Contents

Chapter 1

Electromagnetic Waves

Sound is a compression wave – to travel, it needs a medium to compress: air, water, etc. (Regardless of what you have seen in movies, sound does not travel through a vacuum)

Light is an electromagnetic wave – it causes fluctuations in the electric and magnetic fields that are everywhere. It can cross a vacuum, as it does to reach us from the sun.

Electromagnetic waves travel at about 300 million meters per second in a vacuum. The waves travel slower through things. For example, an electromagnetic wave travels at 225 million meters in water.

Electromagnetic waves come in different frequencies. For example, the light coming out of a red laser pointer is usually about 4.75×10^{14} Hz. The wifi data sent by your computer is carried on an electromagnetic wave too. It is usually close to 2.4×10^6 Hz or 5×10^6 Hz.

Because we know how fast the waves are moving, we sometimes talk about their wavelengths instead of their frequencies. The light coming out of a laser pointer is $300 \times 10^6 / 4.76 \times 10^{14} = 630 \times 10^{-9}$ m, or 630 nm.

Exercise 1 Wavelengths

A green laser pointer emits light at 5.66×10^{14} Hz. What is its wavelength in a vacuum?

Working Space

Answer on Page 33

We have given names to different ranges of the electromagnetic spectrum:

Name	Hertz	Meters
Gamma rays	$\times 10$	$\times 10$
X-rays	$\times 10$	$\times 10$
Ultraviolet	$\times 10$	$\times 10$
Blue	$\times 10$	$\times 10$
Red	$\times 10$	$\times 10$
Infrared	$\times 10$	$\times 10$
Microwaves	$\times 10$	$\times 10$
Radio waves	$\times 10$	$\times 10$

(You may have heard of "cosmic rays" and wonder why they are not listed in this table. Cosmic rays are actually the nuclei of atoms that have been stripped of their electron cloud. These particles come flying out of the sun at very high speeds. They were originally thought to be electromagnetic waves, and they were mistakenly named "rays".)

In general, the lower frequency the wave is, the better it passes through a mass. A radio wave, for example, can pass through the walls of your house, but visible light cannot. The people who designed the microwave oven, chose the frequency of 2.45 GHz because the energy from those waves tended to get absorbed in the first few inches of food that it passed through.

1.1 The greenhouse effect

Humans have dug up a bunch of long carbon-based molecules (like oil and coal) and burned them, releasing large amounts of CO_2 into the atmosphere. It is not obvious why that has made the planet warmer. The answer is electromagnetic waves.

A warm object gives off infrared electromagnetic waves. That's why, for example, motion detectors in security systems are actually infrared detectors: even in a dark room, your body gives off a lot of infrared radiation.

You may have heard of "heat-seeking missiles." These are more accurately called "Infrared homing missiles" because they follow objects giving off infrared radiation – hot things like jet engines.

The sun beams a lot of energy to our planet in the form of electromagnetic radiation: visible light, infrared, ultraviolet. (How much? At the top of the atmosphere directly facing the sun, we get 1,360 watts of radiation per square meter. That is a lot of power!)

Some of that radiation just reflects back into space. 23% is reflected by the clouds and the atmosphere, 7% makes it all the way to the surface of the planet and is reflected back into space.

The other 71% is absorbed: 48% is absorbed by the surface and 23% is absorbed by the atmosphere. All of that energy warms the planet and the atmosphere so that it gives off infrared radiation. The planet lives in equilibrium: The infrared radiation leaving our atmosphere is exactly the same amount of energy as that 71% of the radiation that it absorbs.

(If the planet absorbs more energy than it releases, the planet gets hotter. Hotter things release more infrared. When the planet is in equilibrium again, it stops getting hotter.)

So what is the problem with CO_2 and other large molecules in the atmosphere? They absorb the infrared radiation instead of letting it escape into space. Thus the planet must be hotter to maintain equilibrium.

The planet is getting hotter, and it is creating a multitude of problems:

- Weather patterns are changing, which leads to extreme floods and droughts.
- Ice and snow in places like Greenland are melting and flowing into the oceans. This is raising sea-levels.
- Biomes with biodiversity are resilient. Rapidly changing climate is destroying biodiversity everywhere, which is making these ecosystems very fragile.
- In many places, permafrost, which has trapped large amounts of methane in the ground for millenia, is melting.

That last item is particularly scary because methane is a large gas molecule – it absorbs even more infrared radiation than CO_2. As it is escapes the permafrost, the problem will get worse.

