ELEC 421
Digital Signal and Image Processing

Siamak Najarian, Ph.D., P.Eng.,
Professor of Biomedical Engineering (retired),
Electrical and Computer Engineering Department,
University of British Columbia

Course Roadmap for DIP

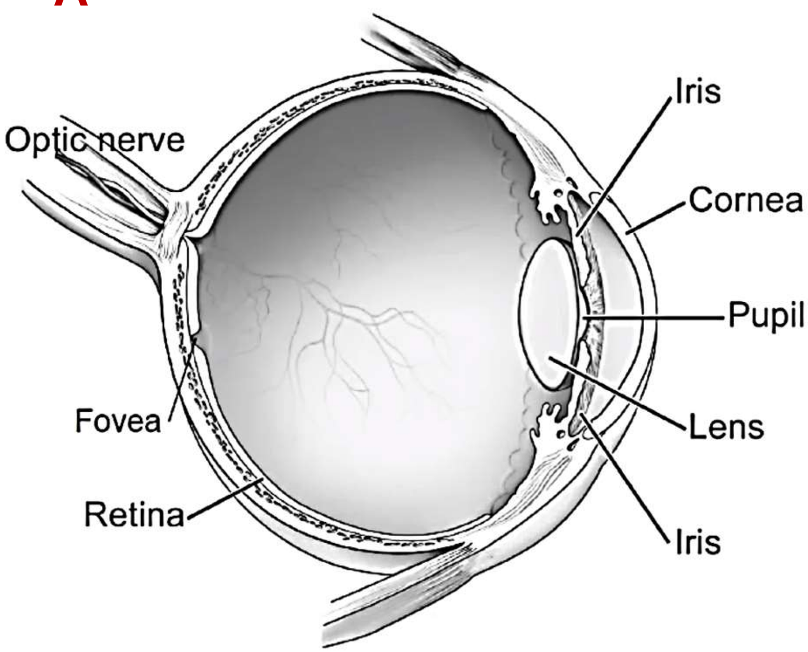
Lecture	Title
Lecture 1	Digital Image Modalities and Processing
Lecture 2	The Human Visual System, Perception, and Color
Lecture 3	Image Acquisition and Sensing
Lecture 4	Histograms and Point Operations
Lecture 5	Geometric Operations
Lecture 6	Spatial Filters

Lecture 2:
The Human Visual System, Perception, and Color

Table of Contents

Anatomy of the human eye

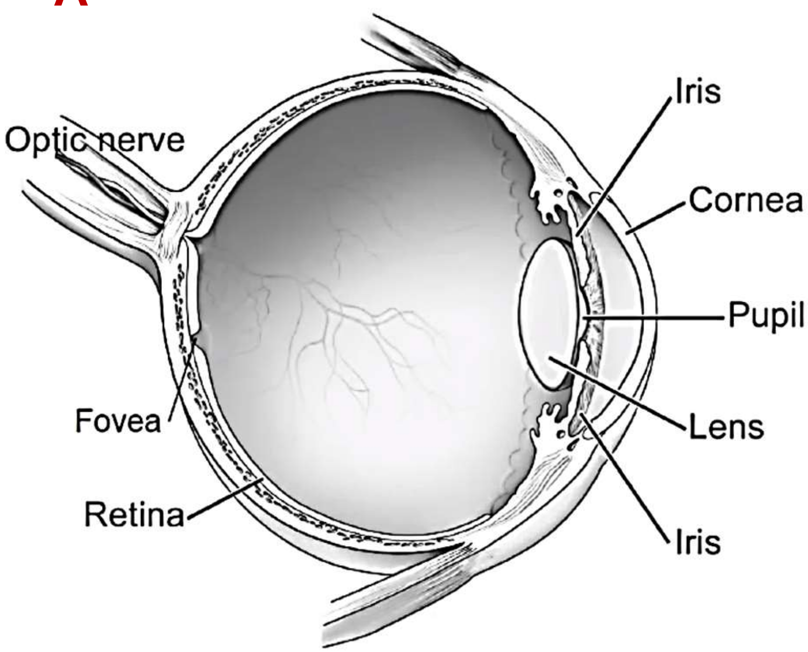
A



- **How do humans see or perceive images in the natural world and how does color work?** Let us start by looking at the anatomy of our eye. In A, we have a picture of the eye and we want to examine the main components of it. Starting from the outer layer, we have got the **cornea**, which is the clear part of the eye and it goes over all the rest of the parts. Cornea is transparent and behind that we have the **iris**. The iris is the part of the eye that gives it its color. The iris can contract or expand to control how much light gets into the eye. So, that is like the aperture of the eye. Then behind the iris we have the **lens**. The lens is this relatively hard blob material, but also jelly-like, that focuses the light onto the back of the **retina**. When people get older, the lens starts to get cloudy, and that is what causes cataracts.
- Now, let us follow **the path of the incoming light**. This light comes through the cornea, then it goes through the hole (the **pupil**), that is defined by the iris, and then it goes through the lens. After passing through the lens, it hits the retina at the back of the eye. The retina is where all of the light sensitive cells are. These cells basically line the back of the eye and this is where all these **rods** and **cones** are. We are going to talk about those a little bit later. Then there is this one special part of the retina called the **fovea**. The fovea is the central part of the retina and this is where the highest concentration of cones or color sensitive cells live.

Anatomy of the human eye

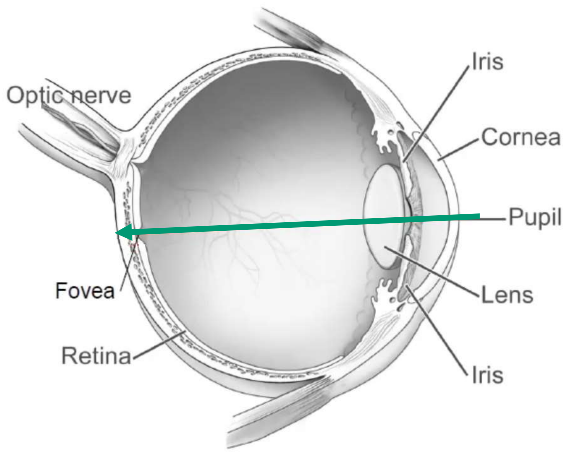
A



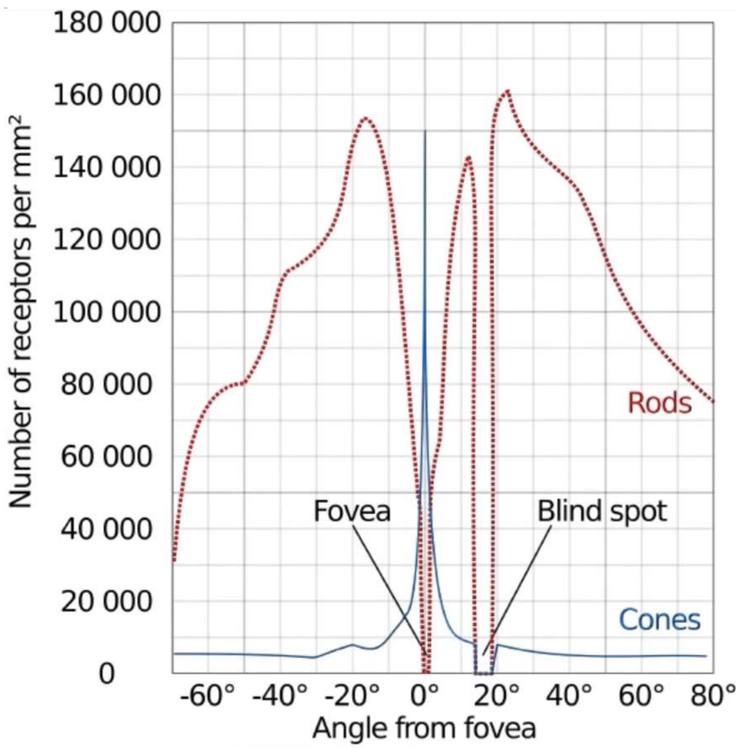
- In some sense, fovea is the only part of the eye that defines for us what seems to be ***in focus***. When we look around, there is always a part that is in focus and then there is our **peripheral vision**, which is kind of fuzzy. So, the fovea is responsible for everything that seems to us, at any given time, to be in focus. Then behind that, there is the **optic nerve**, shown in **A**. The optic nerve is a bundle of nerve fibers that carries all the signals from the rods and the cones back to the brain.
- Of practical importance is the fact that there are no rods and cones at all where the optic nerve connects to the eye. That is, there is actually a region of the retina that has no photosensitive cells and that is called the **blind spot**. And that is something that is really freaky in some sense! This means that behind each of one of our eyes, there is a whole missing chunk of retina that is actually getting no sensory input and ***our brain is filling in what should be happening in that empty region***! It has been demonstrated that there is this effect that when we focus on one thing and they put something blinking in our blind spot, we cannot actually perceive it! So, the fovea is where all the action happens.

