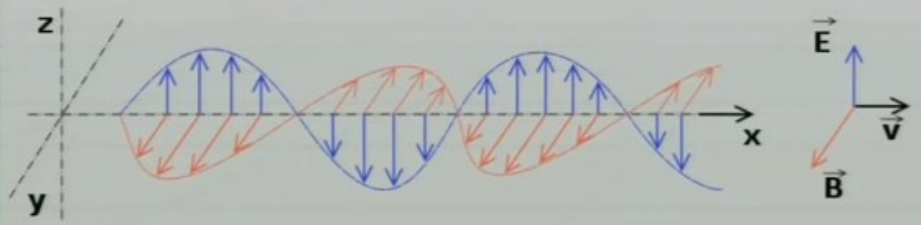
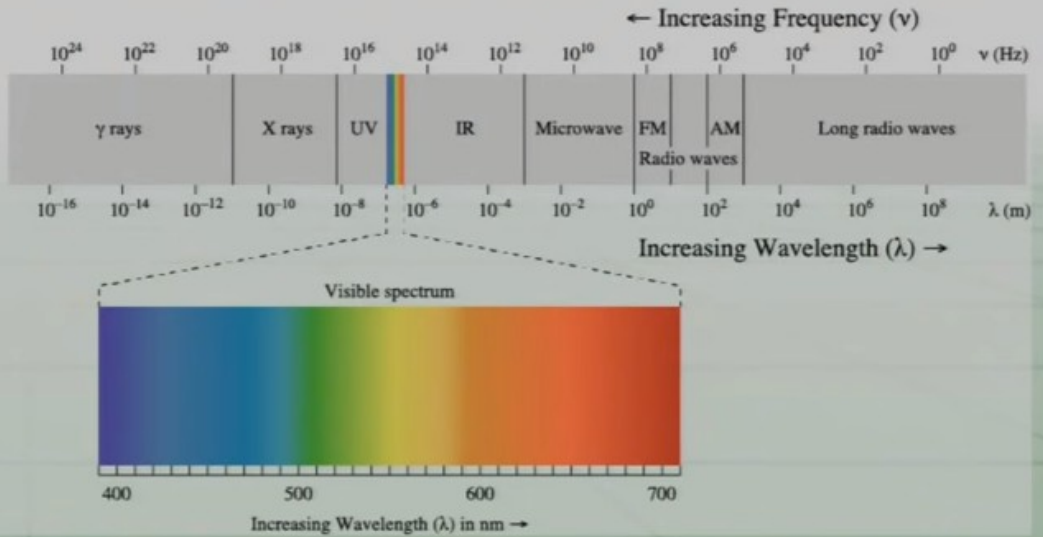
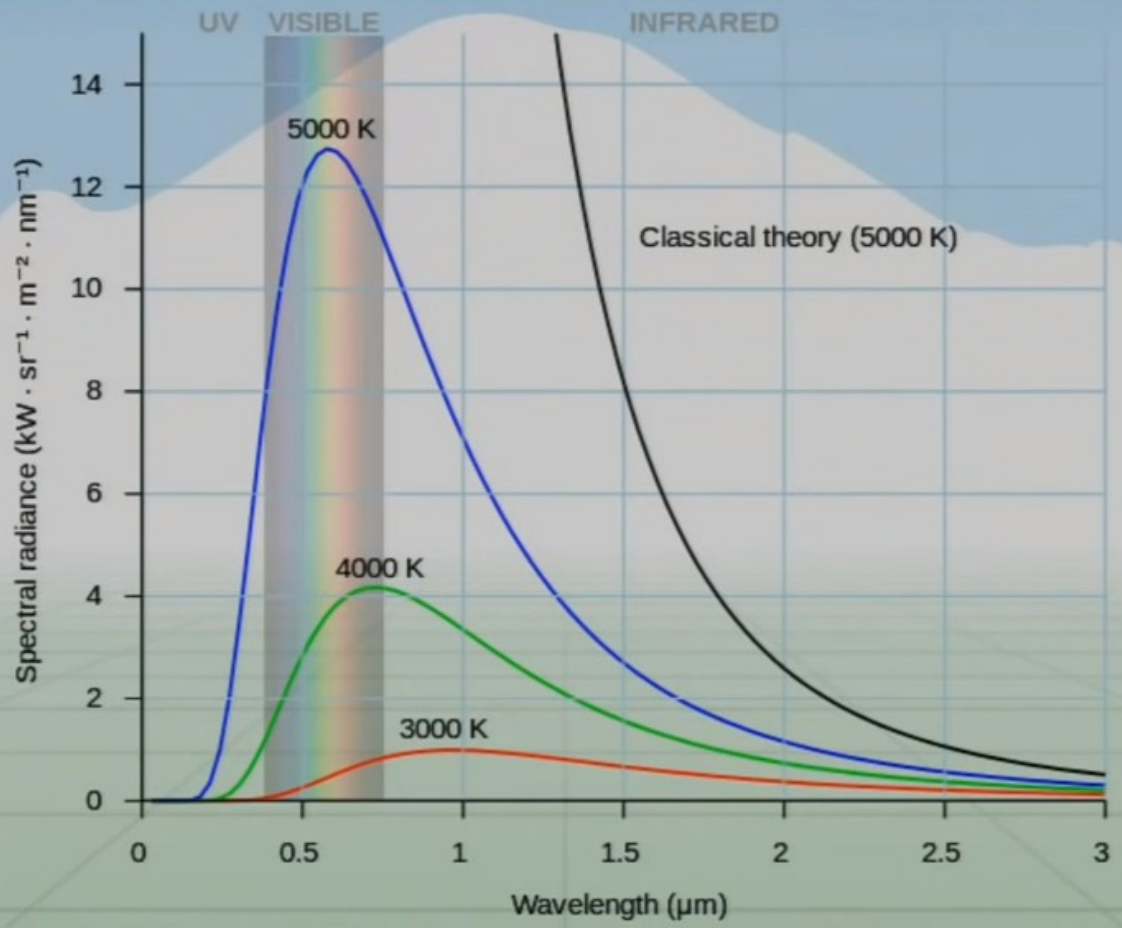
So what are we looking at anyway?