Scientists are working on four kinds of solutions:

- **Stop increasing the amount of greenhouse gases in our atmosphere.** It is hoped that non-carbon based energy systems like solar, wind, hydroelectric, and nuclear could let us stop burning carbon. Given the methane already being released, it maybe too late for this solution to work on its own.
- **Take some of greenhouse gases out of our atmosphere and sequester them somewhere.** The trunk of a tree is largely carbon molecules. When you grow a tree where there had not been one before, you are sequestering carbon inside the tree. There are also scientists that are trying to develop process that pull greenhouse gases out of the air and turn them into solids.
- **Decrease the amount of solar radiation that is absorbed by our planet and its atmosphere.** Clouds reflect a lot of radiation back into space. Could we increase the cloudiness of our atmosphere? Or maybe mirrors in orbit around our planet?
- **Adapt to the changing climate.** These scientists are assuming that global warming will continue, and are working to minimize future human suffering. How will we relocate a billion people as the oceans claim their homes? When massive heat waves occur, how will we keep people from dying? As biodiversity decreases, how can we make sure that species that are important to human existence survive?

What are the greenhouse gases and how much does each contribute to keeping the heat from exiting to space? These numbers are still being debated, but this will give you a feel:

Water vapor	H_2O	36 - 72 %
Carbon dioxide	CO_2	9 - 26 %
Methane	CH_4	4 - 9 %
Ozone	O_3	3 - 7 %

Notice that while we talk a lot about carbon dioxide, the most important greenhouse gas is actually water. Why don't we talk about it? Given the enormous surfaces of the oceans, it is difficult to imagine any way to permanently decrease the amount of water in the air. Also, a lot of water in the air is in the form of clouds that help reflect radiation before it is absorbed.

Chapter 2

How Cameras Work

Let's say it is a sunny day and you are standing in a field a few meters from a cow. You use the camera on your phone to take a picture of the cow. How does that whole process work?

2.1 The Light That Shines On the Cow

The sun is a sphere of hot gas. About 70% of the gas is hydrogen. About 28% is helium. There's also a little carbon, nitrogen, and oxygen.

Gradually, the sun is converting hydrogen into helium through a process known as "nuclear fusion". (We will talk more about nuclear fusion in a later chapter.) A lot of heat is created in this process. The heat makes the gases glow.

How does heat make things glow? The heat pushes the electrons into higher orbitals. When they back down to a lower orbital, they release a photon of energy, which travels away from the atom as an electromagnetic wave.

Heat isn't the only way to push the electrons into a higher orbital. For example, a fluorescent lightbulb is filled with gas. When we pass electricity through the gas, its electrons are moved to a higher orbital. When they fall, light is created.

What is the frequency of the wave that the photon travels on? Depending on what orbital it falls from and how far it falls, the photon created has different amounts of energy. The amount of energy determines the frequency of the electromagnetic wave.

Formula for enegy of a photon

If you want to know the amount of energy E in a photon, here is the formula:

$$E = \frac{hc}{\lambda}$$

where c is the speed of light, λ is the wavelength of the electromagnetic wave, and h Planck's constant: $6.63 \times 10^{-34} m^2 kg/s$

For example, a red laser light has a wavelength of about 630 nm. So the energy in each photon is:

$$\frac{(300 \times 10^6)(6.63 \times 10^{-34})}{630 \times 10^{-9}} = 3.1 \times 10^{-19} \text{ joules}$$

In the sun, there are several kinds of molecules and each has a few different orbitals that the electrons can live in. Thus, the light coming from the sun is made up of electromagnetic waves of many different frequencies.

We can see some of these frequencies as different colors, but some are invisible to humans, for example ultraviolet and infrared.

2.2 Light Hits the Cow

When these photons from the sun hit the cow, the hide and hairs of the cow will absorb some of the photons. These photons will become heat and make the cow feel warm. Some of the photons will not be absorbed – they will leave the cow. When you say "I see the cow," what you are really saying is "I see some photons that were not absorbed by the cow."

Different materials absorb different amounts of each wavelength. A plant, for example, absorbs a large percentage of all blue and red photons that hit it, but it absorbs only a small percentage of the green photons that hit it. Thus we say "That plant is green."

White things absorb very small percentages of photons of any visible wavelength. Black things absorb very *large* percentages of photons of any visible wavelength.

Before we go on, let's review: The sun creates photons that travel as electromagnetic waves of assorted wavelengths to the cow. Many of those photons are absorbed, but some are not. Some of those photons that are not absorbed go into the lens of our camera.

2.3 Pinhole camera

The simplest cameras have no lenses. They are just a box. The box has a tiny hole that allows photons to enter. The side of the box opposite the hole is flat and covered with film or some other photo-sensitive material.

The photons entering the box continue in the same direction they were going when they passed through the hole. Thus, the photons that entered from high, hit the back wall low. The photons that came from the left, hit the back wall on the right. Thus the image is projected onto the back wall rotated 180 degrees: What was up is down, what was on the left is on the right.

