

MSc Computer Games and Entertainment  
Maths & Graphics Unit 2011/12  
Lecturer: Gareth Edwards

# Colour

## Part 1: Colour Vision

## Acknowledgments

- Clive Maxfield and Alvin Brown
- Wikipedia.

## Colour

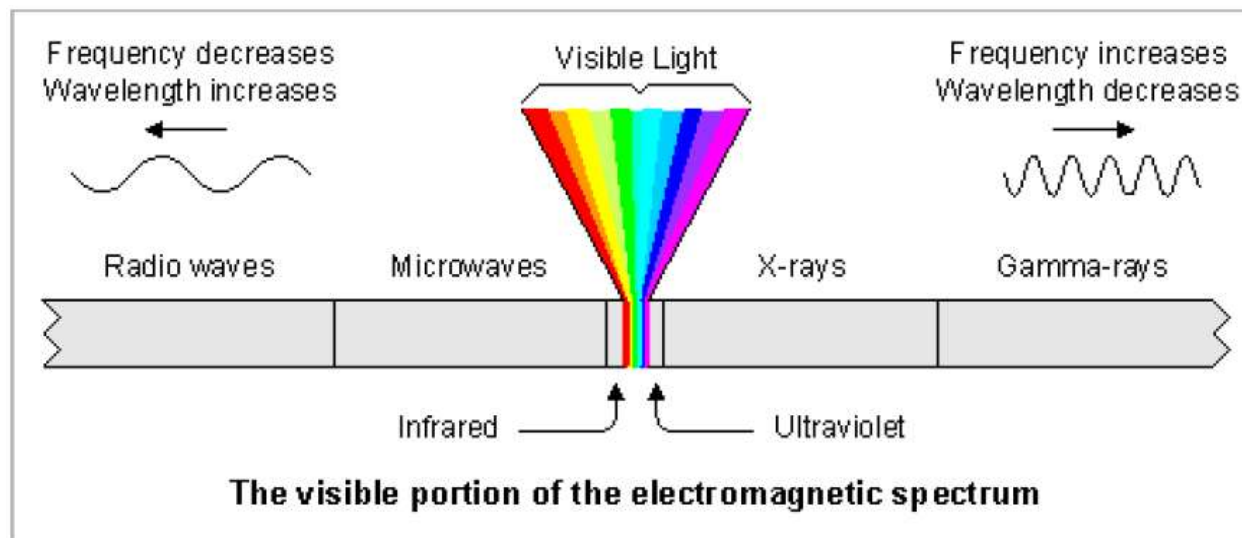
- Following on from last weeks lecture on Shaders this lecture focuses on colour, one of the major topics that was introduced.
- Colour is the human brain and visual cortex perception of light, i.e. power spectrum of electromagnetic radiation
- Colour is a very complicated subjects!
- Colour involves a lot of physiology and psychology!
- Colour is not fully understood.... yet!
- For our purposes we will consider it to be the main colour of an object, surface, polygon, etc.

## Colour Vision

- Evolution has dictated that we are visually orientated.
- The human brain and visual cortex are capable of processing huge amounts of visual data and can quickly and efficiently recognize and extract useful information from this data.
- Studies have shown that we receive approximately 80% of our external information in visual form.
- Generally speaking, however, most of us tend to take our visual capabilities for granted, especially when it comes to colour vision.

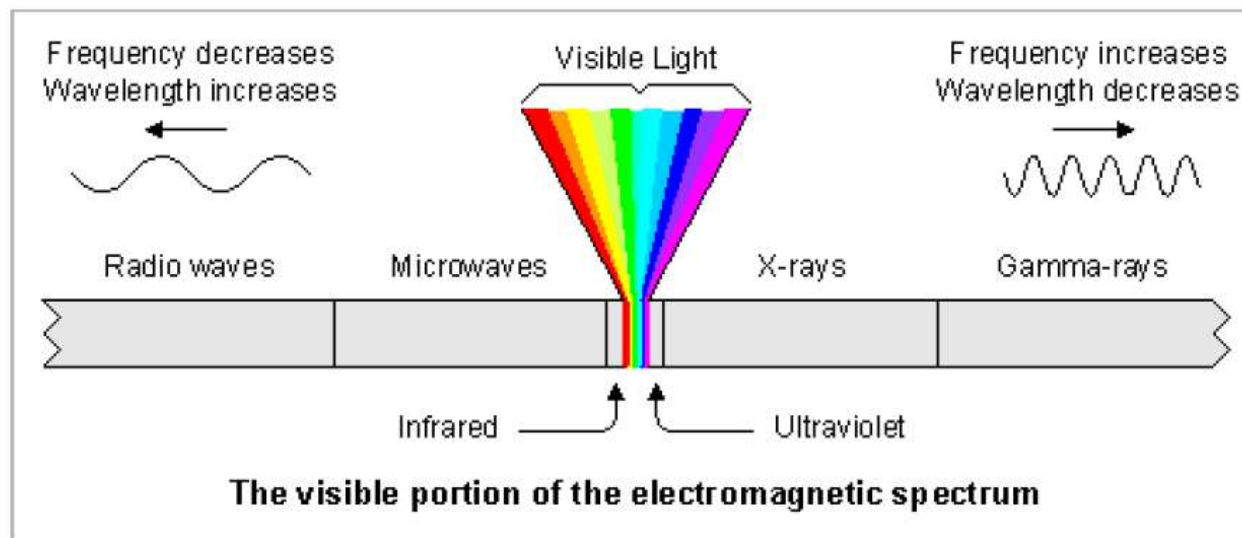
## The Electromagnetic Spectrum

- What we refer to as "light" is simply the narrow portion of the electromagnetic spectrum that our eyes can see (detect and process).....
- Ranging from violet at one end to red at the other, and passing through blue, green, yellow, and orange on the way (at one time, indigo was recognized as a distinct spectral colour, but this is typically no longer the case).



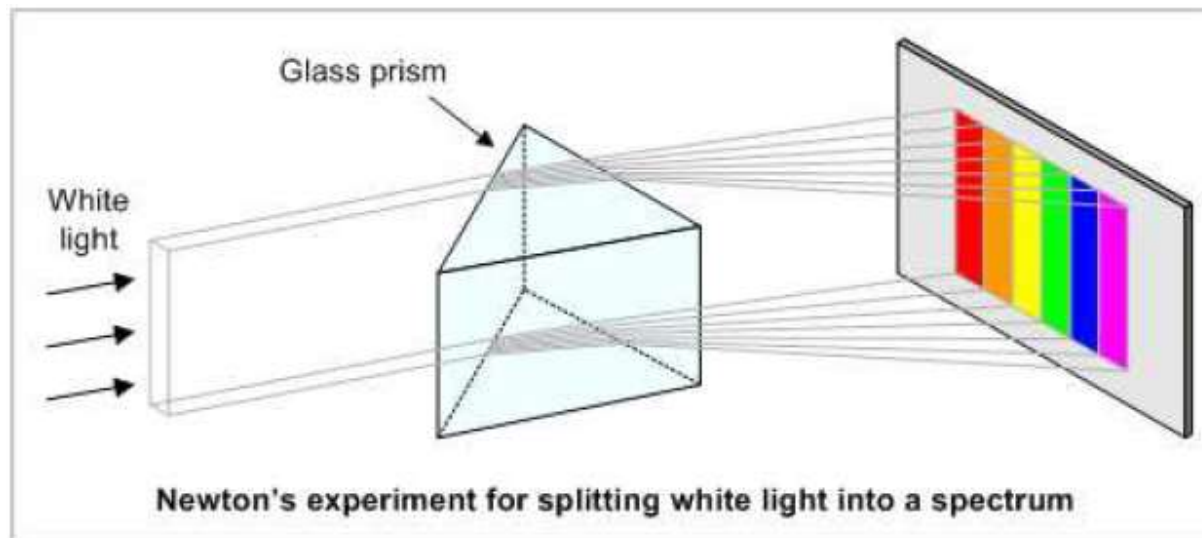
## The Electromagnetic Spectrum

- We use terms like "red", "yellow", "green", and "blue", these are just labels that we have collectively agreed to associate with specific sub-bands of the spectrum.
- Just outside the visible spectrum above violet is *ultraviolet, the component of the sun's rays that gives us a suntan (and skin cancer)*.
- *Similarly, just below red is infrared, which we perceive as heat.*



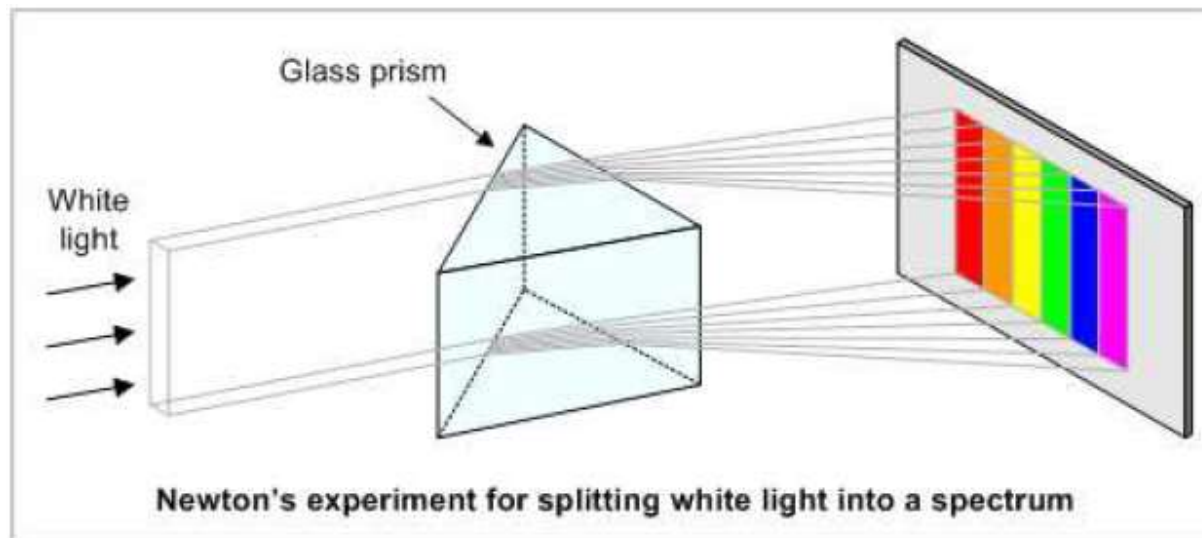
## The Discovery of the Visible Spectrum

- Strange as it may seem when one is first introduced to the idea, white light is a mixture of all of the colours in the visible spectrum.
- This fact was first discovered around 1665-1666 by the mathematician and physicist Sir Isaac Newton (1642-1727), who passed a beam of sunlight through a glass prism to find that it separated into what he called "*a spectrum of colours*".



## The Discovery of the Visible Spectrum

- In reality, even before Newton's famous experiments, a number of other people were using prisms – which were fairly new at that time – to experiment with light.
- Actually, when you come to think about it, it seems more than possible that someone many tens of thousands of years ago observed sunlight passing through a block of natural glass and reappearing as a rainbow of colours.



## The Discovery of the Visible Spectrum

- In Newton's time many thought that it was their prisms that were colouring the light.
- Newton's used a prism to separate white sunlight into his spectrum of colours as shown above.
- Next, he used a piece of card with a slit in it to block all of the colours except one – say green – and then he passed this individual colour through a second prism.
- Newton's thought was that if it was the prism that was colouring the light, then the green light entering the second prism should come out a different colour.
- The fact that it came out the same colour indicated to Newton that it wasn't the prism that was colouring the light.
- Newton then took the spectrum coming out of his first prism and fed it into an "upside down" prism. This caused the individual colours to recombine back into white light.

## The Discovery of the Visible Spectrum

- By these experiments, Newton was the first to prove that white light was made up from all of the colours in the visible spectrum and that his first prism was simply separating these colours out.
- As a point of interest, Newton originally declared that there were eleven colours in the visible spectrum.
- Later, he toned this down to seven in order to make his spectrum fit with contemporary Western ideas about musical harmony (specifically, that there were seven notes/tones in an octave). This is why the spectrum was originally said to include indigo, but more recently is defined as comprising only red, orange, yellow, green, blue, and violet.
- Last but not least, we're used to seeing the same effect as Newton's experiment in the form of a rainbow, which is caused by sunlight passing through droplets of water, each of which acts like a tiny prism. In fact, as far back as the 13th century, the famous Franciscan friar and English philosopher Roger Bacon (1212-1294) suggested that rainbows were caused by the reflection and refraction of sunlight through raindrops, but – at that time – he had no way to prove that this was indeed the case.