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



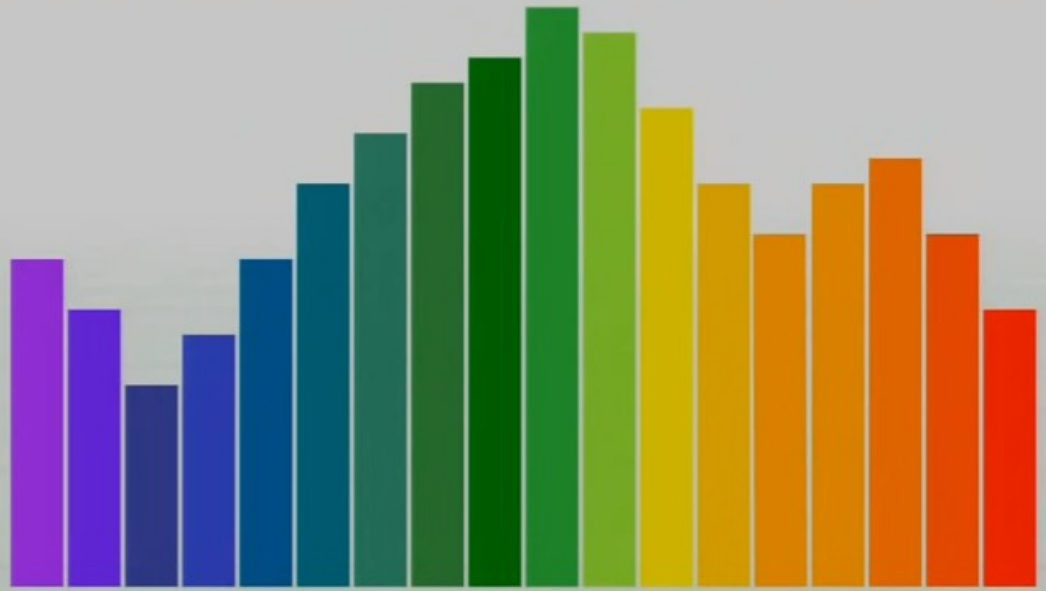


Visible light and the sun

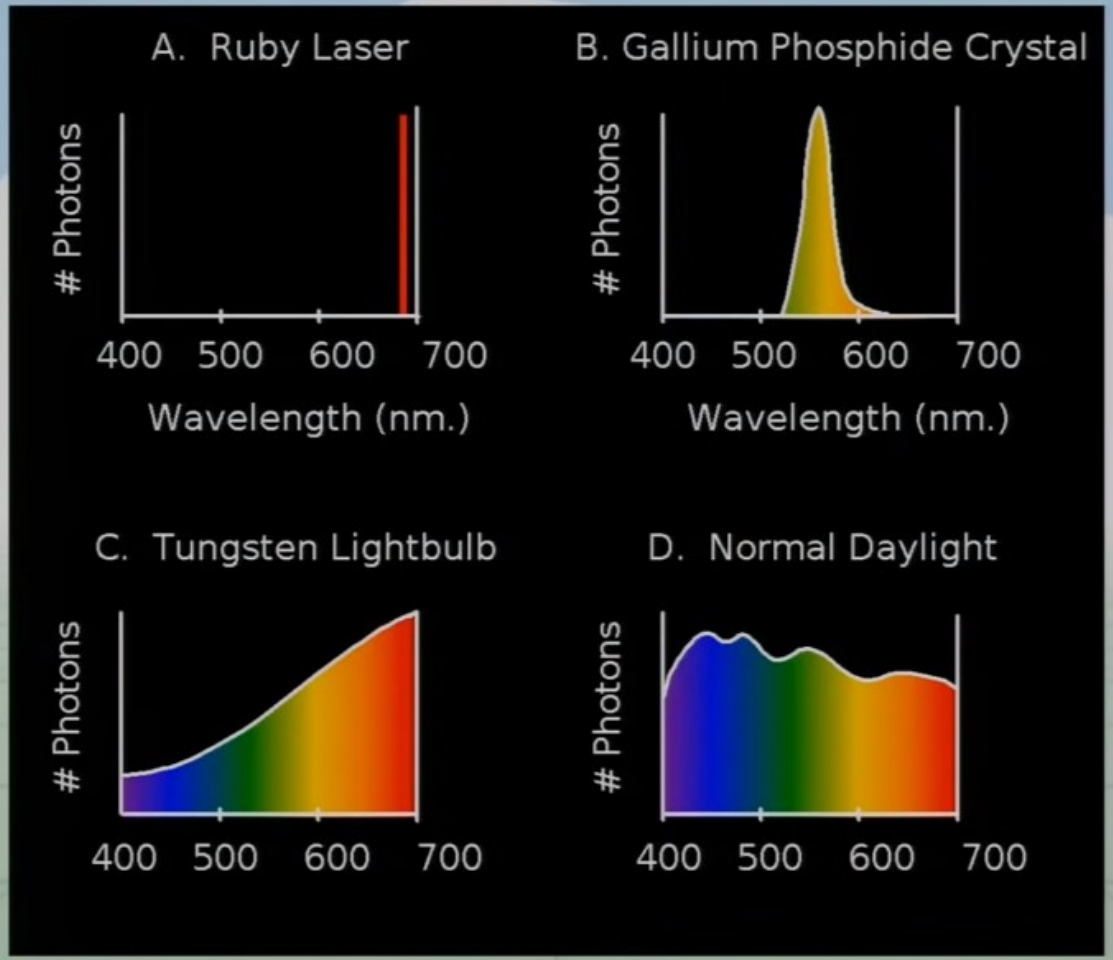


Light is a combination of waves