FIXME: picture here

Exercise 2 Height of the image

Working Space

Let's say that that the pinhole is exactly the same height as the shoulder of the cow and that the shoulder is directly above one hoof. Than the pinhole, the shoulder, and the hoof form a right triangle. Now, let's say that the camera is being held perpendicular to the ground. Now, the pinhole, the image of the shoulder, and the image of the hoof on the back wall of the camera also form a right triangle.
These two triangles are similar.
The shoulder is 2 meters from the hoof. The cow is standing 3 meters from the camera. The distance from the pinhole to the back wall of the camera is 3 cm. How tall is the image of the cow on the back wall of the camera?

Answer on Page 33

2.4 Lenses

Quick review: A photon leaves the sun in some random direction. It travels 150 million km from the sun and hits a cow. It is not absorbed by the cow, and heads off in a new direction. It passes through the pinhole and hits the back wall of the camera. That seems incredibly improbable, right?

It actually is kind of improbable, especially if there isn't a lot of light – like you are taking the picture at dusk. To increase the odds, we added a *lens* to the camera.

If you focus a lens on a wall, and then you draw a dot on the wall. The lens is designed such that all the photons from the dot that hit the lens get redirected to the same spot on the back wall of the camera – regardless of which path it took to get to the lens.

FIXME: illustration here

Note that the image still gets flipped. There is a *focal point* that all the photons pass through.

FIXME: illustration here

The distance from the lens to its focal point is called the lens's *focal length*. Telephoto lenses, that let you take big pictures of things that are far away, have long focal lengths. Wide-angle lenses have short focal lengths.

2.5 Sensors

The camera on your phone has a sensor on the back wall of the camera. The sensor is broken up into tiny rectangular regions called pixels. When you say a sensor is 6000 by 4000 pixels, we are saying the sensor is a grid of 24,000,000 pixels: 6000 pixels wide and 4000 pixels tall.

Each pixel has three types of cavities that take in photos. One of the cavities measures the amount of short wavelength light, like blues and violets. One of the cavities measures the long wavelength light, like reds and oranges. One of the cavities measures the intensity of wavelengths in the middle, like greens.

Thus, if your camera has a resolution of 6000×4000, the image is 72,000,000 numbers: Every one of the 24,000,000 pixels yeilds three numbers: intensity of long wavelength, mid wavelength, and long wavelength light. We call these numbers "RGB" for Red, Green, and Blue.

Chapter 3

How Eyes Work

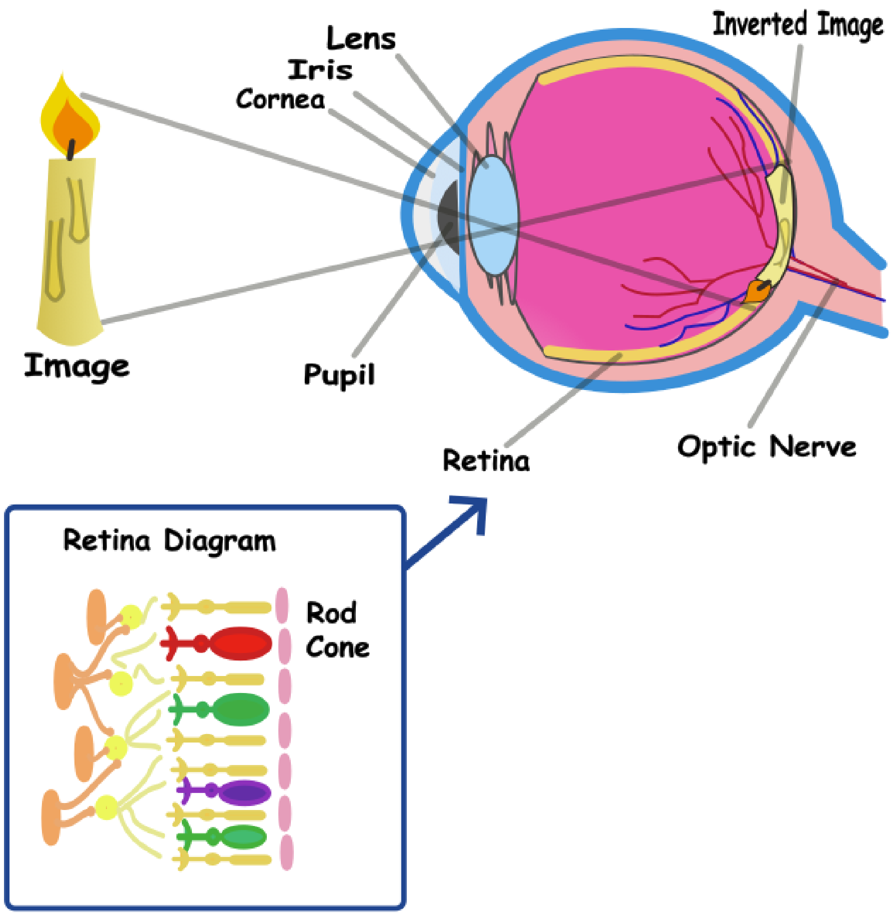
Dr. Craig Blackwell has made a great video on the mechanics of the eye. You should watch it: `https://youtu.be/Z8asc2SfFHM`

Mechanically, your eye works a lot like a camera. The eye is a sphere with two lenses on the front: The outer lens is called the *cornea*, and the second lens is just called "the lens."

