often seen with analog transmission. With digital systems you generally either have a signal or you do not. In analog systems we had artifacts from interlace, from chromatic aliasing due to crosstalk between luminance and color dimensions, and noise from transmission and decoding. In digital systems, most of these artifacts are gone, but we do see blocking artifacts from data compression on occasion. Overall, however, in digital television systems we now have capabilities for HDTV (more spatial resolution), wider color gamuts, non-interlaced (or progressive) transmission and display, more accurate color, surround sound, and the transmission of metadata. It would seem that all of these improvements clearly make digital television systems better than our previous analog systems.

Interlace refers to a process in video whereby every other line of the image is transmitted first for the whole image, followed by the alternate lines for the whole image. It results in artifacts (breakup) for moving subjects as shown above. Interlace was necessary in early video systems to overcome limitations in display refresh speed and transmission bandwidth. Interlace is no longer required.

While the transition to digital and HDTV took a long time, it is now past the critical point where large-screen digital HDTV displays are very affordable commodities. In fact, I recently (August 2010), saw flat-panel HDTV sets simply sitting on a store shelf like a loaf of bread. Customers could put them in a cart to take to the checkout themselves. I think that is a sure sign that HDTV has finally arrived (in the USA, anyway).

Challenge (Level 1)

Q: Quiz Time: What is Color?

The road around Otter Point in Acadia National Park ... leading to new explorations.

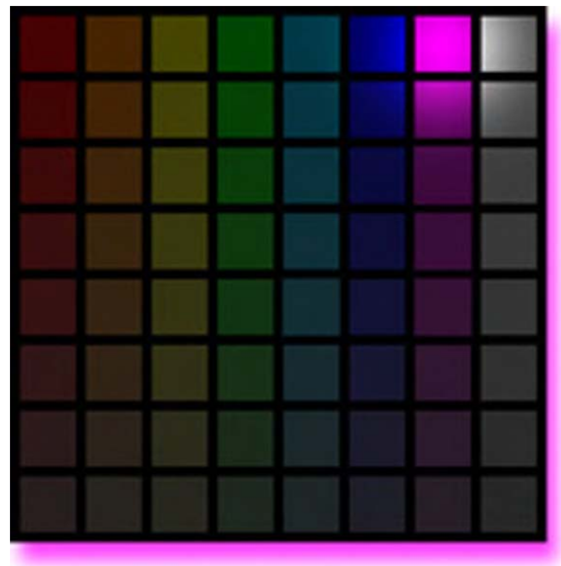
A:

(A) Something About what Light is Made of

(B) Something About what Objects are Made of

(C) Something We See

(D) A Dream!



Have you noticed the pattern in these icons yet?

Challenge (Level 2)

Q: Quiz Time: Can Different People See the Same Rainbow?

Ever wonder what is at the end of a rainbow, or why you can never find it?

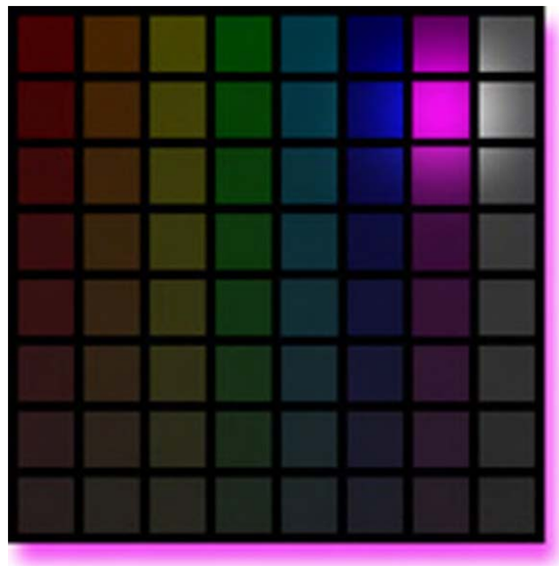
A:

(A) What Else Would They Be Seeing

(B) No, Not Really

(C) Yes, There is Only One Rainbow at Any Given Time

(D) Who Cares



Have you noticed the pattern in these icons yet?

Challenge (Level 3)

Q: Quiz Time: Can a Dog See Color as Well as You?

Do these look like ripe apples in a tree to you? If so, you are probably colorblind!

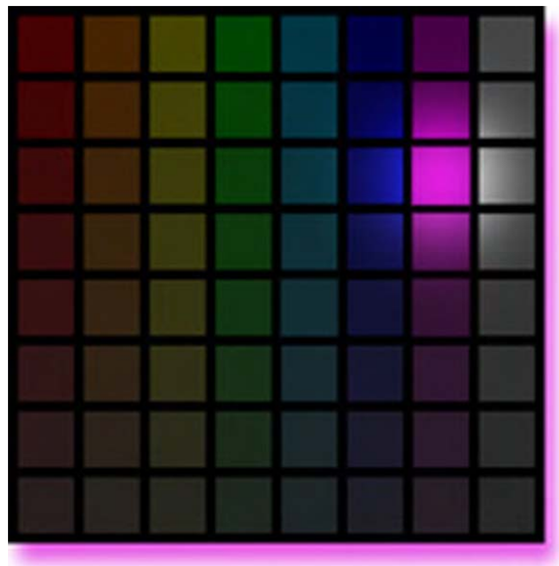
A:

(A) No, Dogs See No Color

(B) Absolutely!