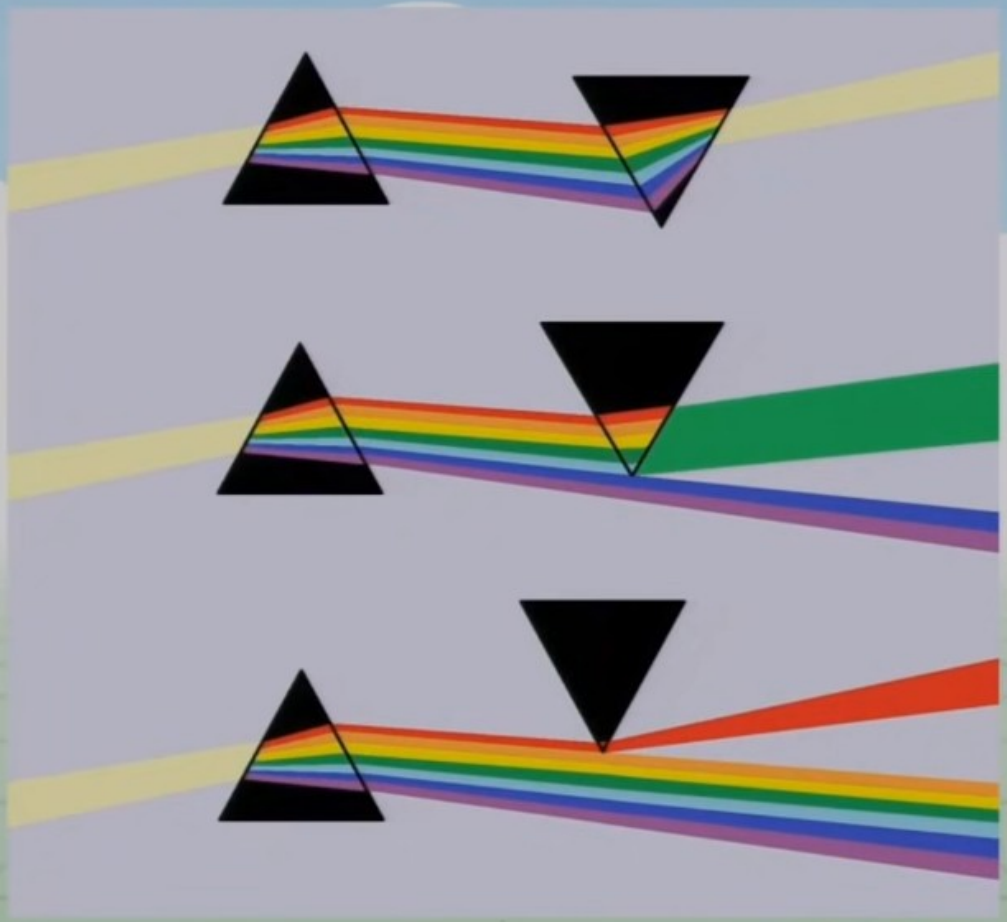
- Like a chord in music
- Can be described as a sum of its parts
- Relative strength of different frequencies



Sources of light are diverse!