## The Discovery of Infrared

- Friedrich Wilhelm Herschel (1738-1822) was born in Hanover, Germany. In 1757 he moved to England, where he became known as the famous astronomer and musician Sir Frederick William Herschel.
- In 1800, Herschel started to wonder if the different colours in the spectrum had different temperatures associated with them (you have to admire someone like that, because this sort of thought simply wouldn't occur to the majority of us).
- He used a thermometer to measure the temperatures of the different colours, and he observed that the temperature rose from violet (with the lowest value) through blue, green, yellow, and orange, until it reached its peak in the red portion of the spectrum.

## The Discovery of Infrared

- Now here's the really clever part – Herschel next moved the thermometer just outside the red portion of the spectrum in an area that – to the human eye – contained no light at all.
- To his surprise, he discovered that what he came to regard as being "invisible rays" in this area had the highest temperature of all.
- Following a series of experiments in which he proved that these invisible rays behaved just like visible light (in that they could be reflected, refracted, and so forth), Herschel christened his discovery *infrared rays* (where the prefix *infra* comes from the Latin, meaning "below").
- In addition to leading us to an understanding of heat, Herschel's discovery was also important because it was the first time anyone had demonstrated that there were forms of radiation ("light" in his terms) that humans couldn't see.

## The Discovery of Ultraviolet

- Johann Wilhelm Ritter (1776-1810) was born in Samitz, Silesia, which is now part of Poland and studied science and medicine at the University of Jena.
- While at the University, Ritter performed numerous experiments with light and – later – electricity.
- After hearing about William Herschel's discovery of infrared light beyond the red end of the visible portion of the spectrum, Ritter decided to see if he could discover his own "invisible rays" beyond the violet end of the spectrum.
- Ritter knew that silver chloride turned black when exposed to light.
- Thus it was that, in 1801, in the same way that Herschel had used a thermometer to measure the temperature of the different colours, Ritter decided to use silver chloride to see if it reacted at a different rate to the different colours.

## The Discovery of Ultraviolet

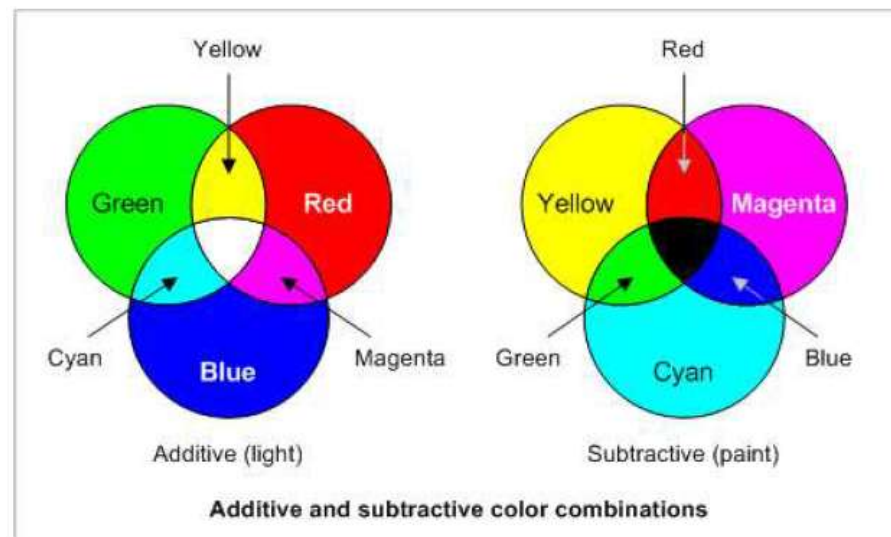
- First, he placed a quantity of the chemical in the path of the red portion of the spectrum and observed that any change was relatively slow.
- Next, he tried orange, followed by yellow, green, blue, and violet, observing that each new batch of silver chloride grew darker faster as he progressed through the spectrum.
- Finally, Ritter placed a quantity of the chemical just outside the violet portion of the spectrum in an area that – to the human eye – contained no light at all.
- To his delight, he discovered that invisible rays in this area had the greatest effect on the silver chloride.
- This new type of radiation eventually came to be known as *ultraviolet light* (where the prefix *ultra* comes from the Latin, meaning "beyond").

## Primary Colours

- In the case of colour televisions and computer screens, each picture element (pixel) is formed from a group of red, green, and blue (RGB) dots.
- If all three of these dots are active (lit up) at the same time, then from a distance we'll perceive the group as a whole as being white.
- If however we looked really closely we'd still see each dot as having its own individual colour.
- If we stimulate just the red and green dots we'll see yellow - the green and blue dots will give us cyan - the red and blue dots will result in magenta (named after the dye – and named after the battle of Magenta, which occurred in Italy in 1859, the year in which the dye was discovered).
- Furthermore, mixing different proportions of the three light sources will result in a gamut of colours, where the word "gamut" means "a complete range or extent".

## Primary Colours

- Now, this may seem counter-intuitive at first, because it doesn't seem to work the way we recall being taught at school, which was that mixing yellow and blue paints together would give us green, mixing all of the coloured paints together would result in black (not white as discussed above), and so on.
- The reason for this is that mixing light is *additive*, while mixing paints or pigments is *subtractive*:



## Primary Colours

- The appellation *primary colours* refers to a small collection of colours that can be combined to form a range of additional colours. In the case of light, the primary colours we typically use are red, green, and blue. Since bringing in new colour components "adds" to the final colour, these are known as the *additive primaries*.
- *By comparison*, when it comes to paints or pigments, the primary colours used by printers are cyan, magenta, and yellow (CMY). In this case (for the reasons discussed in the following topic), bringing in new colour components "subtracts" from the final colour, so these are known as the *subtractive primaries*. *Actually, forming black by mixing cyan, magenta, and yellow inks together is expensive and typically results in a "muddy" form of black, so printers typically augment these primary colours with the use of black ink.*
- The result is referred to as CMYK, where the 'K' stands for "black" (we don't use 'B' to represent "black" because this could be mistakenly assumed to refer to "blue").

## Primary Colours

- *You may remember that at school we were taught that the three primary colours were red, yellow, and blue (RYB); that mixing red and yellow gave orange; combining red and blue gave purple; and blending yellow and blue gave green.*
- However this is based upon knowledge that predates our modern scientific understanding of colour theory.
- In reality, you can pretty much pick any three (or more) colours and call them "primary" colours, and this will be true on the basis that they are your primary colours.
- Mixing two of your primary colours together will result in a *secondary colour*; mixing one of your primary colours with one of your secondary colours will result in a *tertiary colour*, and so forth.

## Primary Colours

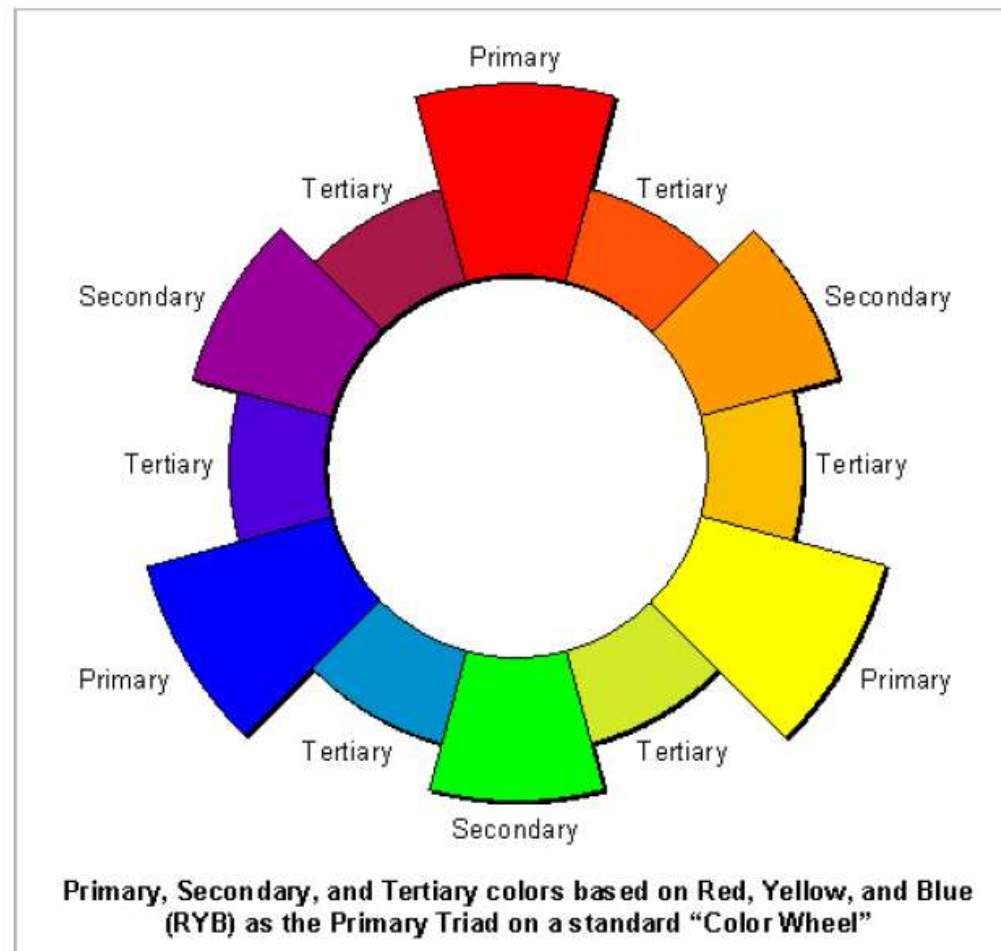
- One example of a non-standard collection of primary colours was an early colour photographic process known as *Autochrome*, which was invented circa 1903-1904 in France by the Lumière brothers, Auguste and Louis.
- This process typically used orange, green, and violet as its primary colours.

## Primary Colours

- In 1666, as part of his experiments with prisms, Sir Isaac Newton developed a circular diagram of colours that is now commonly referred to as a "colour wheel".
- For one reason or another, theorists of that time decided that red, yellow, and blue were the best primary colours for pigments, and – even though we now know that red, yellow, and blue primaries cannot be used to mix all of the other colours – they have survived in colour theory and art education to the present day.
- Purely for the sake of completeness, let's consider a colour wheel based on red, yellow, and blue as its primary triad as shown below:

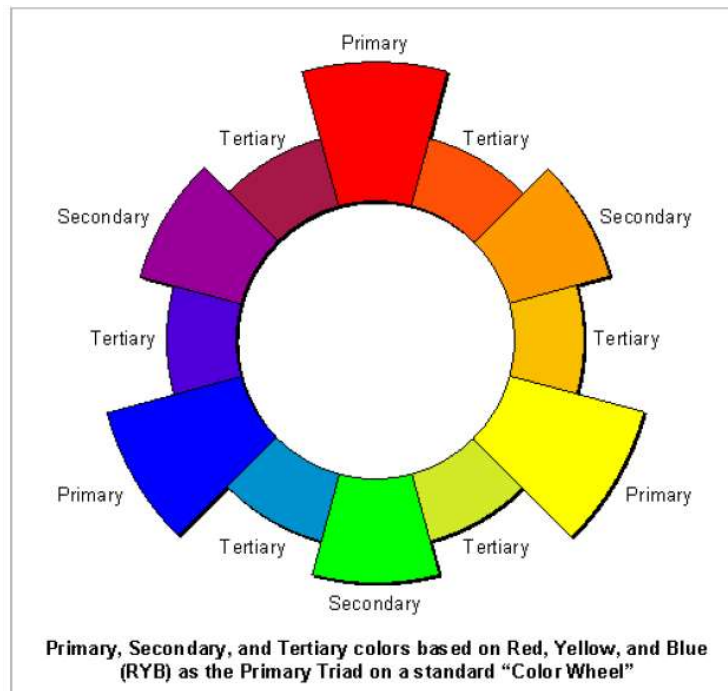
## Primary Colours

- Purely for the sake of completeness, let's consider a colour wheel based on red, yellow, and blue as it's primary triad as shown below:



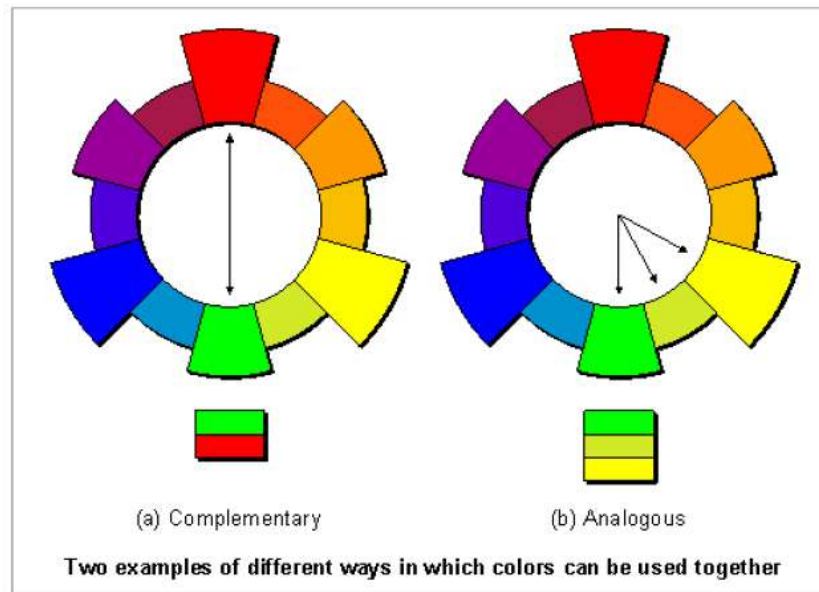
## Primary Colours

- Using our three primary colours as a starting point, we can generate three secondary hues: mixing red and yellow gives orange, yellow and blue gives green, and blue and red gives purple.
- Similarly, mixing the primary colours with their adjacent secondary colours results in six tertiary hues: red-orange, yellow-orange, yellow-green, blue-green, blue-purple, and red-purple.



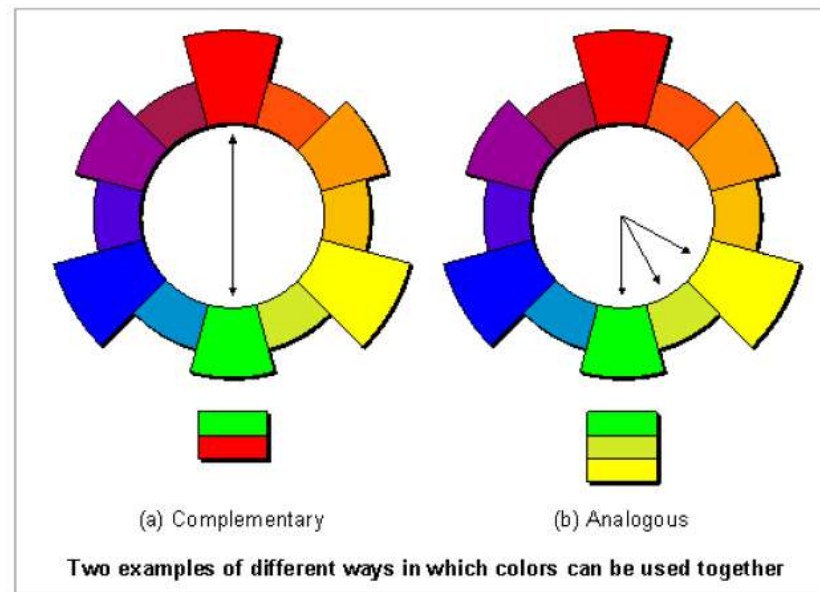
## Primary Colours

- There are lots of different theories regarding the way in which different colours can be used in conjunction with each other so as to produce a pleasing effect to the eye (that is, so that it looks good to humans).
- For example, *complementary colours are any two colours that are directly opposite each other on the colour wheel and provide maximum contrast*, such as red and green, red-orange and blue-green, and so forth.
- By comparison, *analogous colours are any three colours that are side-by-side on the colour wheel*, such as yellow, yellow-green, and green.



## Primary Colours

- The problem is that – the above diagrams notwithstanding – red, yellow, and blue are not well-spaced around a perceptually-uniform colour wheel that embraces the entire spectrum of colours.
- This means that using red, yellow, and blue as primaries yields a relatively small gamut, and it is impossible to mix them so as to achieve a wide range of colourful greens, cyans, and magentas.
- This is the reason why modern colour photography and three-color printing processes employ cyan, magenta, and yellow as primaries, because these offer a much wider gamut of colours.

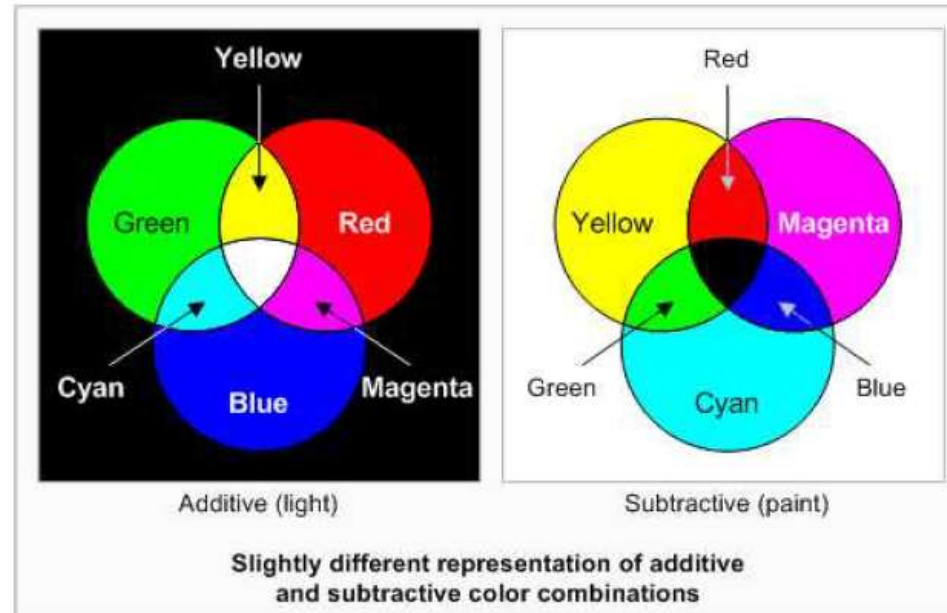


## Primary Colours

- At this juncture, we should perhaps briefly mention terms like *shade*, *tint*, and *hue*.
- *The problem is that all of these words have several different meanings depending on whom you are talking to. For our purposes here, we may say that hue is the quality of a colour that allows us to assign it a name like "greenish-blue" or "reddish-orange".*
- More formally, one might say that the hue is the dominant wavelength of a particular colour – that is, the "colour of a colour".
- Meanwhile, *shade may be described as "the degree of darkness within a hue" and tint may be considered to be "the degree of lightness within a hue". In the case of painting, for example, artists have long used the word "shade" in the context of mixing a colour with black, so a shade is a colour which has been made darker in this way.*
- By comparison, artists use the word "tint" to refer to the mixing of a colour with white, so a tint is a colour which has been made lighter in this way.

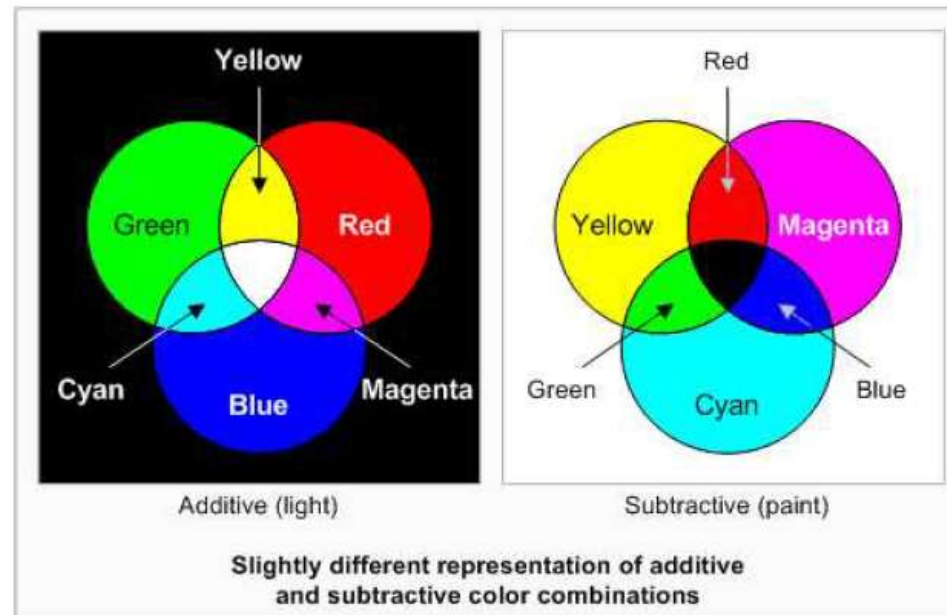
## Primary Colours

- As a further point of interest, it is common to refer to red, yellow, green, blue, white, and black as being the *psychological primaries*, because we *subjectively and* instinctively believe that these are the basis for all of the other colours.
- Furthermore, considering the additive and subtractive colour combinations in the context of Venn Diagrams shown in an earlier slide, a slightly more intuitive representation might be as shown below:



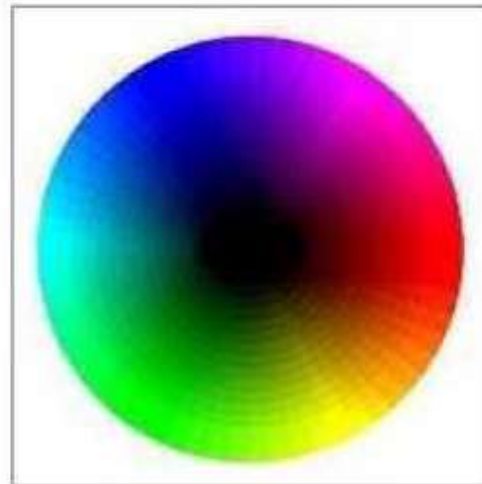
## Primary Colours

- In the case of light, the surrounding "world" (in the form of an empty theatre/stage/room with the lights turned off, for example) should be black, then we *add red, green, and blue light by activating appropriately coloured spotlights; the combination of all of these light sources results in white light.*
- *By comparison, in the case of paint, the surrounding "world" (in the form of a large piece of paper, for example) should be white, then we **subtract colours by applying cyan, magenta, and yellow pigments to the paper; the combination of all of these pigments results in black.***



## Primary Colours

- Another representation of the mixing of primary colours is shown in the following illustration.
- This is similar to one shown in the previous slide, except that this new version is presented as a gradual merge between the various primary colours (the primary colours in this new illustration are not in the same relative locations as for the earlier diagrams).



**Yet another way of looking at things**

(Courtesy of <http://home.wanadoo.nl/paulschils/index.html>)

## Mixing Light versus Mixing Paint

- So why does mixing light work one way while mixing paint works another?
- What colours come to mind when you hear the words "tomato," "grass," and "sky"?
- You almost certainly responded with red, green, and blue, respectively, but why?
- The main reason is that when you were young, a parent or teacher told you that *"Tomatoes are red, grass is green, and the sky is blue,"* and you *certainly had no cause to doubt* their word.
- However, the terms "red," "green," and "blue" are just labels that we have collectively chosen to assign to certain portions of the visible spectrum. If our mothers had told us that *"Tomatoes are blue, grass is red, and the sky is green,"* then we'd all quite happily use those labels instead.