Facts about the fovea

A



B



- Let us look at the graph of the **concentration of rods and cones** at different angles with respect to the ***optical axis***, shown in **B**. As light comes directly into our eye, shown by the **green** arrow in **A**, it hits the fovea at **0 degrees**. In **B**, we are looking at the concentration of cells in various regions. The **solid blue** line is the **cones**, which are the color sensitive cells and have a very sharp peak (high concentration) at around **0°**. The **dotted red** curve is the **rods**, which are the light sensitive cells, but not color sensitive. The rods are responsible for our ***night vision***.
- As can be seen in **B**, we have this **blind spot,** where there is no rods and cones at all. Right at the fovea, there is a very high concentration of cones (about **150,000**/mm^2), the color sensitive cells, and then it drops off drastically as we move away from the fovea on the back of the retina. By the same token, there are not that many rods inside the fovea, but there are lots of rods outside.

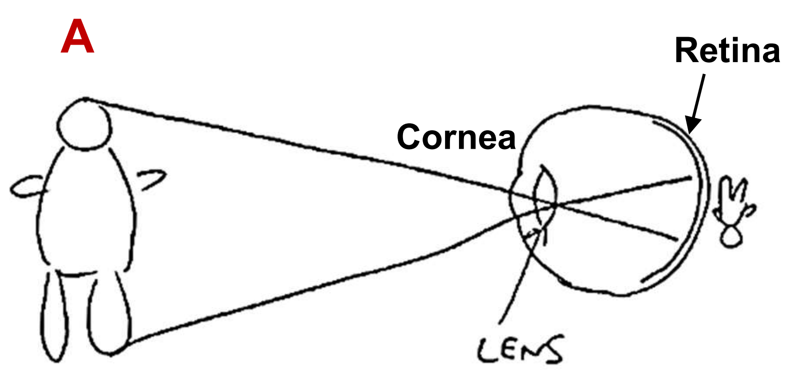
Facts about the fovea

FOVEA: 1.5 mm SQUARE

350 K INDIVIDUALLY ADDRESSABLE COLOR- SENSITIVE RECEPTORS.

- **Fovea:** It is interesting to think about some of the statistics in our eye. The fovea is about **1.5** mm on a side (also, sometimes refer to as diameter). Think about how small that is! This tiny piece of tissue is responsible for all our perception of the visual world. Not only that, but there are only about **350,000** of individually addressable color sensitive receptors in the fovea of one eye. These are sometimes called **pixels**, but not technically quite correct. So, that means that all the visual information is packed into **350,000** kind of pixels in our eye. This number of pixels is much lower than even the lowest end digital camera that we can find these days. Yet, our perception of the world seems so much richer than any digital image.
- That is a testament to how much other stuff is going on inside our head. It is not like just that our eye is a sensor that we point into the world and it is automatically mapped directly into our perception. There is this whole ***filtering*** of our brain in this whole process that uses past experience of things it saw and understanding of how things should be (i.e., ***a lot of image processing***). Our brain kind of hallucinates the things that it does not actually perceive.
- **Conclusion:** The whole physical process of visual perception is quite complicated because there really is not that much visual information in terms of raw bits coming into our retina, but we are able to have this rich visual experience. Our perception is not a straightforward mapping of raw sensory input; it is a complex interplay between our senses and our brain's interpretation.

Facts about the fovea



- In some senses, the way that our eye works is not that different from a camera. In A, we see the **cornea**, the **lens**, and the **retina** all working together to generate an image at the back of the eye. Fundamentally, light is traveling through the lens and hitting the back of the eye, where the retina is. In terms of what the retina is actually responding to, there is going to be this little ***upside down image*** of everything in the world projected on the retina. Our brain automatically flips this image to be the right side up. In that sense, this is not really exactly the same as the way a camera works. For example, it is true that a camera has a way of ***changing the aperture*** and that is similar to what our iris does. But one thing that a physical camera does that our eyes do not do is that if we have a good camera, like a DSLR camera, we have various focal lengths through interchangeable lenses. When we turn the ring, we are actually physically moving the distance between the CCD and the camera and the hole where the light goes through. So, we are actually moving stuff around back and forth.

- Our eye cannot move our iris back and forth with respect to the retina. That distance is fixed. However, our lens is not actually like a hard lens, like a piece of glass in the camera. In our eye, ***the lens physically changes shape and distorts.*** It can flatten or thicken. For example, there is a difference between looking at a piece of paper that is right in front of us and then suddenly looking back at the room and focusing on a picture on the room wall. Here, the lens in our eye is changing shape to accommodate this transition.

Brightness perception

BRIGHTNESS

EYE HAS A HUGE DYNAMIC RANGE
$O(10^{10})$

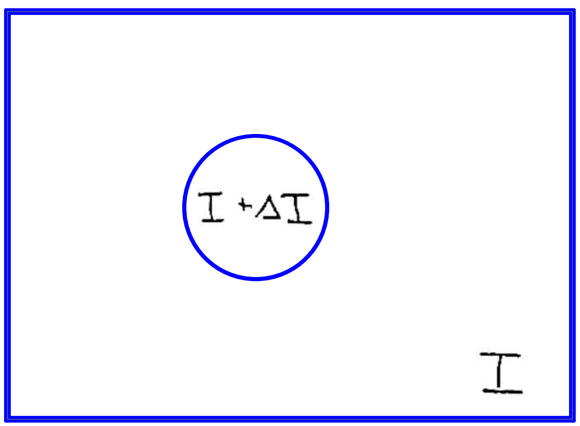
SUBJECTIVE BRIGHTNESS IS (BASICALLY) LOGARITHMIC AS A FUNCTION OF INCIDENT INTENSITY.

BRIGHTNESS ADAPTATION – IRIS OPENS/ CLOSES TO LET IN / RESTRICT AMOUNT OF LIGHT.

- **Brightness:** Another way in which the human visual system is much better than a camera is the way that it can perceive brightness. We can adjust our eyes to a wide range of ambient light intensity levels. The eye has a huge ***dynamic range*** on the order of **10** to the **10th**. That is, the difference between the darkest thing that we can perceive and the lightest we can perceive is quite large. The term "brightness" mostly refers to the ***objective*** physical property of light, measured in units like watts or lumens.
- **Subjective Brightness:** This is related to how bright something actually is in terms of a physical unit that we could measure with an objective device and ***how brightly we perceive it as a human***. The subjective brightness is basically ***logarithmic as a function of incident intensity***.
- **Brightness Adaptation:** We cannot perceive this whole massive dynamic range simultaneously. For example, if we are in a very bright room, we cannot perceive details in the shadows, but our eye can ***adapt*** to the conditions. On the other hand, if we are in a darkened room, for say half an hour, suddenly we are able to perceive shadows and shapes that are actually very low intensity, in terms of the actual physical photons getting into our eye. This is at the low end. At the high end, if we were to squint, we can even see what is happening in a very bright light, like in a very sunny day, which is much brighter than a darkened room. This kind of process of changing the perception is called ***brightness adaptation***. It just means that the iris opens or closes to let in or restrict the amount of light.

Brightness perception

Diagram A

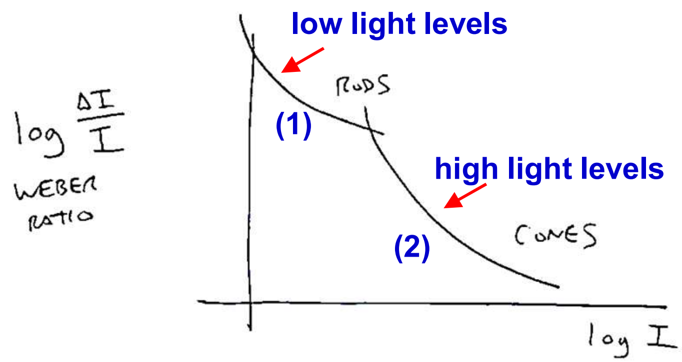


"JUST NOTICEABLE DIFFERENCE"

- There have been a lot of psychophysical experiments in terms of how humans perceive light and brightness adaptation. One of these experiments is depicted in **Diagram A**. This experiment is called the **Just Noticeable Difference (JND)**.
- Here, we take a uniform intensity gray rectangle, which has intensity $\mathbf{I}$. In the middle of it, we put a circle that is a little bit different from $\mathbf{I}$. The circle is not quite the same intensity, it is $\mathbf{I}$ plus some change $\Delta\mathbf{I}$. Essentially, the experiment is trying to answer this question: How much dimmer or brighter must the circle become for a person to notice the difference compared to the background rectangle, while the light is flickering on and off? The experiment introduces a complication by flickering the light source on and off. This flickering can potentially affect our ability to perceive small changes in brightness.
- During this experiment, we constantly flicker the light on and off, and then we ask the subject at what point it seems like this image is just a steady image. So, there is some point where we perceive this circle as being just a constant level of $\mathbf{I}$. But we know if our perception is good, then we can perceive there ***is*** a difference in the flickering light. We run the experiment until we can no longer see the flickering and so this $\Delta\mathbf{I}$ is like the **perceptible threshold**. This is the minimum change in a stimulus (in this case, circle brightness) that a participant can consistently detect. So, the experiment records the minimum change in circle brightness that the participant could detect while the light was flickering.

Brightness perception

Graph A



- **Weber Ratio:** If we were to make a plot of how people actually respond to this kind of test, what we see is the following. In **Graph A**, we have the plot of **log(ΔI/I)** vs. **log I**. The brighter the light is, the more off to the right we are on the **x**-axis. Here, ΔI/I is called the **Weber Ratio**. The **y**-axis is like a measurement of the minimum percentage change in the original intensity ΔI/I that we can still perceive as a difference.