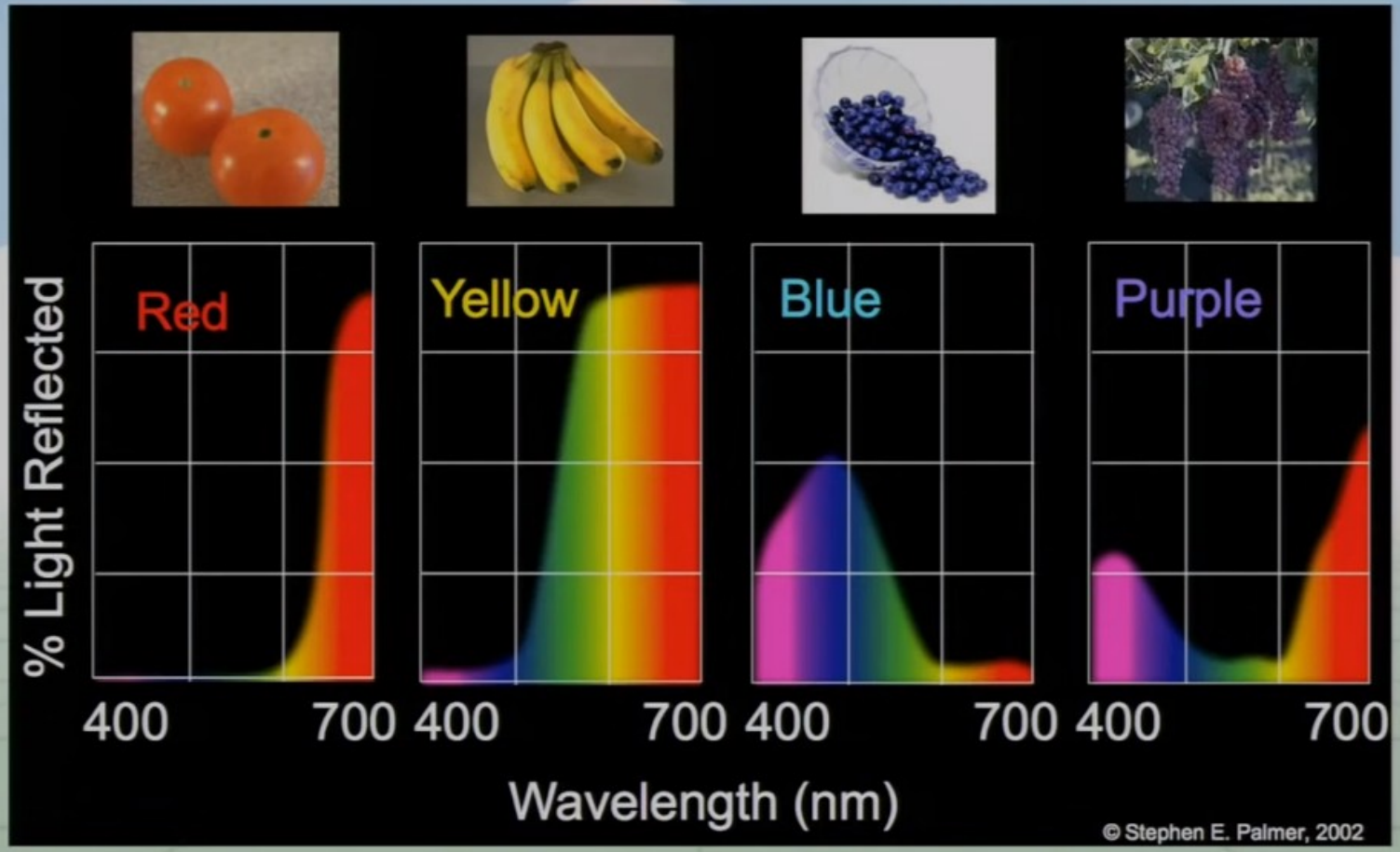


“White” light - all wavelengths



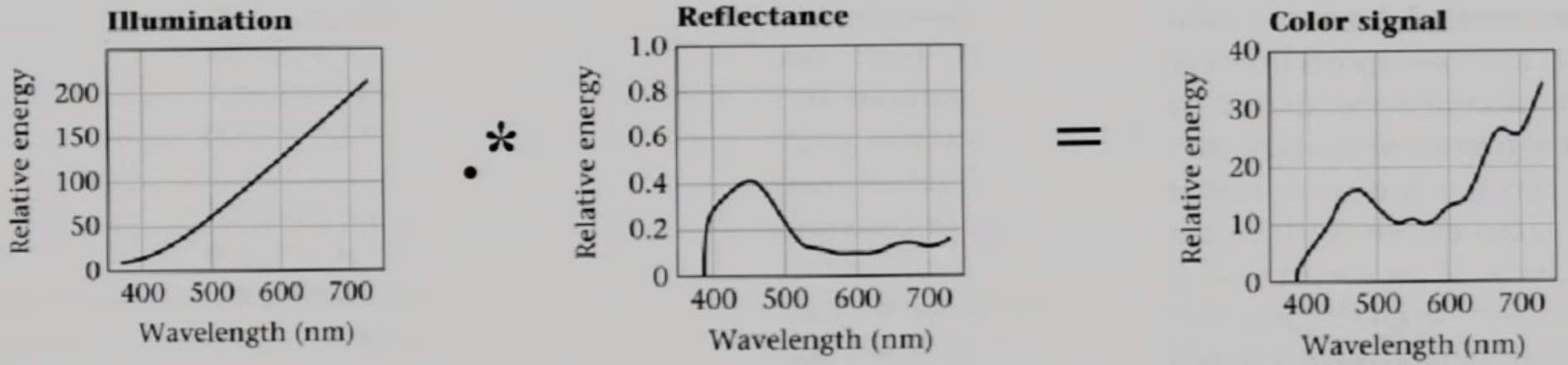