(C) Dogs are Completely Blind; They Use Their Noses

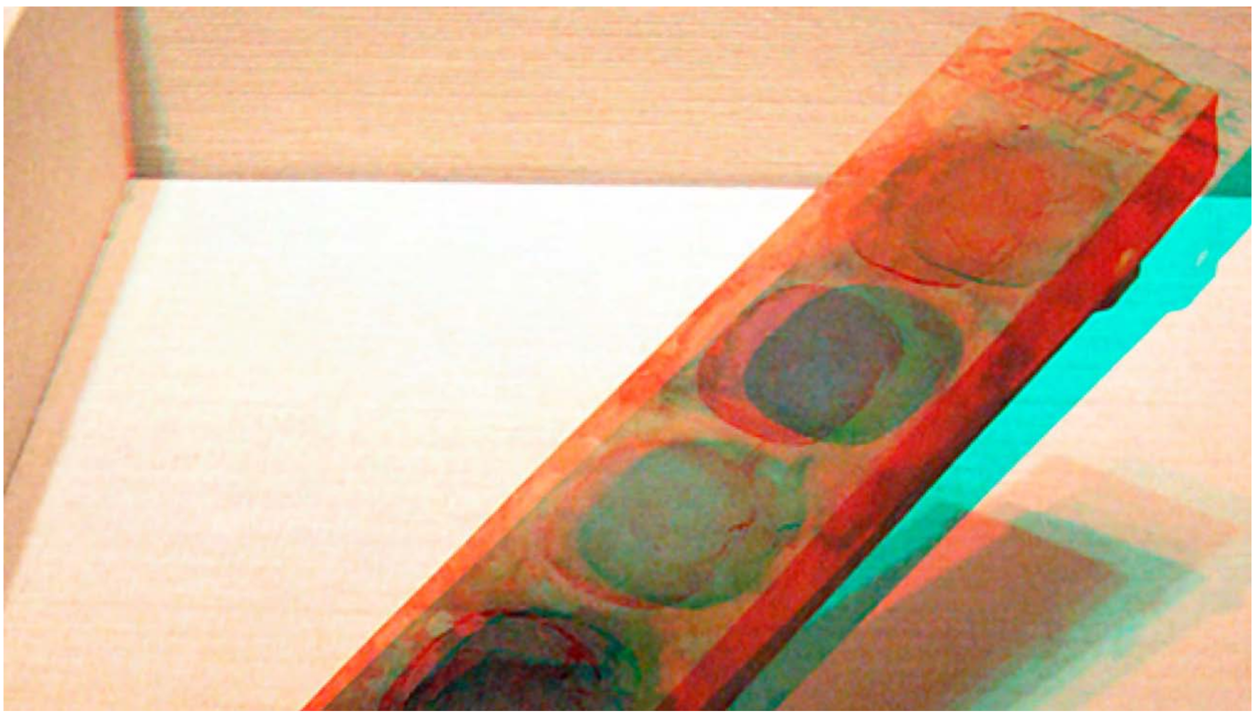
(D) Maybe, If You Are Color Blind



Have you noticed the pattern in these icons yet?

Challenge (Level 4)

Q: Quiz Time: Given 50 Women and 50 Men, About How Many will be Color Blind?



Did you know that there are also people who are stereo blind? That means that they cannot see 3D images and movies. In fact 3D movies can give them severe headaches. There are probably more stereo blind people in the world than color blind people (I'm one of them!). Some estimates are as high as 30% of the population with some deficiency in stereo vision. This is a picture of Egyptian red, green, and blue paint from about 1420 BCE that is still intact and colorful (now in the Cleveland Museum of Art).

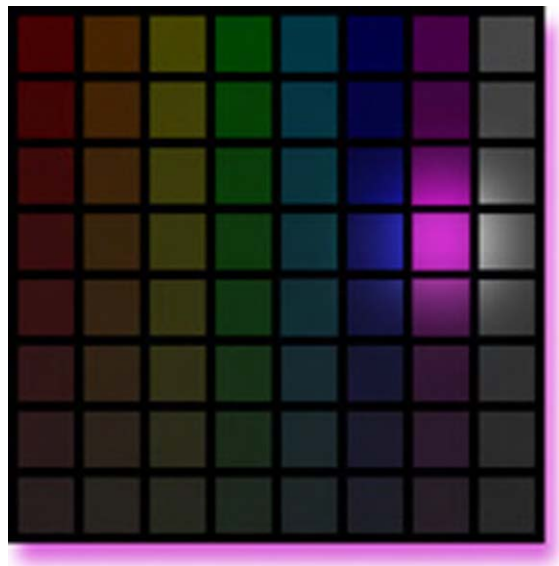
A:

(A) 0 Men and 8 Women

(B) 4 Men and 0 Women

(C) 4 Men and 4 Women

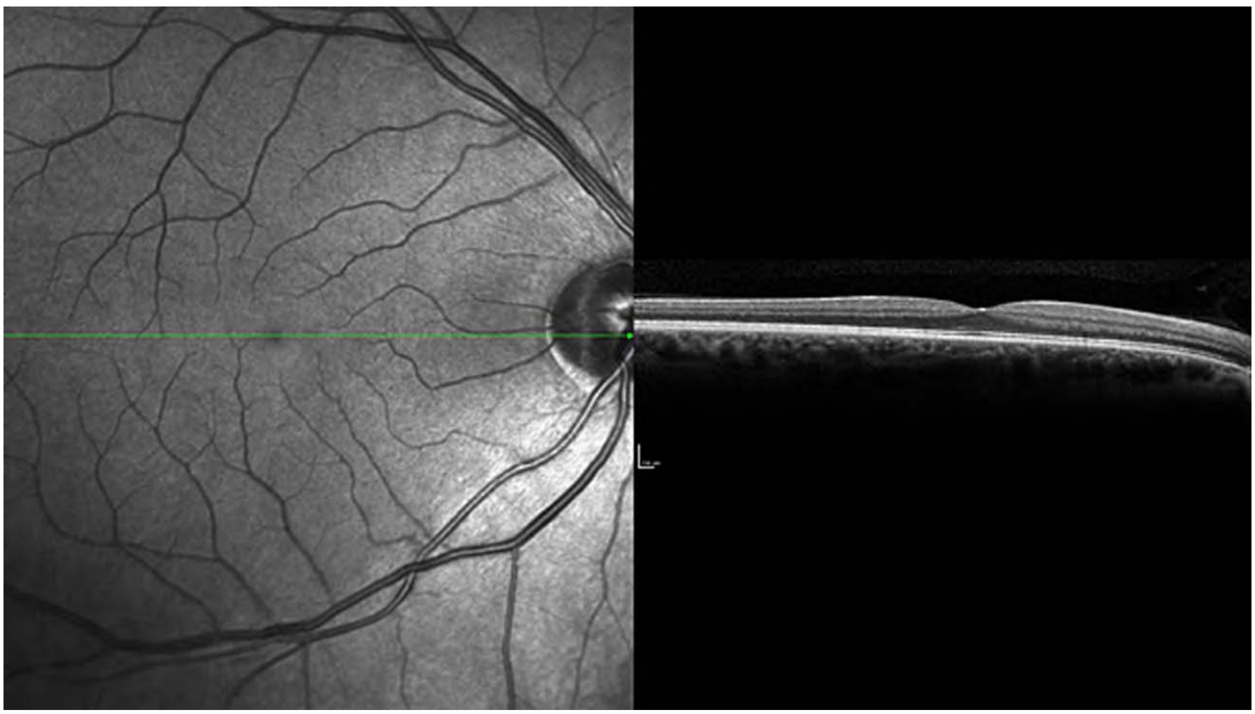
(D) All of Them!



I'm sure you figured something out by now!

Challenge (Level 5)

Q: Quiz Time: What Is the Functional Difference Between Rods and Cones?



These are images of my retina (the back surface of my right eye). In the left panel you can see the blood vessels, the beginning of the optic nerve (right edge of image) and my fovea (near the center with no blood vessels). The right panel is a cross section of the area marked with the green line. You can see a slice through my fovea (the pit where the nerve fibers are pulled away to allow better vision) and the various layers of cells in my retina. The rod and cone inner segments are the dark gray area near the middle of the cross section.

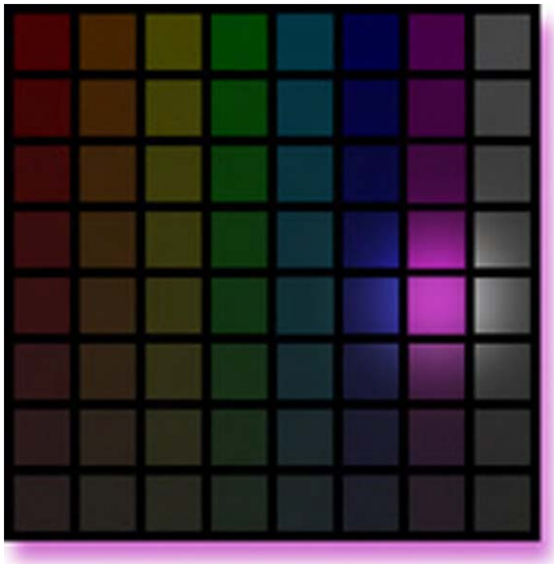
A:

(A) Nothing; They Are Exactly the Same

(B) Cones Hold More Ice Cream

(C) Cones Are Capable of Detecting Color; Rods Are Not

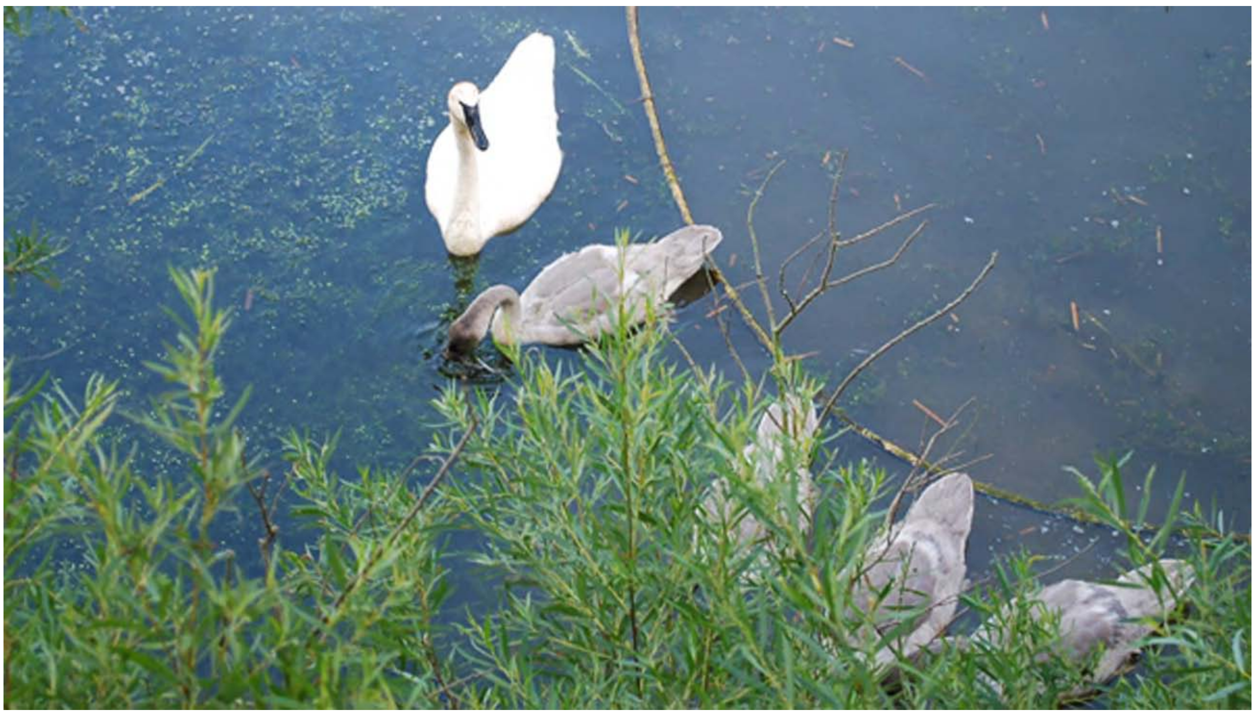
(D) Cones Respond to Light; Rods Respond to Dark



I'm sure you figured something out by now!

Challenge (Level 6)

Q: Quiz Time: What Is Adaptation?



Another kind of adaptation is how animals adapt to the environment in which they live. This is not the same as perceptual adaptation, but like perceptual adaptation it is an adjustment made to the prevailing environmental conditions. However, animal adaptations don't occur within a single organism like perceptual adaptation, they occur over evolutionary periods. These swans have at least two adaptations, webbed feet to help them swim and flattened bills to help them dig for food.

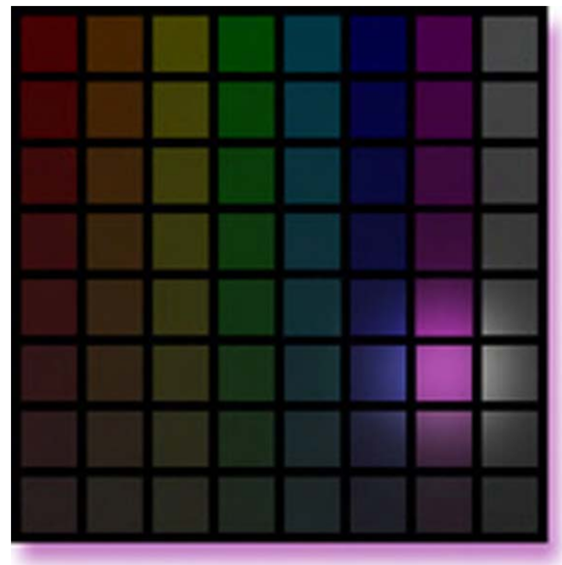
A:

(A) Your Ability to Ignore Your Parents

(B) When a Family Brings Home a New Pet

(C) The Ability of the Visual System (All Sensory Systems) to Adjust to Prevailing Conditions

(D) Falling Asleep During Boring Class Lectures



I'm sure you figured something out by now!

Challenge (Level 7)

Q: Quiz Time: How is Color Perception Different From Hearing?

Different animals also perceive the world differently. While my daughter and her horse both have eyes and ears that function in similar manners, they have different capabilities. My daughter can see colors and fine details better than her horse. He can probably see a little better in dim light than she can. Hearing wise, the horse is probably sensitive to different frequencies and tuned into different important sounds (like the buzzing of flies rather than the sound of her mother's voice).