- If we are in a dark room, this percentage can be fairly high, which basically means that it is hard for us to distinguish serious change of intensity, shown by **(1)**. In this region of **Graph A**, we see the action of the rods, which are the non-color sensitive ones. On the other hand, if we are in a bright room, **(2)**, our cones start to take over and then we are much more easily able to define in a room the difference between a white patch and a slightly less white patch. So, things get better as the room gets brighter, which makes sense since brightness adaptation is poor in low light and it is better when we have a brighter background.

- **Conclusion:** The Weber Ratio explains why our eyes can adjust to a wide range of lighting conditions. **(1) Low Light Conditions:** In dim light, the visual system is less sensitive to small changes in intensity because rods, while sensitive, are affected by noise. Hence, a larger relative change (ΔI/I) is required for perception. **(2) Bright Light Conditions:** In brighter or higher light environments, the cones take over, and the visual system becomes more precise. The required relative change in intensity decreases, meaning that even small changes are easily noticeable.

Optical illusions/perceptual phenomena

A

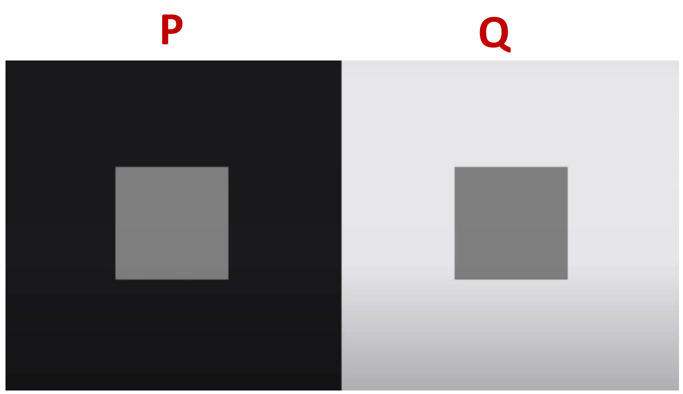
- The thin lines of “bands” along the gradient are illusory. The bands appear darker near the edge of the dark bar and lighter near the edge of the light bar.

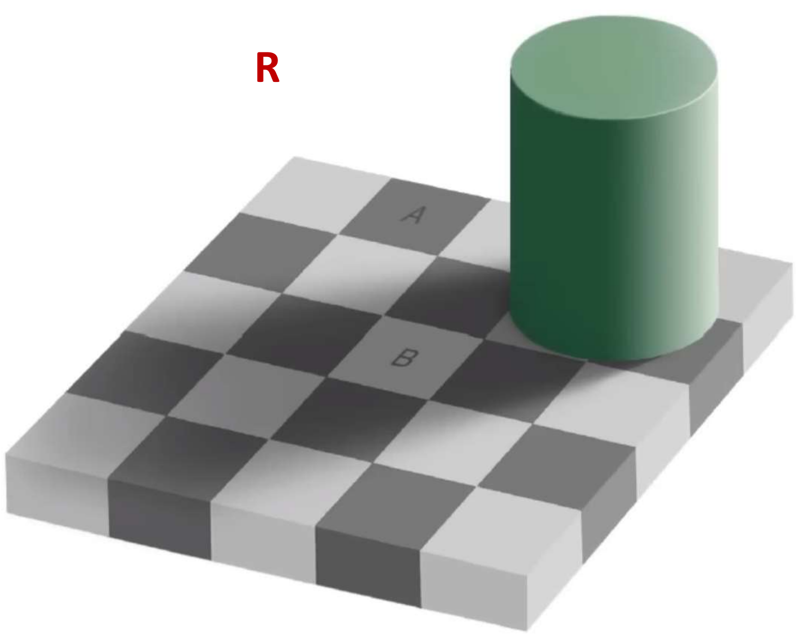
- **Mach Bands Illusion:** The perception of brightness is not a straightforward mapping of light intensity to perceived brightness. Instead, our brain applies various psychological processes, one of which is the **Mach Bands** phenomenon. Diagram **A** depicts a gradient of gray shades transitioning from dark to light. At the points where the gray shades change abruptly, our brain may exaggerate the contrast, creating the illusion of a thin dark stripe next to the light area and a thin light stripe next to the dark area. This effect is due to our visual system’s edge enhancement, which helps us detect boundaries but also introduces these artificial bands.

- These surprising dark and light stripes that appear at the edges where the gray changes are called the ***Mach bands illusion***. They create the illusion of lighter and darker bands at the edges where areas of slightly different brightness meet. Even though the actual gray may change smoothly, our brain creates these extra bands to make the edges seem even sharper. It is like a magic trick our brain plays with brightness and is a type of optical illusion!

- In medical imaging, we need to be aware of Mach bands to avoid misinterpreting them as abnormalities in X-rays or other medical images.

Optical illusions/perceptual phenomena

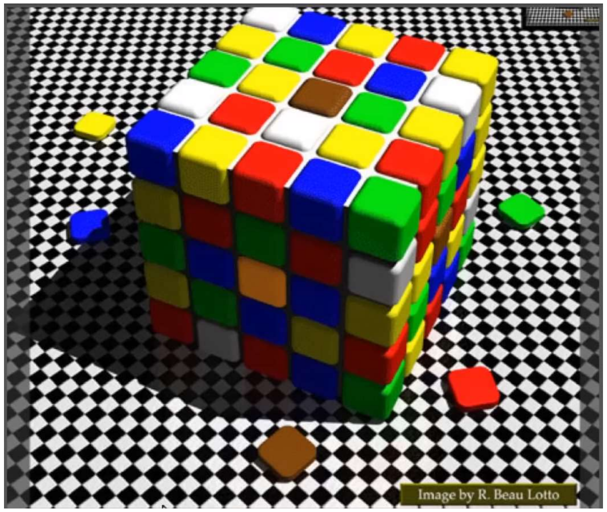




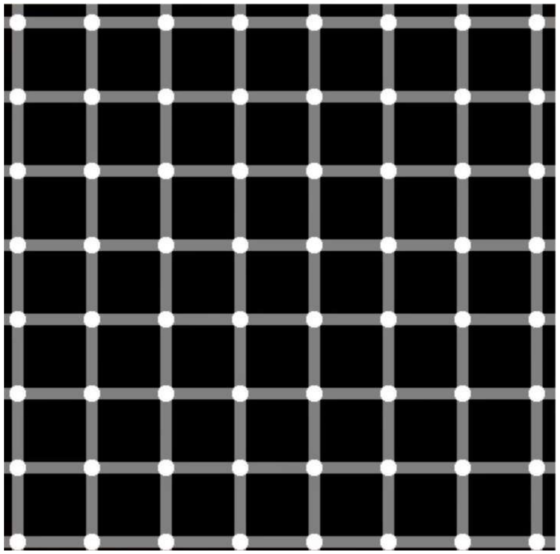
- **Another optical illusion:** In **P** and **Q**, which one of these two central squares is darker? Most people will say that the right hand one, **Q**, is darker. But, in fact, they are both exactly the same gray level. Here, our perception of them is affected by the fact that the one on the left, **P**, is surrounded by black and the one on the right, **Q**, is surrounded by white.
- Here is an even more freaky one! In **R**, the question is which of these squares is darker **A** or **B**? In fact, **A** and **B** are exactly the same intensity! In this case, it is our brain that is thinking, the block that has letter **B** in it is in the shadow of the cylindrical object and we automatically perceive **A** to be much darker than **B**. Whereas if we were to actually use a Photoshop dropper to sample the colors, we will see that they are exactly the same gray level!

Optical illusions/perceptual phenomena

A



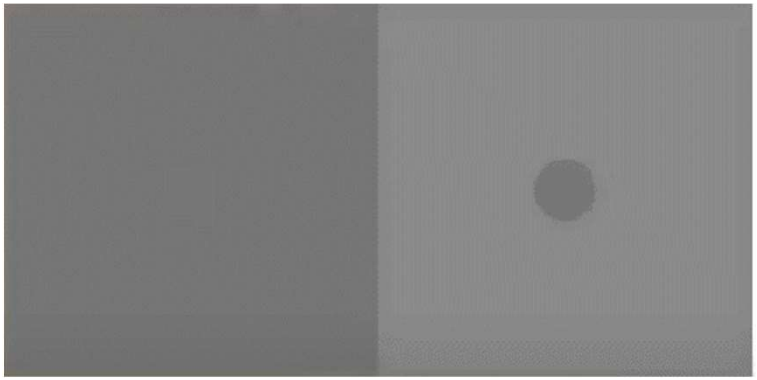
B Scintillating Grid



- This gets even worse in terms of color. In **A**, in fact, the central square on the top (the **brown** one) and the central square on the left (looks as if it is **orange**) are exactly the same color. They are both **brown**! Whereas we would swear that the one on the left is super orange and the one on the top is super brown!
- In **B**, If we look around in the neighboring figure, we will notice the appearance and disappearance of ***black dots at the crossings***. That is, if we got to look at this as a big picture, it seems like there are these little black dots in the centers of these grids. Our eyes are trying to chase these black dots around, but they are not actually there. There is nothing there! It is just like our eye is trying to fill them in somehow. This is called a **scintillating grid**.
- For each illusion, there are always some ***psychophysical explanation*** of why people think that is true. So, there are these cases where the actual physical input to our visual system is unambiguous, but our brain is doing all sorts of things with the image and generates illusions that we know are not real!