Between the two lenses is an aperture that opens wide when there is very little light, and closes very small when there is bright light. The opening is called the *pupil* and the tissue that forms the pupil is called the *iris*. When people talk of the color of your eyes, they are talking about the color of your iris. The blackness at the center of your iris is your pupil.

There are two types of photoreceptor cells in your retina: rods and cones. The rods are more sensitive; in very dark conditions, most of our vision is provided by the rods. The cones are used when there is plenty of light, and they let us see colors.

The white part around the outside of the eyeball? That is called the *sclera*.



The walls of the eye are lined inside with the *retina*, which has sensors that pick up the light and send impulses down the optic nerve to your brain.

Just like a camera, the images are flipped when they get projected on the back of the eye.

3.1 Eye problems

Now that you know the mechanics of the eye, let's enumerate a few things that commonly go wrong with the eye.

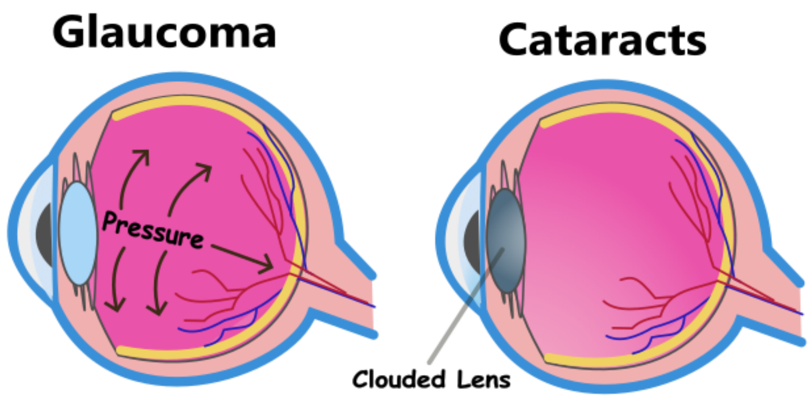
3.1.1 Glaucoma

The space between your cornea and lens is filled with a fluid called *aqueous humor*. To feed the cells of the cornea and lens, the aqueous humor carries oxygen and nutrients like blood would, but it is transparent so you can see. Aqueous humor is constantly being pumped into and out of that chamber. If aqueous humor has trouble exiting, the pressure builds up and can damage the eye. This is known as *glaucoma*.

3.1.2 Cataracts

The lens should be clear. As a person ages (and it can be accelerated by diabetes, too much exposure to sunlight, smoking, obesity, and high blood pressure), the proteins in the lens break down and clump together, becoming opaque. From the outside, the eye will look cloudy. This is called a *cataract*, and it makes it difficult for the person to see.

The problem can be corrected: The person's cloudy lens is removed and replaced with a



clear, manufactured lens.

3.1.3 Nearsightedness, farsightedness, and astigmatism

If you are in a dark room and a tiny LED is turned on, the photons from that LED can pass through your cornea in many different places. If your eye is focusing on that light correctly, all the photons should meet up at the same place on the retina.

