The Ancient Secrets of Computer Vision

Previously On

the

Ancient Secrets of Computer Vision

Low-Level Vision

Photo manipulation

- Size
- Color
- Exposure
- X-Pro II

Feature extraction

- Edges
- Oriented gradients
- Segments

Mid-Level Vision

Image <-> Image
- Panoramas

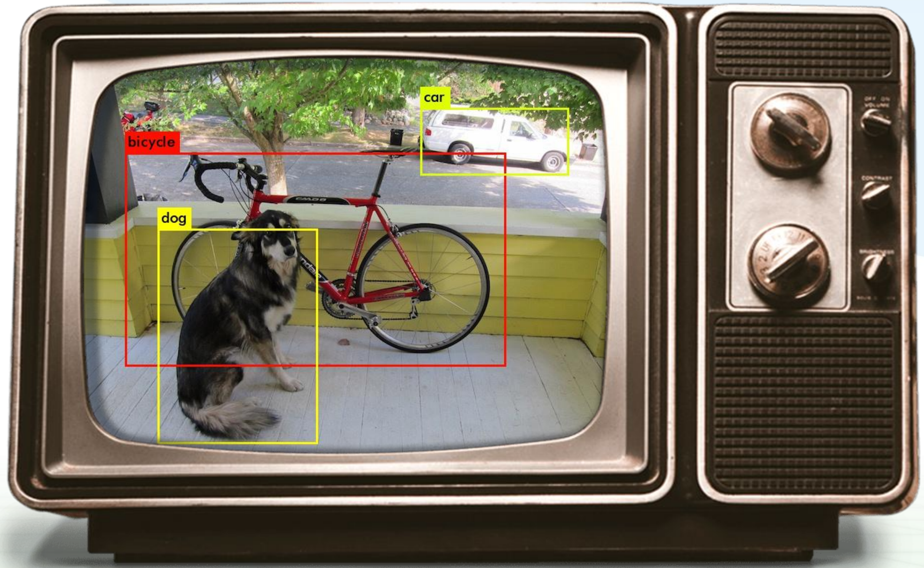
Image <-> World
- Multi-view stereo
- Structure from motion
- Structured light
- LIDAR

Image <-> Time
- Optical flow
- Time lapse

High-Level Vision

Image <-> Semantics!
- Image classification
- Object detection
- Segmentation

Applications
- Retrieval
- Robots?
- and...????



High-Level: Semantics -> Images

Chapter Two

wait...

Human Vision?

Is vision easy or hard for humans?

- Discuss with your neighbors
- 2 minutes
- Report back

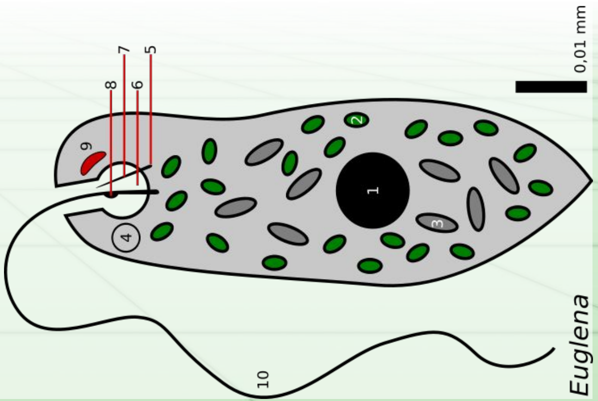
Eyes - The Sensors for Vision

Why do things have eyes?

- To see other things!
- Visual stimulus is an important signal
- Started as photoreceptive protein (eyespots)

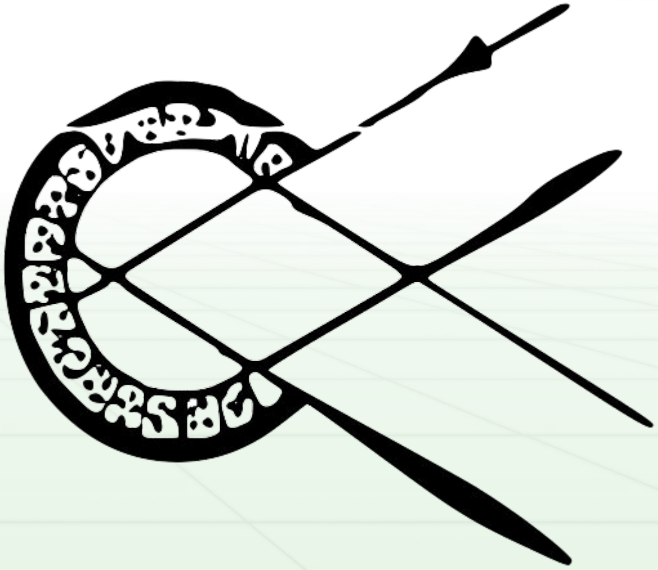
Eyespots - the beginning of vision

- Eyespots are sensitive to ambient light
- Just rough direction:
  - Euglena swim towards light for better photosynthesis
  - Snails move away from light
- No nerves, brain, or processing
- Very low acuity (light from many directions all hits same sensitive area)
- Started EVOLVING…



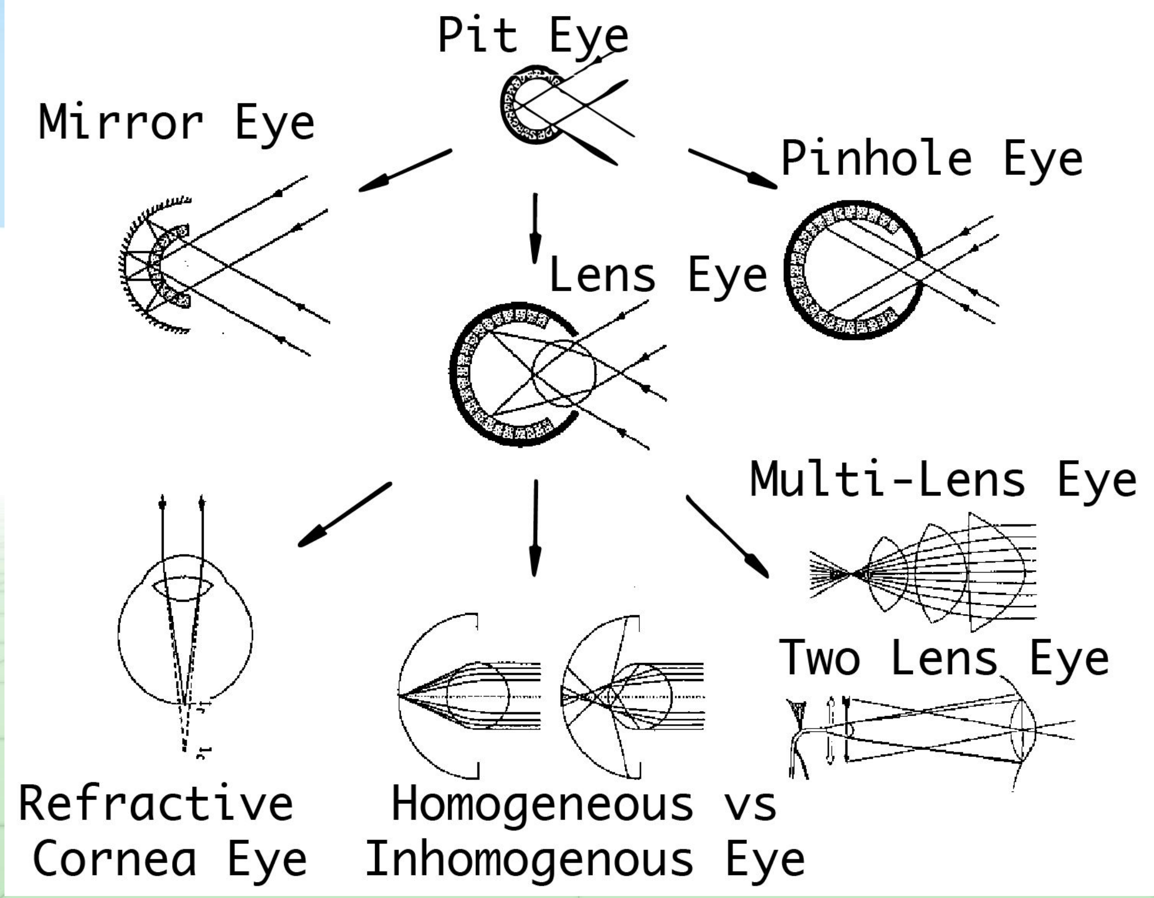
Pit eyes - the first eyes?

- Photosensitive cells in pits
- Block some light
- More information about where light direction
- Very common
  - Evolved 40-65 times
  - 28 of 33 animal phyla have them
- Very simple, low acuity