Optical illusions/perceptual phenomena

A

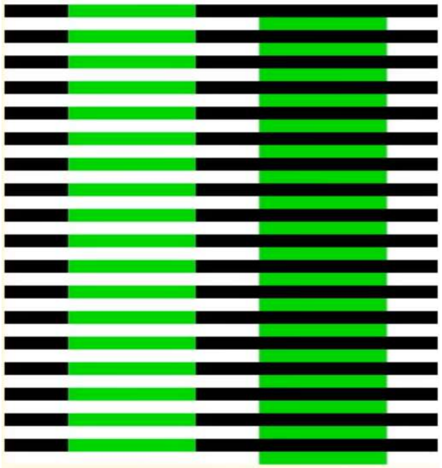


B

- In clip **A**, we have two center square blocks inside which we have two circles. We would probably swear that the inner colored circles are changing grays scale intensity, but in fact, they are staying exactly the same. Our perception of which one is lighter or darker is changed by the ***dynamic motion*** of the surrounding gray scale. A snapshot of the dynamic clip in **A** is shown in **B**.

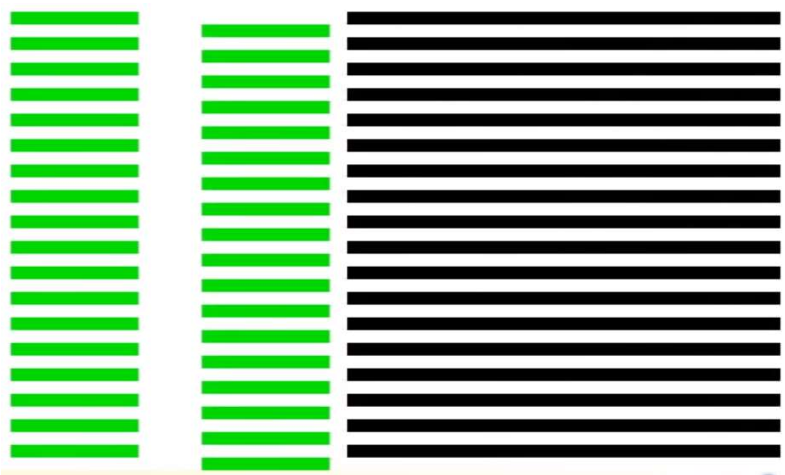
Optical illusions/perceptual phenomena

Munker-White Illusion



A

B

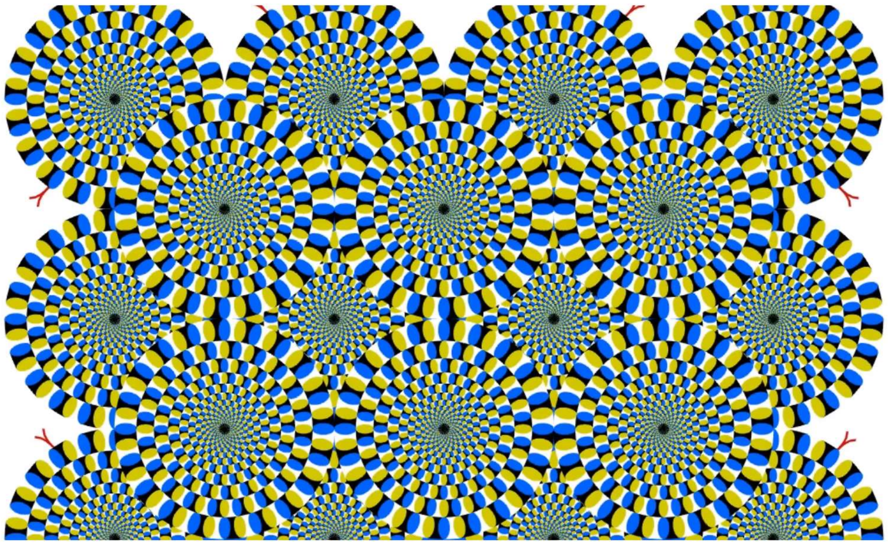


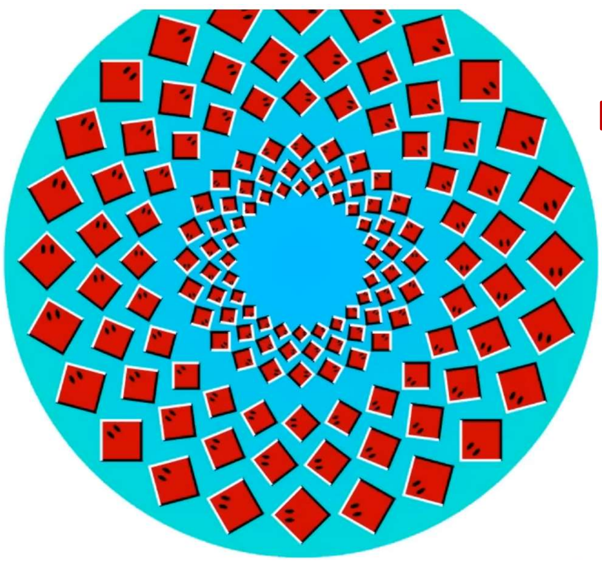
- In **Munker-White Illusion**, shown in **A**, there is an even stronger influence of these sorts of illusions. Again, one would swear that the right hand green bars are darker green than the left hand green bars. However, as shown in **B**, if we move the black bars out of the way (i.e., move them to the right), we can see clearly see that both green bars are actually the same color green!

Optical illusions/perceptual phenomena

Kitaoka's Illusions

A





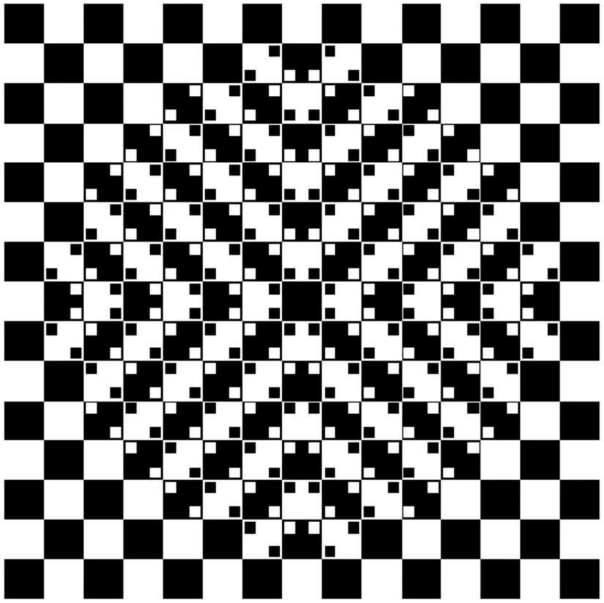
B

- **Kitaoka's Illusions:** In these illusions, none of the images are dynamic. In A, there is this extremely compelling feeling that these discs are somehow rotating. If we try and focus on which one is moving, every time our eyes move to one, it seems like it stops moving and something else in our peripheral vision is moving. In B, if we are looking at it up close, it seems like these rings are somehow counter rotating.

Optical illusions/perceptual phenomena

Kitaoka's Illusions

C



- In **C**, it seems like things are somehow curved, but in fact, all these things are just squares. But it has this very serious feeling like things are bulging out.
- **Conclusion:** As we can imagine, these illusions can make modeling in image processing pretty complicated. We are not going to deal with this in our class, but it is worth understanding that it is not just like a turn the crank and we understand what our eye sees. There is a lot of other stuff that is mediated by our brain that is difficult to model and difficult to even understand why it works.
- One of the reasons that things like ***image compression*** works ***is*** illusions. In image compression, we are saying we have got this image and we have got these RGB pixels that came from our camera or scanner. Now, we would think that we cannot change those RGB pixels at all in order to preserve what is in the image. But it turns out that we actually ***can*** change those quite a bit. As a human, we do not really see where the differences are. The reason that we do not see those is due to some of these ***psychophysical phenomena***. Note that psychophysical phenomena refers to how our brains perceive and interpret sensory information, including vision. In this case, it highlights how our vision has limitations and ***can be*** "tricked" by certain visual illusions.
- Essentially, image compression "plays" with the RGB values in a way that minimizes the impact on the final image we see. This is possible because our vision can be fooled by certain visual tricks.