FIXME: Diagram here

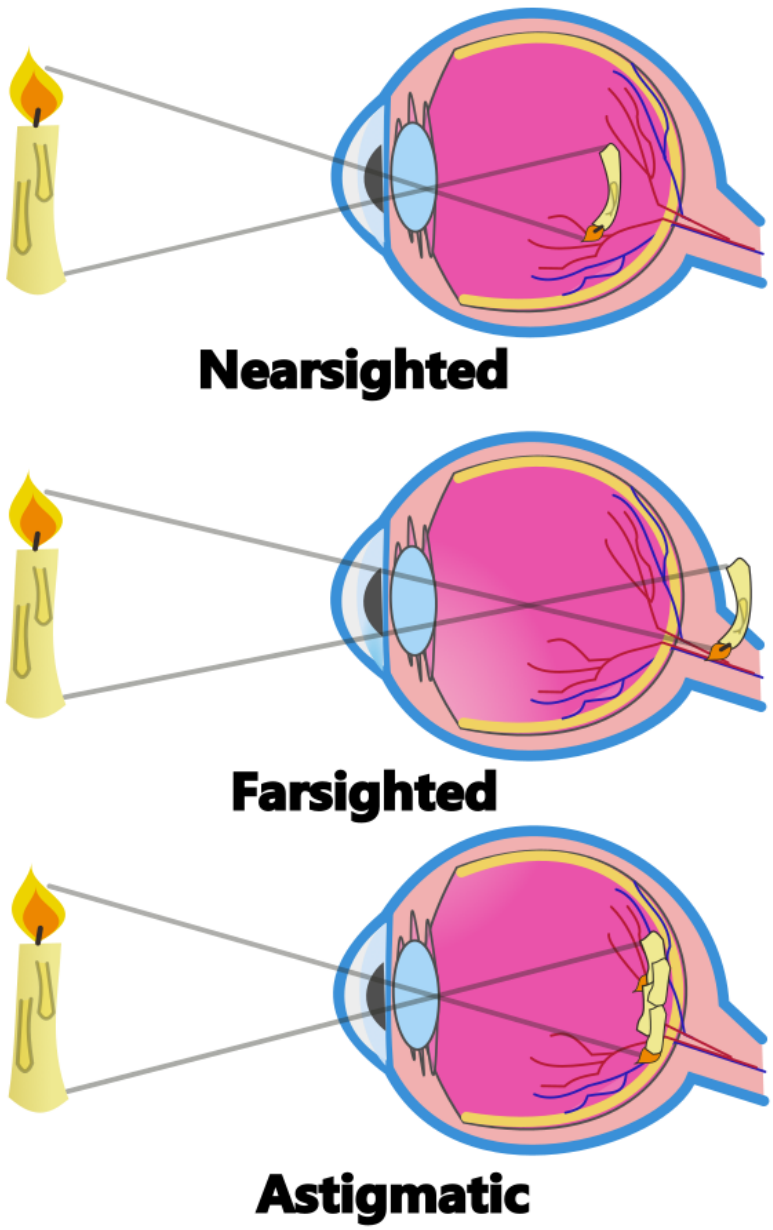
If the lenses are bending the light too much, the photons meet up before they hit the retina and get smeared a bit across the retina. To the person, the LED would appear blurry. The eye is said to be *nearsighted* or *myopic*.

If the lenses are not bending it enough, the photons would meet up behind the retina. Once again, they get smeared a bit across the retina and the LED looks blurry to the person. The eye is said to be *farsighted* or *hyperoptic*.

Your lenses are supposed to bend the photons the same amount vertically and horizontally.

If one dimension is focused, but the other is myopic or hyperoptic, the eye is said to have *astigmatism*.

Myopia, hyperoptia, and astigmatism can be corrected with glasses or contact lenses. Doctors can also do surgical corrections, usually by changing the shape of the cornea.

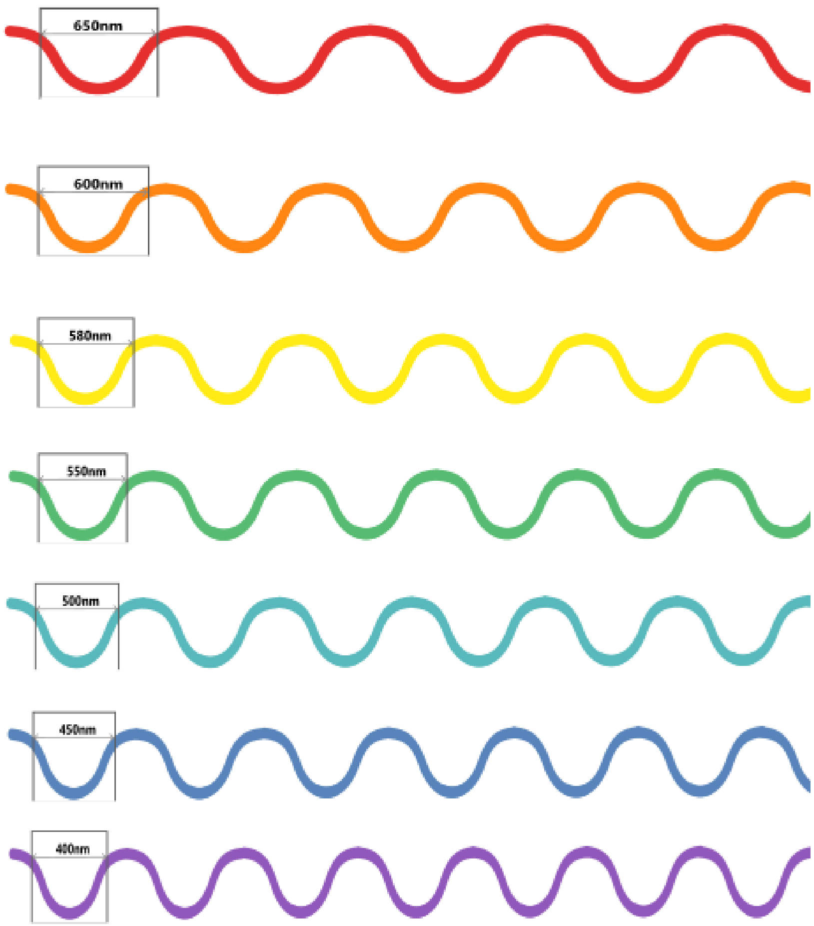


3.2 Seeing colors

TED-Ed has made a good video on how we see color. Watch it here: `https://youtu.be/l8_fZPHasdo`