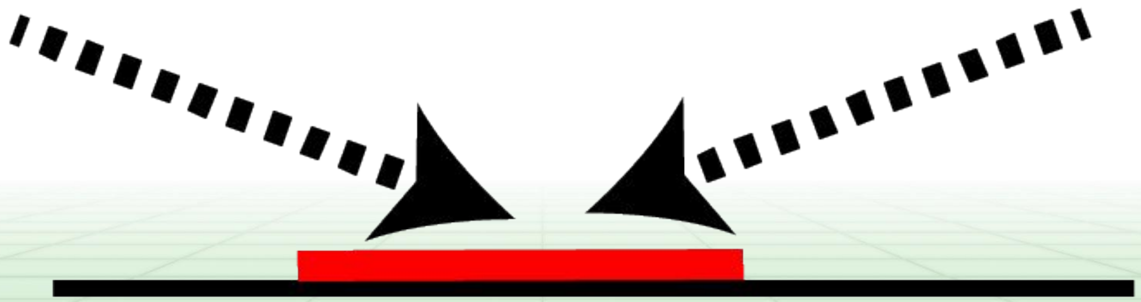


http://www.rctn.org/vs265/landfernald92.pdf

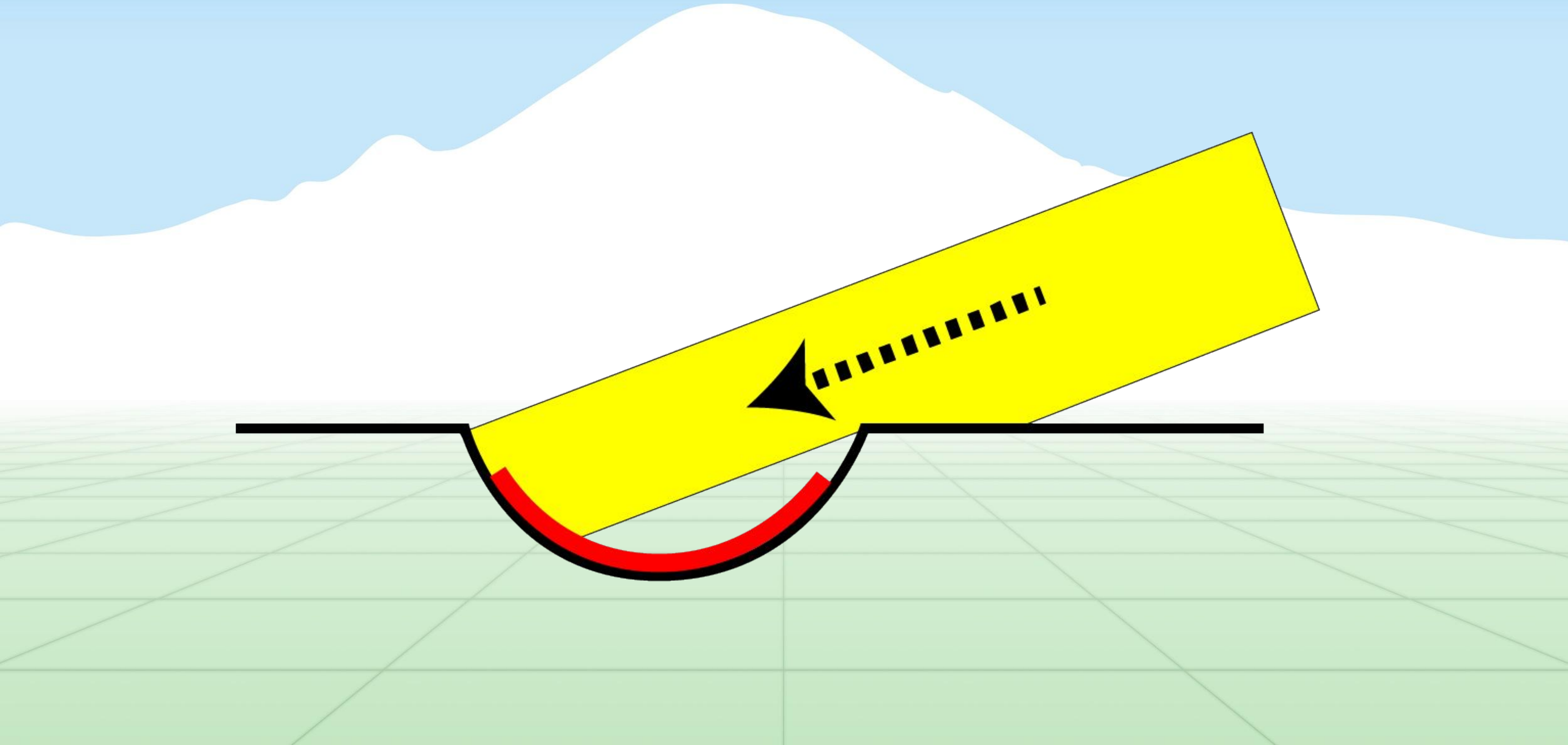
Simple -> complex eyes



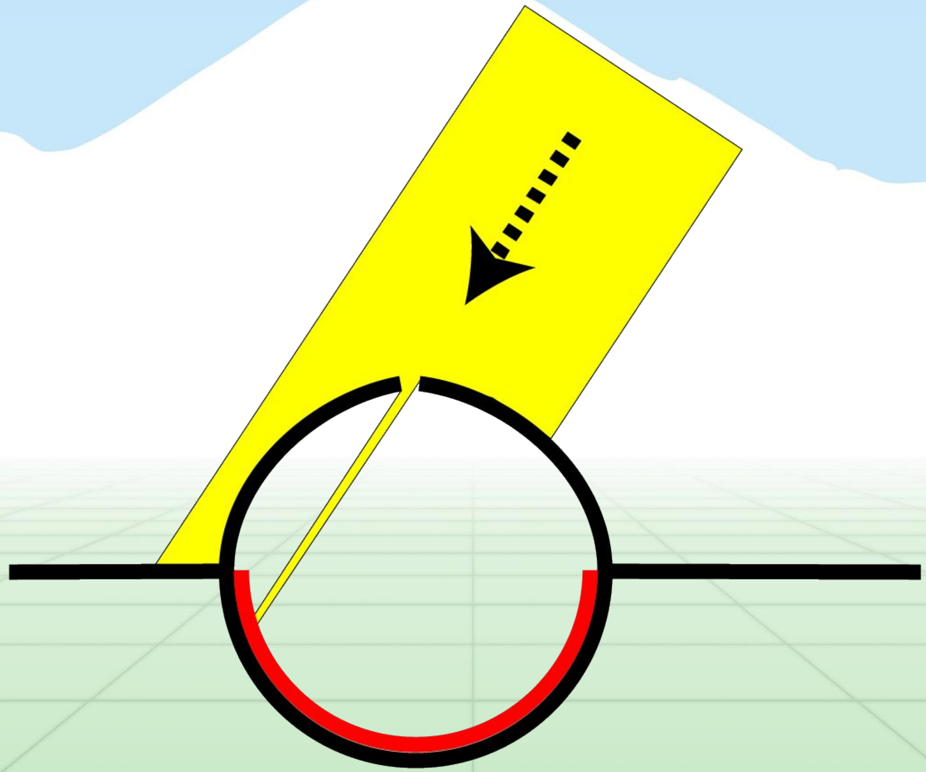
Eyespots - no acuity



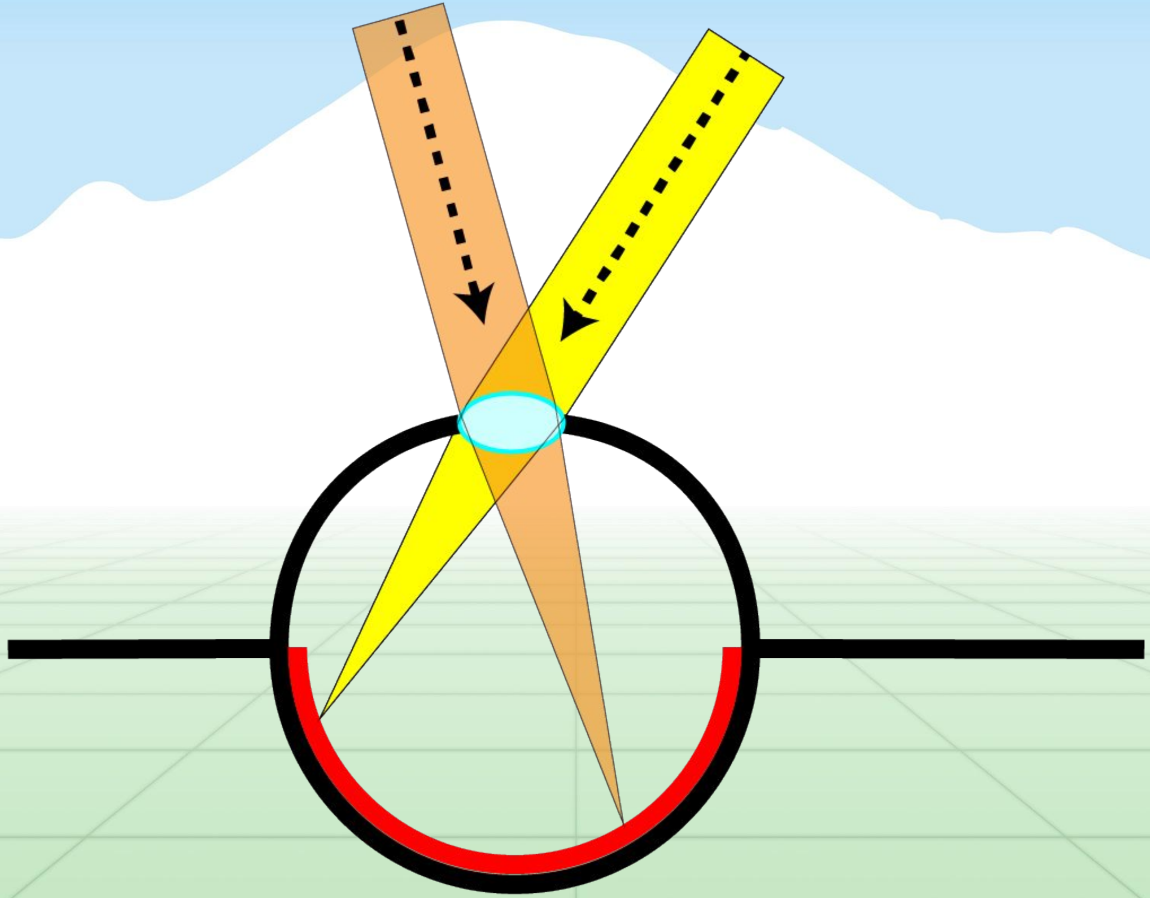
Pit eyes - some acuity



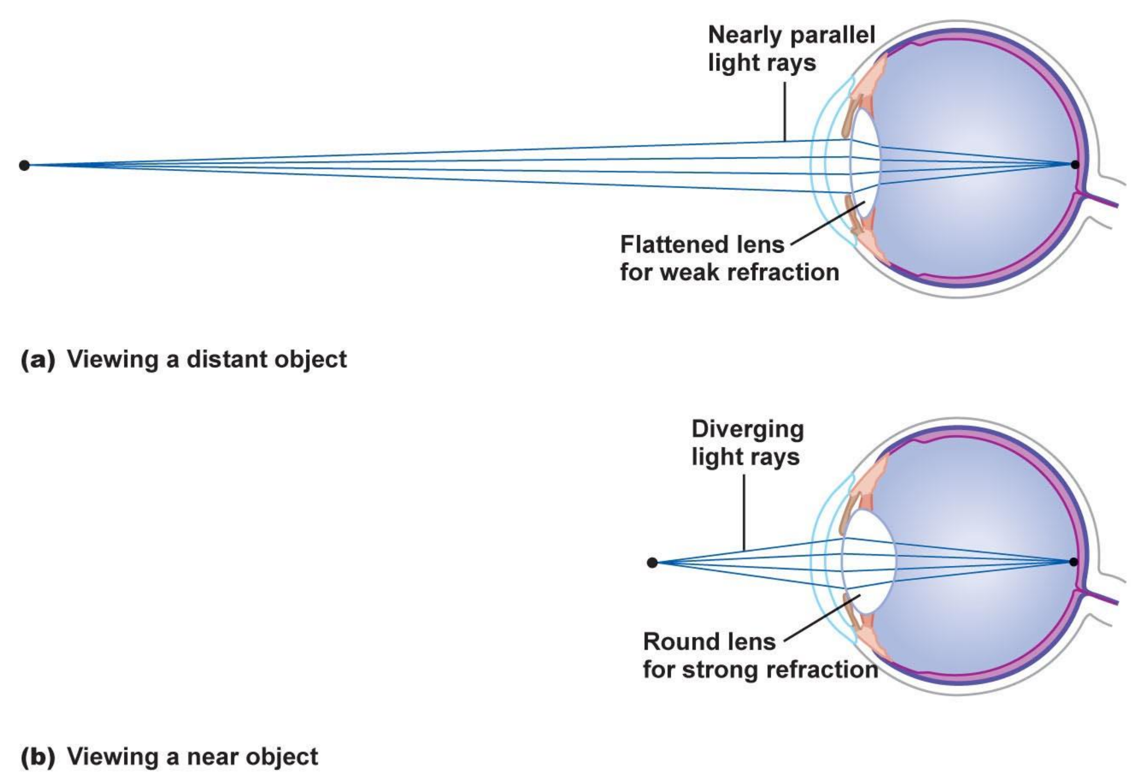
Complex eyes - high acuity



Refraction: more light + acuity!



Focussing: changing refraction

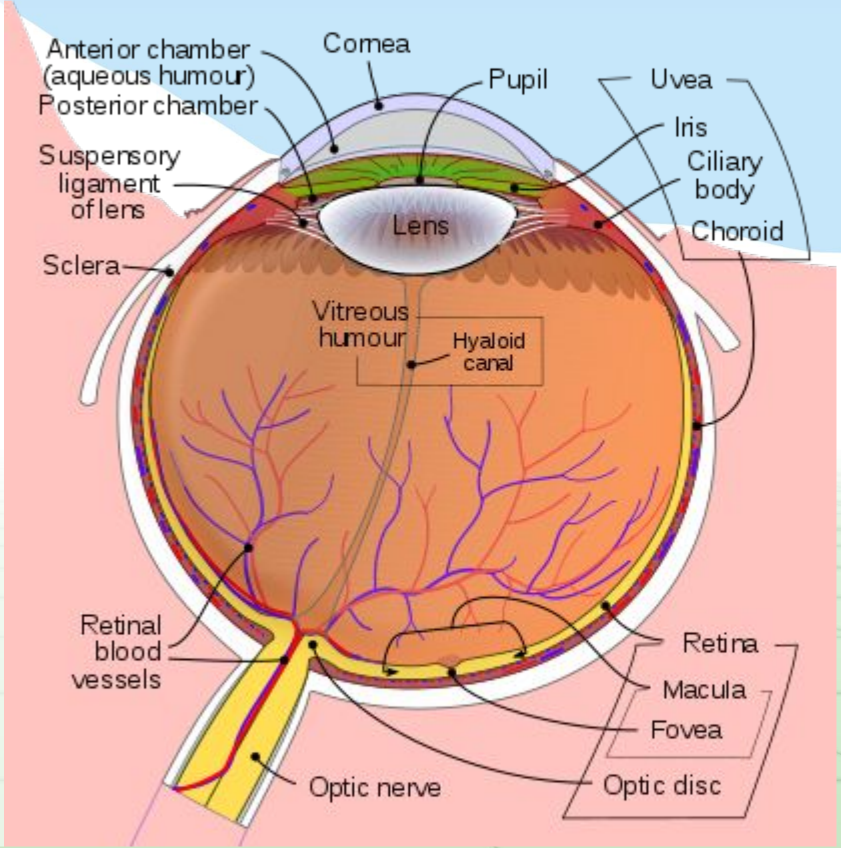


Complex eyes - a huge advantage

- Many different styles, mechanisms
  - >= 10, accounting for many of the ways our cameras work now
- Same goal: better visual acuity (resolution)
- Rare: 6 of 33 animal phyla
- Beneficial: 96% of known species
  - Is it all because of the eyes??
- Image forming - high enough acuity to perceive shapes, objects, etc.

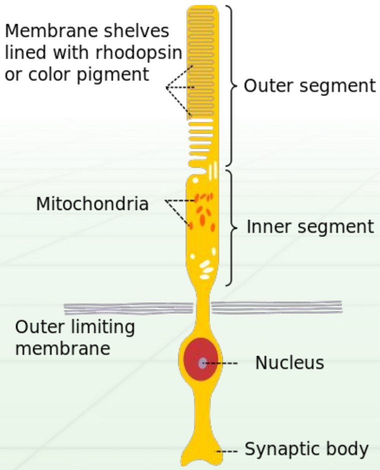
So how do human eyes work?

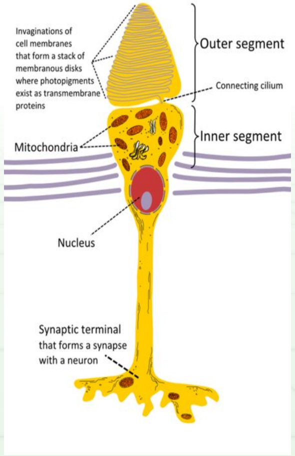
- Complex!
- Light passes through
  - Cornea, humours, lens refract light to focus
- Hit the retina
- Absorbed by photosensitive cells
- Info transmitted through optic nerve, processed by visual cortex

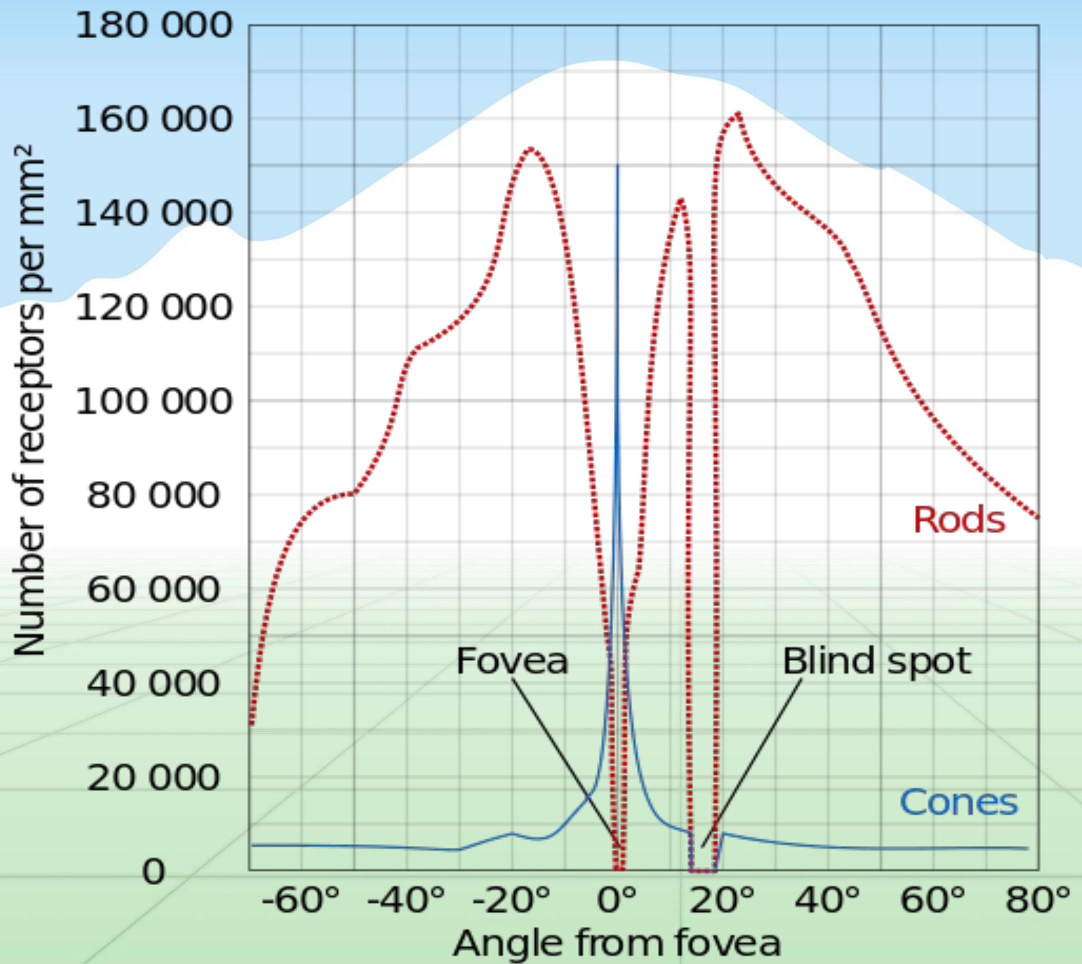


How do we process this light?

- Hit photoreceptive cells (rods and cones)
- ~120 million of them in retina
- Not all the same, not evenly distributed







180 000
160 000
140 000
120 000
100 000
80 000
60 000
40 000
20 000
0
Number of receptors per mm²
Rods
Cones
Fovea
Blind spot
-60°
-40°
-20°
0°
20°
40°
60°
80°
Angle from fovea

Rods - low light, monochrome vision

- ~120 million
- Sensitive to 1 photon
- Can pool responses
- Slow response time
- Only operate in low-light conditions
- Saturate quickly in lots of light
- Take ~7 minutes to adjust (night vision)

Cones - detailed, color vision

- ~6 million
- Need many photons to activate, bright light
- Fast response time
- Fine details
- Fast changes over time
- Responsible for most daytime vision
- Mostly packed into one region: Fovea

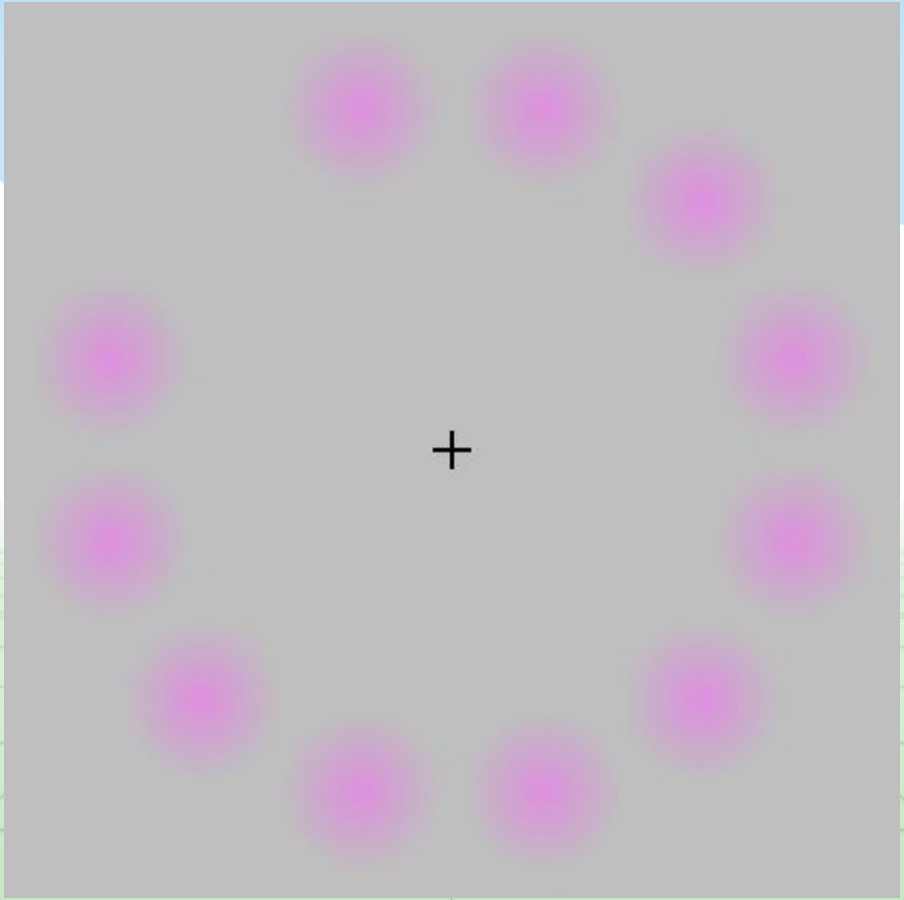
Fovea: where it’s all happening

- Small circle on the retina, 1.5mm
- Densely packed with cones
  - 200,000 cones/mm2
- Highest visual acuity
- Reading: move your eyes so the text is centered in fovea

Peripheral vision: don’t get eaten

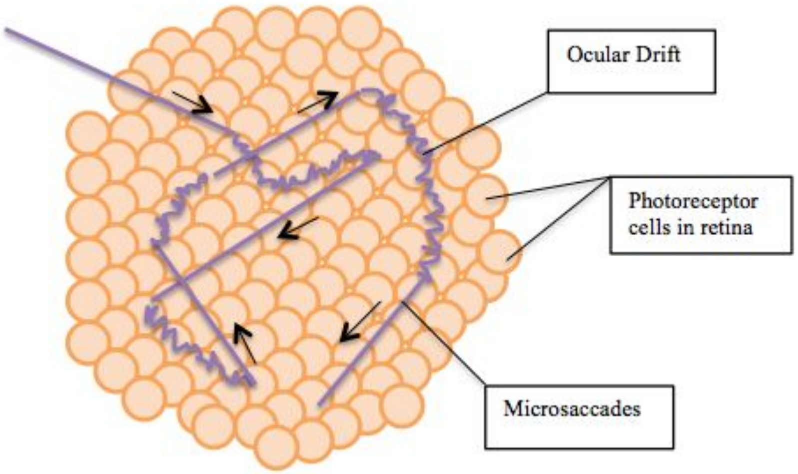
- Few cones
  - Low acuity
  - Low perception of color
- Lots of rods, good at night
- At night: look at stars straight on vs slightly next to them. Brighter when you don’t look right at them!

Photoreceptors need change!



Fixational eye movement

- Receptors adjust, lose sensitivity over time
- Eye keeps moving to expose new parts to light
- Microsaccades
  - Short linear movement
  - Sporadic
- Ocular drift
  - Constant slow movement
- Microtremors
  - Tiny vibrations
  - Synchronized between eyes
  - For seeing fine details



The Brain - A Visual Processor

Brains (maybe) came after eyes!