## Mixing Light versus Mixing Paint

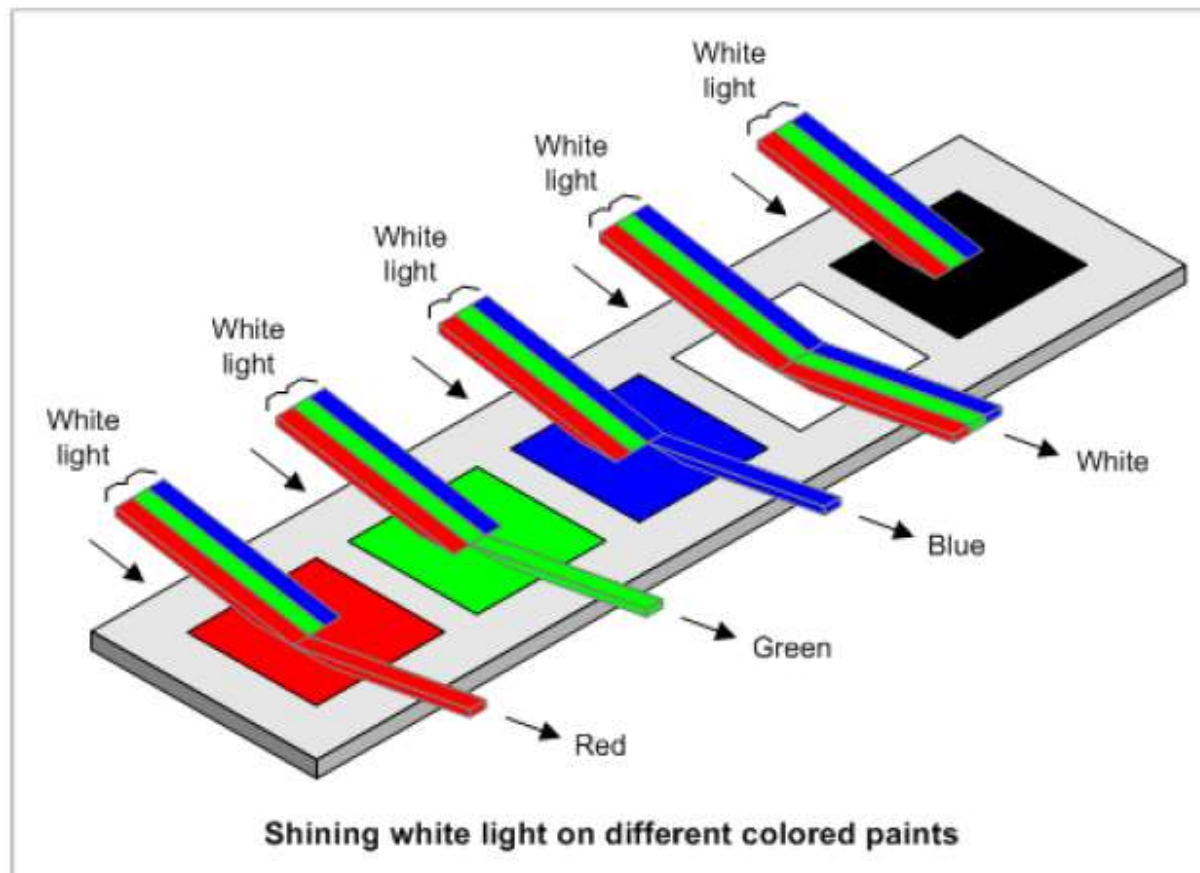
- What we can say is that, using an instrument called a spectrometer, we can divide the visible part of the spectrum into different bands of frequencies, and we've collectively agreed to call certain of these bands "red," "green," and "blue."
- Of course everyone's eyes are slightly different, so there's no guarantee that your companions are seeing exactly the same colours that you are.
- Also, as we shall see, our brains filter and modify the information coming from our eyes, so a number of people looking at the same scene will almost certainly perceive the colours forming that scene in slightly different ways.

## Mixing Light versus Mixing Paint

- Here's another question for you: "*Why is grass green?*"
- *In fact we might go so far as to ask: "Is grass really green at all?"*
- *Surprisingly, this isn't as stupid a question as it might seem, because from one point of view we might say that grass is a mixture of red and blue; that is, anything and everything except green!*
- The reason we say this is that, when we look at something like grass, what we actually see are the colours it *didn't absorb*.
- *For example, consider what happens when we shine white light on patches of different coloured paint:*

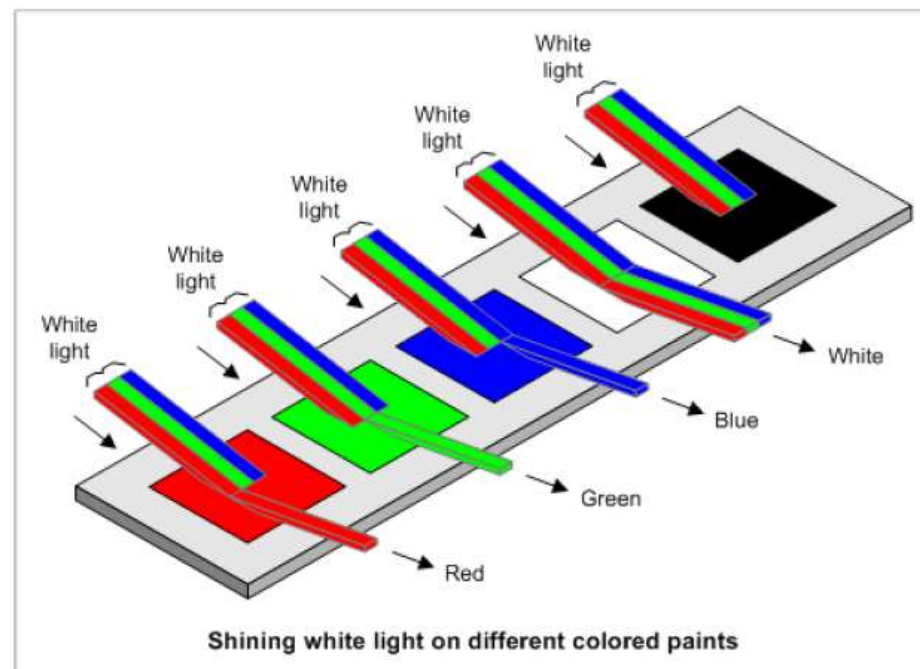
## Mixing Light versus Mixing Paint

- *For example, consider what happens when we shine white light on patches of different coloured paint:*



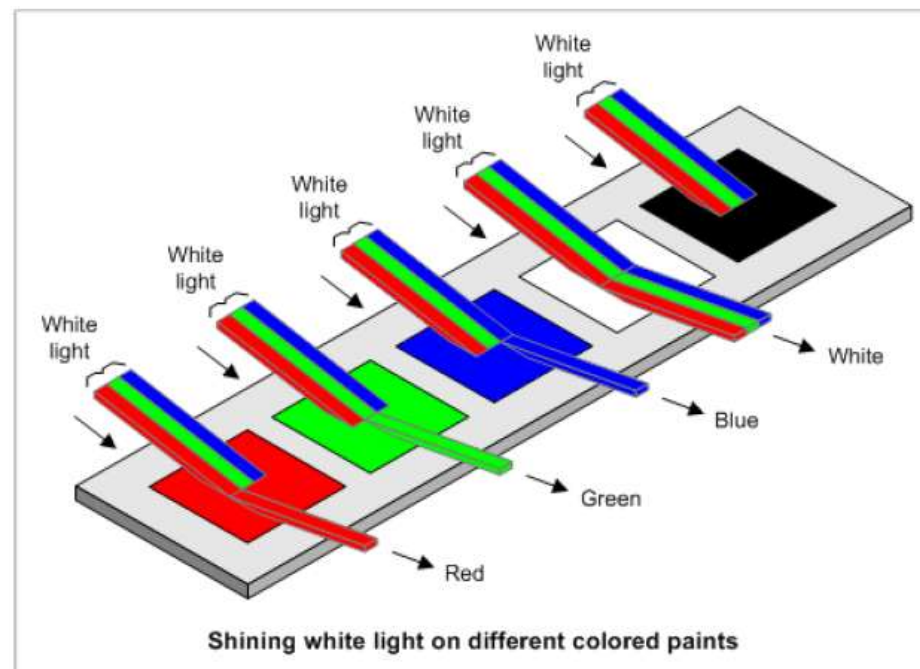
## Mixing Light versus Mixing Paint

- The red paint absorbs the green and blue light, but it reflects the red light, which is what we end up seeing.
- Similarly, the green paint absorbs the red and blue light and reflects the green, while the blue paint absorbs the red and green and reflects the blue.
- The white paint reflects all of the colours and the black paint absorbs them all, which means that black is really an absence of any colour.



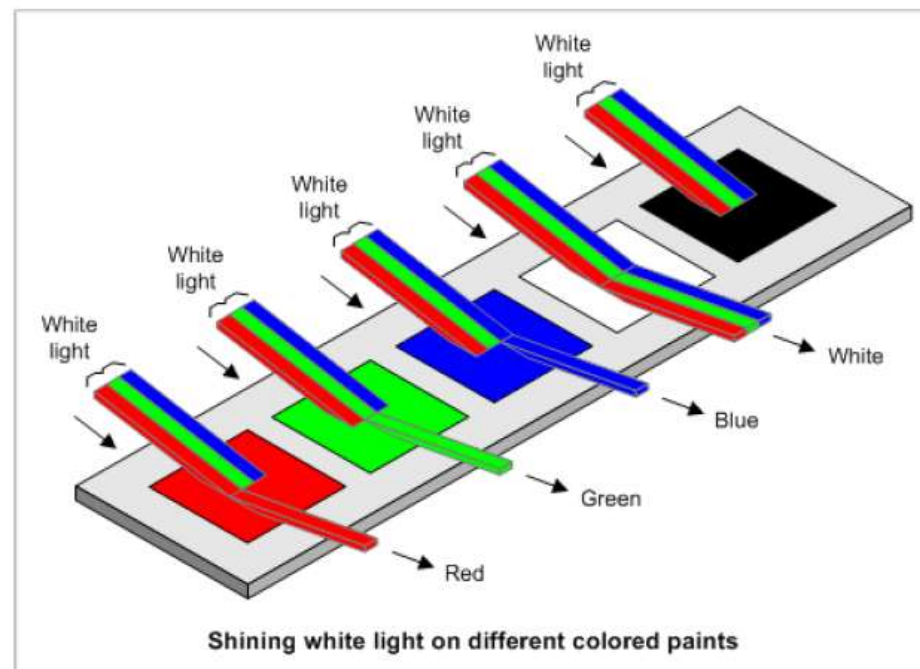
## Mixing Light versus Mixing Paint

- Thus, returning to our original question about the colour of grass: we could say that grass is green because that's the colour that it reflects for us to see, or we could say that grass is both blue and red because those are the colours it absorbs.
- This explains why mixing paints is different from mixing light. If we start off with two tins of paint – say cyan and yellow – and shine white light at them, then each of the paints absorbs some of the colours from the white light and reflects others.



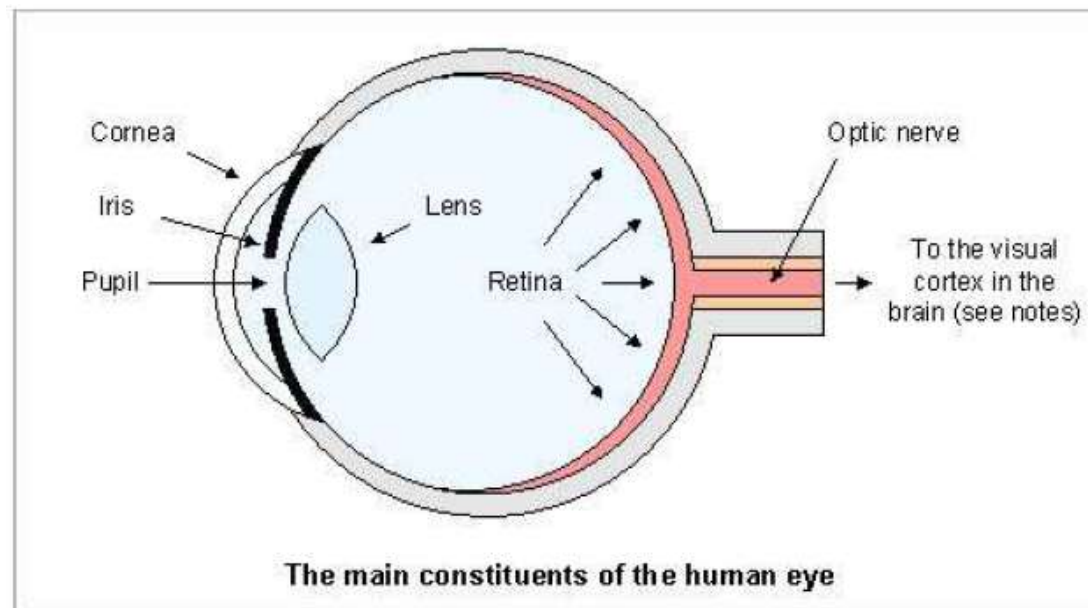
## Mixing Light versus Mixing Paint

- If we now mix the two paints together, they each continue to absorb the same colours that they did before, so we end up seeing whichever colours neither of them absorbed, which is green in this case.
- This is why we say mixing paints is *subtractive*, because the more paints we mix together, the greater the number of colours the combination *subtracts* from the white light.