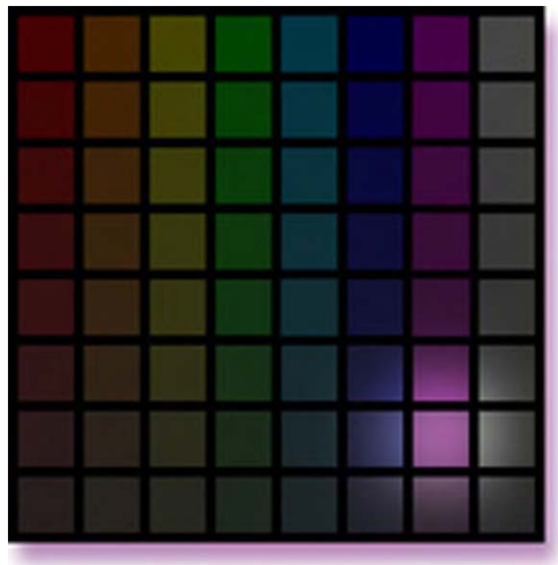
A:

(A) We Can't See Frequencies of Light (Wavelengths), Like We Can Hear Frequencies of Sound (Notes)

(B) We Can See Spectra, But Only Hear Certain Combinations of Notes (Chords)

(C) There Are Three Cone Types, But Only Two Types of Hearing Receptors

(D) We Can Localize Objects With Vision, But Not With Hearing



Both hue and chroma have a meaning.

Challenge (Level 8)

Q: Quiz Time: What is Metamerism?

Are there metameric matches in nature, or are they a man-made phenomenon? I have often wondered about this, but never had the time (and instrumentation available) to make a detailed search for natural metamers. One theory I have is that gray squirrel fur is metameric with tree bark. What do you think? Squirrels and trees do not have the same pigments. Squirrels do blend in well. Is it metamerism? Or is it just good camouflage with similar distributions of colors

A:

(A) A Process for Deciding Whether to Have White or Red Wine with Dinner

(B) Two Stimuli that Match in Color Despite Spectral Differences

(C) A Love of Information About Mermaids

(D) The Combination of Light and Object that Matches a Stimulus

There are different hues for the different disciplines (topics) and different chroma levels for the different levels (decreasing chroma with increasing level).

Explorations (Levels 1-8)

Books

Level 1

Monique Felix, *The Colors*, Creative Editions, Mankato (1993).

Alan Baker, *White Rabbit's Color Book*, Kingfisher, New York (1995).

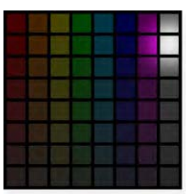
Margaret Wise Brown, *Goodnight Moon*, Harper Collins, New York (1947).

Bentley & Cahoon, *Good Night, Sweet Butterflies: A Color Dreamland*, Little Simon, New York (2003).

Eric Carle, *My Very First Book of Colors*, Penguin, New York (2005).

Bill Martin Jr. and Eric Carle, *Brown Bear, Brown Bear, What Do You See?*, Henry Holt, New York (1967).

Level 2



Ruth Heller, *Color*, Putnam & Grosset, New York (1995).

Shane DeRolf, *The Crayon Box that Talked*, Scholastic, New York (1996).

Dr. Seuss, *My Many Colored Days*, Knopf, New York (1996).

Dr. Seuss, *One fish, two fish, red fish, blue fish*, Random House, New York (1960).

Hervé Tullet, *Pink Lemon*, Milet, London (2001).

Joanna Cole, *The Magic School Bus Makes a Rainbow: A Book About Color*, Scholastic, New York (1997).

Level 3

Betsy Maestro, *Why Do Leaves Change Color?*, Scholastic, New York (1994).

Anita Ganeri, *Nature's Patterns: Season to Season*, Heinemann Library, Chicago (2005).

Monica Hughes, *Nature's Patterns: Water Cycle*, Heinemann Library, Chicago (2004).

Samuel G. Woods, *Crayons from Start to Finish*, Blackbirch Press, Woodbridge (1999).

"Editors of Klutz", *Oddball Eyeballs: A Book on Vision and How Weird it is*, Klutz, Palo Alto, (2006).

"Editors of The New Book of Popular Science", *Color Me Science*, Scholastic, New York, (2008).

Level 4

Jon Richards, *The Science Factory*, Copper Beech, Brookfield (2000).

Wendy Mass, *A Mango-Shaped Space*, Little, Brown Young Readers (2003).

Judy Galens and Nancy Pear, *The Handy Answer Book for Kids (and Parents)*, Visible Ink, Detroit (2002).

Al Seckel, *Incredible Visual Illusions: You won't believe your eyes!*, Arcturus, London (2003).

David M. Schwartz, *Q is for Quark: A Science Alphabet Book*, Tricycle Press, Berkeley (2001).

Jayne Parsons, Robin Kerrod, Sharon Ann Holgate, *The Way Science Works*, DK Children, New York (2002).

David Macaulay, *The New Way Things Work*, Houghton Mifflin, New York (1998).

Level 5

Pat Murphy, Ellen Macaulay *et al.*, *Exploratopia*, Little Brown, New York (2006).

M. Luckiesh, *Visual Illusions: Their Causes, Characteristics & Applications*, Dover, New York (1965).

Oliver Sacks, *An Anthropologist on Mars: Seven Paradoxical Tales*, Vintage, New York (1996).

Christopher Griffith, *Fall*, powerHouse, New York (2004).

Faber Birren, *Principles of Color*, Schiffer, Atglen (1987).

Richard D. Zakia and Hollis N. Todd, *Color Primer I & II*, Morgan & Morgan, Dobbs Ferry (1974).

Josef Albers, *Interaction of Color*, Yale, New Haven (1972).

Odeda Rosenthal and Robert H. Phillips, *Coping with Color-Blindness*, Avery, Garden City Park (1997).