- Animals that rely on visual input but not brains
  - Eyes connect straight to muscle tissue
  - Some jellyfish
- No reason to have a brain without sensory input
- Brains <-> Eyes coevolve
  - As the eyes get more complex, visual cortex expands
- So maybe the reason you have a brain is because of your eyes!

https://academic.oup.com/jhered/article/96/3/171/2187545

Ganglia transmit info to brain

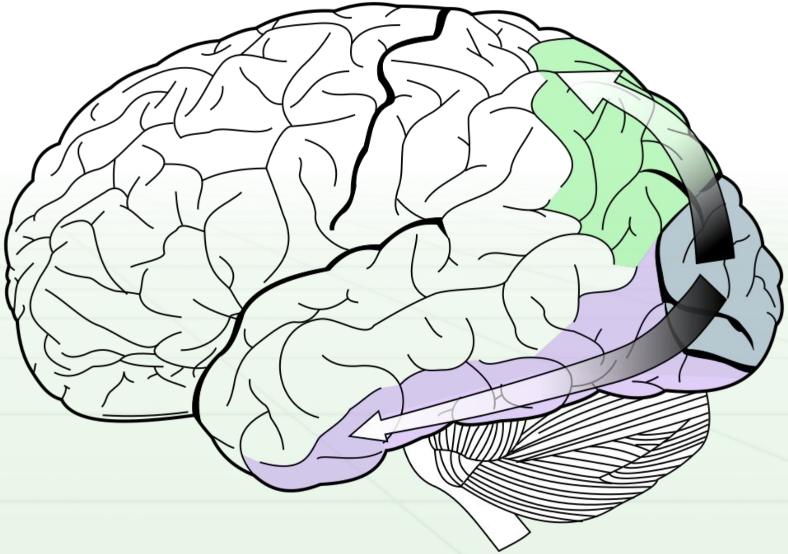
- ~ 1 million of them
- Different ganglia connect to different kinds of photoreceptors, sensitive to different things
- M cells: depth, movement, orientation/position of objects
- P cells: color, shape, fine details

Visual cortex interprets data

- More than 30 different substructures in the brain for processing visual data
- V1: primary visual cortex
  - Edge detection
  - Highly spatially sensitive
- V2: secondary visual cortex
  - Size, color, shape, possibly memory
  - Sends signals onward to V3, V4, V5
  - Sends strong feedback back to V1
- Many of these system functions are not well understood

Visual cortex is split (maybe)

- Ventral/dorsal hypothesis
- Information goes through V1 and V2
- Splits into streams for different purposes



Ventral vs dorsal stream

Factor	Ventral system	Dorsal system
Function	Recognition/identification	Visually guided behaviour
Sensitivity	High spatial frequencies - details	High temporal frequencies - motion
Memory	Long term stored representations	Only very short-term storage
Speed	Relatively slow	Relatively fast
Consciousness	Typically high	Typically low
Frame of reference	Allocentric or object-centered	Egocentric or viewer-centered
Visual input	Mainly foveal or parafoveal	Across retina
Monocular vision	Generally reasonably small effects	Often large effects e.g. motion parallax

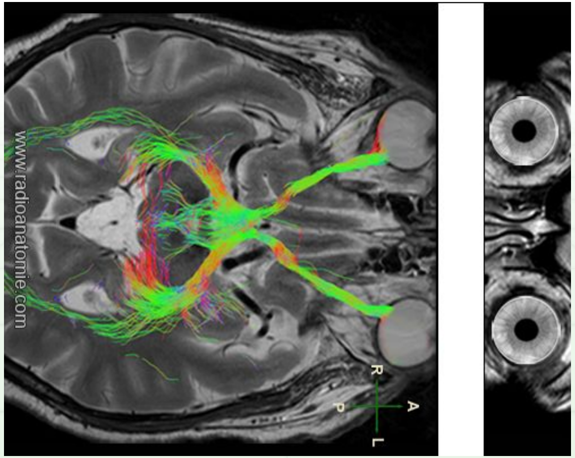
What does this split mean?

- Recognition and action are split!
- Damage to dorsal system:
  - Can recognize objects
  - Poor visual control for tasks like grasping
- Damage to ventral system
  - Cannot recognize objects
  - Can still manipulate them, grasping, etc.
- Much of the information in the dorsal system is not consciously accessible

Blindsight: vision without sight

The brain and vision

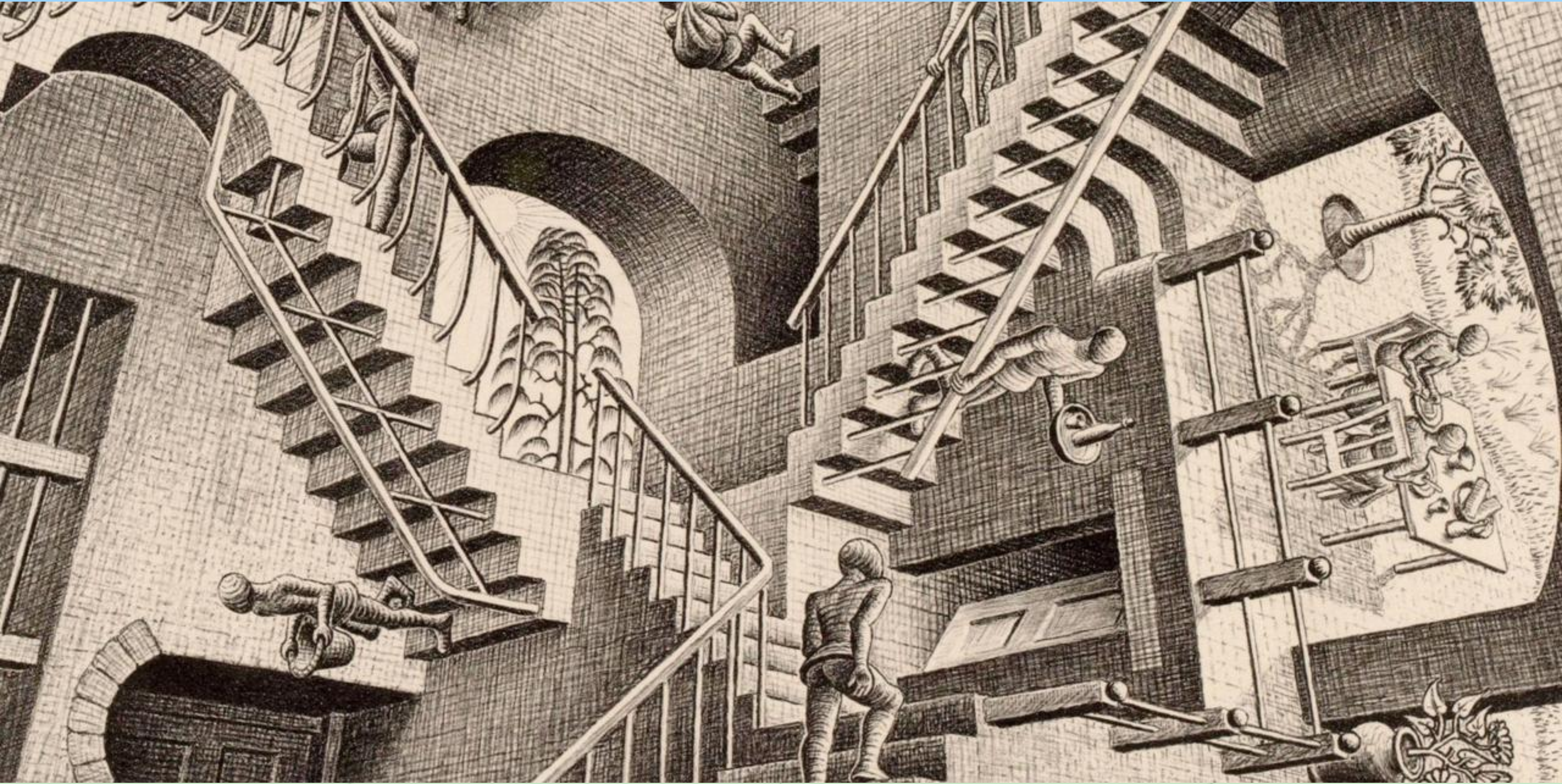
- Enormous processing power devoted to vision
- Visual cortex is largest “system” in the brain
  - 30% of the cerebral cortex
  - ⅔ of the electrical activity
- Lots of processing happening “subconsciously”



Case study: How the brain sees 3d

- One eye
  - Focus - how much your lens must change to make object clear
  - Blur - objects that are blurry are at different depth
  - Parallax - observer or object moves, gets multiple views
- Two eyes
  - Stereopsis - images from eyes are different
  - Convergence - where your eyes are pointing
- Brain
  - Kinetic depth - infer 3d shape of moving objects
  - Occlusion - objects in front are closer
  - Familiar objects - you know how big a car is…
  - Shading - 3d shape from light/shadow cues


NOSTRAND



We don’t really understand vision

- Visual cortex - highly studied part of the brain
- Only rough idea of what different components do
- New discoveries in vision all the time
  - Eye uses blinking to reset its rotational orientation
  - Visual cortex can make some “high-level” decisions

Is vision easy or hard for humans?

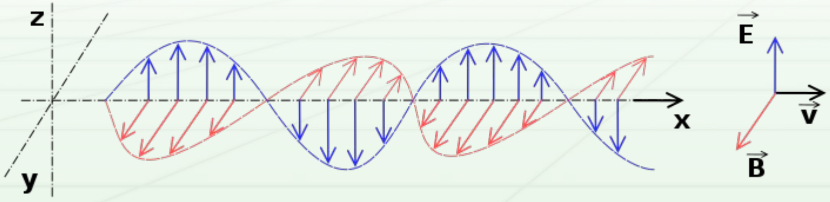
- What do you think now?

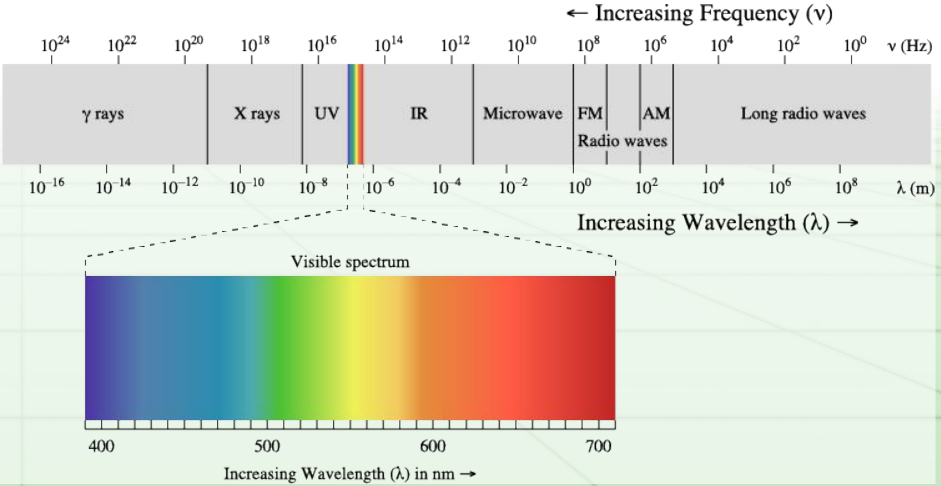
Is vision easy or hard for humans?

- What do you think now?

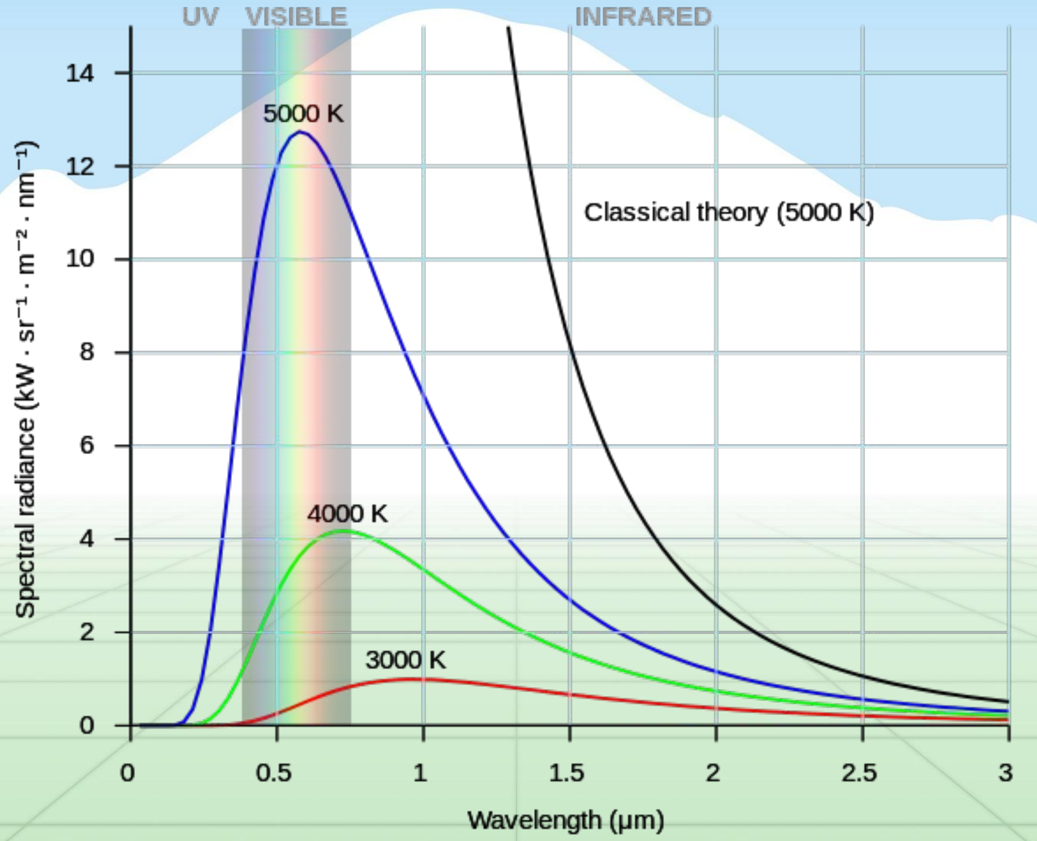
So what are we looking at anyway?

- Electromagnetic radiation
  - Wave? Particle?
- Photon - single particle of light
- Visible light: ~400-700 nanometers
- Why that range?



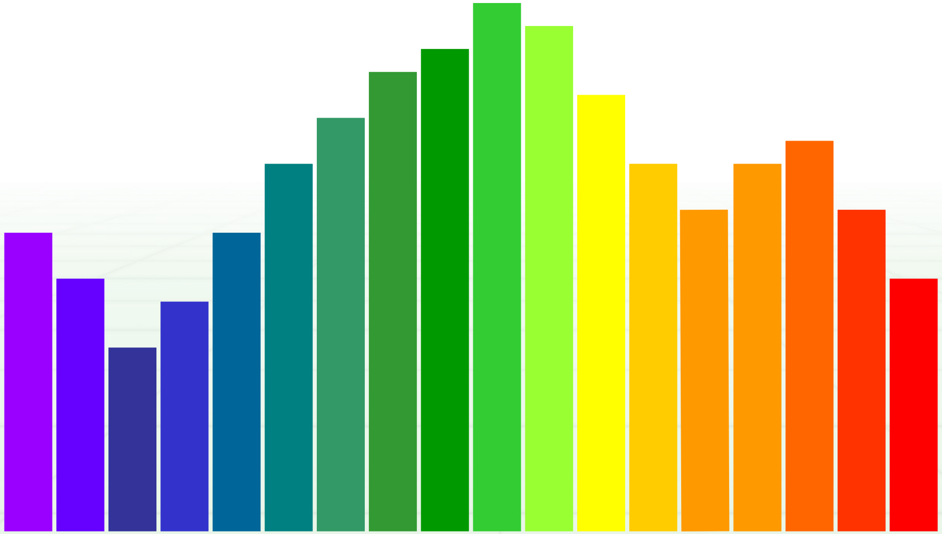


Visible light and the sun

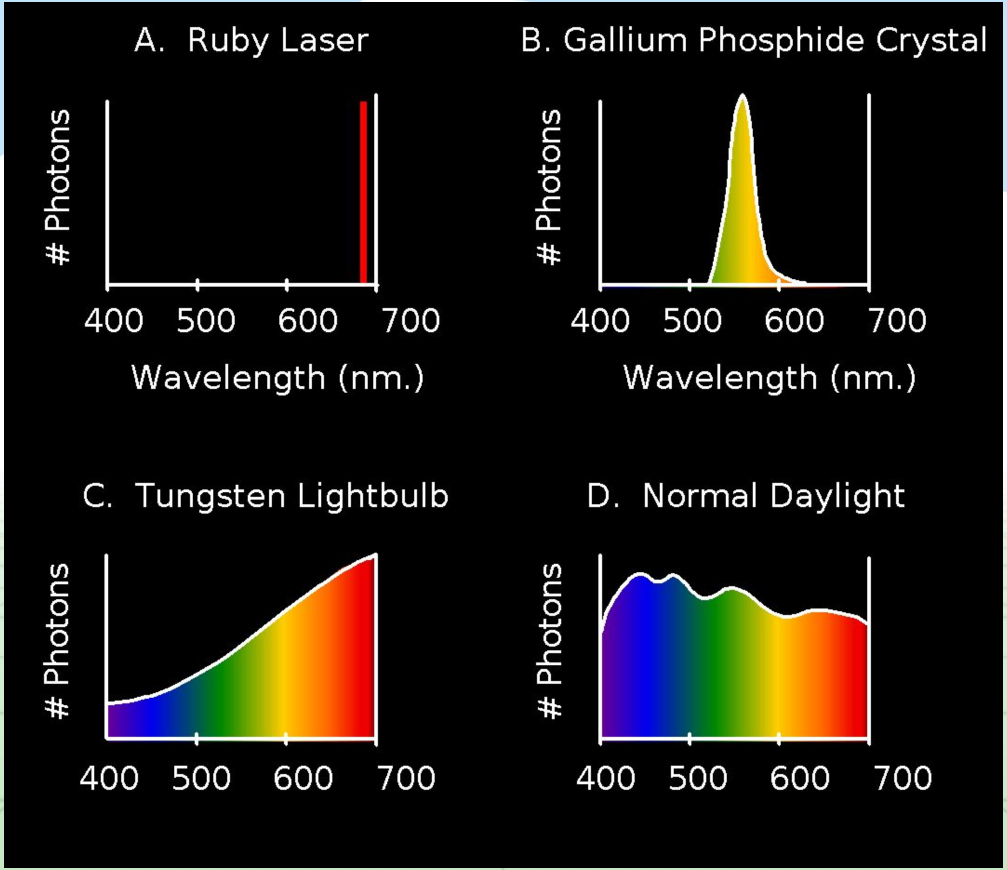


Light is a combination of waves

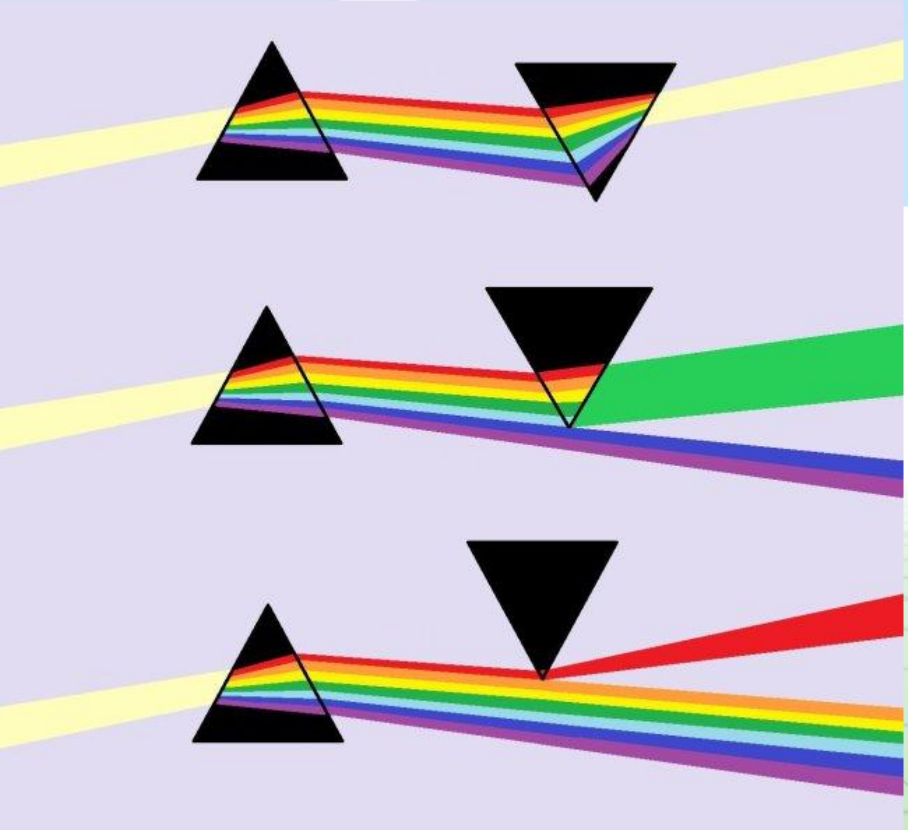
- Like a chord in music
- Can be described as a sum of its parts
- Relative strength of different frequencies



Sources of light are diverse!