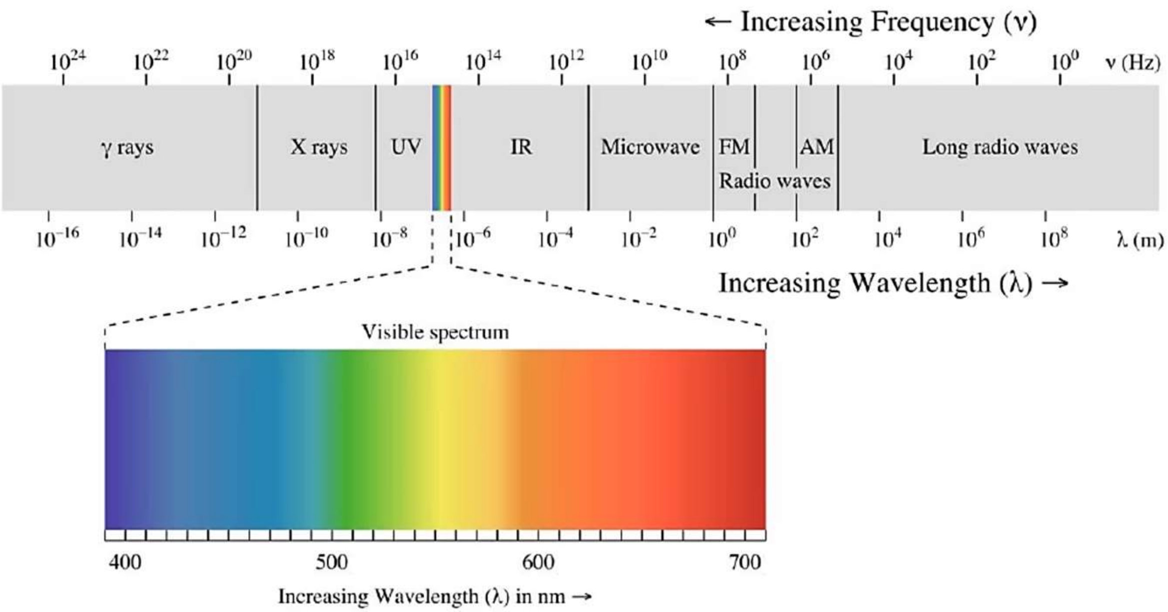
Optical illusions/perceptual phenomena

CRITICAL FUSION FREQUENCY

- An important ***temporal parameter*** in DIP is called the **Critical Fusion Frequency (CFF)**. Those who play video games are familiar with the fact people are always complaining about video game ***frame rate***. They always want the videos to be **60** frames a second or higher. One of the reasons for that is our visual system. Imagine the experiment where we have a light that is just blinking on and off at a regular rate. At some point, if the light is blinking fast enough, we perceive it as a steady light. That is exactly the principle behind movies. Movies are discrete chunks of image shown to us in succession and there is a ***blank region*** while the projector goes from one image to the next. But we perceive it as a steady image. So, movies are shown at about **30** frames per second. For video games, we want our frame rate maybe up closer to be more like **60** frames a second. Even some of the fancier LCD and plasma TVs will try to upsample the frame rate to be like about **100** Hz, **600** Hz, respectively, to make this kind of smoother experience. Again, this is a thing that is due to the way that our eye perceives light. If we perceived light that was turning on and off that fast, then suddenly movies would be a bit confusing and disorienting to us.
- In summary, **Critical Fusion Frequency (CFF)**, also known as **Flicker Fusion Threshold (FFT)**, is all about how fast our eyes can handle flickering light before we see it flicker. The CFF is the speed of flickering where we just barely perceive it as flickering. It is like the tipping point for our vision. Any faster flickering, and our brain blends the flashes together into a seemingly constant light.
- **Conclusion:** CFF is the key reason we perceive smooth motion in movies, TV shows, and ultrasound imaging. These displays rely on rapidly presenting a sequence of still images in quick succession. Because of our CFF, our brain integrates these flashes into a continuous, fluid motion rather than seeing them as separate, individual images. This principle is what makes video playback appear seamless to the human eye.

Optical illusions/perceptual phenomena

A



- Let us talk a little about **light** and **color**. In the electromagnetic spectrum, shown in **A**, we have got gamma rays on the far left end and radio waves on the far right end, and there is a slice in the middle that corresponds to ***visible imaging***. And, that is again where we care about for the most part in this class, from about **400 nm** to **700 nm**. Here, we have got the range of visible colors from **blue** to **red**.
- In terms of wavelength, blue is at the low end and red is at the high end. On this picture, even though it looks like as if there is some abrupt change of colors, like suddenly it is green in one region and blue in another region, there is actually this ***continuous color shift*** from one to the other.
- Also, it is interesting to note that, in this picture, it seems like there is a lot more blue and red than there is green. So, in this electromagnetic spectrum, it is not like the colors are evenly distributed, like a rainbow.

Optical illusions/perceptual phenomena

EMITTED RADIATION (W)

FILTERED BY HVS (lumens)

BRIGHTNESS (PERCEPTUAL)

- **How do we perceive light and color?** First, we have got **emitted radiance**. That is what the light source is emanating and it is measured in **watts**. Then we have the amount of light that gets to our eye. That is **filtered by the human visual system** and it is measured in **lumens**. Finally, we have the **brightness** that we see in our head, which has not got any real physical units. That is just like the **human perception** or **perceptual**.

Facts about rods and cones

A

RODS	CONES
V. SENSITIVE TO LIGHT INTENSITY NIGHT "SCOTOPIC" VISION	ONLY SENSITIVE TO DIRECT LIGHT "PHOTOPIC" VISION
ACHROMATIC	CHROMATIC (3 "COLORS")
LOW ACUITY (MANY PER NERVE END)	CONCENTRATED IN FOVEA (1 PER NERVE END)
PERIPHERAL VISION	HIGH VISUAL ACUITY, SPATIAL RESOLUTION
SLOW RESPONSE	FAST RESPONSE
75-150 M / RETINA	6-7 M / RETINA

- Let us take a closer look at rods and cones. There are two kinds of light sensitive cells in the eye, **rods** and **cones**. Let us make a chart, **A**, and compare them side-by-side.
- The **rods** are very sensitive to light intensity and they are responsible for our **night vision** or what is called **scotopic vision**. Anything that we can see in the dark is due to the rods.
- The **cones** are only sensitive to ***direct light*** and that is what is called **photopic vision**. As pointed out earlier, the cones are highly concentrated in the fovea, which is the part of the retina that is receiving the direct light.
- The density of cones drops off a lot in the peripheral regions of our retina. That is because the cones cannot do anything with that light, given that they are not sensitive enough. Whereas the rods are all over our retina. In fact, the rods are concentrated away from our fovea, but they are highly sensitive to light. That is why they are back in the other parts of the retina. The rods are not sensitive to color at all, so we call them **achromatic**, whereas the cones are sensitive to color, so we call them **chromatic**. The cones respond to **3** different colors, so we got **3** different kinds of cones, which are coarsely **red**, **green**, **blue** cones but not exactly, as we will talk about shortly.

Facts about rods and cones

A

RODS	CONES
V. SENSITIVE TO LIGHT INTENSITY NIGHT "SCOTOPIC" VISION	ONLY SENSITIVE TO DIRECT LIGHT "PHOTOPIC" VISION
ACHROMATIC	CHROMATIC (3 "COLORS")
LOW ACUITY (MANY PER NERVE END)	CONCENTRATED IN FOVEA (1 PER NERVE END)
PERIPHERAL VISION	HIGH VISUAL ACUITY, SPATIAL RESOLUTION
SLOW RESPONSE	FAST RESPONSE
75-150 M / RETINA	6-7 M / RETINA

- The rods have what is called **low visual acuity**, meaning that there are ***many rods per nerve ending***. So, the information from many rods at once is getting aggregated and carried along a single nerve. Whereas the cones are concentrated in the fovea, and there is ***1 cone per nerve ending***. That means we are getting a lot more information from the cones than we are from every single rod. The rods are responsible for our peripheral vision and the cones are responsible for our **high visual acuity** and **spatial resolution**.
- We are definitely perceiving color in our peripheral vision as well, yet there are very few color sensitive cells that are acting there. Again, our brain is filling in what color should an object be from ***very sparse information in our peripheral vision***. The rods are slow to respond to light. So, even though they are very sensitive, they have a slow response, whereas the cones have a fast response. We notice that when we are in a darkened room, it takes some time for the rods to begin to acclimate or adapt to what is going on in the room. Even then, we are not going to be able to perceive fast moving objects in a dark room.
- Finally, there are a lot more rods than cones. There are up to about **150** million of rods in our retina (i.e., per retina), whereas there are only about **6** to **7** million of cones per retina.