Level 6

Hazel Rossotti, *Colour: Why the World Isn't Grey*, Princeton (1983).

Pat Murphy and Paul Doherty, *The Color of Nature*, Chronicle Books, San Francisco (1996).

Gideon Defoe, *The Pirates! In an Adventure with Scientists*, Pantheon, New York (2004).

Robert Greenler, *Rainbows, Halos, and Glories*, Cambridge (1980).

Jean Bourges, *Color Bytes: Blending the Art and Science of Color*, Chromatics Press, Forest Hills (1997).

Faber Birren, *Color and Human Response*, Wiley, New York (1978).

Jim Long and Joy Turner Luke, *The New Munsell Student Color Set, 2nd Ed.*, Fairchild, New York (2001).

Thomas D. Rossing and Christopher J. Chiaverina, *Teaching Light & Color*, AAPT, College Park (2001).

David P. Jackson, Priscilla W. Laws, and Scott V. Franklin, *Explorations in Physics: An Activity-Based Approach to Understanding the World*, Wiley, New York (2003).

Level 7

Trevor Lamb and Janine Bourriau, *Color: Art and Science*, Cambridge (1995).

David K. Lynch and William Livingston, *Color and Light in Nature*, Cambridge (2001).

Samuel J. Williamson and Herman Z. Cummins, *Light and Color in Nature and Art*, Wiley, New York (1983).

Maureen C. Stone, *A Field Guide to Digital Color*, A.K. Peters, Natick (2003).

Richard D. Zakia, *Perception and Imaging, 2nd Ed*., Focal, Boston (2002).

Pete Turner, *The Color of Jazz*, Rizzoli, New York (2006).

Austin Richards, *Alien Vision: Exploring the Electromagnetic Spectrum with Imaging Technology*, SPIE, Bellingham (2007).

William L. Wolfe, *Optics Made Clear: The Nature of Light and How We Use It*, SPIE Press, Bellingham (1999).

Thomas D. Rossing and Christopher J. Chiaverina, *Light Science: Physics and the Visual Arts*, Springer, New York (1999).

David Falk, Dieter Brill, and David Stork, *Seeing the Light: Optics in Nature, Photography, Color, Vision, and Holography*, Wiley, New York (1986).

Graham Saxby, *The Science of Imaging: An Introduction*, IoP, Bristol (2002).

Ralph M. Evans, *Eye, Film, and Camera in Color Photography*, Wiley, New York (1959).

Richard Jackson, Lindsay MacDonald, and Ken Freeman, *Computer Generated Color*, Wiley, Chichester (1994).

Michael Pollan, *The Botany of Desire: A Plant's-Eye View of the World*, Random House, New York (2002).

Diane Ackerman, *A Natural History of the Senses*, Vintage Books, New York (1990).

Level 8

Kenneth R. Fehrman and Cherie Fehrman, *Color: The Secret Influence, 2nd Ed.*, Pearson Prentice Hall, New Jersey (2004).

David A. Goss and Roger W. West, *Introduction to the Optics of the Eye*, Butterworth Heinemann, Boston (2002).

Margaret Livingstone, *Vision and Art: The Biology of Seeing*, Harry N. Abrams, New York (2002).

Leo M. Hurvich, *Color Vision*, Sinauer, Sunderland (1981).

Harvey Richard Schiffman, *Sensation and Perception: An Integrated Approach, 4th Ed.*, Wiley, New York (1996).

Dale Purves and R. Beau Lotto, *Why We See What We Do: An Empirical Theory of Vision*, Sinauer, Sunderland (2003).

Philip Ball, *Bright Earth: Art and the Invention of Color*, Farrar, Straus And Giroux, New York (2001).

Raymond L. Lee and Alistair B. Fraser, *The Rainbow Bridge: Rainbows in Art, Myth, and Science*, Penn State Press (2001).

Heinrich Zollinger, *Color: A Multidisciplinary Approach*, Wiley, Weinheim (1999).

John Gage, *Color and Meaning: Art, Science, and Symbolism*, University of California Press, Berkeley (1999).

John Gage, *Color and Culture: Practice and Meaning from Antiquity to Abstraction*, University of California Press, Berkeley (1993).

Rolf G. Kuehni, *Color: Essence and Logic*, Van Nostrand Reinhold, New York (1983).

Rolf G. Kuehni, *Color: An Introduction to Practice and Principles, 2nd Ed.*, Wiley, New York (2005).

Rolf G. Kuehni and Andreas Schwarz, *Color Ordered: A Survey of Color Systems from Antiquity to the Present*, Oxford University Press, New York (2008).

Kurt Nassau, *The Physics and Chemistry of Color: The Fifteen Causes of Color*, Wiley, New York (1983).

R.W.G. Hunt, *The Reproduction of Colour, 6th Ed.*, Wiley, Chichester (2004).

Roy S. Berns, *Billmeyer and Saltzman's Principles of Color Technology, 3rd Ed.*, Wiley, New York (2000).

E. Reinhard, E.A. Khan, A.O. Akyüz, G.M. Johnson, *Color Imaging: Fundamentals and Applications*, A.K. Peters, Wellesley (2008).