When a rainbow forms, you are seeing different wavelengths separating from each other. In the rainbow:

- Red is about 650 nm.
- Orange is about 600 nm.
- Yellow is about 580 nm.
- Green is about 550 nm.
- Cyan is about 500 nm.
- Blue is about 450 nm.
- Violet is about 400 nm.



If you shine a light with a wavelength of 580 nm on a white piece of paper, you will see yellow.

However, if you shine two lights with wavelengths of 650 nm (red) and 550 nm (green), you will also see yellow.

Why? Our ears can hear two different frequencies at the same time. Why can't our eyes see two colors in the same place?

As mentioned above, the cone photoreceptors in our eyes let us see colors. There are three kinds of cones:

- Blue: Cones that are most sensitive to frequencies near 450nm.
- Green: Cones that are most sensitive to frequencies near 550nm.
- Red: Cones that let us see the frequencies up to about 700nm.

When a wavelength of 580 nm hits your retina, it excites the red and green receptors, and your brain interprets that mix as yellow.

Similarly, when light that contains both 650 nm and 550 nm waves hits your retina, it excites the red and green receptors, and your brain interprets that mix as yellow.

You can't tell the difference!

Now we know why the sensors on the camera are RGB. The camera is recording the scene as closely as necessary to fool your eye.

A TV or a color computer monitor only has three colors of pixels: red, green, and blue. By controlling the mix of them, it creates the sensation of thousands of colors to your eye.

3.3 Pigments

A color printer works oppositely: Instead of radiating colors, it puts pigments on the paper that absorb certain frequencies. A pigment that absorbs only frequencies near 650 nm (red) will appear to your eye as cyan. This makes sense because the sensation of cyan is created when your blue and green receptors are activated.

Thus, pigment colors come in:

- Cyan: absorbs frequencies around red
- Magenta: absorbs freqencies around green
- Yellow: absorbs frequencies around blue

If you buy ink for a color printer, you know there is typically a fourth ink: black. If you put cyan, magenta, and yellow pigments on paper, the mix won't absorb all the visible spectrum in a consistent manner, and our eyes are pretty sensitive to that, so we would see brown. So we add black ink to get pretty grays and blacks.

We call this approach to color CMYK (as opposed to RGB). If an artist is creating an image to be viewed on a screen, they will typically make an RGB image. If they are creating an image to be printed using pigments, they typically create a CMYK image. (Most of us don't care so much – we just let the computer do conversions between the two color spaces for us.)

Chapter 4

Reflection

Light reflection is the phenomenon where light waves bounce off a surface upon encountering it. It obeys the law of reflection, which states that the angle of incidence, denoted as θ_i, is equal to the angle of reflection, denoted as θ_r. This law can be mathematically expressed as:

$$\theta_i = \theta_r$$

where θ_i is the angle between the incident light ray and the normal to the surface, and θ_r is the angle between the reflected light ray and the normal.

To understand the math behind light reflection, we can consider a plane mirror as an example. When a light ray hits a plane mirror, it is reflected back in a way that the incident angle is equal to the reflected angle with respect to the mirror's surface.

Let's assume the incident light ray is represented by a vector $\mathbf{i}$ and the normal to the mirror's surface is represented by a vector $\mathbf{n}$. The angle of incidence, θ_i, can be calculated using the dot product between the incident ray and the normal:

$$\cos(\theta_i) = \frac{\mathbf{i} \cdot \mathbf{n}}{\|\mathbf{i}\|\|\mathbf{n}\|}$$

where $\cdot$ denotes the dot product and $|\mathbf{i}|$ and $|\mathbf{n}|$ represent the magnitudes of the incident ray and the normal vector, respectively.

Since the law of reflection states that $\theta_i = \theta_r$, we can calculate the angle of reflection, θ_r, using the inverse cosine function:

$$\theta_r = \cos^{-1}\left(\frac{\mathbf{i} \cdot \mathbf{n}}{\|\mathbf{i}\|\|\mathbf{n}\|}\right)$$

Once we have the angle of reflection, we can obtain the reflected ray by rotating the incident ray by an angle of $2\theta_r$ with respect to the mirror's surface. This can be done using rotation matrices or trigonometric functions, depending on the coordinate system being used.