Facts about rods and cones

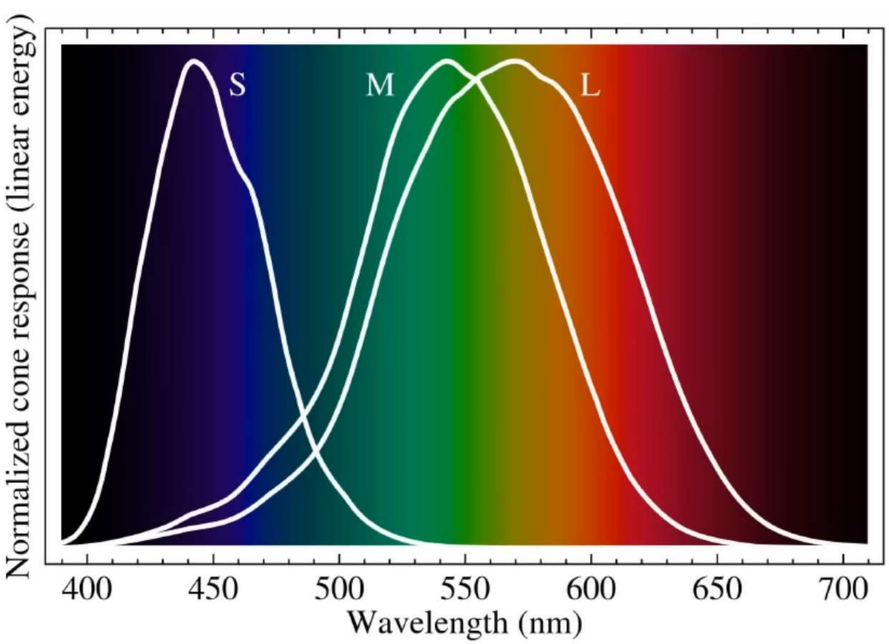
CONES ENABLE COLOR PERCEPTION;
3 TYPES

L SENSITIVE TO "RED" ACTUALLY MORE YELLOW-GREEN

M "GREEN" GREENISH-BLUE

S "BLUE" BLUISH-PURPLE

A



- Let us talk a little more about the **cones**. The cones allow us to perceive color. There are **3** basic types of cones that enable **color perception**. Technically, they are called **L (long) cones**, **M (medium) cones**, and **S (short) cones** based on their wavelength. The long is sensitive to **red**, the medium is sensitive to **green**, and the short is sensitive to **blue**. But, as we will see shortly, the red is actually more of a yellowish-green, the green is more of a greenish-blue, and the blue is more like a bluish-purple.
- Graph **A** shows the **spectral responses** of the long, medium, and short cones. The **y**-axis indicates the sensitivity level of each cone type to different wavelengths of light. A higher value on the **y**-axis means that the cone type is more responsive or sensitive to that particular wavelength, effectively detecting more light at that wavelength.
- We can see it is not like the long cones are peaking in the hardcore red region of the visible spectrum, instead, the peak is really more in the yellowy-green range. The long ones are really the only ones that that are very sensitive to reddish color, but the peak of the response is not close to red. Actually, the long and the medium cones have pretty similar spectral responses. The medium is a little skewed towards green and the short ones are definitely skewed towards blue.

Facts about rods and cones

CONES ENABLE COLOR PERCEPTION;
3 TYPES

ACTUALLY MORE YELLOW-GREEN

L SENSITIVE TO "RED" 65%

GREENISH-BLUE

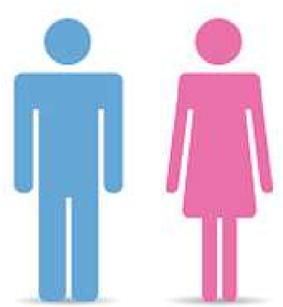
M "GREEN" 33%

BLUISH-PURPLE

S "BLUE" 2%
BUT MOST SENSITIVE

- The **proportions of these cones** are also different. It is not like we have a third of each kind of cone in our eyes. We have lots of these reddish cones (the **L**'s are **65%**), relatively lots of these green cones (the **M**'s are **33%**), and very few of these small cones (the **S**'s are **2%**).
- The ratio for each person varies quite a bit so these percentages are just ballpark numbers. We might think, given the low percentage for the **S**'s, i.e., **2%**, **how do we even see blue at all?** It turns out that the small cones are the most sensitive ones. So, there is a trade-off between how many of each of type of cone we have and how sensitive they are. In general, our eye is really the most sensitive to **greenish** light. The overlap of sensitivity curves means that green light (around 530 nm) stimulates both M- and L-cones effectively.
- **Conclusion:** In summary, our eyes prioritize green sensitivity because it strikes a balance between the abundance of green light in our environment, the overlap of cone sensitivities, and the need for efficient vision. So, while blue-sensitive cones exist, green remains the dominant color for our visual system.

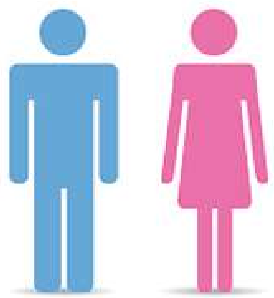
Facts about rods and cones



- **Color Blindness:** There are some interesting facts about color and cones. One of them is that the long and the medium cones are coded on the X chromosome. We know that women have double X chromosomes and men have XY chromosomes. That means if something goes wrong with the X chromosome, it is much more likely to happen to a man than to a woman. That is where **color blindness** comes from. Color blindness is when we are not able to distinguish between these two types of cones. One of the most common problems with color blindness is a problem with the medium cones. That means we may have a problem of distinguishing between red, yellow, and green. About **5%** of males are apparently susceptible to this kind of color blindness, whereas women are basically never color blind. In fact, there are studies that show that women actually may have more cones. That is, they may have **4** different kinds of cones, which means that ***women may have a kind of enhanced color perception than men!***

- **Animals and Colors:** Another interesting thing is that different animals have different kinds of cones and may see colors differently. We know whales and dolphins can only see in one color. Most mammals, like cats and dogs maybe are seeing in two colors, and fish and birds maybe are seeing in four or five colors. So, the idea is that different animals maybe seeing the world differently than us! For example, what looks to us like two similar red flowers may look to a bird like two very different colors. Two flowers that look the same to us might not look the same to a bird. That means one of the flowers may be much more appealing to a bird than the other one! The scientists can tell how many different types of cones different animals have. This is done by taking samples of animal eyes and put them in a centrifuge, after which, they can see which different color cones come out to the edges.

Facts about rods and cones



- **Color and Culture:** The way that we perceive the world, and the way we talk about color to other people have an effect on our everyday relationship and cultural interactions. When we talk about green and blue to our friends, maybe they are not really seeing the same color! There is also a lot of ***cultural color difference***. For example, in Japan they call green traffic lights with the word that we would use for blue. So, we may say an object is green, and someone else says no, that is blue! So, color is tied up with our visual system, our brain, and with our culture.

Color spaces; Additive color spaces (RGB)

CIE STANDARD

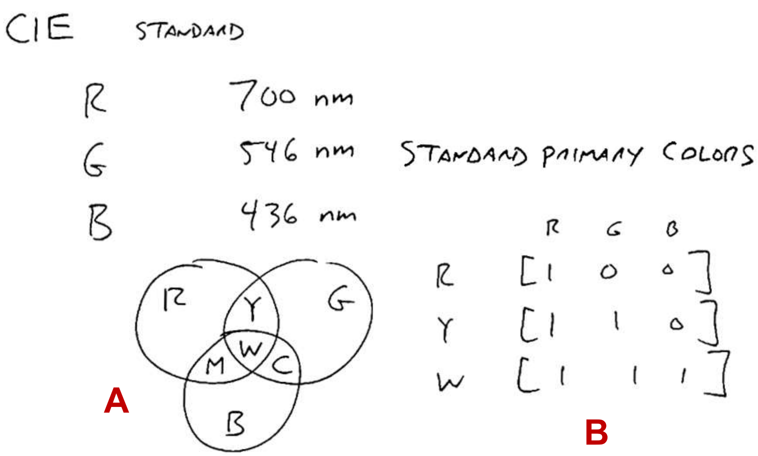
R 700 nm

G 546 nm STANDARD PRIMARY COLORS

B 436 nm

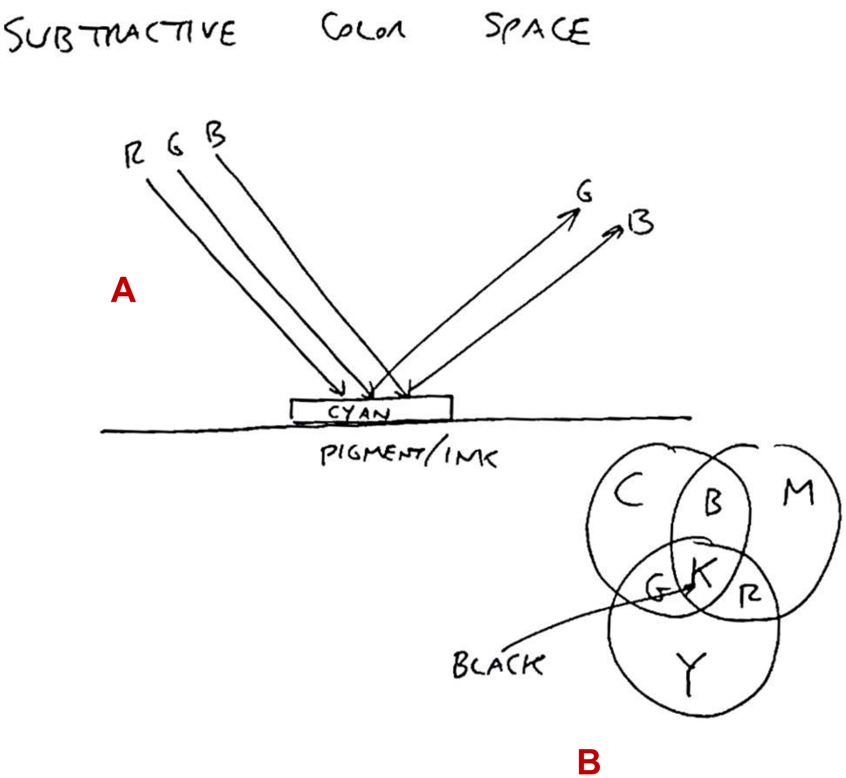
- For the purposes of being able to talk about color in a more scientific way, there have been various commissions on color and illumination. They have laid down some standards.
- The **CIE standard of colors**, established by the International Commission on Illumination (Commission Internationale de l'éclairage), is a system for describing and measuring color in a way that is objective and independent of the device or observer. Overall, the CIE standard of colors provides a framework for understanding, measuring, and communicating color information. It plays a crucial role in various fields that rely on accurate and consistent color representation.
- In CIE standard, the wavelength of **red** (**R**) is at **700** nm, **green** (**G**) at **546** nm, and **blue** (**B**) at **436** nm. These are called the **standard primary colors**. So, image acquisition devices like cameras and image reproduction devices like TVs and computer monitors are basically trying to capture and combine the responses and emissions of these primitive colors. This is done so that we could hopefully agree on what color should red be, what color should green be, and what color should blue be, especially in the context of monitors, TVs or LCDs.