We know this thanks to Newton!

Objects reflect only some light

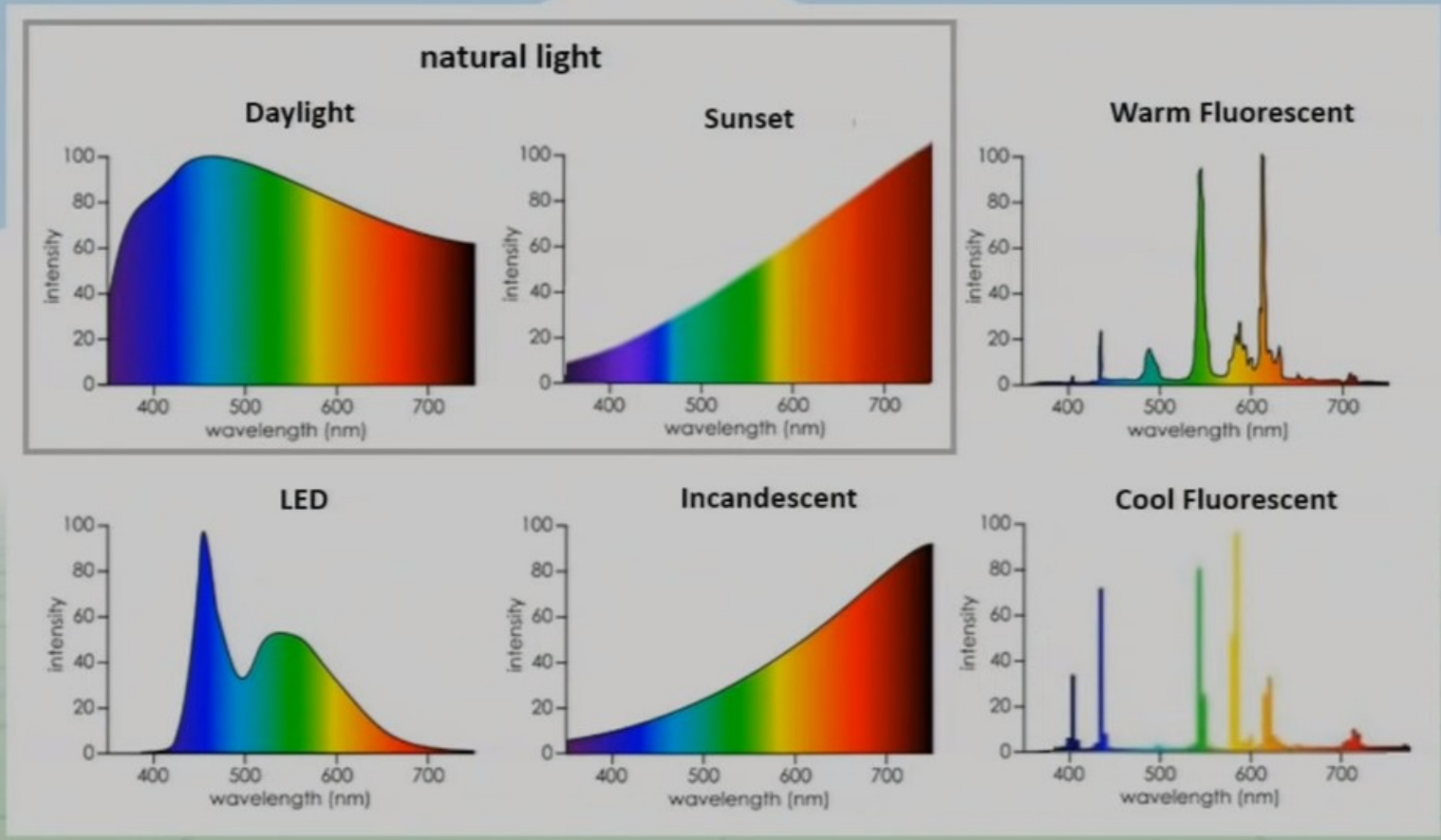


What color is the object?