Mark D. Fairchild, *Color Appearance Models*, 2nd Ed., Wiley, Chichester (2005).

Links

Level 1

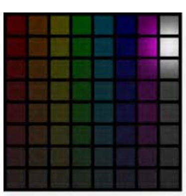
Linda's Learning Links (Colors)
A website for teachers and parents of young children. Tidbits collected and provided by a kindergarten teacher.

Crayola
Learn about crayons and other color topics (like favorite colors). Lots of activities too. Here is a direct link to the pages with information on America's favorite colors.

Color Can be Healthy for Kids!
Five a Day the Color Way! A fun site for kids that uses color to help remind everyone to eat their veggies and fruits.

FOSSweb
A site with educational resources for students, teachers, and parents. Includes a variety of interactive science modules in three collections (K-2, 3-6, and Middle School). Great fun and great resources. FOSS stands for "Full Option Science System".

Level 2



Earth Science Picture of the Day
Astronomy Picture of the Day
National Geographic Photo of the Day
Three very interesting "picture-of-the-day" sites.

NASA Images
NASA Images offers public access to NASA's images, videos and audio collections. NASA Images is constantly growing with the addition of current media from NASA as well as newly digitized media from the archives of the NASA Centers. The goal of NASA Images is to increase our understanding of the earth, our solar system and the universe beyond in order to benefit humanity.

Why Leaves Change Color

Here is a concise and accurate explanation from the US Dept. of Agriculture.

Maple Syrup Color

Maple syrup is done when it reaches 7.5 degrees above the boiling point of water (at a density that is 67% sugar and 33% water). It is not made darker by boiling it longer (or lighter and therefore more expensive by boiling for less time). The colors of various grades come from the nature of the sap. This site provides a brief explanation and other information about Maple syrup.

Liquid Sculpture - Water Art

Fun high-speed images of water droplets doing various things in various colors. It is interesting to observe the various color mixtures and formations in the images and ponder how they were made.

Level 3

Neuroscience for Kids

"Discover the exciting world of the brain, spinal cord, neurons and the senses. Use the experiments, activities and games to help you learn about the nervous system. There are plenty of links to other web sites for you to explore".

Infrared Zoo

Part of a site on infrared astronomy at Caltech, CoolCosmos. The entire site is worth exploring. The link goes right to their "infrared zoo" that has images of various animals made with a thermal infrared camera (images of emitted heat, rather than reflected light). The only downside is that they make the all-too-common mistake of calling infrared energy, "infrared light". If you can't see it, it's not light!

Coloring Carnations

A nice experiment on making carnations different colors. The site also includes other interesting experiments and other resources.

Color in Motion

"An interactive experience of color communication and color symbolism."

"Science Myths" in K-6 Textbooks and Popular Culture

If someone is taught something incorrectly first, it is very difficult to "unlearn" that mistake and "learn" the correct information. This website points out some errors and misconceptions that creep into students educational experiences. There is also a lot of other information to explore there.

Ames Room Explanation

A nice explanation of the visual illusion of distorted space and size known as the Ames Room. Also explore the links to the "Hall of Illusions".

Level 4

Optical Illusions and Visual Phenomena
A wonderful collection of visual phenomena with great interactive demonstrations and detailed explanations.

Optical Illusion Time
Another great collection of links to optical illusions. This one was sent to me by a teacher who had it pointed out to her by a fourth-grade student. Enjoy!

Optics for Kids
"Exploring the science of light" for kids from the Optical Society of America.

A Very Cool Illusion
My original link has expired, but here is a link to an explanation of a very cool illusion that has been popular on the internet. This one demonstration shows both how stimuli fade in the periphery and illustrates chromatic adaptation.

Selective Perception
Follow these instructions before you click the link...

In the video you will see a group of basketball players, some in white and some in black, passing two balls around. Your goal is to count how many times the ball is passed by those wearing white shirts. It's that simple. Remember, count just the passes of the ball by those wearing white. Once the movie is over, write down the number of passes you have counted.

Now WATCH THE VIDEO.
Did you see anything strange? Watch the video again without following the basketball.

More Visual Illusion Links

Several people have submitted links to pages with visual illusions. Here is a list of some of them. (Thanks, Seth!)

Ted Adelson's Discounting-the-Illuminant Demo on APOD.

Grand Illusions.

Mo' Illusions.

Archimedes' Laboratory.

UML Illusions Gallery.

Level 5

Project LITE at Boston University

A fantastic web site full of Flash demos of various visual phenomena. The interactive demos can be used online, or downloaded for use in presentations, etc. Definitely worth some exploration.

More Complex Visual Contrast Illusions/Effects

Some very interesting visual stimuli illustrating the complexities of human color perception and the importance of contrast. Also includes detailed explanations and links to other "illusions" pages.

"About" Photography: Understanding Colour

An article from photography.about.com that explains some basics of color, particularly in digital photography.

MadSciNet: The 24-Hour Exploding Laboratory

"MadSci Network represents a collective cranium of scientists providing answers to your questions. For good measure we provide a variety of oddities as well."

Ask-A-Scientist

The US Dept. of Energy's Ask-A-Scientist site. An extensive archive of questions and answers.

Level 6

Last Word

NewScientist's interactive science Q&A page. Another resource of science questions and answers.