Additive color spaces (RGB)



- **Combining R, G, and B (Additive Color Space):** We can attempt to combine the emissions of these primitive colors to get all the colors that we want. If we combine red light and green light, shown in **A**, we should perceive yellow. If we combine red light and blue light, we should perceive **magenta**. If we combine green and blue, we should get **cyan**. And if we combine them all, we should get **white**.
- **RGB in MATLAB:** As shown in **B**, MATLAB represents a digital image with every pixel having an **RGB value**. Here, red will be vector **[1 0 0]**, yellow will be **[1 1 0]**, and white will be **[1 1 1]**. These three RGB vectors represent colors in MATLAB's color format, which uses a **1×3** row vector to specify the red (**R**), green (**G**), and blue (**B**) components of a color on a scale of **0** (zero intensity, off, or black) to **1** (full intensity).
- As an example, vector **[1 1 0]** represents the color yellow. Its break down is as follows: **Red** = **1**: The red component remains at its maximum of **1**. **Green** = **1**: The green intensity is also **1**, meaning both red and green are fully turned on. **Blue** = **0**: Blue is off, with no contribution to the color. Mixing full red and full green light creates the perception of yellow.
- Sometimes MATLAB, instead of using a scale of **0** to **1**, it uses **0** to **255**, which we will be discussed later.

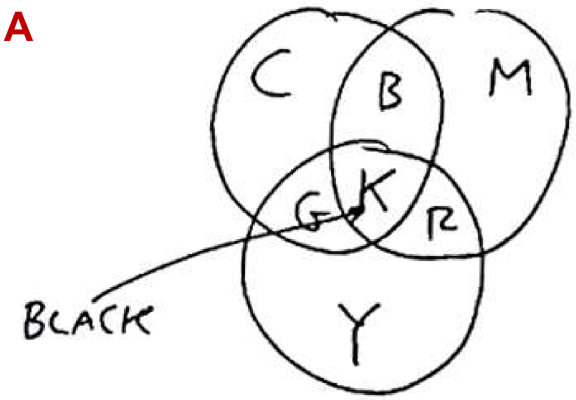
Subtractive color spaces (CMYK)



- **Subtractive Color Space (CMYK Color Space):** Things are different when we talk about how ink and printing is combined. For ink and printers, we use the concept of **Subtractive Color Space** also called **CMYK Color Space**. Let us see what it means. When we look at something that is red on a page, it is not like there is red light shining out of that object. Instead, what is happening is that the ambient white light is coming in and what is getting reflected back to our eye is red.
- In practice, what is happening with ink on a paper is as follows. Let us say we have a patch of cyan paint on a piece of paper, as shown in **A**. This is like **pigment** or **ink**. Assuming that the incoming light is white, which means that red, green, and blue light is coming in. Here, the cyan paint is sucking up the red light and transmitting out just the green and the blue right. This is called a **subtractive color model**, because instead of combining different pigments, we are actually taking incoming light and removing different colors from it. As shown in **B**, combing **B** and **G** looks like **C** (i.e., cyan), and hence, the pigment on the page has cyan color.

Subtractive color spaces (CMYK)

A



- In practice, the subtractive model means that we can start with the inks that are cyan, magenta, and yellow. Now, as shown in A, if we put cyan and yellow together, what shows is green. If we put cyan and magenta together, we get blue. If we put magenta and yellow together, we get red. If we put all three of them together, we should get **black**. MATLAB uses **K** as the abbreviation for blac**k**, and we used the same abbreviation here as well.
- For example, if we want to print red, we should superimpose blotches of magenta and yellow ink and that will look red to us. ***In theory***, if we wanted to print black, we should put cyan, magenta, and yellow on top of each other and that ***should*** look like black. But, in practice, because of the way that physical ink combines, that generally looks like a kind of crummy black, not like the deep black. So, in a printer, if we want deep black, we have got to replace the CMY with the black isolated cartridge. Here, if we have to print black on our printer, it will be using the dedicated black cartridge, not trying to combine the colors to produce some sort of a crummy black. That is also called **true black**, i.e., we use a **K cartridge** or a **black ink cartridge**. This is where four-color printing comes from.

Hue, saturation, value (HSV)

COLOR TERMS

BRIGHTNESS / INTENSITY / VALUE = "HOW MUCH" LIGHT THERE IS

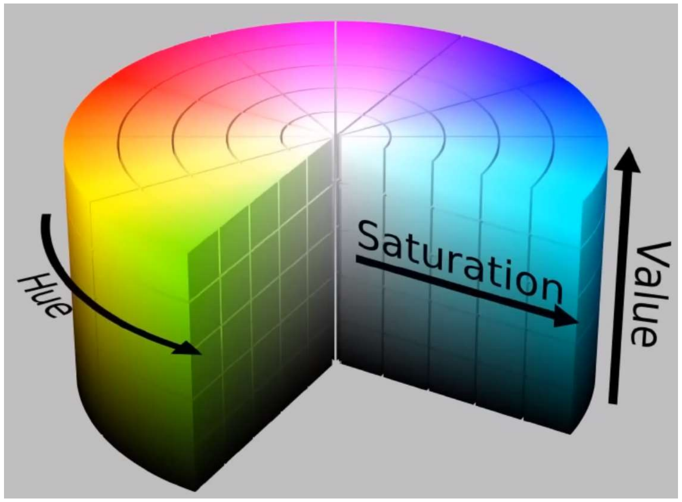
HUE = DOMINANT COLOR

SATURATION = PURITY / STRENGTH COLOR

- **Color Terms:** There are some words or terms that we may use that are related to color.
- **Brightness or Intensity or Value:** This term corresponds to the notion of ***how much light there is*** or how bright the color is or how intense the color is.
- **Hue:** This term is related to the ***dominant color***, e.g., is it greenish? is it reddish? or is it purplish? Hue refers to the actual color we perceive, such as red, green, blue, yellow, etc. It is essentially the "name" of the color.
- **Saturation:** This term is related to what we would call ***the purity or the strength of the color***. The difference between a pastel or ***pale*** or the tint of a color. So, the lower the saturation is, the paler the color seems to be. It basically describes how much "color" a color has. Imagine taking a pure red color and mixing increasing amounts of gray into it. As we add more gray, the red becomes less saturated and duller.
- **HSV:** This term stands for Hue-Saturation-Value.

Hue, saturation, value (HSV)

A



COLOR TERMS

BRIGHTNESS / INTENSITY / VALUE = "HOW MUCH" LIGHT THERE IS

HUE = DOMINANT COLOR

SATURATION = PURITY / STRENGTH COLOR

HUE + SATURATION DEFINE THE CHROMATICITY OF A COLOR.

- **HSV Color Wheel:** This tool is used as color wheel description of different colors. If we look at something like Photoshop, it will give us a way of picking a color. Either we can pick a color out of an **RGB palette** or we can pick a color out of a hue-saturation-value palette, an **HSV pallete**.
- The HSV pallete (HSV Color Wheel) is shown in **A**. As we go around the circle, we get different colors, **hues**. And, as we go from the middle to the outside, it goes from paler to more **saturated**, with kind of white being in the middle. And then, as we go from the bottom of **value** to the top of the value, it is like the amount of **brightness** that there is in that color.
- This HSV color space is very common for switching back and forth between RGB and HSV. Biological/medical image analyzers, Photoshop users, and graphic designers refer to these charts and use them all the time.
- The hue and the saturation together define what is called the **chromaticity** of a color. Note that the value, i.e., the vertical arrow in the chart, is only about the intensity of the color. It is like saying if we were to turn this image to gray scale, then the ***brightness*** from black to white of that pixel would be the ***value***. However, all the ***color information*** is coded in the ***hue*** and ***saturation*** together. So, generally, we want to have one number that tells us the kind of overall intensity and two numbers that tell us where in the color space we are. So, hue plus saturation define the chromaticity of a color.

Tristimulus values

AMOUNTS OF REFERENCE CIE PRIMARIES NEEDED TO FORM A COLOR ARE CALLED THE TRISTIMULUS VALUES

X, Y, Z.