In summary, light reflection follows the law of reflection, where the incident angle is equal to the reflected angle. By calculating the dot product between the incident ray and the surface's normal, we can determine the angles of incidence and reflection. Then, by rotating the incident ray, we can find the direction of the reflected ray.

Chapter 5

Refraction

Refraction of light is the phenomenon where light changes its direction when it passes from one medium to another. The change in direction is due to a change in the speed of light as it moves from one medium to another.

This phenomenon is explained by Snell's law, which states:

$$n_1 \cdot \sin(\theta_1) = n_2 \cdot \sin(\theta_2) \tag{5.1}$$

where:

- n_1 and n_2 are the indices of refraction for the first and second media, respectively. The index of refraction is the ratio of the speed of light in a vacuum to the speed of light in the medium. It is a dimensionless quantity.

- θ_1 and θ_2 are the angles of incidence and refraction, respectively. These angles are measured from the normal (perpendicular line) to the surface at the point where light hits the boundary.

The angle of incidence (θ_1) is the angle between the incident ray and the normal to the interface at the point of incidence. Similarly, the angle of refraction (θ_2) is the angle between the refracted ray and the normal.

When light travels from a medium with a lower refractive index to a medium with a higher refractive index, it bends towards the normal. Conversely, when light travels from a medium with a higher refractive index to one with a lower refractive index, it bends away from the normal.

Chapter 6

Lenses

Lenses are optical devices with perfect or approximate axial symmetry that transmit and refract light, converging or diverging the beam. There are two main types of lenses, distinguished by their shape and the way they refract light:

- **Converging (or Convex) Lenses:** These are thicker at the center than at the edges. When parallel light rays enter a convex lens, they converge to a point called the focal point. Examples of converging lenses include magnifying glasses and camera lenses.
- **Diverging (or Concave) Lenses:** These are thinner at the center than at the edges. When parallel light rays enter a concave lens, they diverge or spread out. These lenses are often used in glasses to correct nearsightedness.

6.1 Focal Length

The focal length of a lens is the distance between the center of the lens and the focal point. It is determined by the lens shape and the refractive index of the lens material. For a converging lens, the focal length is positive, and for a diverging lens, the focal length is negative.

6.2 Refractive Index

The refractive index of a material is a measure of how much the speed of light is reduced inside the material. The refractive index n of a material is given by the ratio of the speed of light in a vacuum c to the speed of light v in the material:

$$n = \frac{c}{v}$$

The refractive index affects how much a light ray changes direction, or refracts, when entering the material at an angle. A higher refractive index indicates that light travels slower in that medium and the light ray will bend more towards the normal.

Lenses work by refracting light at their two surfaces. By choosing the right lens shape and material, lenses can be designed to bring light to a focus, spread it out, or perform more complex transformations.

Chapter 7

Images in Python

An image is usually represented as a three-dimensional array of 8-bit integers. NumPy arrays are the most commonly used library for this sort of data structure.

If you have an RGB image that is 480 pixels tall and 640 pixels wide, you will need a $480 \times 640 \times 3$ NumPy array.

There is a separate library (imageio) that:

- Reads an image file (like JPEG files) and creates a NumPy array.
- Writes a NumPy array to a file in standard image formats

Let's create a simply python program that creates a file containing an all-black image that is 640 pixels wide and 480 pixels tall. Create a file called `create_image.py`:

```
import NumPy as np
import imageio
```

```
import sys

# Check command-line arguments
if len(sys.argv) < 2:
    print(f"Usage {sys.argv[0]} <outfile>")
    sys.exit(1)

# Constants
IMAGE_WIDTH = 640
IMAGE_HEIGHT = 480

# Create an array of zeros
image = np.zeros((IMAGE_HEIGHT, IMAGE_WIDTH, 3), dtype=np.uint8)

# Write the array to the file
imageio.imwrite(sys.argv[1], image)
```

To run this, you will need to supply the name of the file you are trying to create. The extension (like .png or .jpeg) will tell imageio what format you want written. Run it now:

```
python3 create_image.py blackness.png
```

Open the image to confirm that it is 640 pixels wide, 480 pixels tall, and completely black.