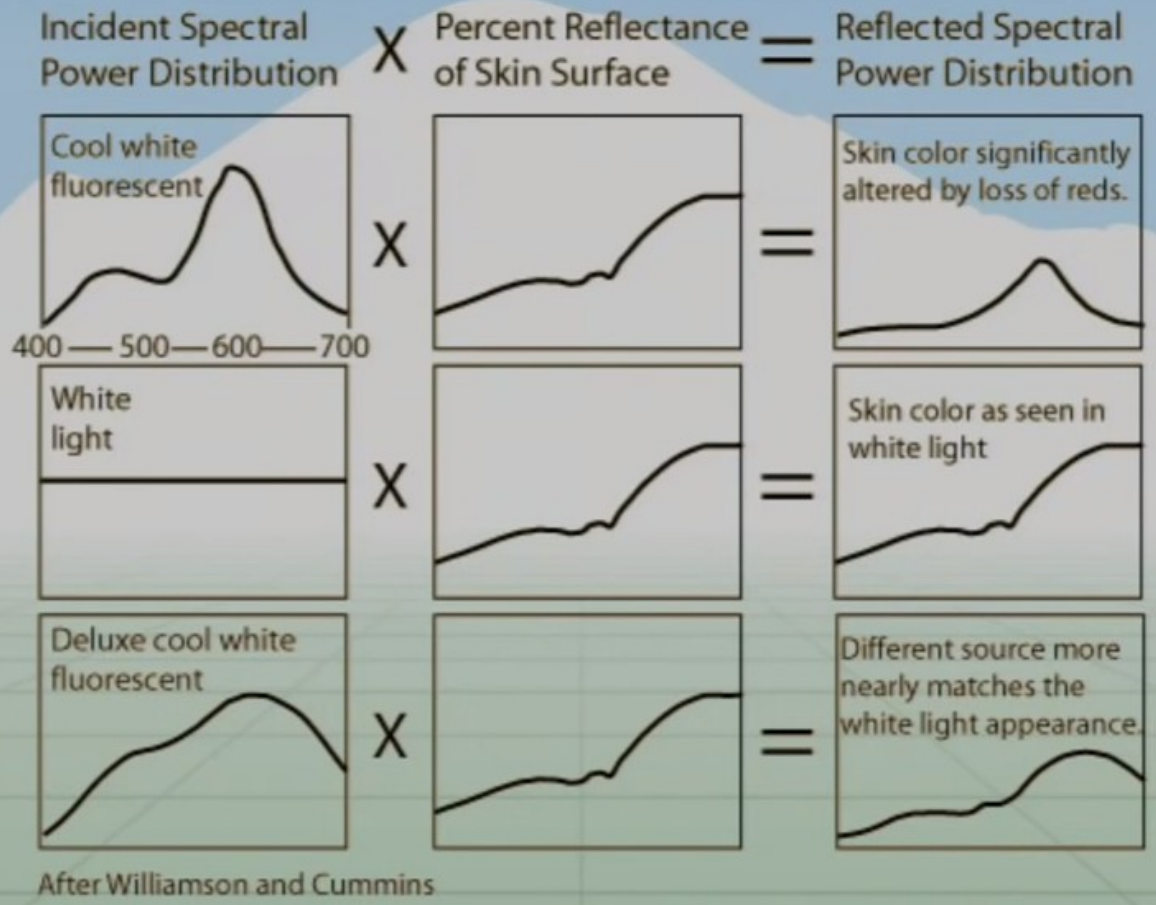
- The “color” of an object depends on both the incident light and the objects reflectance:



Different illumination matters!