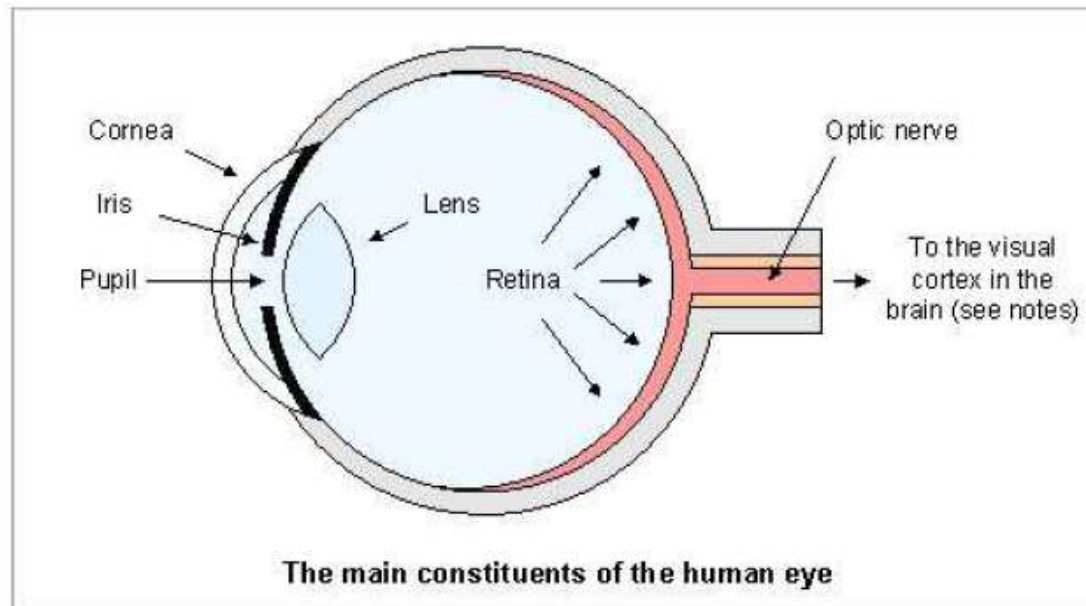
## How Colour Vision Works

- First, light from the outside world passes through the *cornea*, which acts like a clear, transparent, protective "window". Just inside the cornea we find the *iris*, which gives our eyes their distinctive colour.
- When we say "she has blue eyes," for example, we are talking about the colour of that person's irises.
- The hole in the middle of the iris is called the *pupil*, which determines how much light is passed into the body of the eye. The iris causes the pupil to shrink in bright light and to enlarge in dim light.



## How Colour Vision Works

- Next, the lens is used to focus the light on the back of the eye, which is covered by a layer called the *retina*. *The retina often used to be compared to the film in a conventional camera, but it is actually more akin to the sensor element in a modern digital camera.*
- Amongst other things, the retina contains special photoreceptor nerve cells that convert rays (photons) of light into corresponding electrical signals. After some processing in the eye itself, these signals are passed along the optic nerve into the visual cortex region of the brain (actually, this is something of a simplification).



## How Colour Vision Works

- In a moment we're going to introduce the concept of color photoreceptor cells called *cone cells*.
- *The point is that when we say things like "blue cones" or "cones that respond to blue light," we really mean "photoreceptor cells that are tuned to respond to the range of frequencies in the electromagnetic spectrum that we perceive as being blue".*
- *However, although the scientists amongst us would prefer this more precise terminology, it's a lot easier to refer to things like "blue cones," so if we occasionally slip, you'll know what we mean.*

## How Colour Vision Works

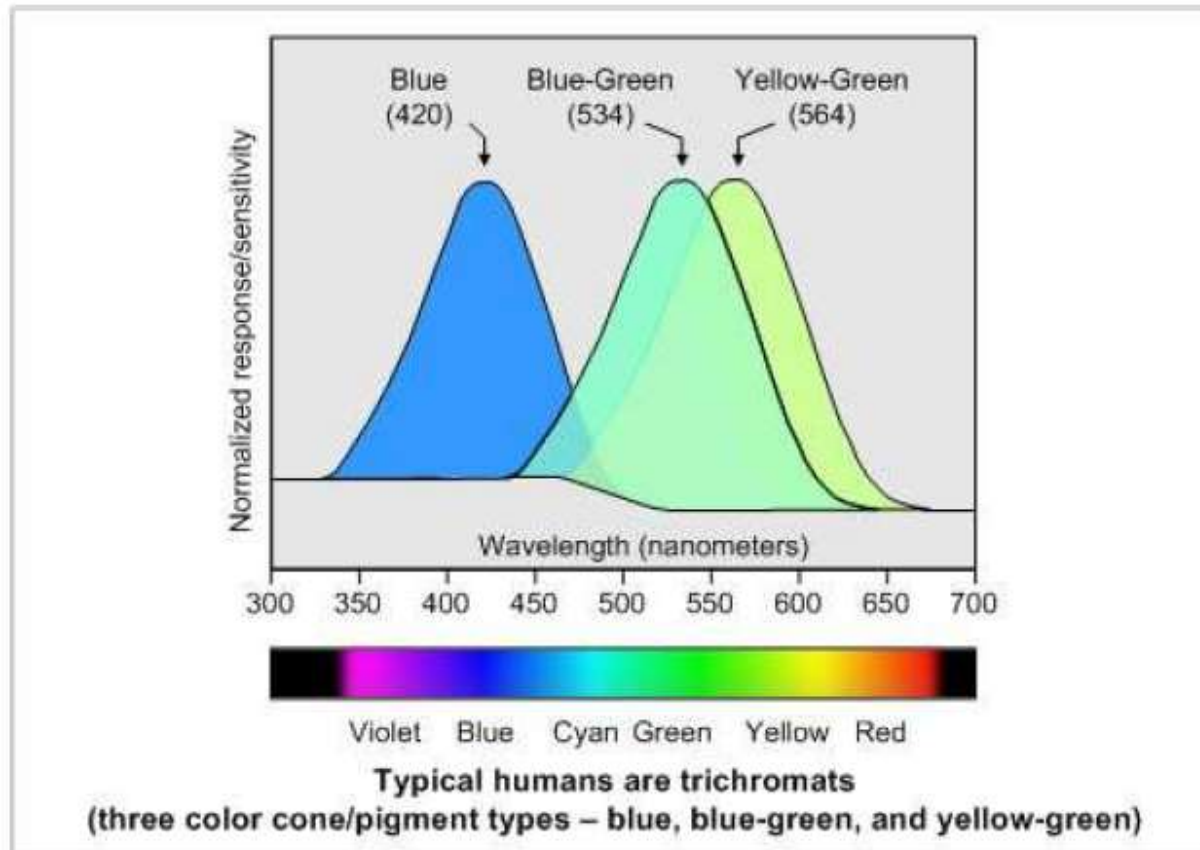
- The reason most references talk about red, green, and blue receptors in the human eye dates back to around 1801-1802, when the English physician Thomas Young (1773-1829) performed a series of experiments and proposed his "*trichromatic theory*."
- Young's hypothesis originated in observations by artists, clothing manufacturers, and so forth, who recognized that if you had three different pigments you could mix them to form any other colour.
- Prior to Young, people had suggested that there were three different types of light, so Young's recognition that the "three" was due to human anatomy and physiology rather than the physics of light was a major conceptual breakthrough.
- Young's hypothesis, which was refined around 50 years later by the German scientist Hermann von Helmholtz (1821-1894), proposed that the human eye constructed its sense of colour using only three receptors for red, green, and blue light.
- Based on this theory, humans are known as *trichromats*.

## How Colour Vision Works

- It was originally assumed that the electrical signals from the different types of colour receptor cells were fed via the optic nerve directly into the visual cortex portion of the brain, which used these signals to determine different colours.
- However, we now know that the truth is a little more complex.
- We'll start by saying it is true that the human boasts three types of colour receptors called *cone cells* (so-named because they have a somewhat conical appearance when viewed under a microscope).
- There are about 6 million of these cells in each eye.
- Each type of cone cell covers a range of frequencies, but is primarily sensitive to a particular portion of the spectrum.

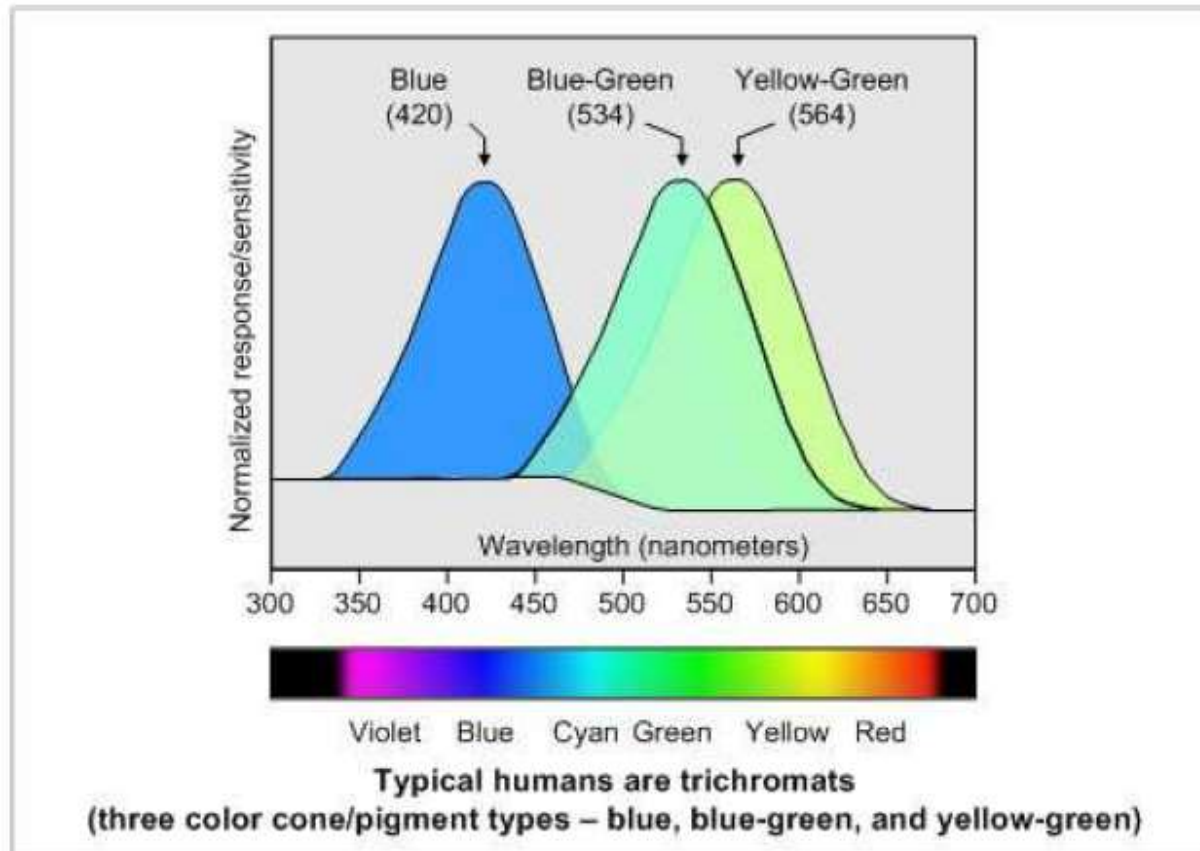
## How Colour Vision Works

- As it happens, one kind of cone cell is primarily sensitive to *bluish-violet light*, but the other two are most sensitive to greens; one peaks at a bluish-green and the other peaks at a yellowish-green as shown in the illustration below.