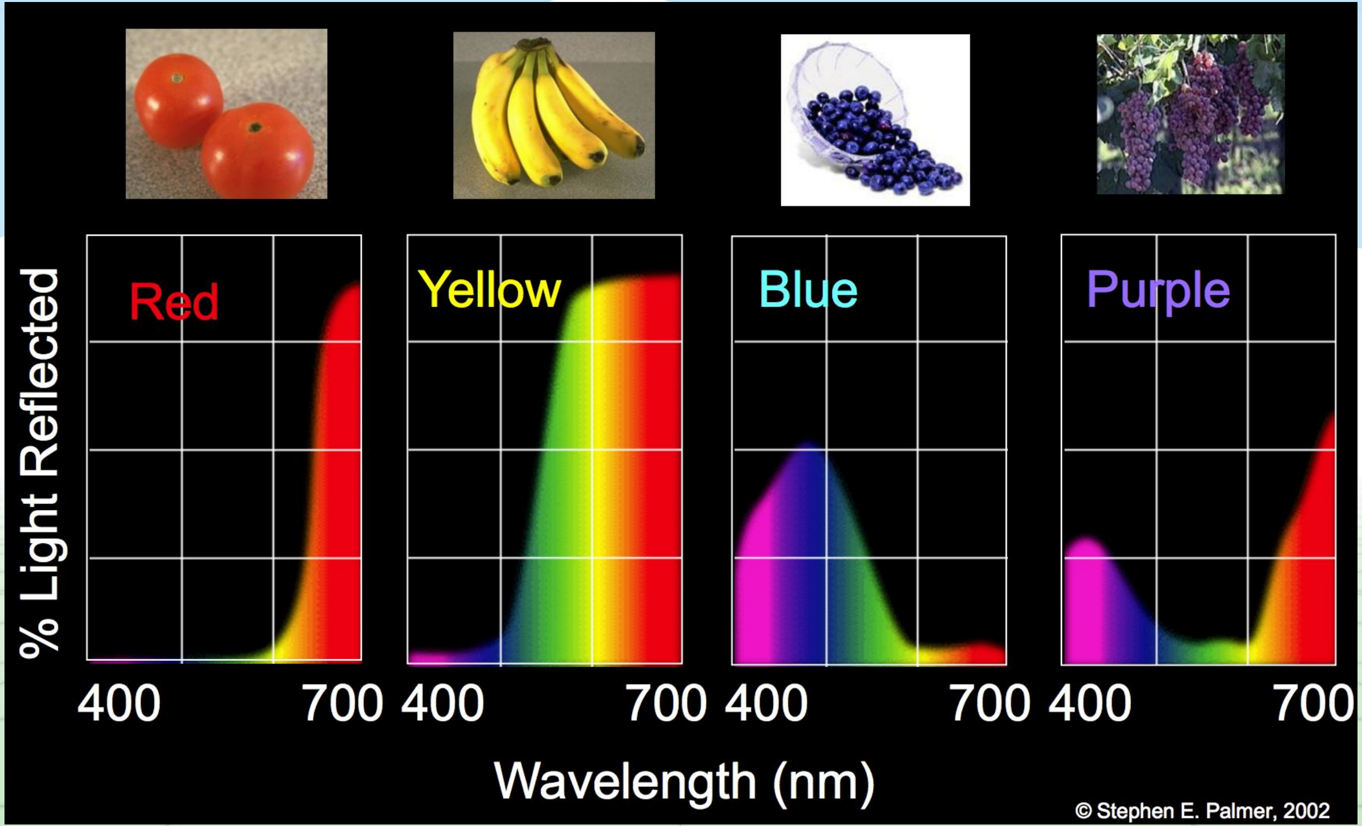


“White” light - all wavelengths



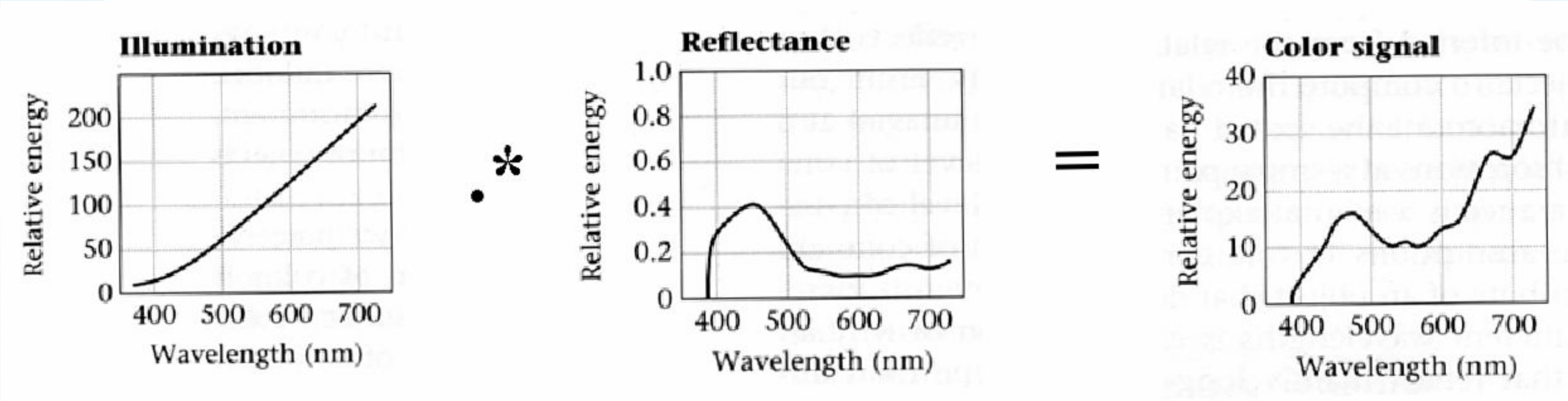
We know this thanks to Newton!

Objects reflect only some light

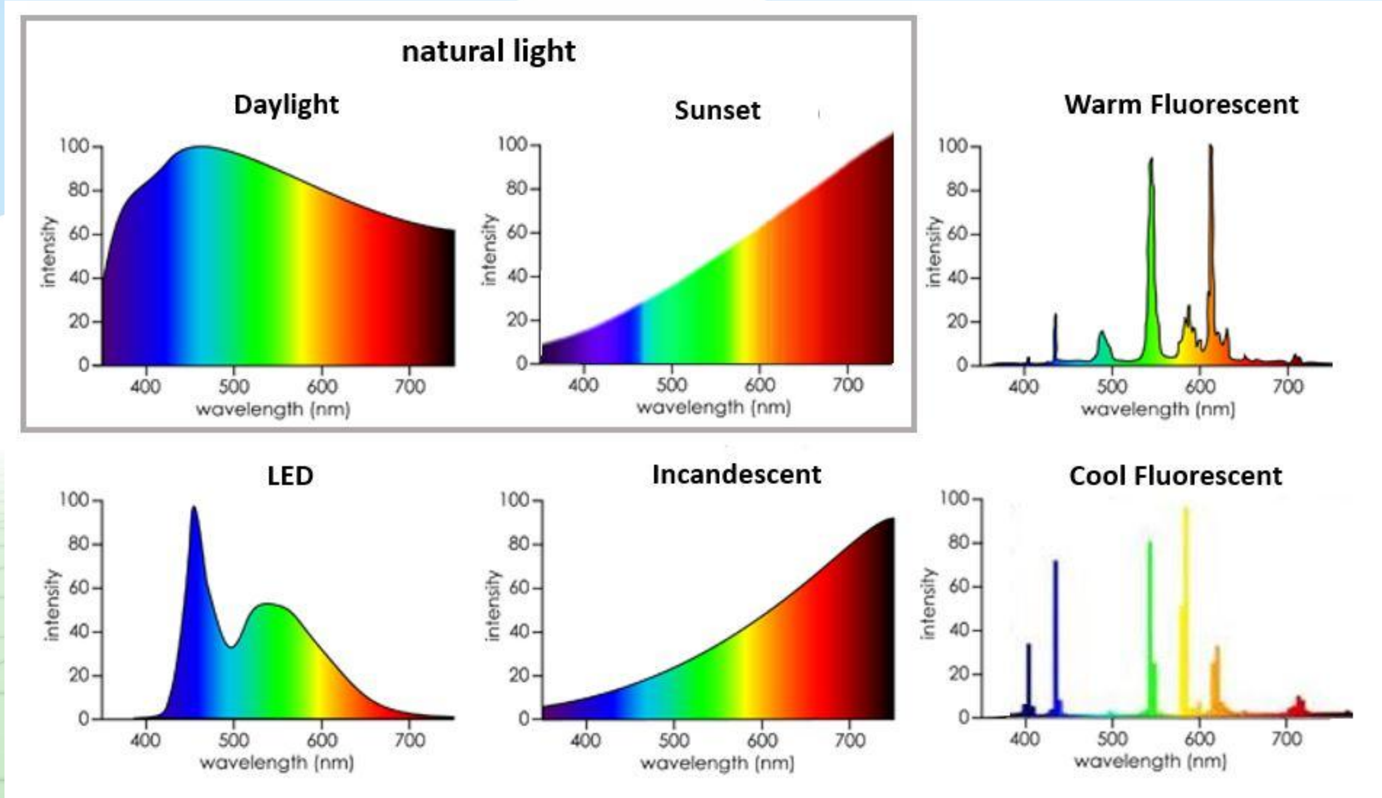


What color is the object?

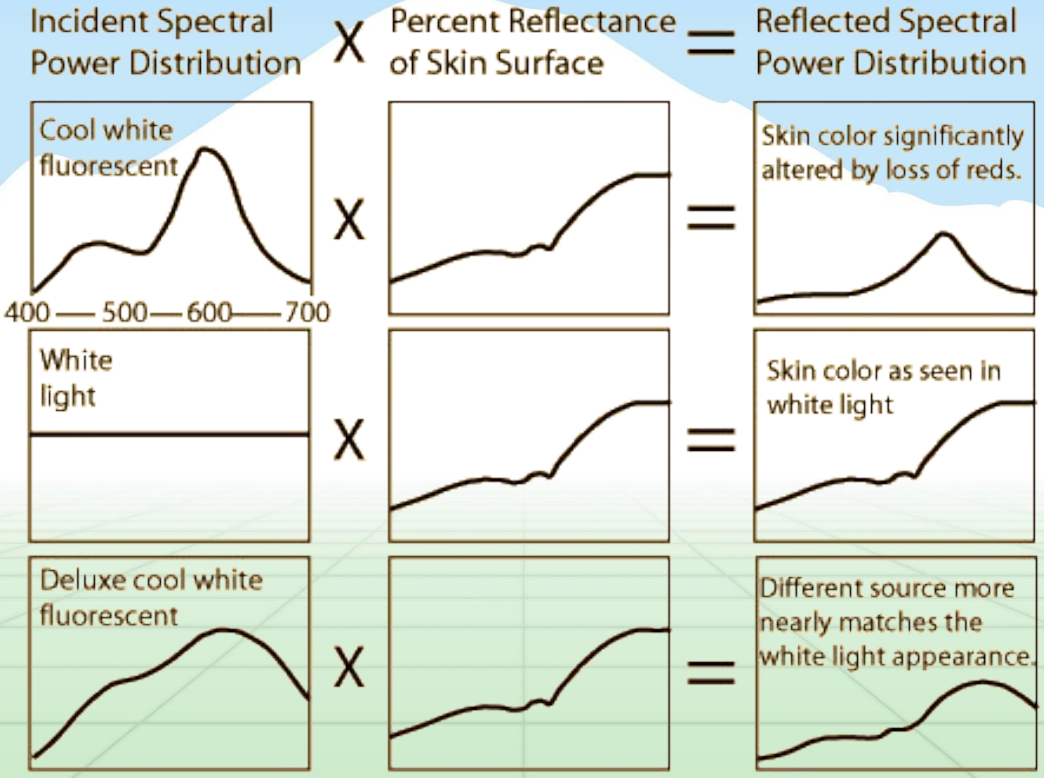
- The “color” of an object depends on both the incident light and the objects reflectance:



Different illumination matters!



Case study: makeup application

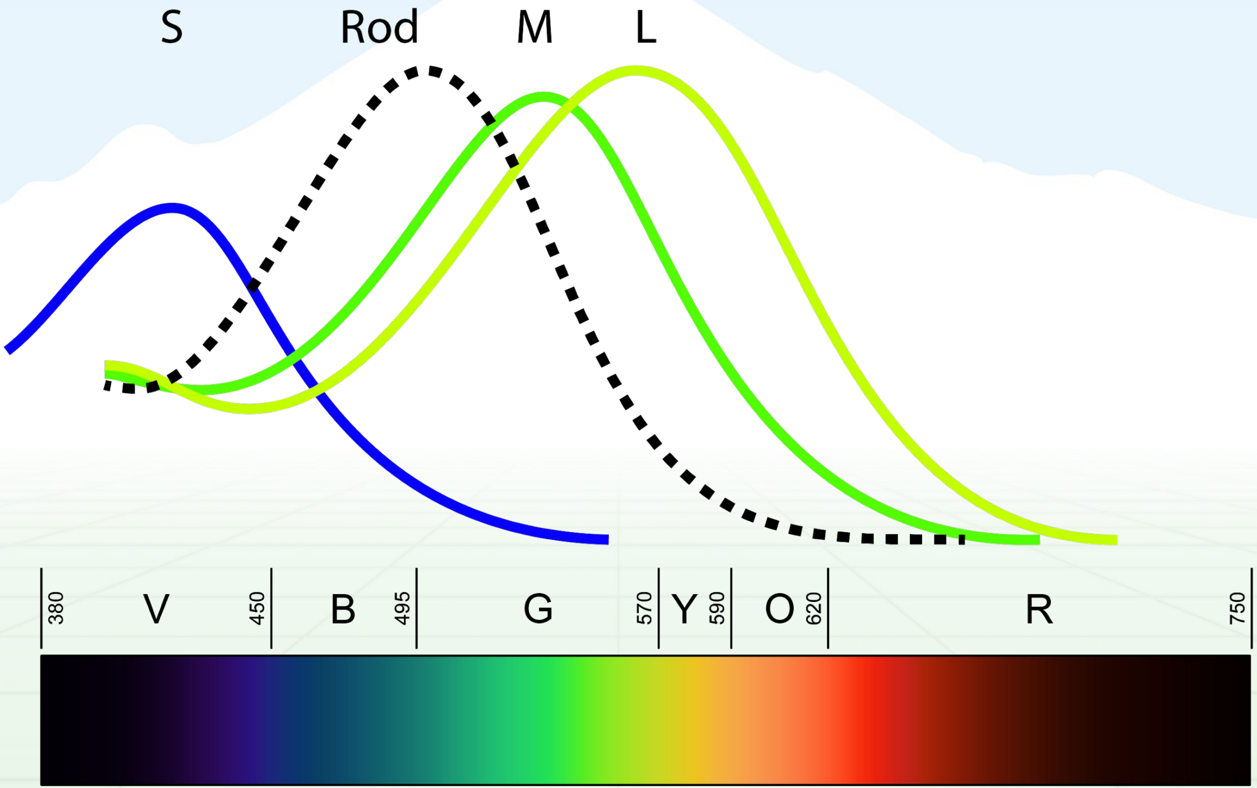


After Williamson and Cummins

Photoreceptors and light

- Each receptor has a responsiveness curve
- Receptors more responsive to some wavelengths, less responsive to others
- Rods: peak around 498 nm
- Cones: 3 kinds
  - Short: peak around 420 nm
  - Medium: peak around 530 nm
  - Long: peak around 560 nm