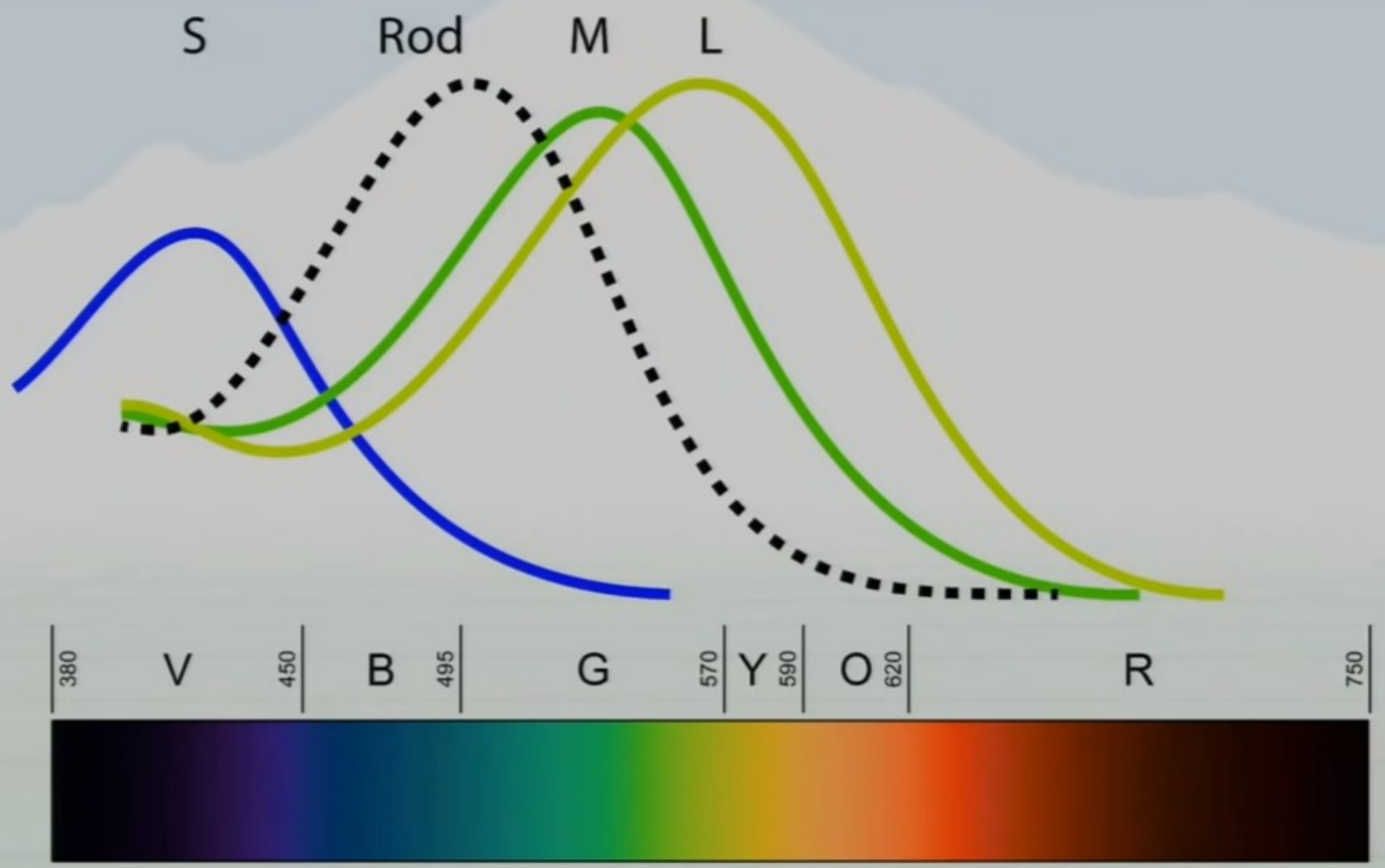
Case study: makeup application



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

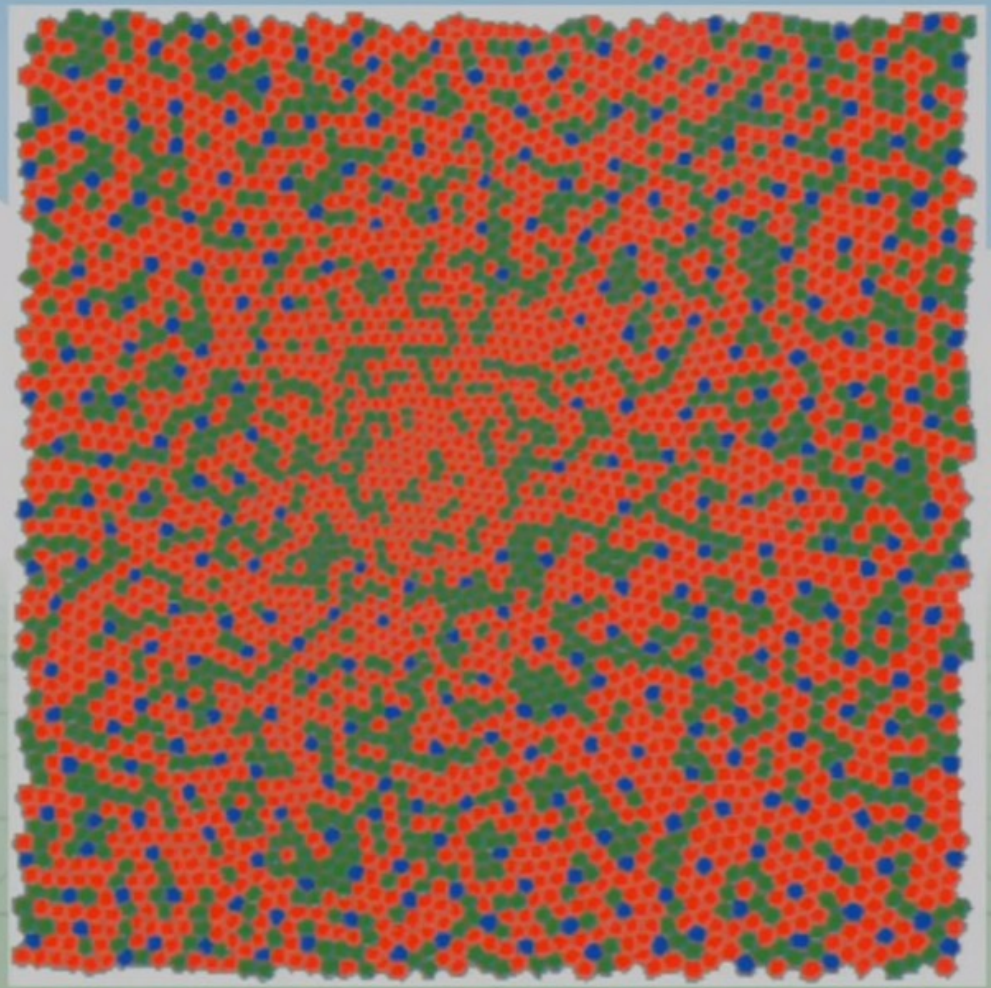