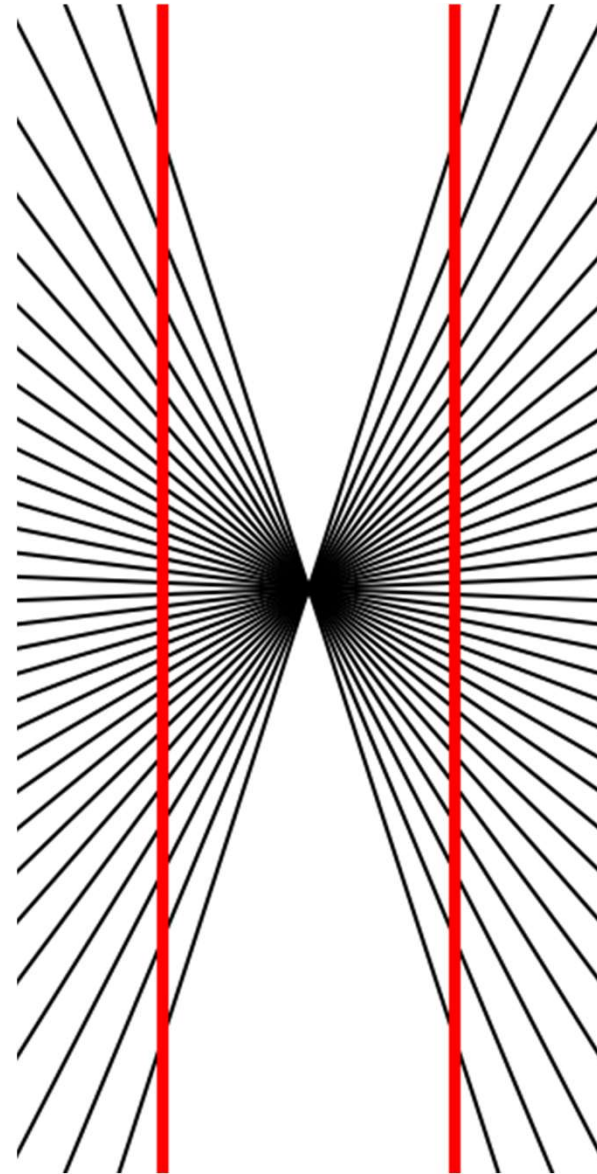
## How Colour Vision Works

- As there are around an order of magnitude fewer bluish-violet cone cells than the other two types – and as the other two types are both sensitive to greens – this explains why the human eye is particularly sensitive to variations in the green portion of the spectrum (the actual ratio of bluish-violet to bluish-green to yellowish-green cone cells is about 1:10:20.)



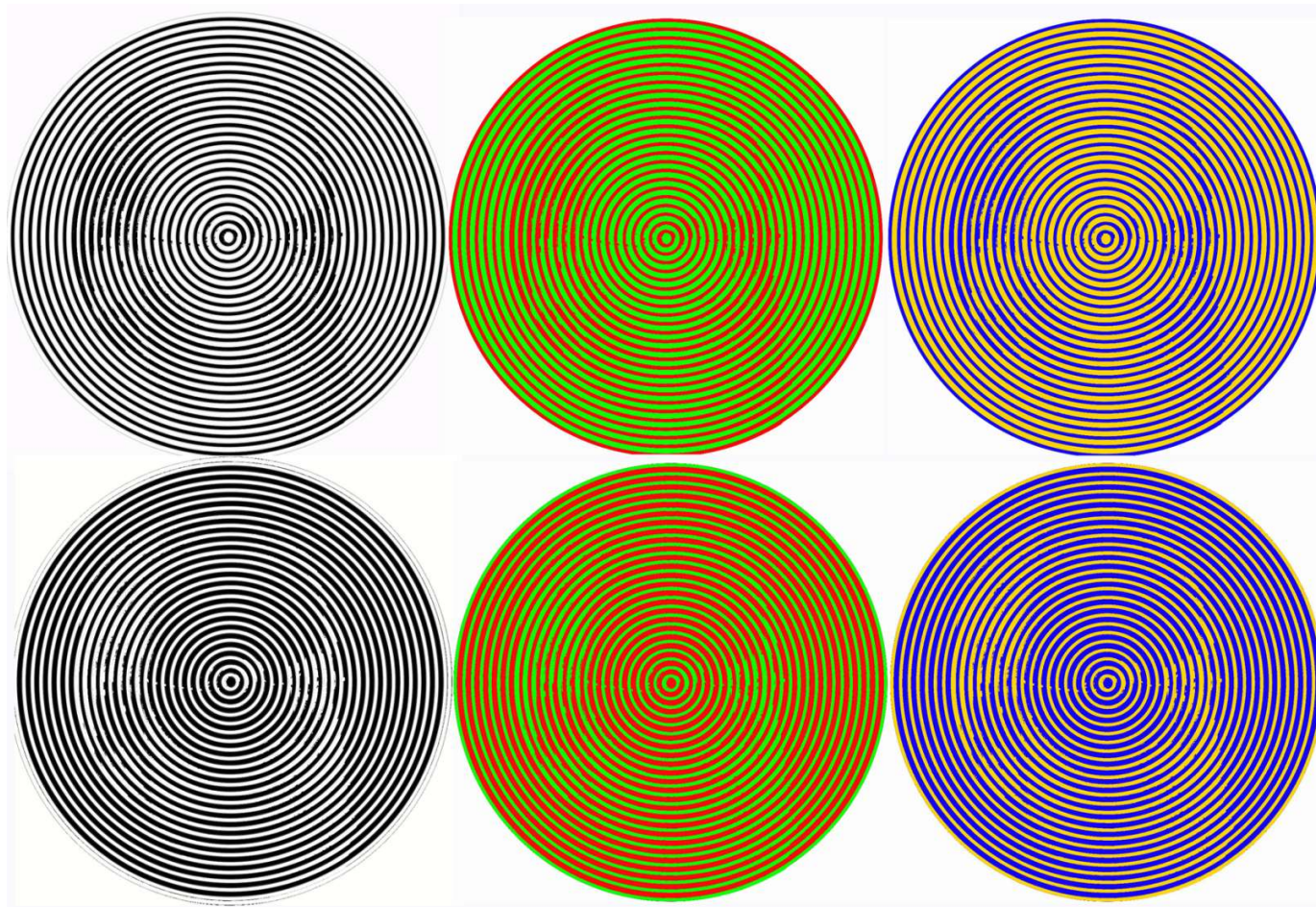
## How Colour Vision Works

- Young's trichromatic theory was extremely successful and became generally accepted wisdom for almost 175 years.
- However, as opposed to our perceiving different colours by directly accessing the signals being generated by our cone cells, we now know that our colour perception is based on something called the *opponent process*.
- This alternate theory was first proposed by the German physiologist and psychologist Karl Ewald Hering (1834-1918), but the opponent process didn't gain a wide following in the scientific community until the 1970s.



## How Colour Vision Works

- His work concerned space perception, eye movements, colour vision and contrast phenomena.
- Hering based his opponent-process theory on colour appearances rather than on mixing lights of different wavelengths.



## How Colour Vision Works

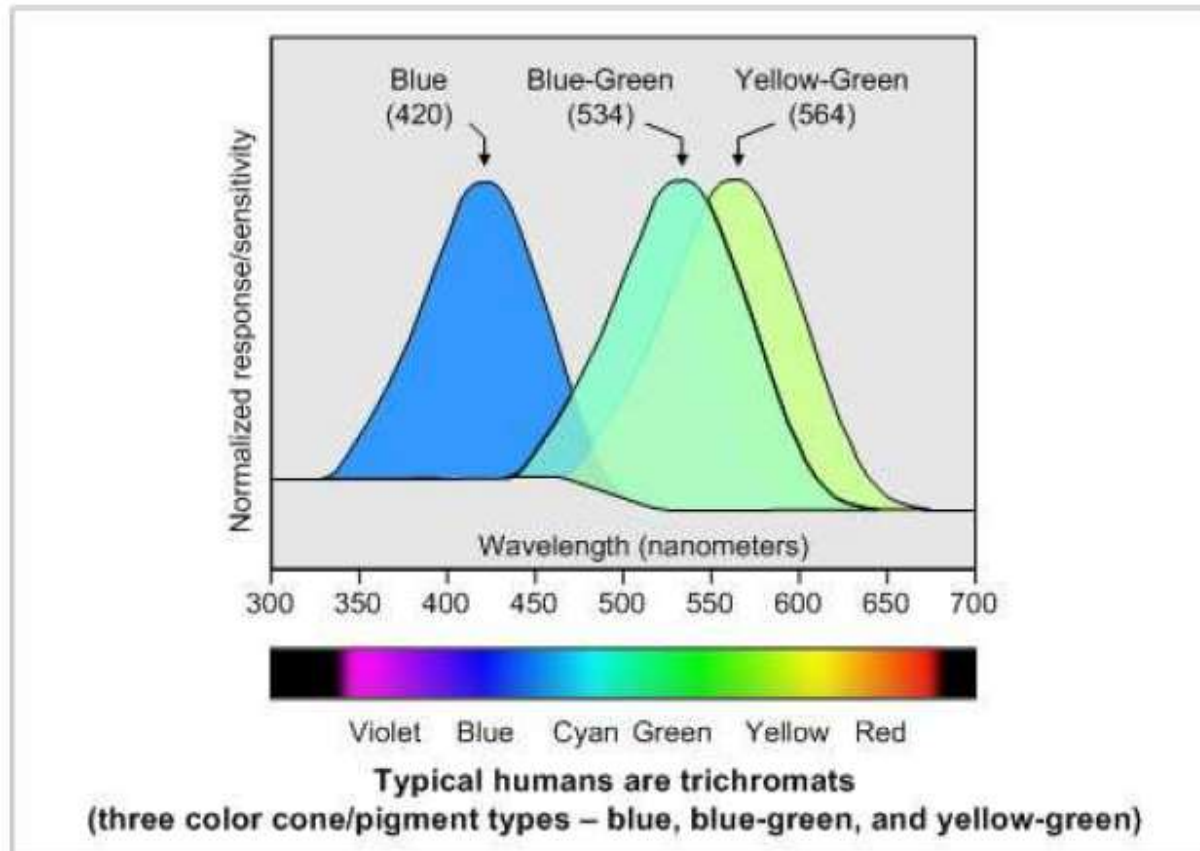
- The idea behind the opponent process is that – although their sensitivities peak at different frequencies – there is a large amount of overlap with regard to the wavelengths of light to which the three types of cone cells respond, so our visual systems are designed to detect *differences between the responses of the different cones*.
- In order to achieve this, the retina boasts large numbers of "comparator" cells – each of these cells compares the signals being generated by a number of different cone cells, and it is the signals coming out of the comparator cells that provide colour information to the brain.
- The end result is that we perceive the colour yellow when our yellowish-green cones are stimulated *slightly more than our bluish-green cones, for example; similarly, we perceive the colour red when our yellowish-green cones are stimulated significantly more than our bluish-green cones*.

## How Colour Vision Works

- Actually, it's worth taking a little time to make sure that we more fully understand the way in which this works.
- Observe how the response curves for the blue-green and yellow-green receptors in the illustration above strongly overlap each other.
- Now, remember that these images were created in Photoshop and that the spectrums at the, so these are just approximations.
- Having said this, if you look toward the right of the curve associated with the yellow-green receptors where it's over the yellow area of the spectrum, you'll see that – at this frequency – these receptors are being stimulated more than are the blue-green receptors, and thus we end up perceiving this portion of the spectrum as being yellow.

## How Colour Vision Works

- Now, move a little to the left into the green portion of the spectrum. Once again, the yellow-green receptors are being stimulated more than the blue-green receptors – but the trick here is that both types of receptors are being stimulated more than they were for the yellow portion of the spectrum, so we perceive this as being green.