7.1 Adding color

Now, let's walk through through the image, pixel-by-pixel, adding some red. We will gradually increase the red from 0 on the left to 255 on the right.

```
import NumPy as np
import imageio
import sys

# Check command-line arguments
if len(sys.argv) < 2:
    print(f"Usage sys.argv[0] <outfile>")
    sys.exit(1)

# Constants
IMAGE_WIDTH = 640
IMAGE_HEIGHT = 480
```

```
# Create an array of zeros
image = np.zeros((IMAGE_HEIGHT, IMAGE_WIDTH, 3), dtype=np.uint8)

for col in range(IMAGE_WIDTH):

    # Red goes from 0 to 255 (left to right)
    r = int(col * 255.0 / IMAGE_WIDTH)

    # Update all the pixels in that column
    for row in range(IMAGE_HEIGHT):
        # Set the red pixel
        image[row, col, 0] = r

# Write the array to the file
imageio.imwrite(sys.argv[1], image)
```

When you run the function to create a new image, it will be a fade from black to red as you move from left to right:

Now, inside the inner loop, update the blue channel so that it goes from zero at the top to 255 at the bottom:

```
    # Update all the pixels in that column
    for row in range(IMAGE_HEIGHT):

        # Update the red channel
        image[row,col,0] = r

        # Blue goes from 0 to 255 (top to bottom)
        b = int(row * 255.0 / IMAGE_HEIGHT)
        image[row,col,2] = b

imageio.imwrite(sys.argv[1], image)
```

When you run the program again, you will see the color fades from black to blue as you go down the left side. As you go down the right side, the color fades from red to magenta.

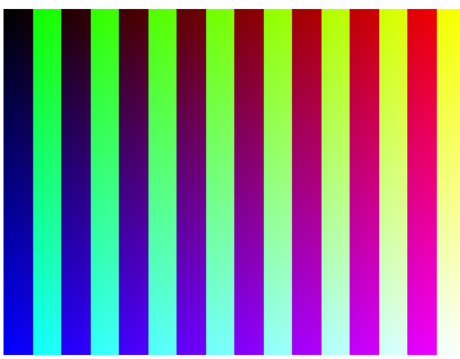
Notice that red and blue with no green looks magenta to your eye.

Now let's add some stripes of green:

```
import NumPy as np
import imageio
import sys

# Check command line arguments
if len(sys.argv) < 2:
    print(f"Usage sys.argv[0] <outfile>")
    sys.exit(1)

# Constants
IMAGE_WIDTH = 640
IMAGE_HEIGHT = 480
STRIPE_WIDTH = 40
pattern_width = STRIPE_WIDTH * 2

# Create an image of all zeros
image = np.zeros((IMAGE_HEIGHT, IMAGE_WIDTH, 3), dtype=np.uint8)

# Step from left to right
for col in range(IMAGE_WIDTH):

    # Red goes from 0 to 255 (left to right)
    r = int(col * 255.0 / IMAGE_WIDTH)

    # Should I add green to this column?
    should_green = col % pattern_width > STRIPE_WIDTH

    # Update all the pixels in that column
```

```
    for row in range(IMAGE_HEIGHT):

        # Update the red channel
        image[row,col,0] = r

        # Should I add green to this pixel?
        if should_green:
            image[row,col,1] = 255

        # Blue goes from 0 to 255 (top to bottom)
        b = int(row * 255.0 / IMAGE_HEIGHT)
        image[row,col,2] = b

imageio.imwrite(sys.argv[1], image)
```

When you run this version, you will see the previous image in half the stripes. In the other half, you will see that green fades to cyan down the left side and yellow fades to white down the right side.



7.2 Using an existing image

imageio can also be used to read in any common image file format. Let's read in an image and save each of the red, green, and blue channels out as its own image.

Create a new file called `separate_image.py`:

```
import imageio
import sys
import os

# Check command line arguments
if len(sys.argv) < 2:
```

```
    print(f"Usage {sys.argv[0]} <infile>")
    sys.exit(1)

# Read the image
path = sys.argv[1]
image = imageio.imread(path)

# What is the filename?
filename = os.path.basename(path)

# What is the shape of the array?
original_shape = image.shape

# Log it
print(f"Shape of {filename}:{original_shape}")

# Names of the colors for the filenames
colors = ['red','green','blue']

# Step through each of the colors
for i in range(3):

    # Create a new image
    newimage = np.zeros(original_shape, dtype=np.uint8)

    # Copy one channel
    newimage[:,:,i] = image[:,:,i]

    # Save to a file
    new_filename = f"{colors[i]}_{filename}"
    print(f"Writing {new_filename}")
    imageio.imwrite(new_filename, newimage)
```

Now you can run the program with any common RGB image type:

```
python3 separate_image.py dog.jpg
```

This will create three images: `red_dog.jpg`, `green_dog.jpg`, and `blue_dog.jpg`.

Appendix A

Answers to Exercises

Answer to Exercise 1 (on page 4)

$$\frac{300 \times 10^6}{5.66 \times 10^{14}} = 530 \times 10^{-9} = 530 \text{ nm}$$

Answer to Exercise 2 (on page 10)

The two triangles are similar, one is 2 m and 3m. The other is x cm and 3 cm.

The image of the cow is 2 cm tall.

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