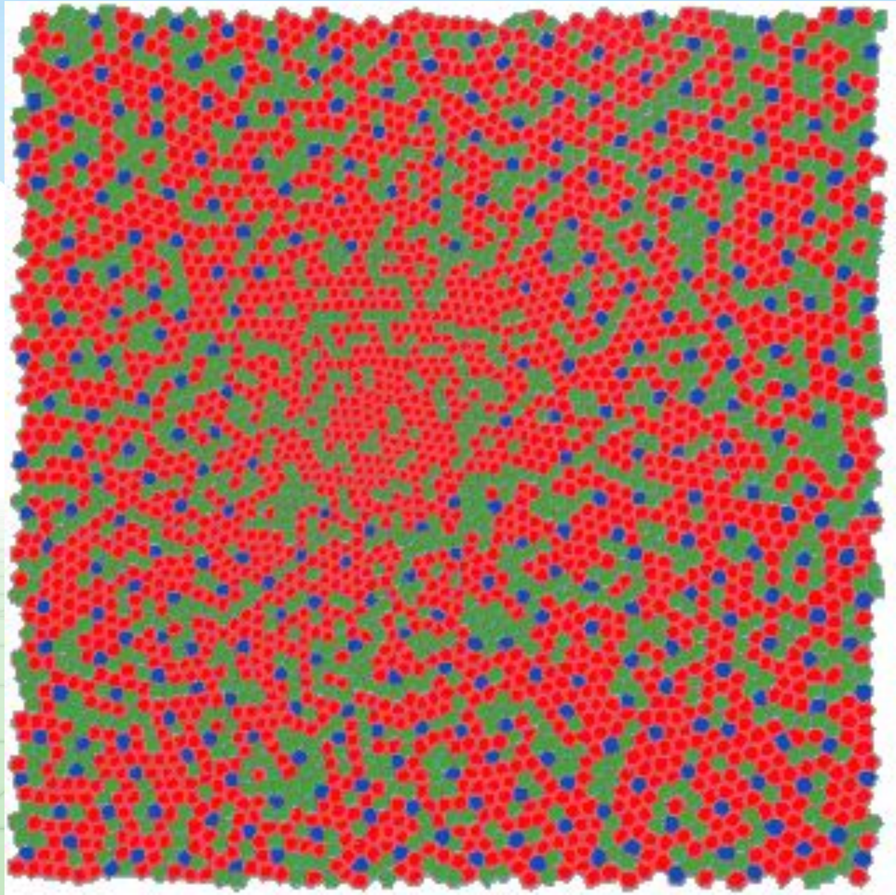
Photoreceptors and light



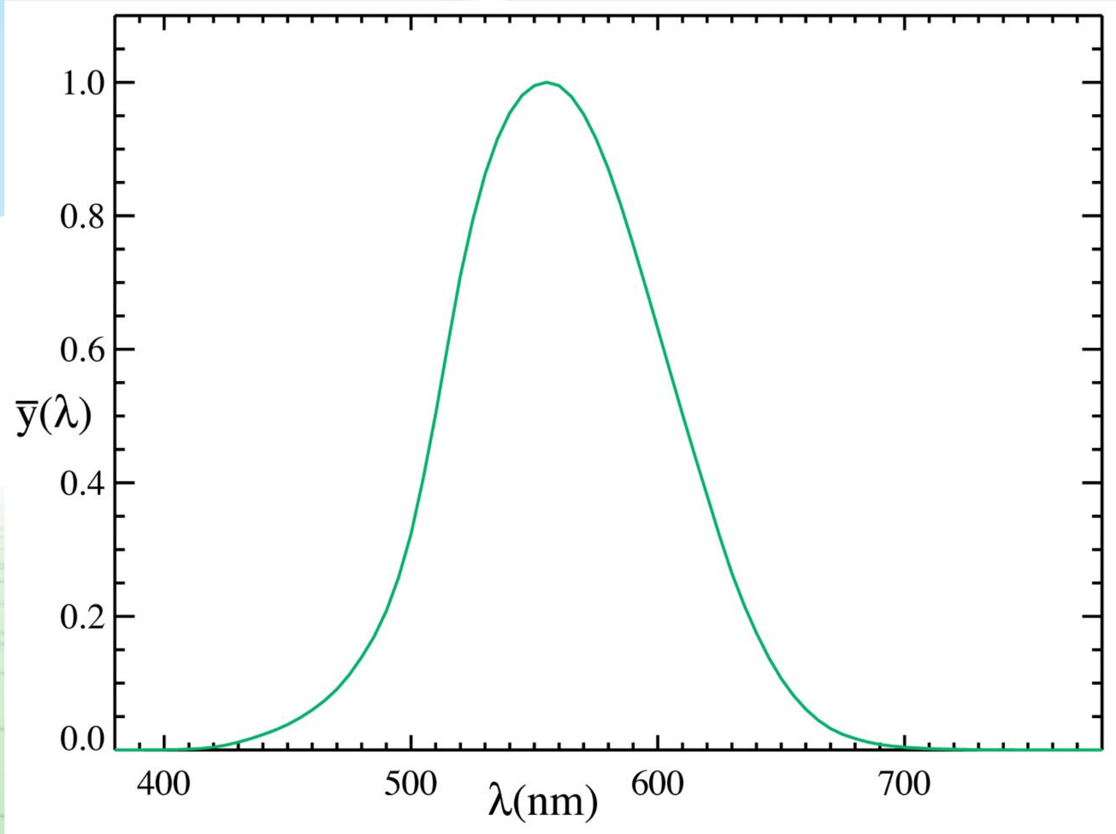
Cones and color

- Our perception of color comes from cones
- Different waveforms provoke different responses
- Each cone has essentially one “output”
- To calculate:
    - Multiply input waveform by response curve
    - Integrate area under the curve
- The “color” we see is the relative activation of the 3 kinds of cones

All cones are not equal



Different wavelengths are brighter



This is hard to read

This is easier to read

Many variations, what do they see?

State	Types of cone cells	Approx. number of colors perceived	Carriers
Monochromacy	1	100	marine mammals, owl monkey, Australian sea lion, achromat primates
Dichromacy	2	10,000	most terrestrial non-primate mammals, color blind primates
Trichromacy	3	1 million	most primates, especially great apes (such as humans), marsupials, some insects (such as honeybees)
Tetrachromacy	4	100 million	most reptiles, amphibians, birds and insects, rarely humans
Pentachromacy	5	10 billion	some insects (specific species of butterflies), some birds (pigeons for instance)

Why don’t rods contribute to color?

Discuss for 2 minutes with your neighbors

Color is our *perception* of waves

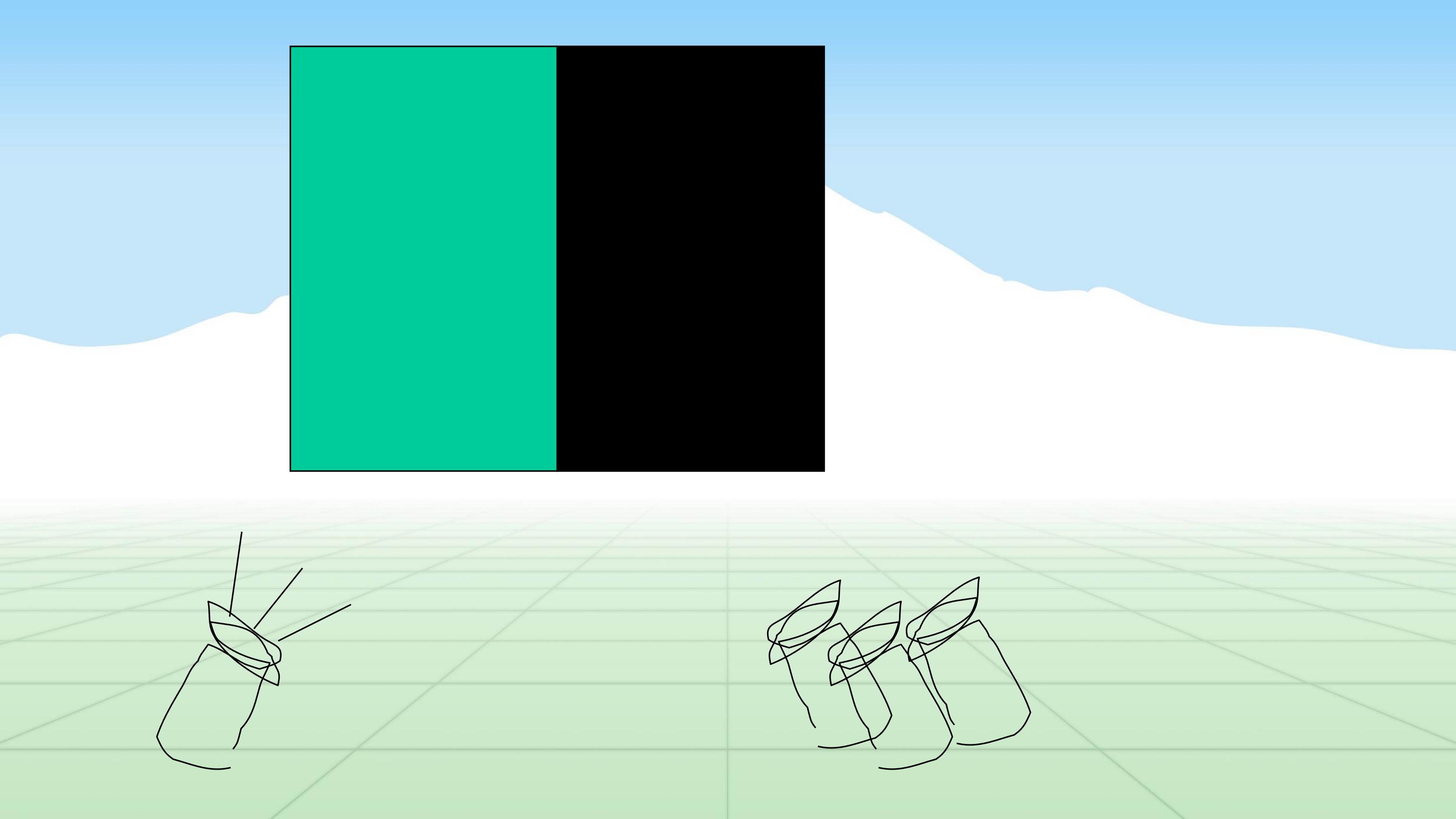
- Not the actual wave itself
- We only have 3 cones, have to represent color with just 3 outputs
- Many waveforms look the same: metamers
- Is this a problem??

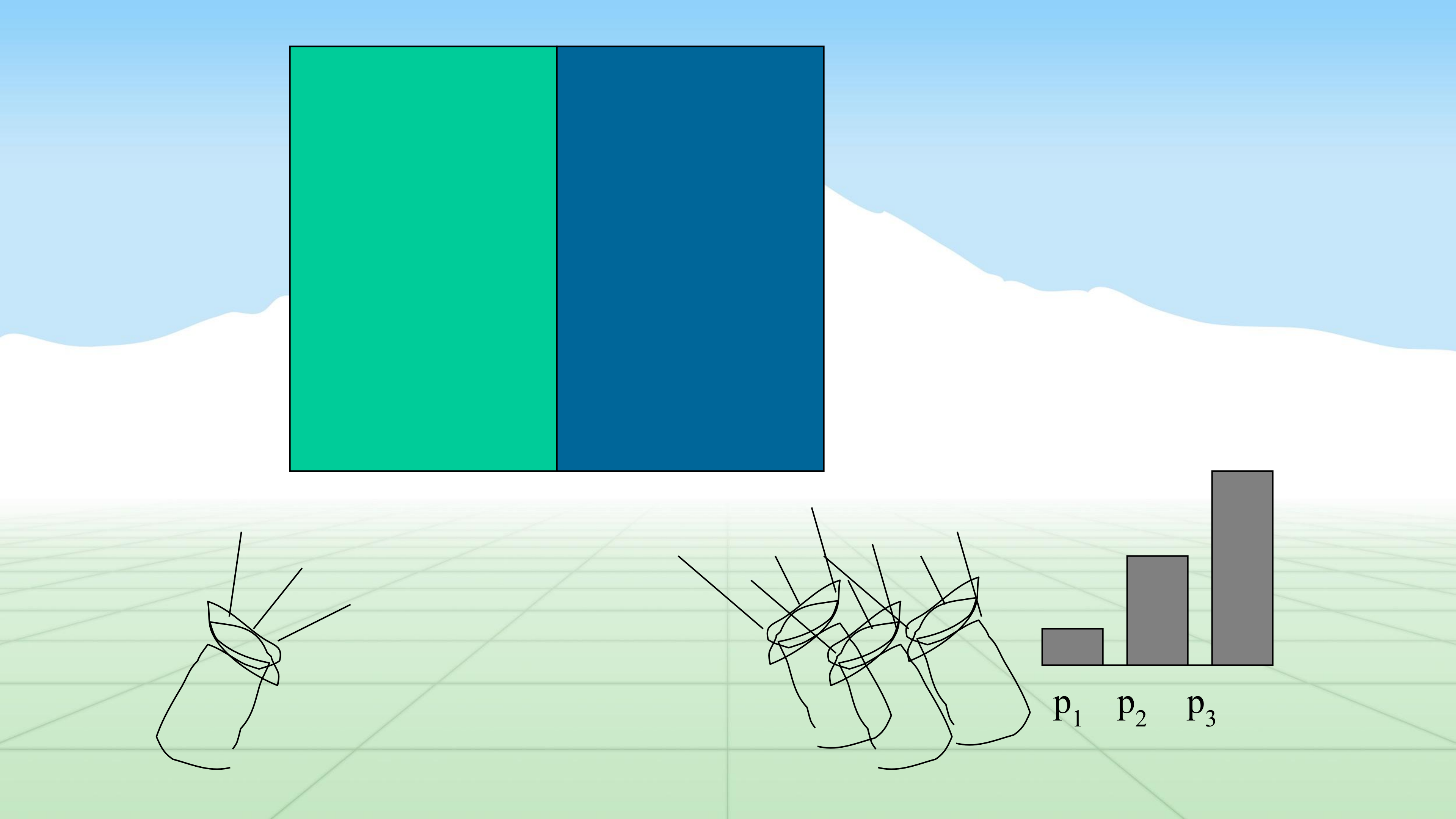
Metamers are great!

- Imagine we could perfectly perceive waveforms:
    - To duplicate a color you would have to duplicate the wave
    - TVs would be really hard to make
    - Color printers would require thousands of inks
- But not with the power of metamers!
    - Can recreate many colors just by selectively stimulating cones

CIE 1931 and Color Matching

- Late 1920s William Wright and John Guild experimented with colors! (and people)
- Subjects get controls to 3 “primary” lights
- Show them a light
- Subject adjusts their lights to match the given light