Color Matters

A fun collection of information and resources about color ... some science, some not. All interesting! I often refer people to their page on Baker-Miller Pink when they are curious about it. Also lots of people ask about color and heat absorption. There is a page with details of a heat absorption experiment.

Color Symbolism

A topic of much interest and confusion. While there are no definitive answers, this site provides some resources on common symbolism for various colors.

SDC Colour Museum

A fun and informative interactive site from the Society of Dyers and Colourists Colour Museum (now simply the "Colour Experience") in Bradford, UK.

WebExhibits

An online museum with "exhibits" about color, vision, art, pigments, and a number of other topics. Their Causes of Color resource is particularly enjoyable.

ColorAcademy

An online encyclopedia covering many aspects of color. In their own words it "is a truly unique resource of ideas and information about colour. Compiled by a number of prominent art experts, our encyclopedia can provide the required colour information for any visitor be they a primary school student or an architect."

HowStuffWorks

A great place to learn about how stuff works, from mood rings, to human vision, to rainbows, to color television, etc. One of the most common questions I receive is about how mood rings work. I always point to the HowStuffWorks explanation. It also has great explanations of things like light, fireworks, TV, etc.

Optics for Teens

"Exploring the science of light" for teens from the Optical Society of America.

TryScience

A gateway to over 400 science centers. In their own words, TryScience is a "gateway to experience the excitement of contemporary science and technology through on and offline interactivity with science and technology centers worldwide. Science is exciting, and it's for everyone! Ideas for experiments, field trips, etc.

Exploratorium

Too much to even describe. Spend some time exploring their resources, projects, etc. etc. etc. I love the "Science Snacks".

Ontario Science Centre: Science Resources

Another fine science museum. Thankfully there are a lot of them. This link is directly into their resources for teachers and students, such as science fair tips.

Rochester Museum and Science Center

I can't neglect our local science museum, especially since they have assisted with this project and hosted our students many times. I am particularly a fan of their Cumming Nature Center (mmm ... maple syrup).

Arbor Scientific

Arbor Scientific sells inexpensive materials and equipment for science teachers, including much on light and color. They also have online resources such as their newsletter. This issue has nice discussions of atmospheric optics, like rainbows.

One Planet Many People

An example of how imaging and science can help us understand the planet and our impact upon it. "Through a combination of ground photographs, current and historical satellite images, and narrative based on extensive scientific evidence, this publication illustrates how humans have altered their surroundings and continue to make observable and measurable changes to the global environment."

29+ Evidences for Macroevolution

Evolution is helpful in understanding much about color and perception. I have been asked about my "assumptions" that evolution actually happens and have used this link to provide some sound scientific evidence. Enjoy if you are curious.

TED: Ideas worth spreading

"TED stands for Technology, Entertainment, Design. It started out (in 1984) as a conference bringing together people from those three worlds. Since then its scope has become ever broader." The website includes high-quality videos of fascinating talks on a wide variety of topics and is updated regularly.

The Dimensions of Colour

Essentially on online textbook/tutorial on appearance, or "the dimensions of colour and light" written from the perspective of artists. The site is very nicely done and blends technical and artistic information well.

Joy of Visual Perception

An extensive web book on visual perception with many links to other resources.

Vischeck

Learn about color blindness and make images that simulate what people with color vision deficiencies might see.

Level 7

Bruce MacEvoy's handprint

A great site that is mainly about watercolor, but has lots of other information and wonderful explanations of color vision and color science topics.

What Color Eyes...?

A fun and informative exploration of the genetics of eye color. Includes an eye color calculator for your children and also explanations of how eye color is determined and inherited.

Virtual Color Museum

Detailed explanations of 59 color systems from throughout history along with other information on color order, color and culture, etc. Content is available in multiple languages.

BruceLindbloom.com

A non-commercial site with some interesting and useful color calculators, definitions of equations, and general information for those interested in digital color imaging.

Level 8

CVRL Color & Vision Database

A collection of fundamental data (e.g., color matching functions, cone responsivities, etc.) that are useful in computations for colorimetry and color vision.

Webvision

An online graduate level textbook on vision. Very extensive.

Review Papers on Color Vision

A special issue of "Clinical and Experimental Optometry" with a collection of outstanding review papers on many facets color vision. A great resource for college-level teaching.

Munsell Color Science Laboratory

Our lab at RIT.

Mark D. Fairchild is the Associate Dean for Research and Graduate Education of RIT's College of Science and Professor of Color Science and Imaging Science in the Chester F. Carlson Center for Imaging Science's Munsell Color Science Laboratory. He grew up in Trumansburg, NY where he graduated from C.O. Dickerson High School with a love for science, photography, nature, and golf. He enrolled in RIT's unique program in Photographic Science and Instrumentation completing his B.S. and M.S. degrees there (meanwhile the program was renamed to Imaging Science) and joining the faculty in color science. Mark completed a Ph.D. in Vision Science at the University of Rochester performing research on chromatic adaptation and color appearance. He remained with the RIT faculty to this day and continues to teach color science, perform research on the perception of color and images, and work to enhance all the research programs in the College of Science. He also continues to practice photography and golf, sometimes simultaneously. Mark can be reached at <mdf@cis.rit.edu>.