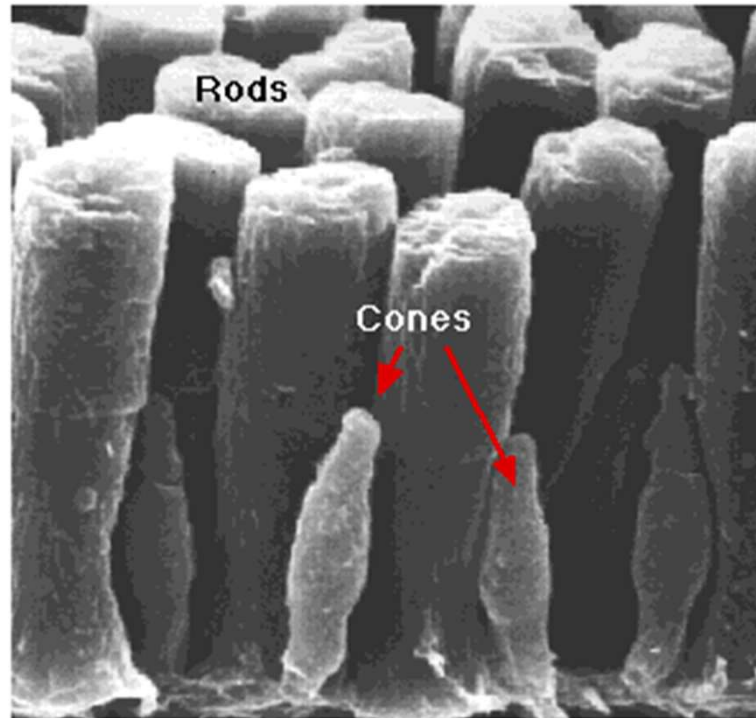


## How Colour Vision Works

- This is where things start to get a little tricky, because you could just say: *"But that's just a matter of intensity!"* Sad to relate, this is where I pass *beyond* the scope of my knowledge.
- All of this serves to explain why, when the day draws towards dusk, we lose the ability to see red first.
- This is because – even in reasonably bright light – we are only obtaining a relatively small amount of stimulation in that part of the spectrum; thus, as the overall intensity of the ambient light starts to fall, this stimulation ceases first.
- It also explains why – in the middle of the night (assuming a full moon) – we can still see hints of green, because the main spectral component of moonlight is relatively close to the most sensitive portion of the response curve for our blue-green receptors.

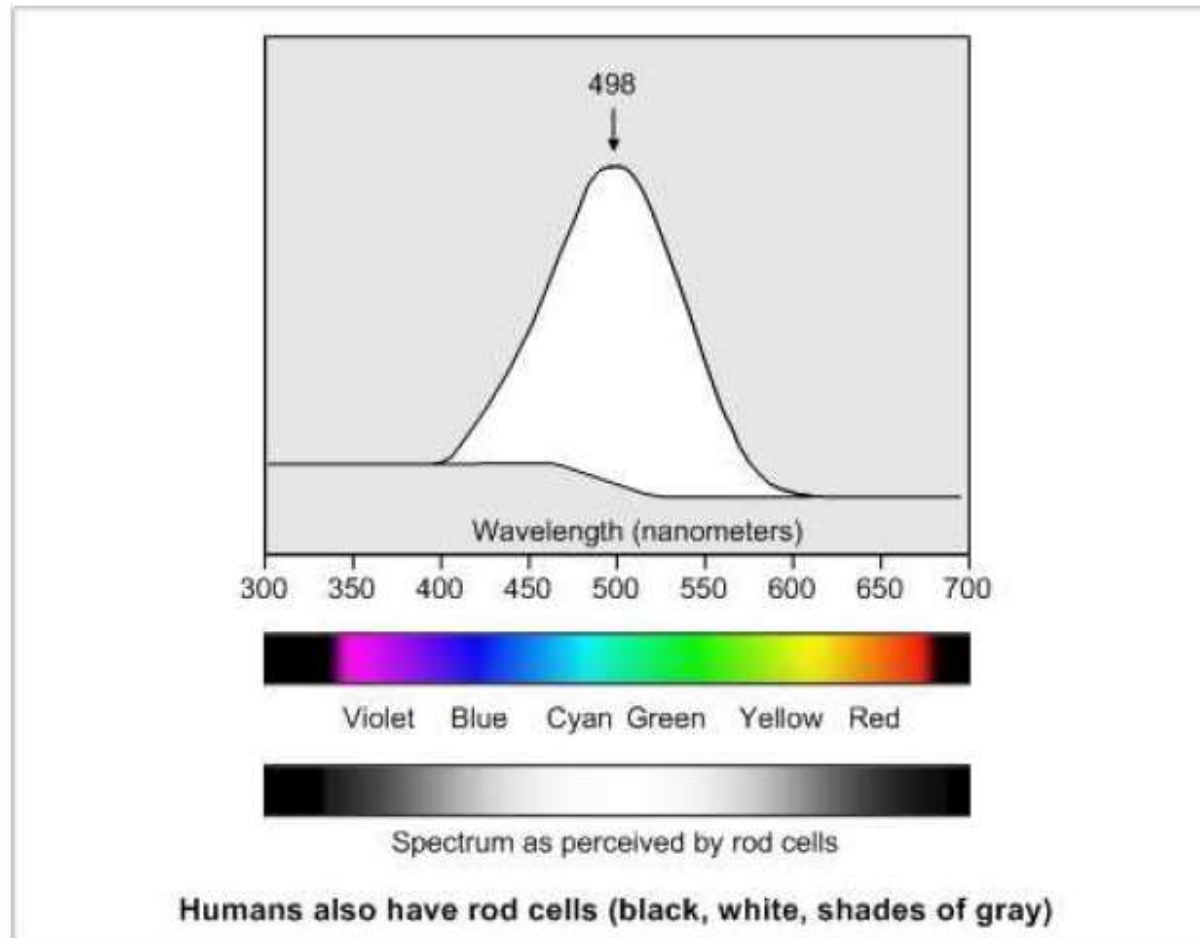
## How Colour Vision Works

- In addition to cones, the human eye also has a fourth (dim light) type of receptor called *rods*, which are so-named because of their shape when viewed under a microscope.
- These cells, which are much more sensitive than cone cells, come into play in low-light conditions like dusk and throughout the night.



## How Colour Vision Works

- Rod cells, which outnumber their cone cell companions by a factor of around 20-to-1, have their peak sensitivity around 498 nanometres (nm).

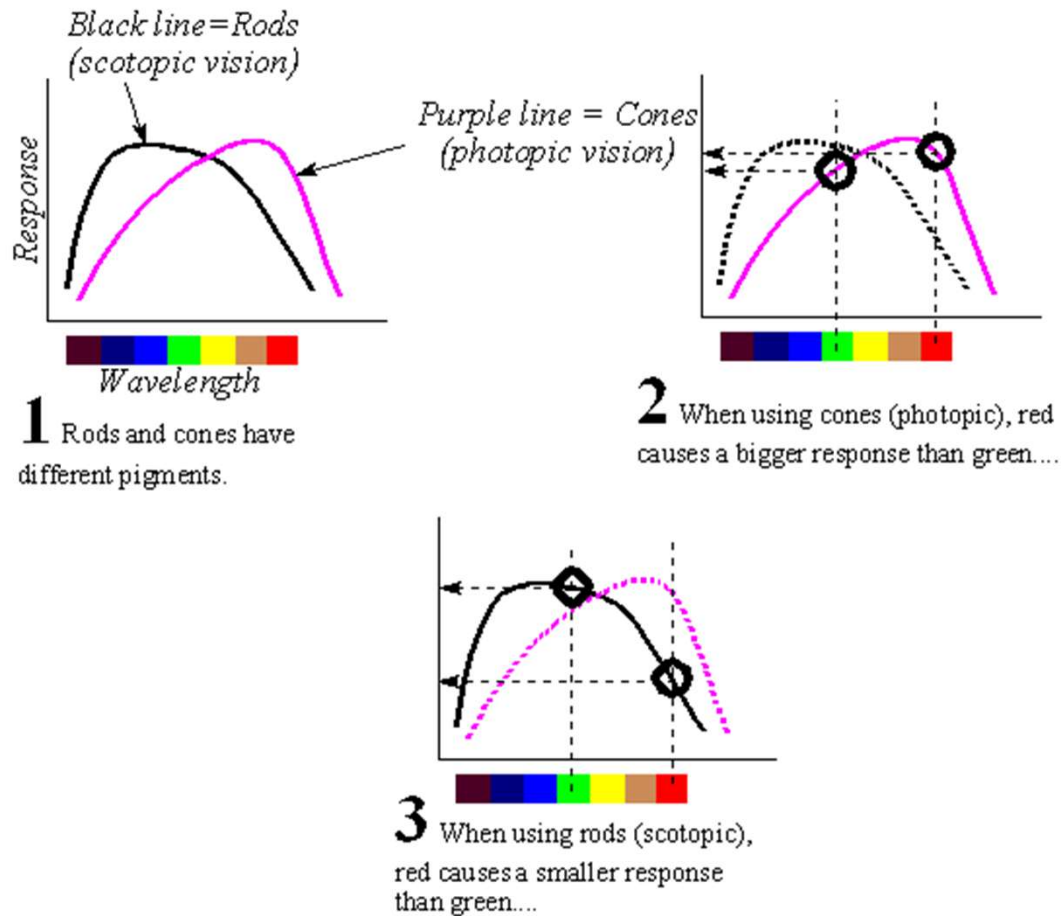


## How Colour Vision Works

- The fact that rod cells are so much more sensitive to dim light than are cone cells, and also the fact that there are so many rod cells, explains why our sense of colour drops as the level of ambient light falls.
- In bright light, our peak sensitivity is to the bluish-green and yellowish green cones, which we use to perceive colours like green, yellow, and red.
- Under these bright light conditions, our rod cells are being completely over-stimulated and are not providing any useful information whatsoever.
- As the day heads toward dusk and the ambient light dims, however, our peak sensitivity switches to bluish-violet and bluish-green, which is why we still see blue and green hues after the other colours have faded away.

## How Colour Vision Works

- This effect, which is known as the *Purkinje Shift*, is named after the Czech physiologist Jan Evangelista Purkinje (1787-1869).



## How Colour Vision Works

- Finally, when the ambient light becomes very faint, our cone cells effectively shut down and only our rod cells remain functional to supply us with our night vision capabilities.
- Night vision devices turn night into day for the user.
- NV devices can be hand-held scopes, rifle sights or goggles worn like glasses.
- They work by electronically amplifying whatever ambient light is present or by making use of normally invisible light such as infra-red.



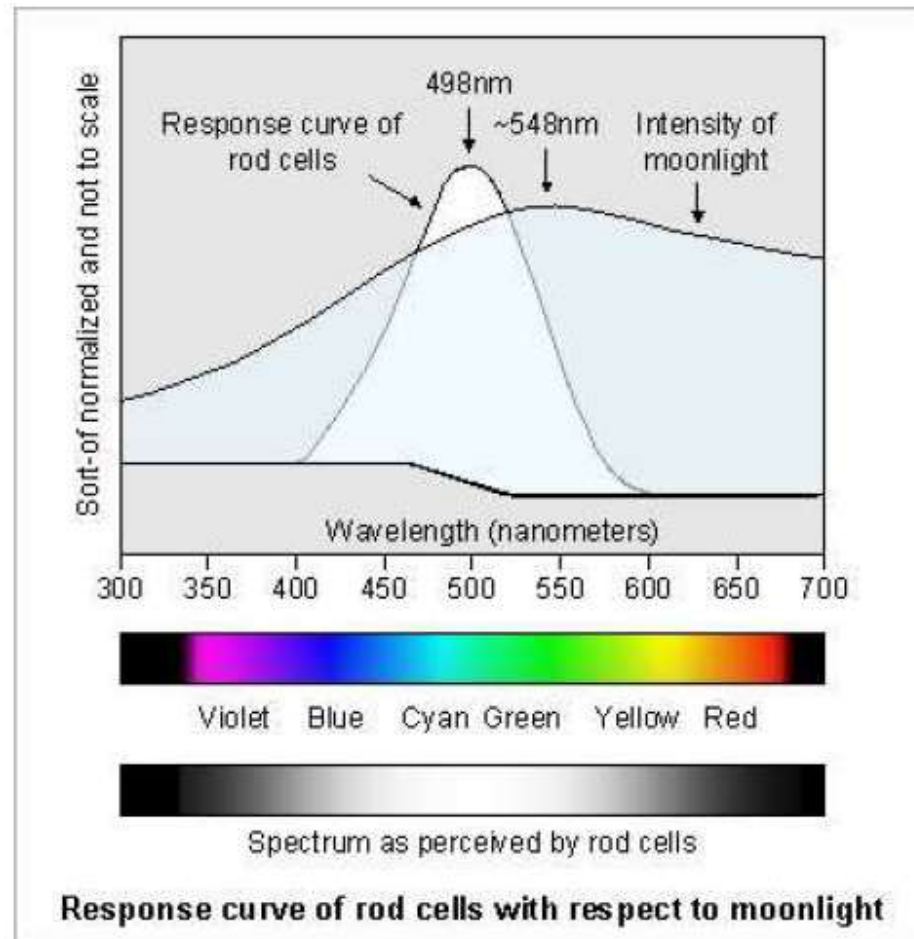
## How Colour Vision Works

- At this point, it may be worth noting that some references state that the peak sensitivity of rod cells is close to the main spectral component of moonlight.
- Based on this, one might hypothesize that rod cells first evolved in nocturnal animals.
- Alternatively, one might propose that the evolution of rod cells facilitated certain animals becoming nocturnal.