WE CHARACTERIZE A COLOR BY

(1) $\frac{X}{X+Y+Z}$, (2) $\frac{Y}{X+Y+Z}$, (3) $\frac{Z}{X+Y+Z}$

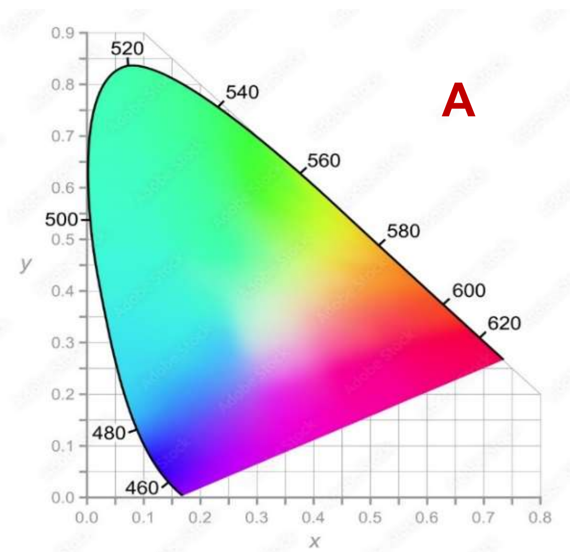
$$X = \int_0^\infty \underbrace{I(\lambda)}_{\text{SPECTRUM POWER DIST.}} \cdot \underbrace{x(\lambda)}_{\text{COLOR-MATCHING FUNCTION "RED"}} \, d\lambda$$

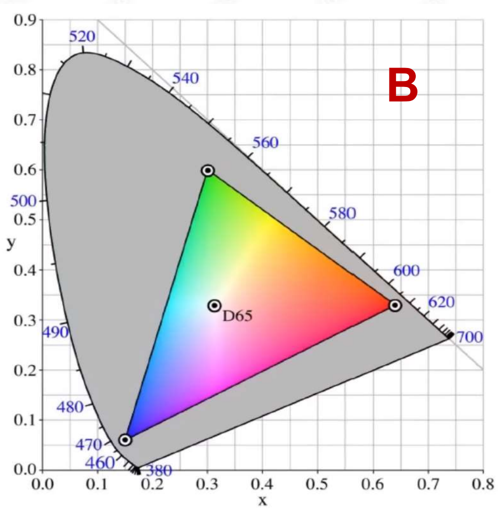
- In color science, tristimulus values are a fundamental concept that defines a color based on how it stimulates the three types of cone cells in the human eye: red, green, and blue. These values provide an objective way to quantify color perception, independent of the specific light source or device displaying the color.

- **Tristimulus Values:** It is important to find the ***amounts*** of red, green, and blue that we have to add up to get a new color, given these primaries. The CIE color organization defined the curves that are **reference spectra** for red, green, and blue. So, if we want to make a new color, we have to know what combination of these reference spectra we need. It is basically like a linear combination of say **0.5** of one color, plus **0.3** of another color, plus **0.2** of the other color that will give us the color that we are trying to make. The amounts of the ***reference CIE primaries*** needed to form a color are called the **tristimulus values** and sometimes we see these are shown by **X**, **Y**, and **Z**.

- Here, we characterize a color by the fraction of each, i.e., by **(1)**, **(2)**, and **(3)**. That leads to how we can get something like **X**. First of all, note that **X** is a number. And, the way it really works is that we get **X** by integrating the ***spectral power distribution (SPD)*** of the new color at a given **wavelength**, $\mathrm{I}(\lambda)$, times ***color matching function (CMF) "red"***, **X(λ)**. Here, we are multiplying our new color by ***the official red***, and we then we integrate to get the number **X**. This number tells us how much red there is in our new color.

Color gamuts





- **Chromaticity Diagram:** This is a plot of all the colors that humans are able to see as a function of **X**, the amount of **red**, and **Y**, the amount of **green**.
- As shown in **A**, this is just a representation in a sketchy space. It is not like we can reproduce all the colors that human can see on this one picture. It is just a sketch of the **range** or the **gamut** of the human vision system.
- We can only get at a certain fraction of these colors with any given device. For example, if we have an LCD monitor that has certain red phosphors, green phosphors, and blue phosphors, then the only thing that we can do is we can combine different amounts of those phosphors up to as much as the monitor can go. That means for any given three channel emission system, we can only get at some triangle inside what the human visual system is able to perceive, as shown in **B**. So, it is definitely true that we cannot see on a monitor every color we can see in the real world. That is, the monitor cannot go infinitely bright, and also there would still be some colors that are not combinable directly by these three numbers. We cannot exactly project the real world color onto this linear combination of three primaries. By the same token, we cannot print everything that we can see on our monitor, because inks are different than phosphors.
- Some graphic designer always struggle with the situation of how they can show their clients something on the TV screen or on the computer monitor and then print it in such a way that they can be sure that the clients see what they want. We have got all these figures on our screen that look great and then we want to send them to the printer. First, of course, they have to get converted from RGB color space to CMYK color space, and then, we face the challenge that the conversion is not exact.

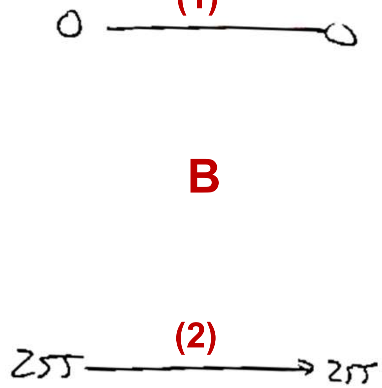
Image manipulation in MATLAB

Black

White

A

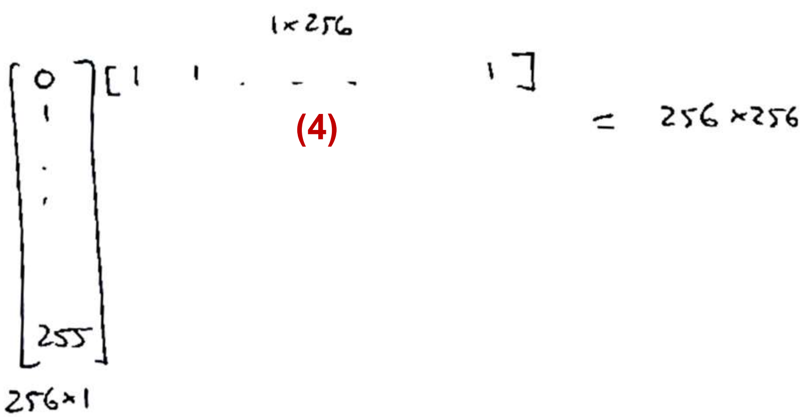
(1)



(2)

B

C



(4)

(3)

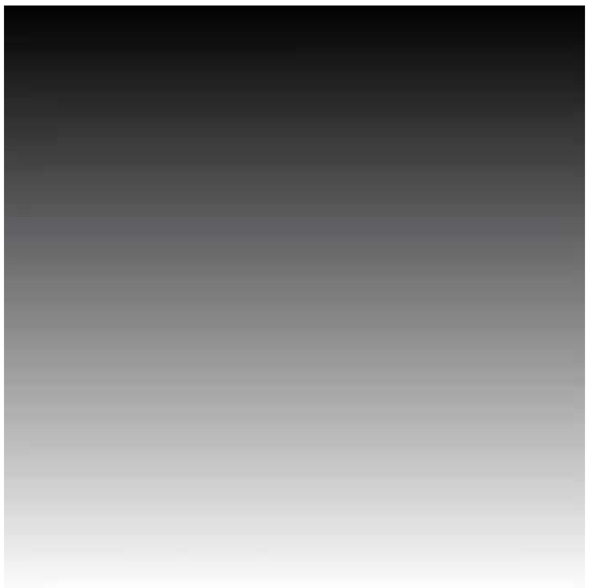
- **Making a Black and White Image in MATLAB:** Let us make an **intensity image**. Suppose we want to make an image that is **stripey**. So, it should start at black, at the top, and it should go down to white, at the bottom, as shown in **A**. We want the structure shown in **B**. That is, **(1)** should be **0**, like a row of zeros, and **(2)** should be a row of **255**’s.
- Mathematically, we take a column vector that goes from **0** to **255** and multiply it by a constant row vector of **1**’s. Now, we have a **256x1** vector, **(3)**, and a **1x256** vector, **(4)**. What we get out is going to be a **256x256** vector, and that is going to have constant rows.

Image manipulation in MATLAB

```
>> im  = [0:255]'*ones(1,256);
>> imshow(im,[])
```

A

B



- The list of commands are shown in **A**. Here, the **imshow** command has empty brackets, which says that we ***scale*** the darkest colors in this image to black and the whitest colors in this image to white. The output is shown in **B**.
- Let us break down the MATLAB code step-by-step:
- **Creating the Image Matrix:** The code initializes a matrix called **im**. The first part, **[0:255]**, generates a row vector from **0** to **255** (inclusive) with increments of **1**. The apostrophe (**'**) transposes this row vector into a column vector. The second part, **ones(1,256)**, creates a row vector of ones with **256** elements. The outer product of these two vectors, *****, results in a **256x256** matrix where each row contains the same sequence of numbers from **0** to **255**.
- **Displaying the Image:** The **imshow(im, [ ])** command displays the image represented by the matrix **im**. The empty brackets **[ ]** indicate that the display range should be automatically determined based on the minimum and maximum pixel values in **im**.
- **Interpretation:** The resulting image is a vertical gradient (**ramp**) that smoothly transitions from black (**0**) at the top to white (**255**) at the bottom. Each row corresponds to a different intensity level, creating the ***gradient effect***.

End of Lecture 2