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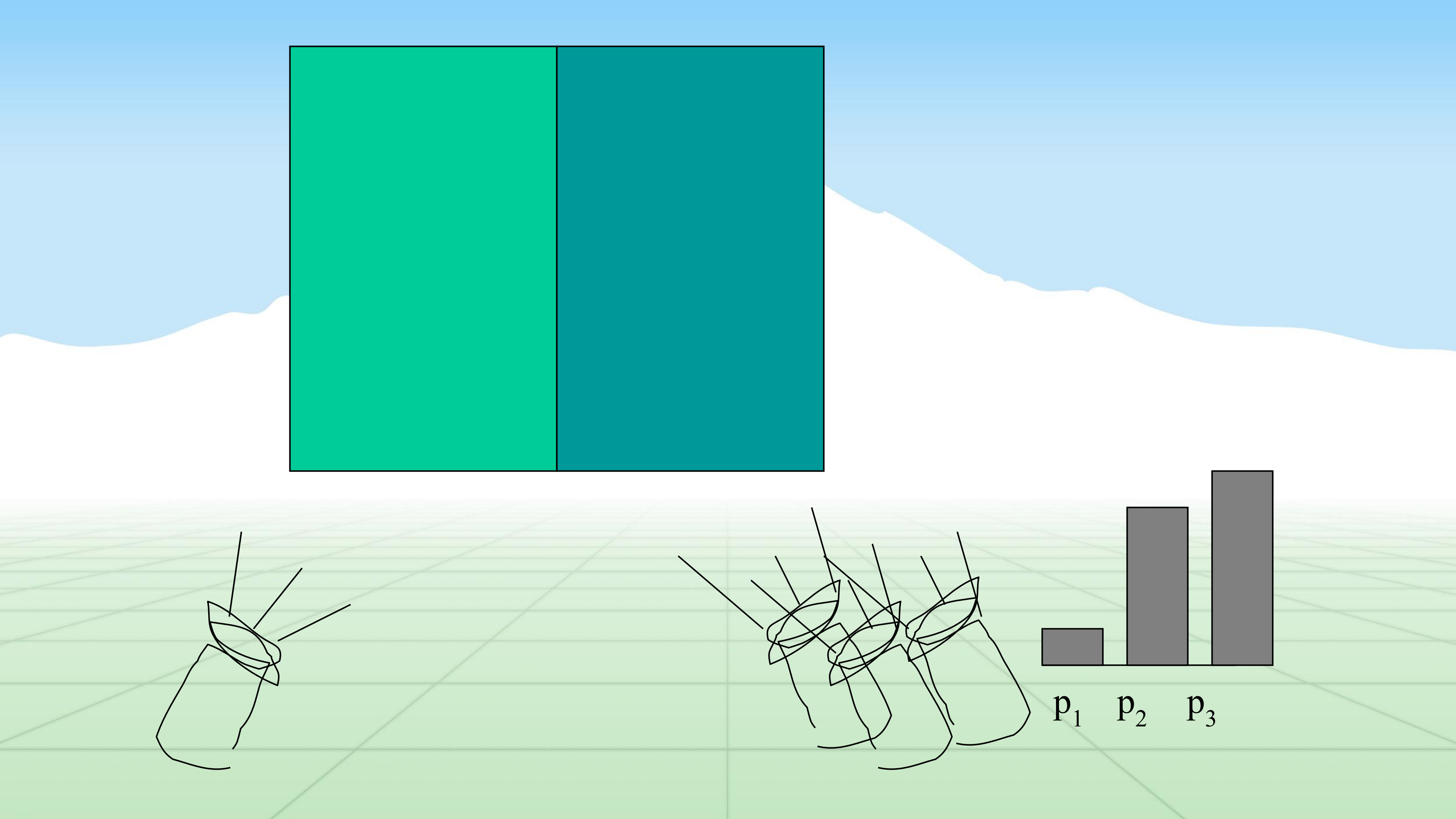
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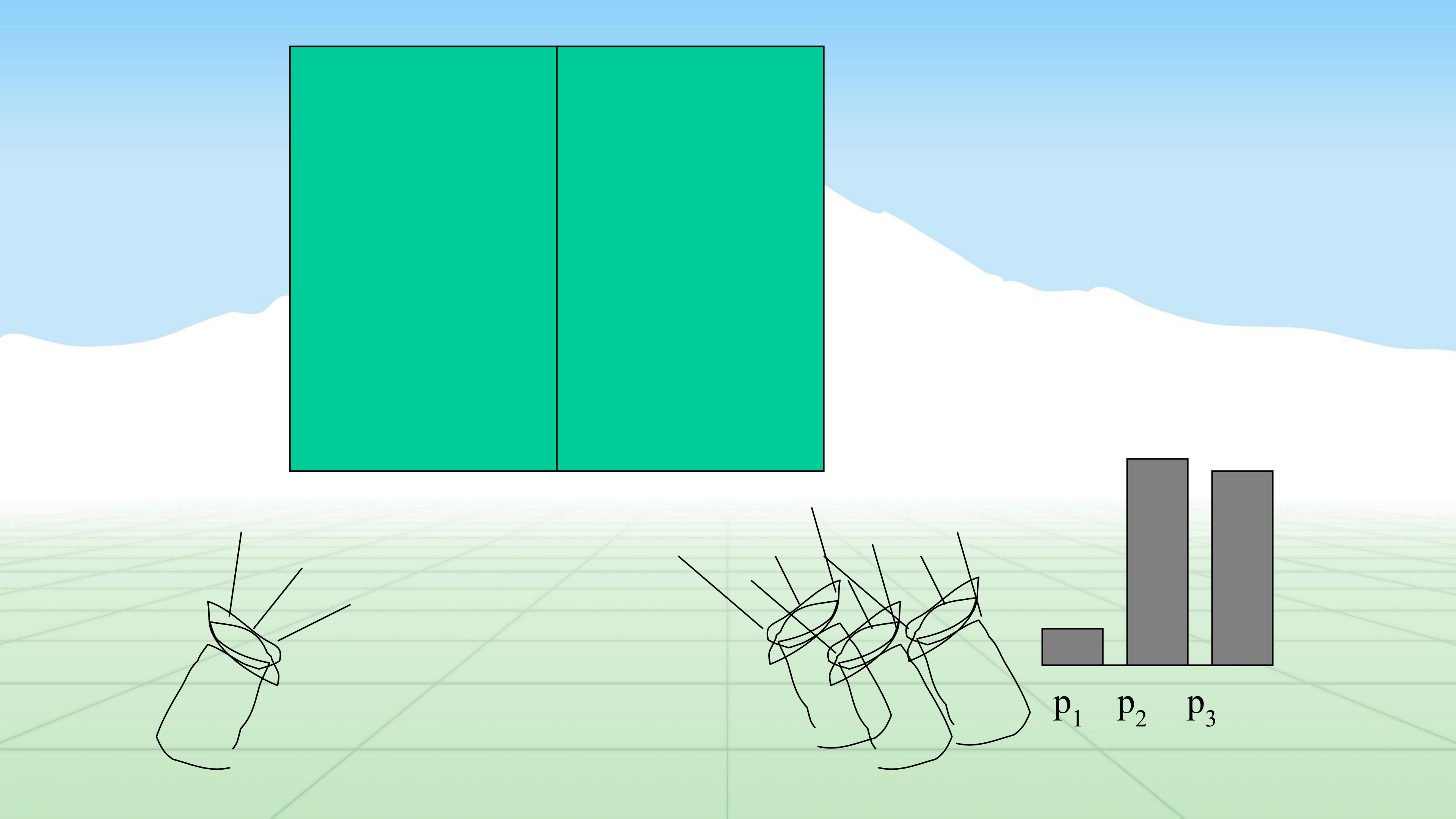
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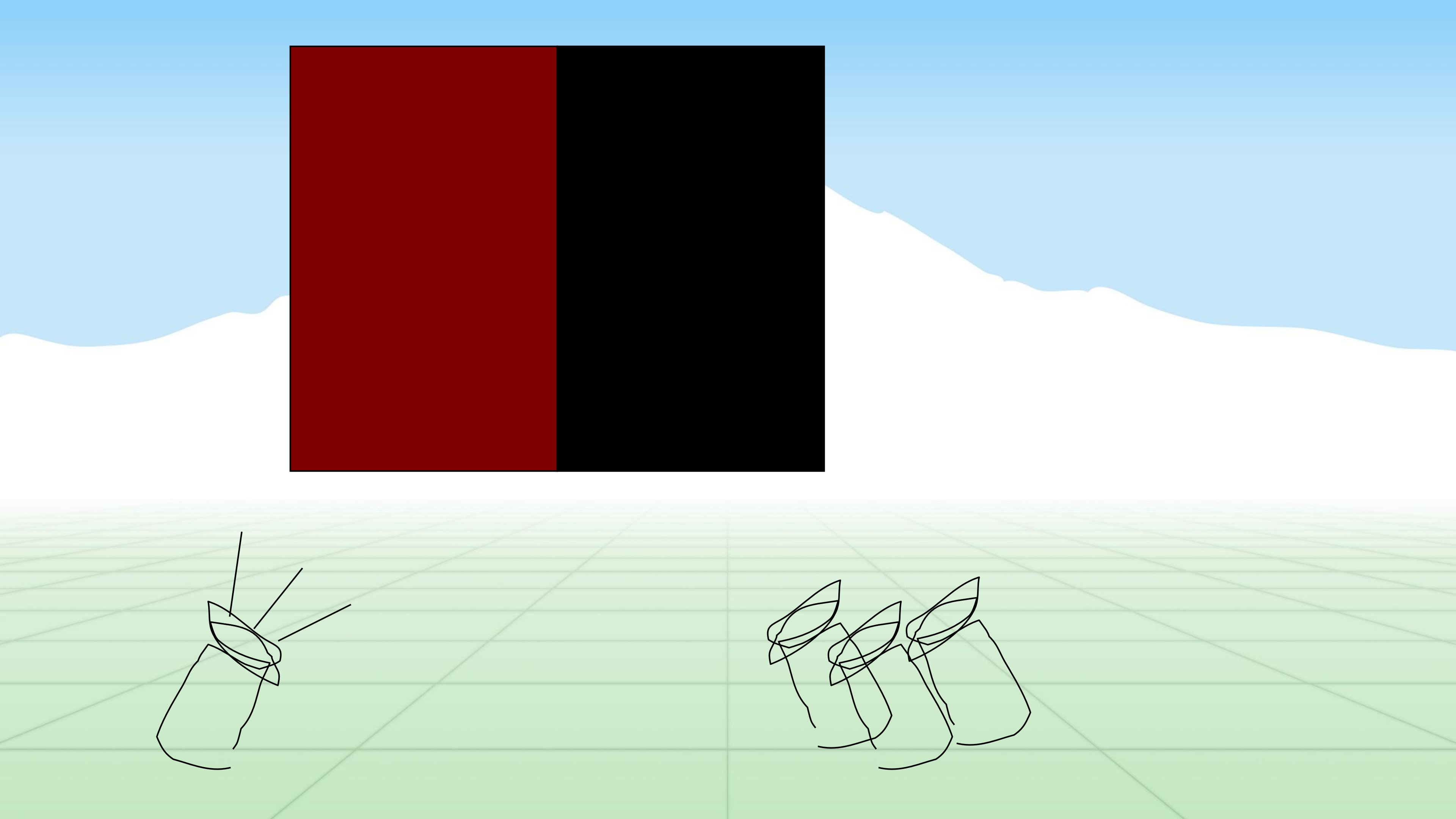

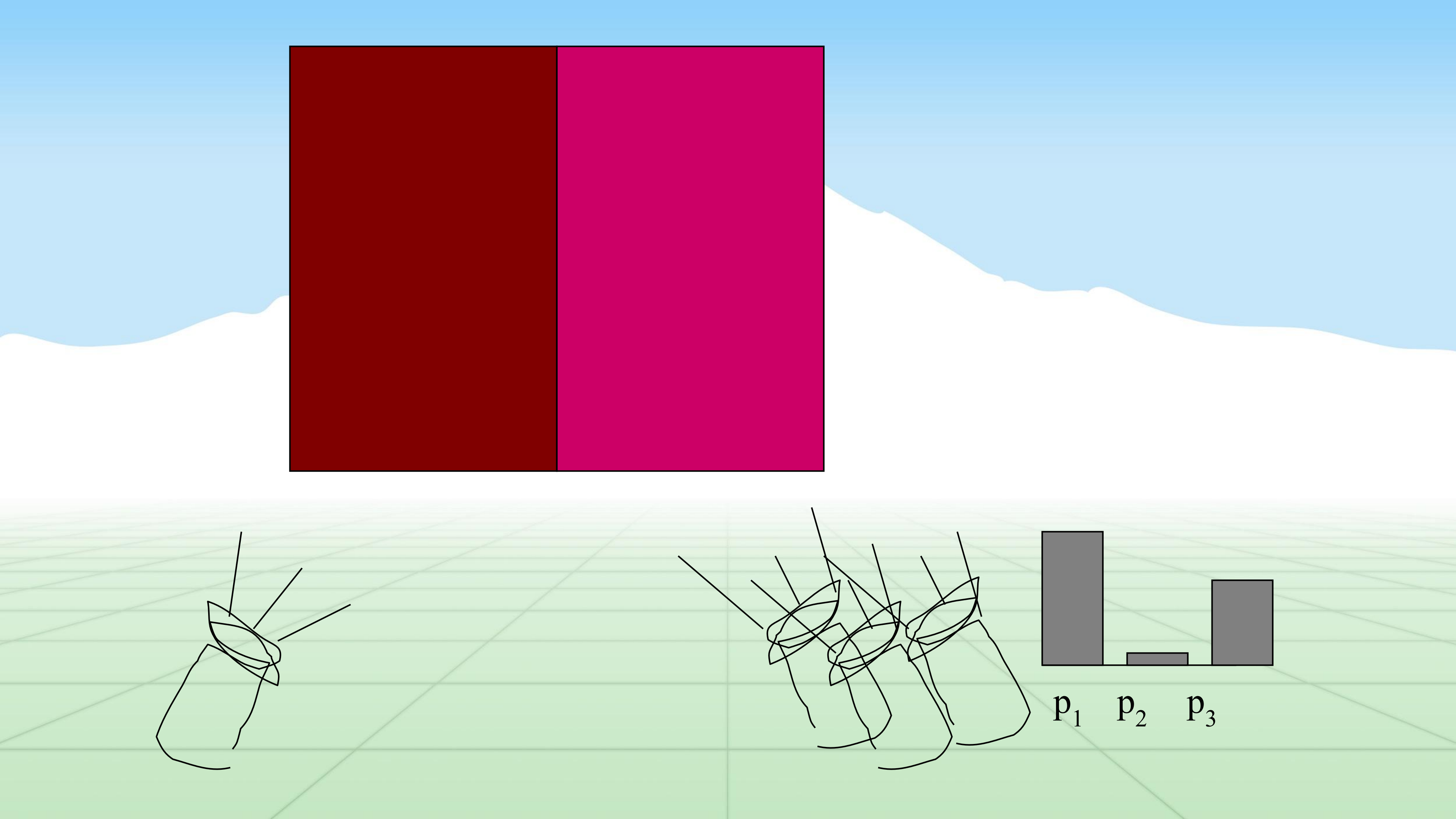
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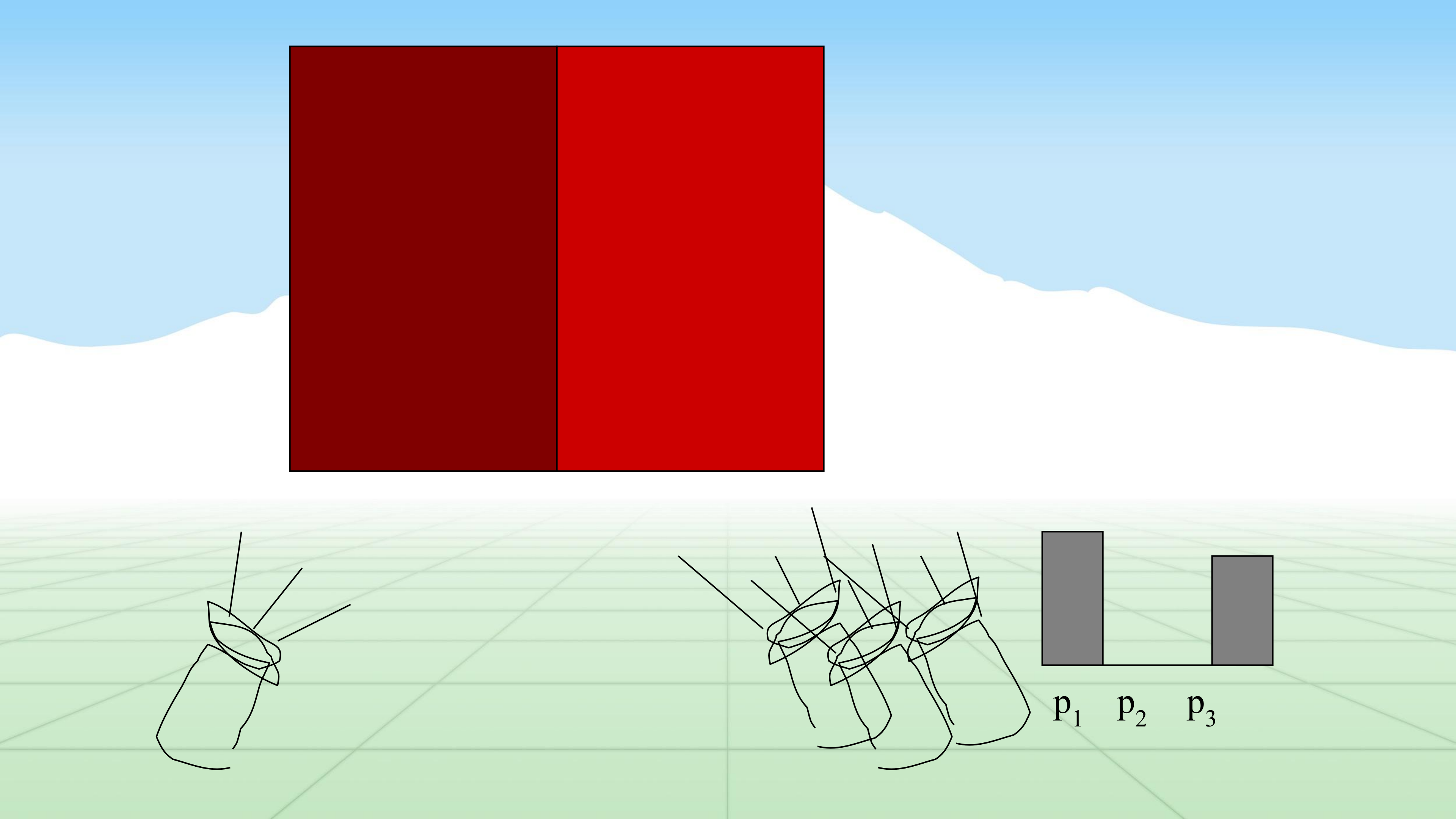

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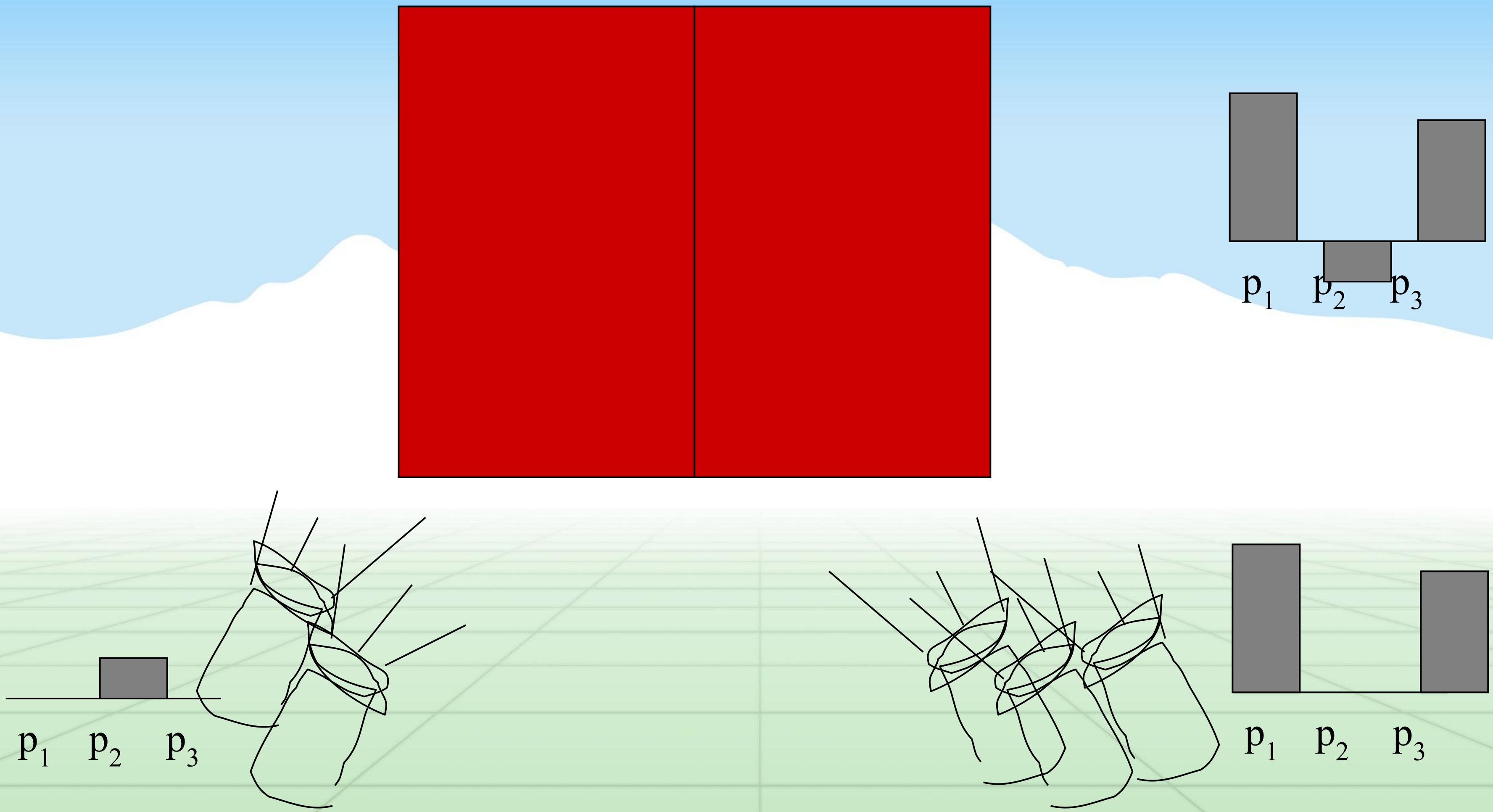