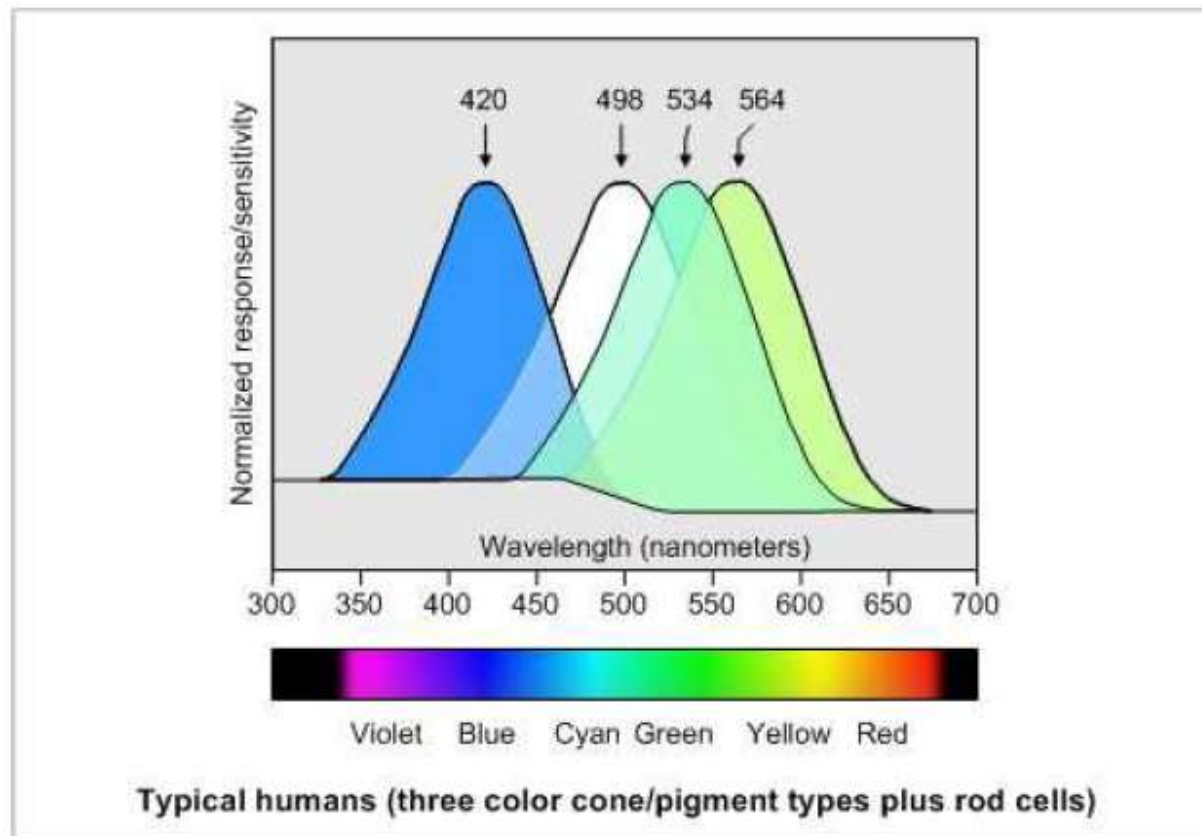
## How Colour Vision Works

- In fact, irrespective as to whether or not rod cells first evolved in nocturnal animals, their peak absorption is *not particularly close to the main* spectral component of moonlight, which actually occurs at anywhere between 548 and 575 nanometres depending on your source of data.



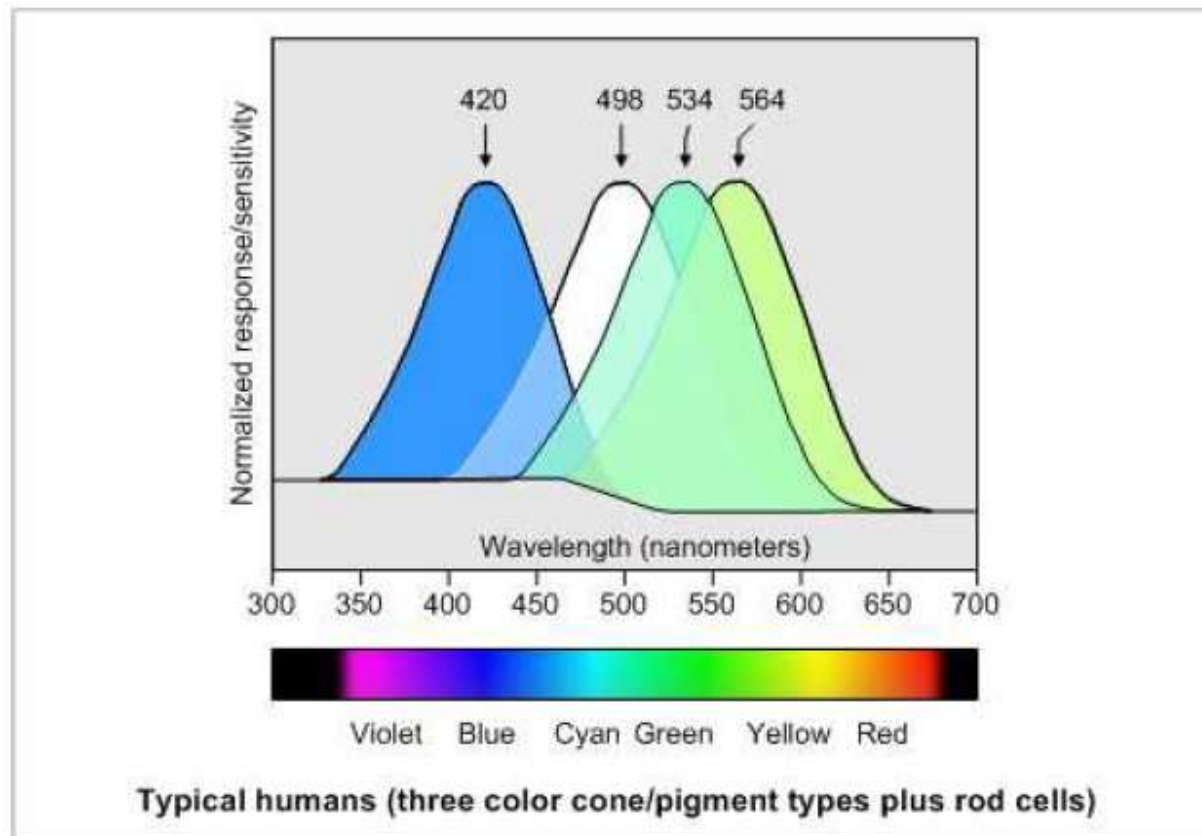
## How Colour Vision Works

- Before we consider the evolution of colour vision let's briefly summarize what we've learned thus far:
  - **First**, the typical human eye has three different types of cone photoreceptors that require bright light, that let us perceive different colours, and that provide what is known as *photopic vision*.



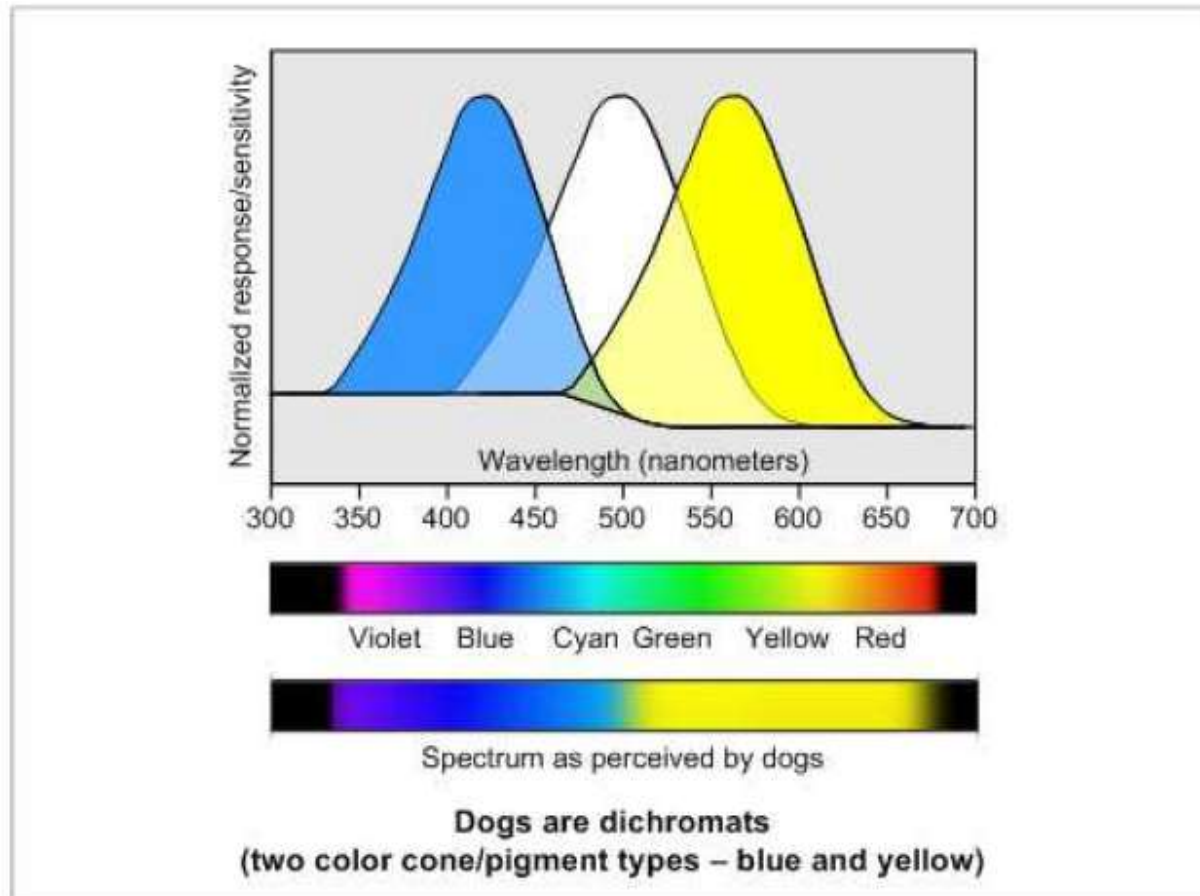
## How Colour Vision Works

- Before we consider the evolution of colour vision let's briefly summarize what we've learned thus far:
  - **Second**, we have rod photoreceptors that are extremely sensitive in low levels of light, that cannot distinguish different colours, and that provide what is known as *scotopic vision*.



## How Colour Vision Works

- As one final point of interest, some animals have only two types of cone receptors, so these animals are referred to as being *dichromats*.
- The dog has some cones that are primarily sensitive to blue light and others that are primarily sensitive to yellow light.



## How Colour Vision Works

- It's a bit difficult to conceive what this might look like.
- A “normal” picture is shown on the left below.
- A picture to simulate the effects of having only blue and yellow cones like a dog as shown on the right below.



The way a mammalian trichromat (three cones) would see a scene



The way a mammalian dichromat (two cones) would see the same scene

**END of Part 1**