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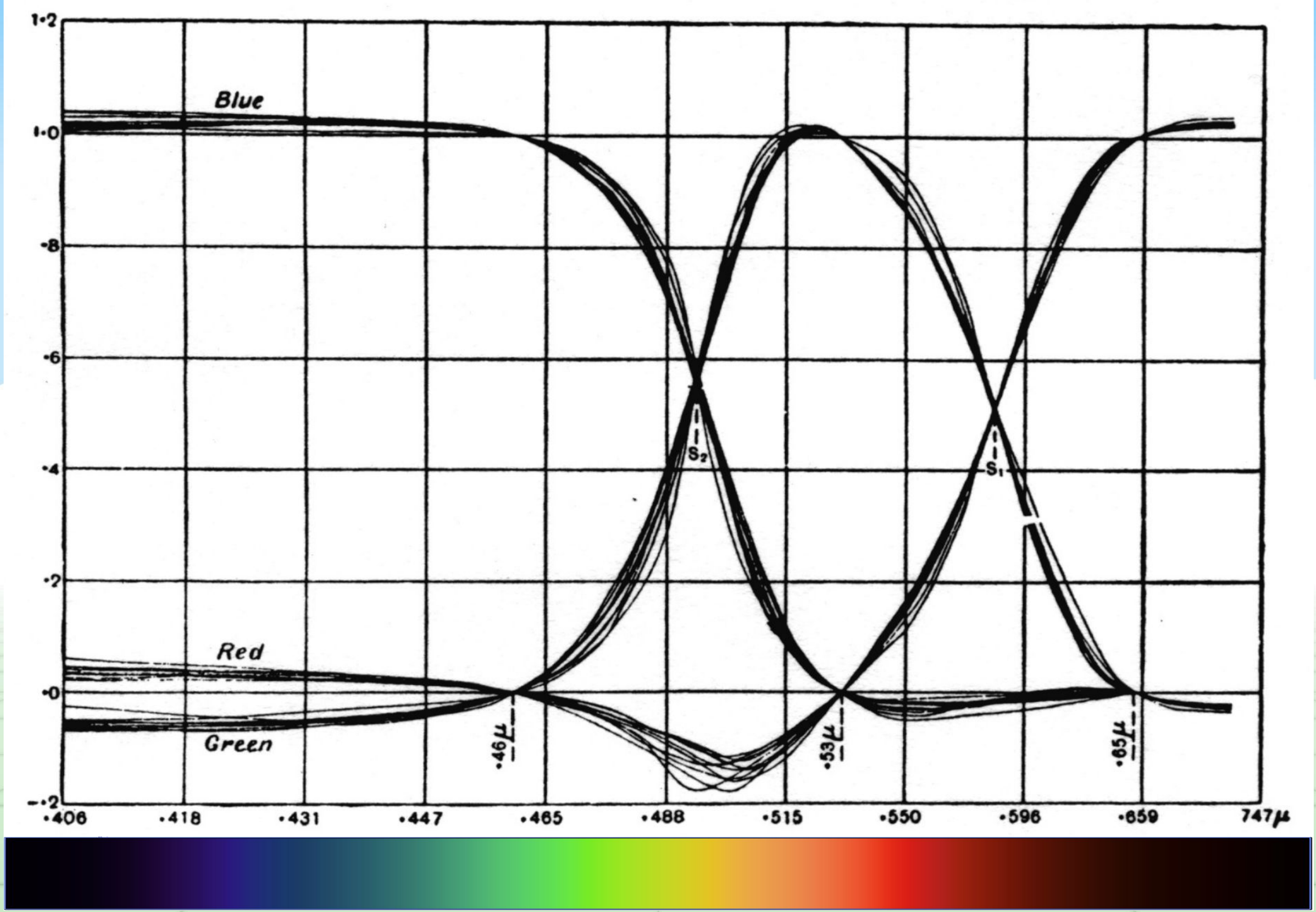

1·2
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Blue
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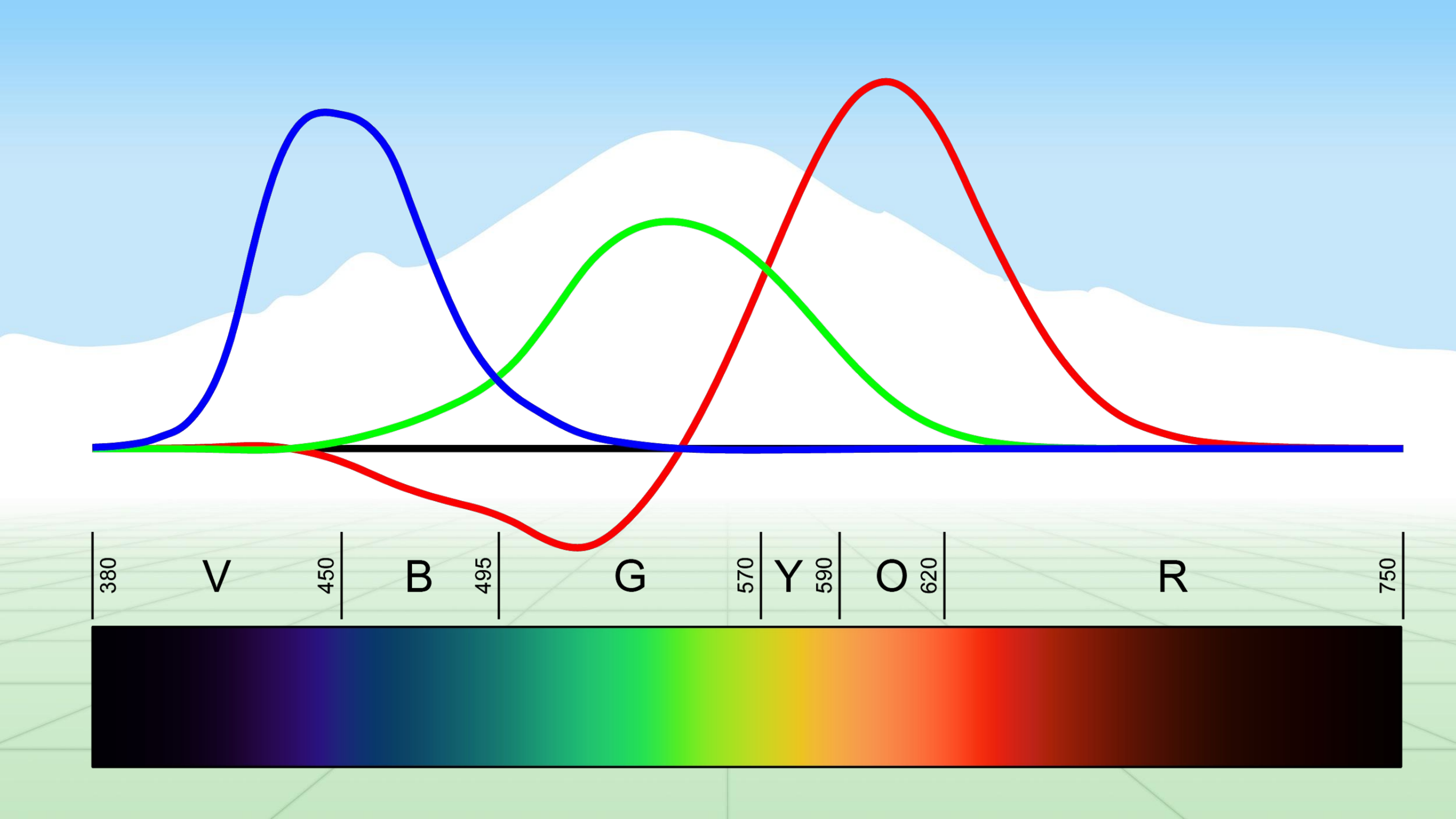
747μ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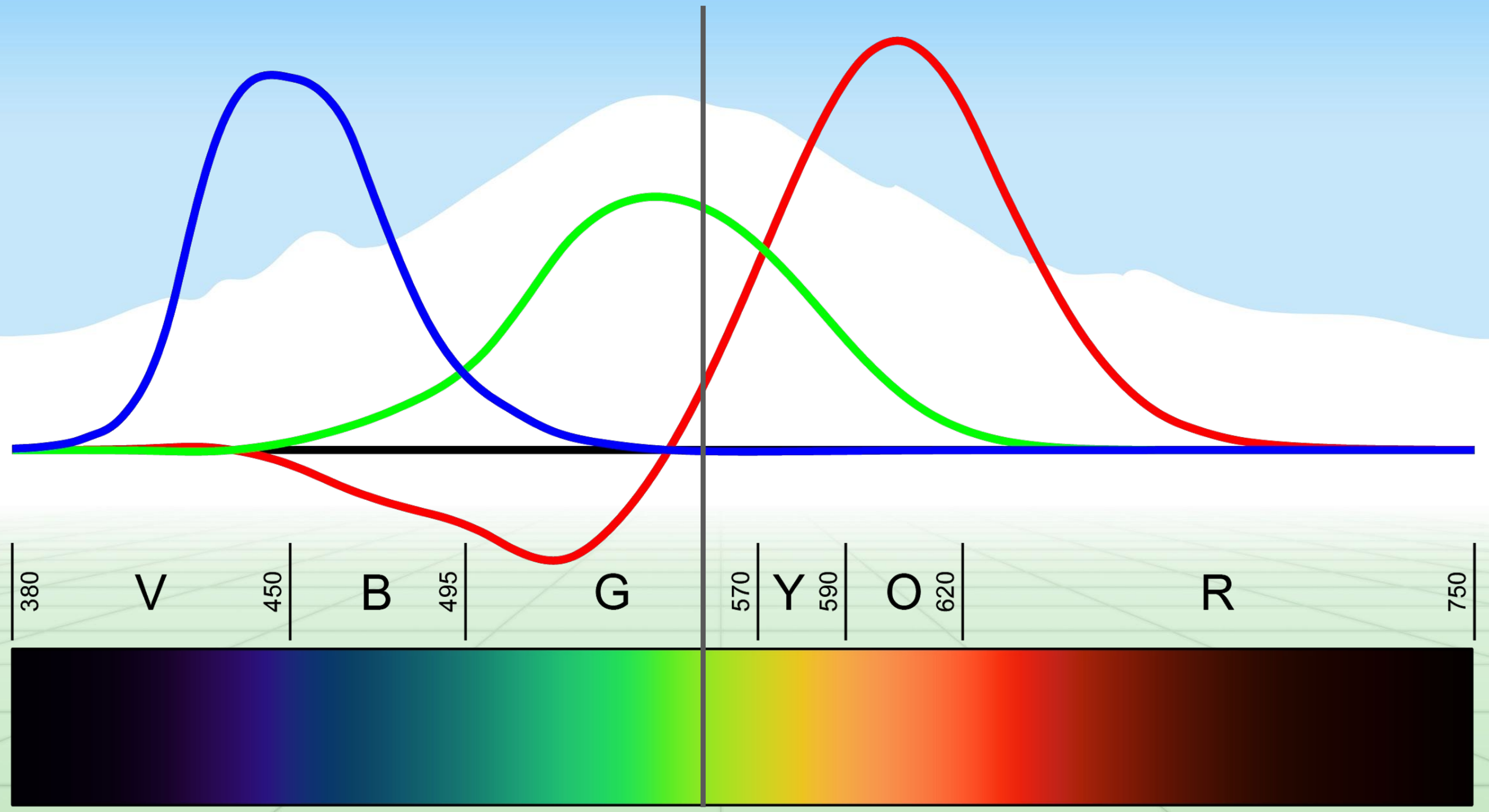
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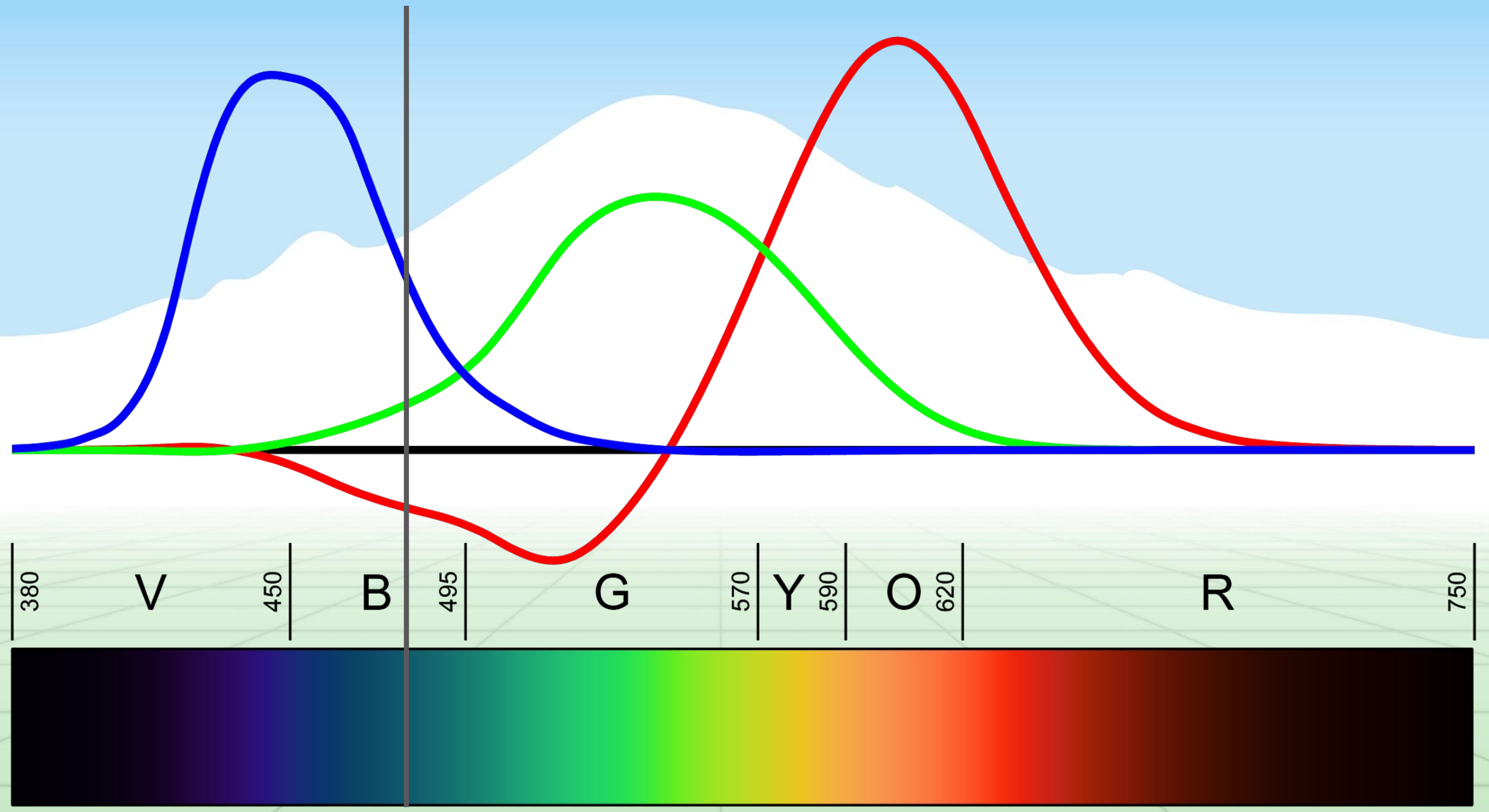
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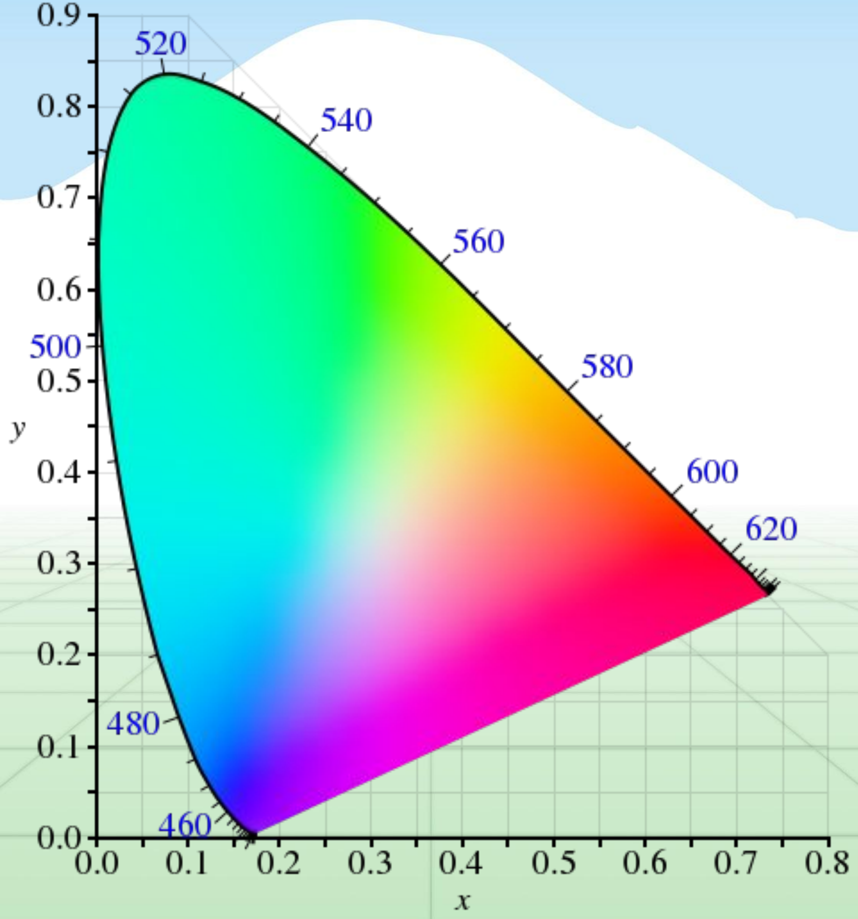
Results:

- Given 3 primaries people can match any color
- People select very similar distributions for a given color
- Colors seem to follow nice, linear rules: Grassman’s laws!
  - A=B+C => A+D=B+C+D
  - A=B+C => nA=nB+nC
  - A=B+C and D=B+C => A=D
- Light is combinations of individual wavelengths
  - If we can match any wavelength we can match any light

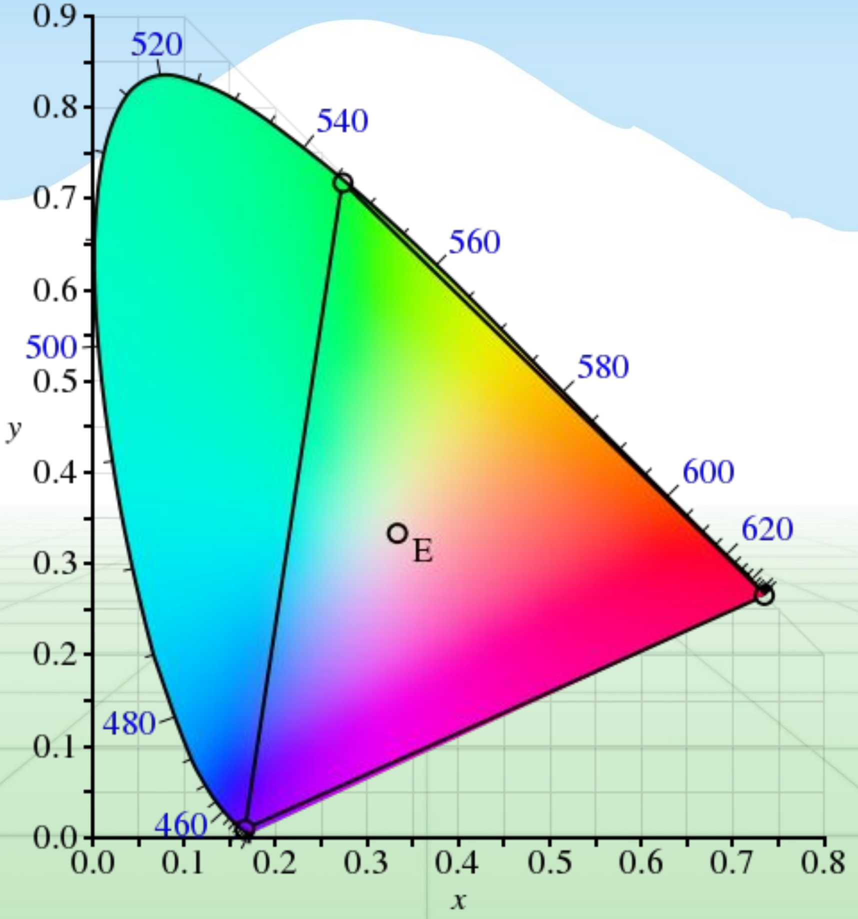
Now we can make a map of color



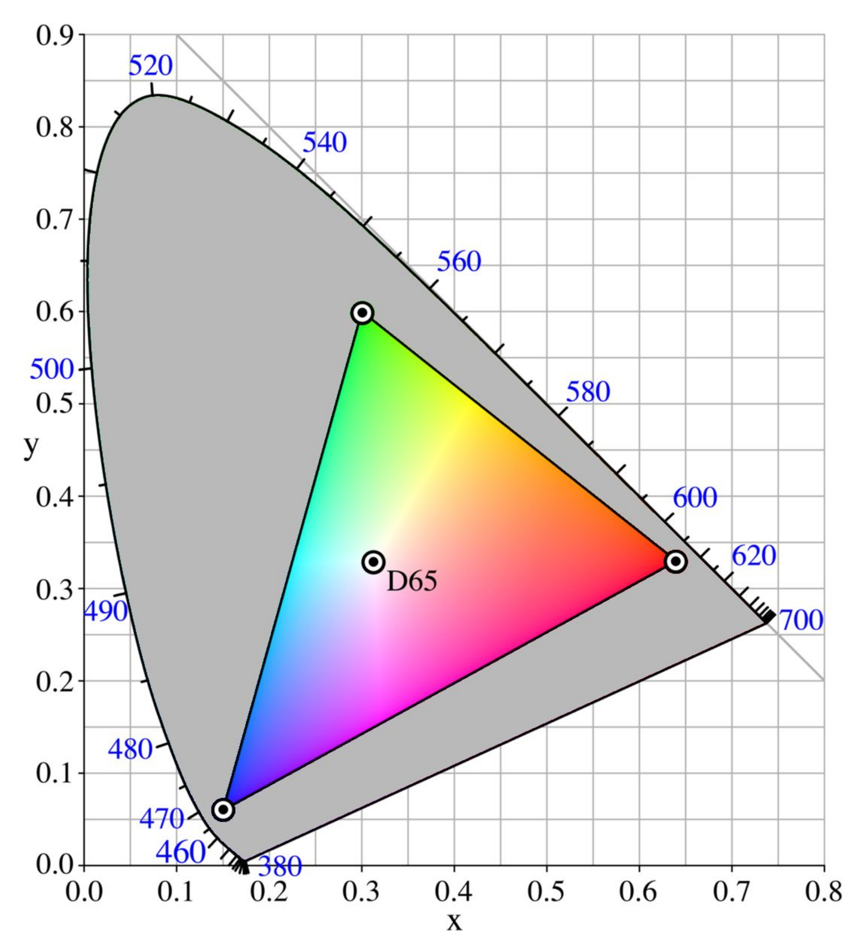
Linear colorspace

- Pick some primaries
- Can mix those primaries to match any color inside the triangle

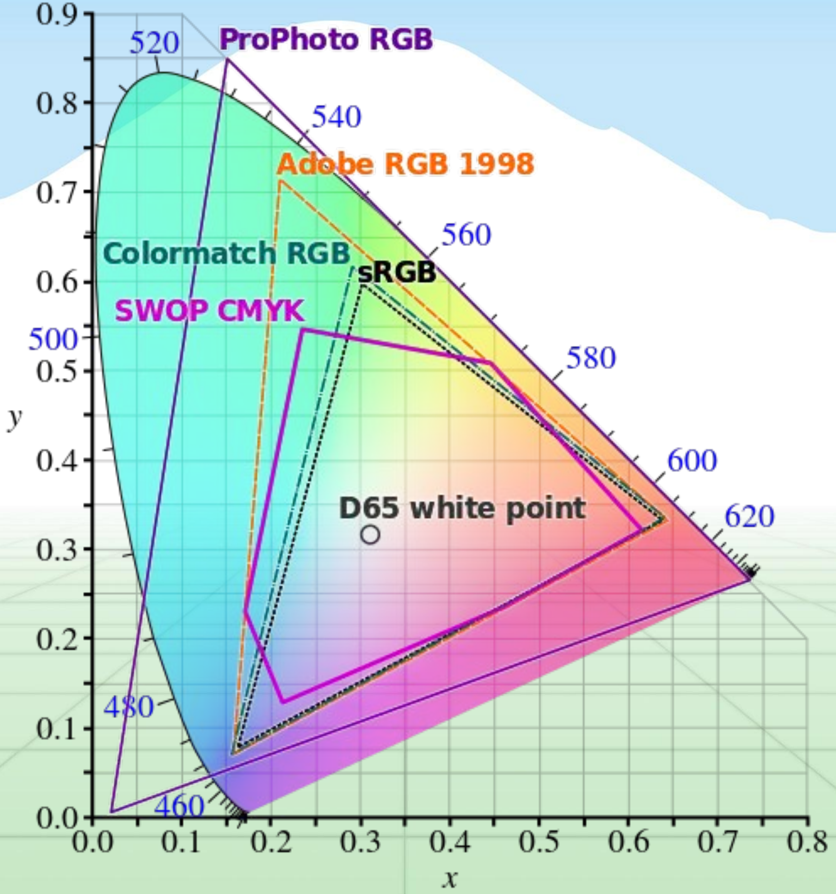
“Theoretical” CIE RGB primaries



Practical sRGB primaries, MSFT 1996



MANY different colorspaces

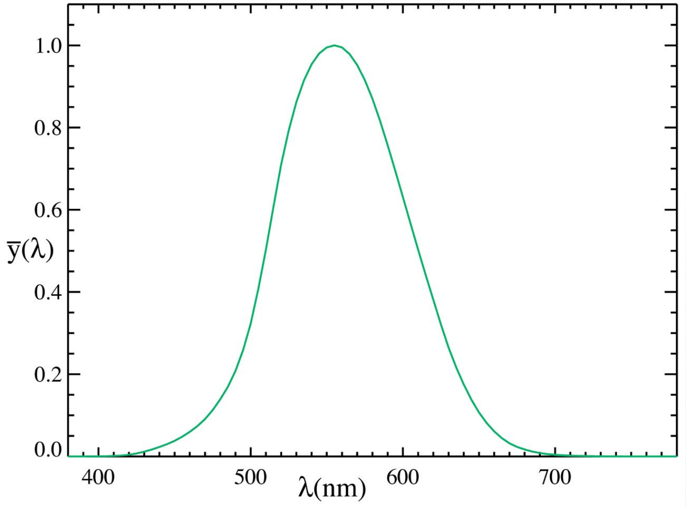


What does this mean for computers?

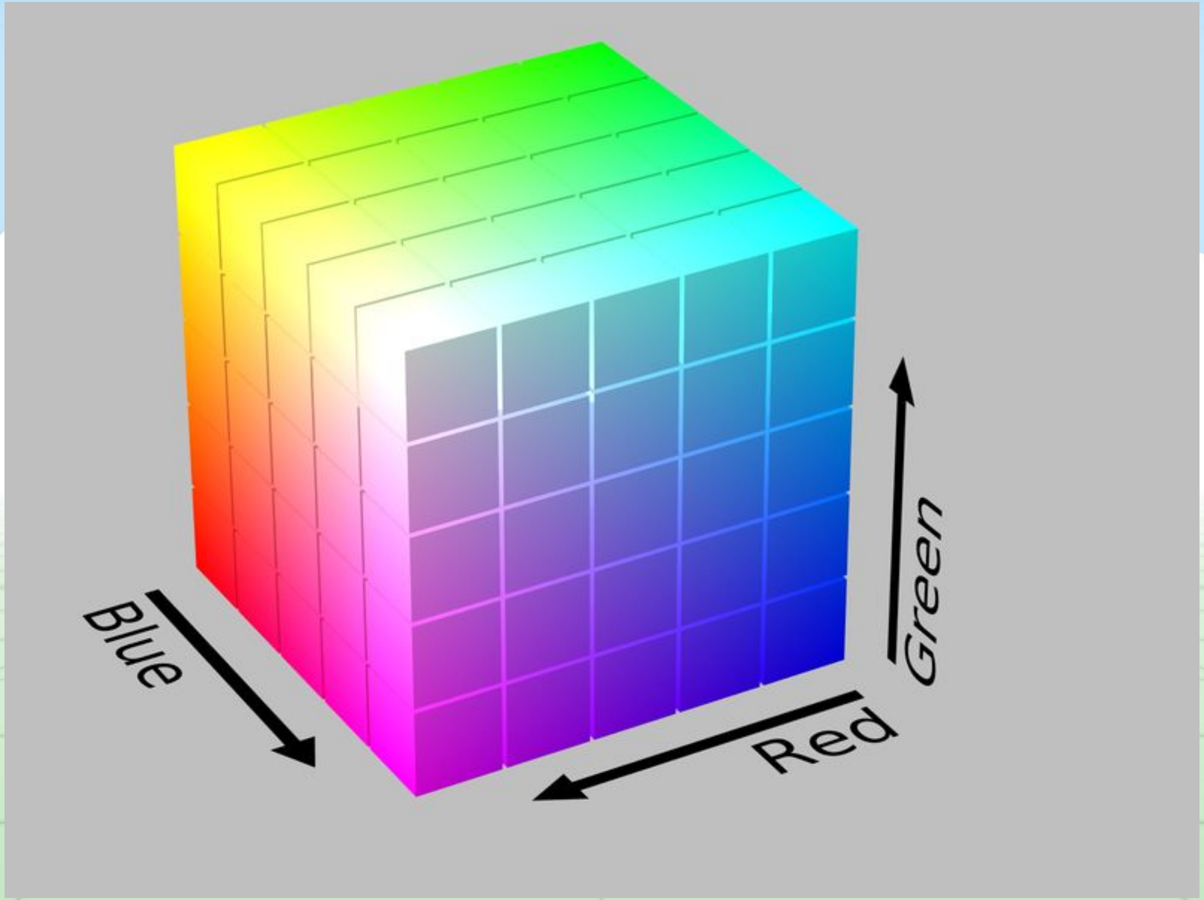
- We represent images as grids of pixels
- Each pixel has a color, 3 components: RGB
- Not every color can be represented in RGB!
  - Have to go out in the real world sometimes
- RGB is made to trick humans, not be accurate
- sRGB is not actually linear, gamma compressed
  - Humans see differences between dark tones more than bright
  - Compress light tones, expand dark tones, more efficient
- Can represent color with 3 numbers
  - #ff00ff; (1.0, 0.0, 1.0); 255,0,255; etc....

Grayscale - making color images not

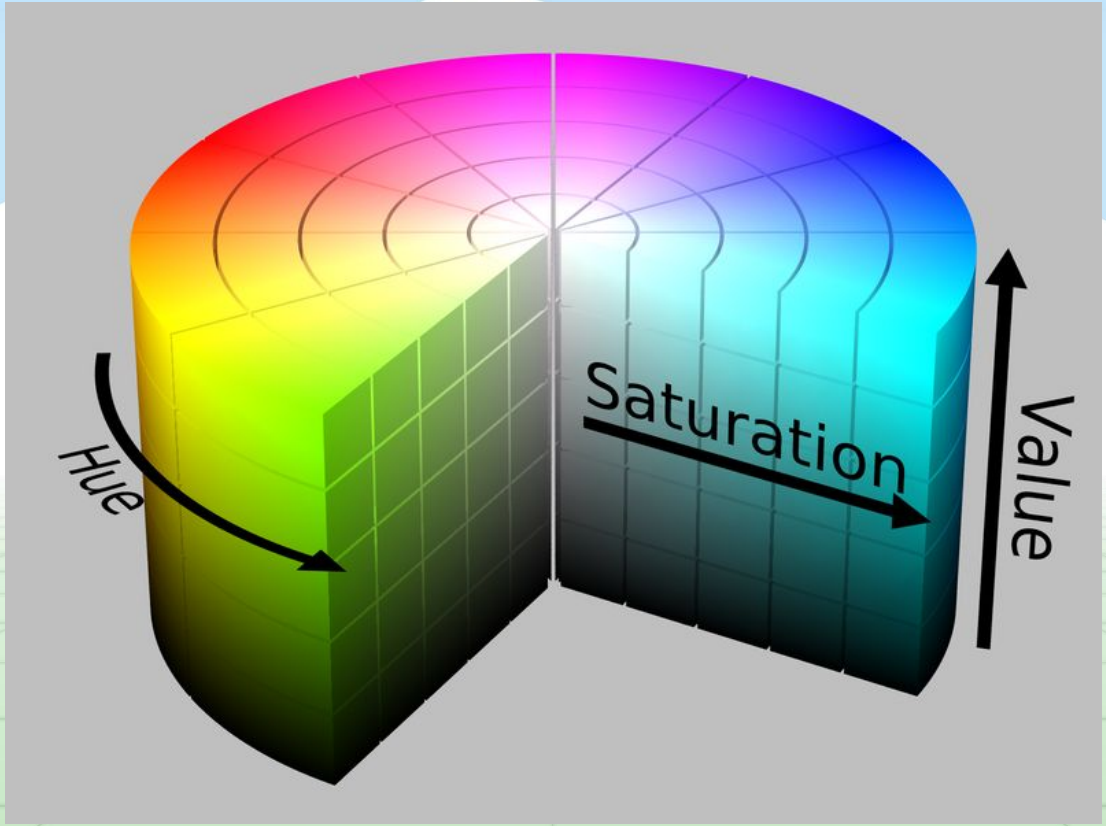
- We can simulate monochromatic images from RGB
- Want a good approximation of how “bright” the image is without color information
- (R+B+G/3) - looks weird
- We *should*
  - Gamma decompress
  - Calculatight lightness
  - Gamma compress
- We can just operate on sRGB
  - Typically ~ .30R + .59G + .11B



RGB is a cube...

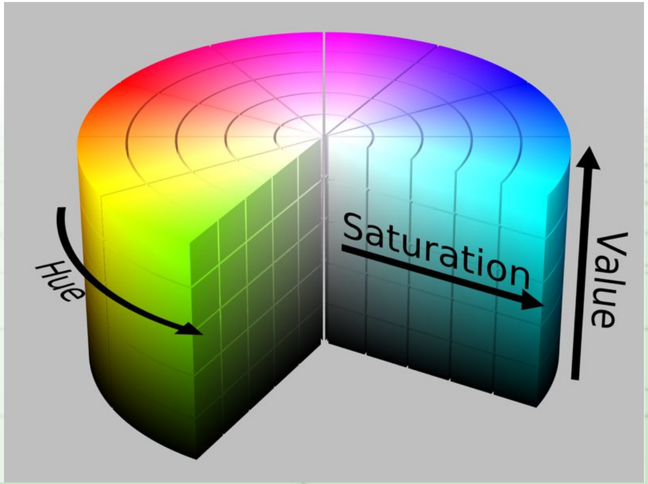


Hue, Saturation, Value: cylinder!



Hue, Saturation, Value

- Different model based on perception of light
- Hue: what color
- Saturation: how much color
- Value: how bright
- Allows easy image transforms
  - Shift the hue
  - Increase saturation



This is your homework, yay!