Photoreceptors and light



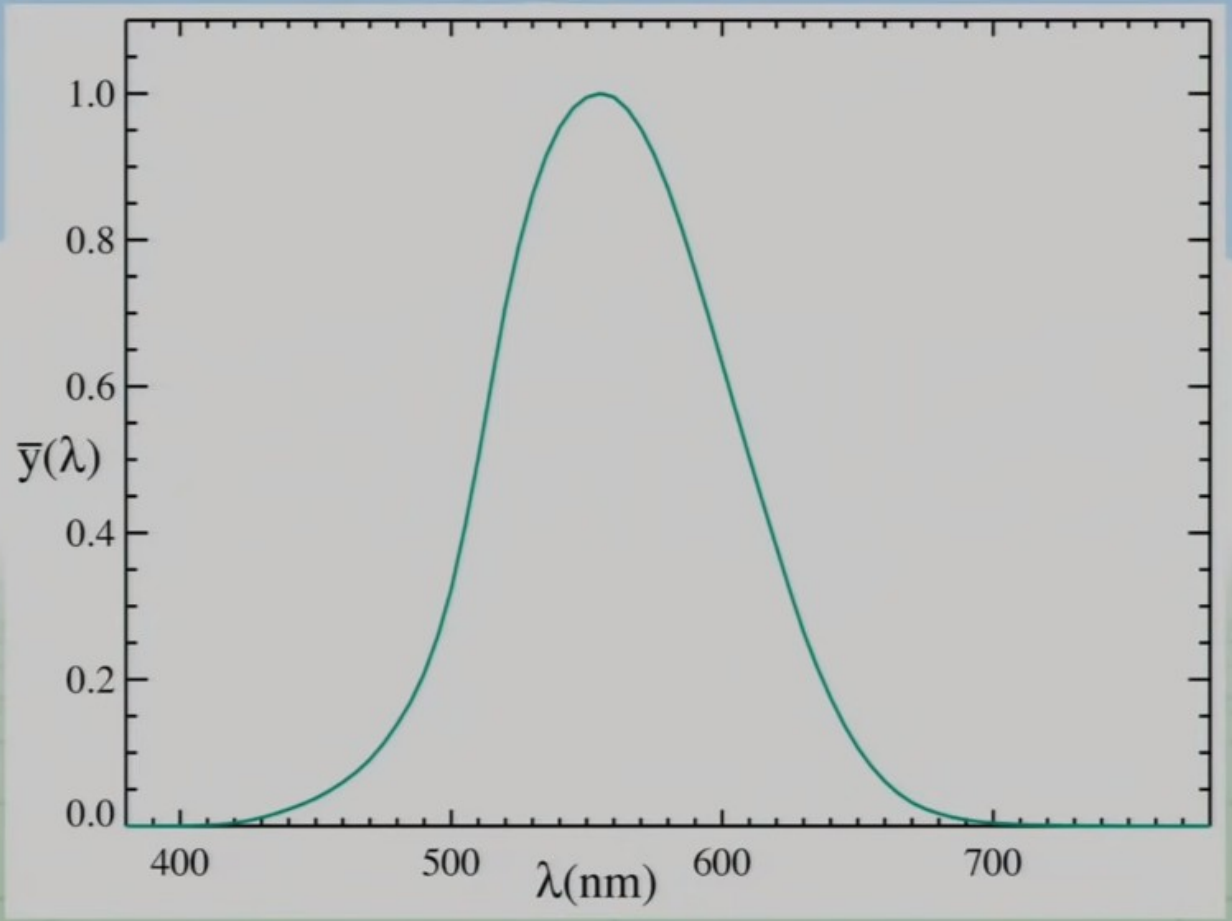
Cones and color

- 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

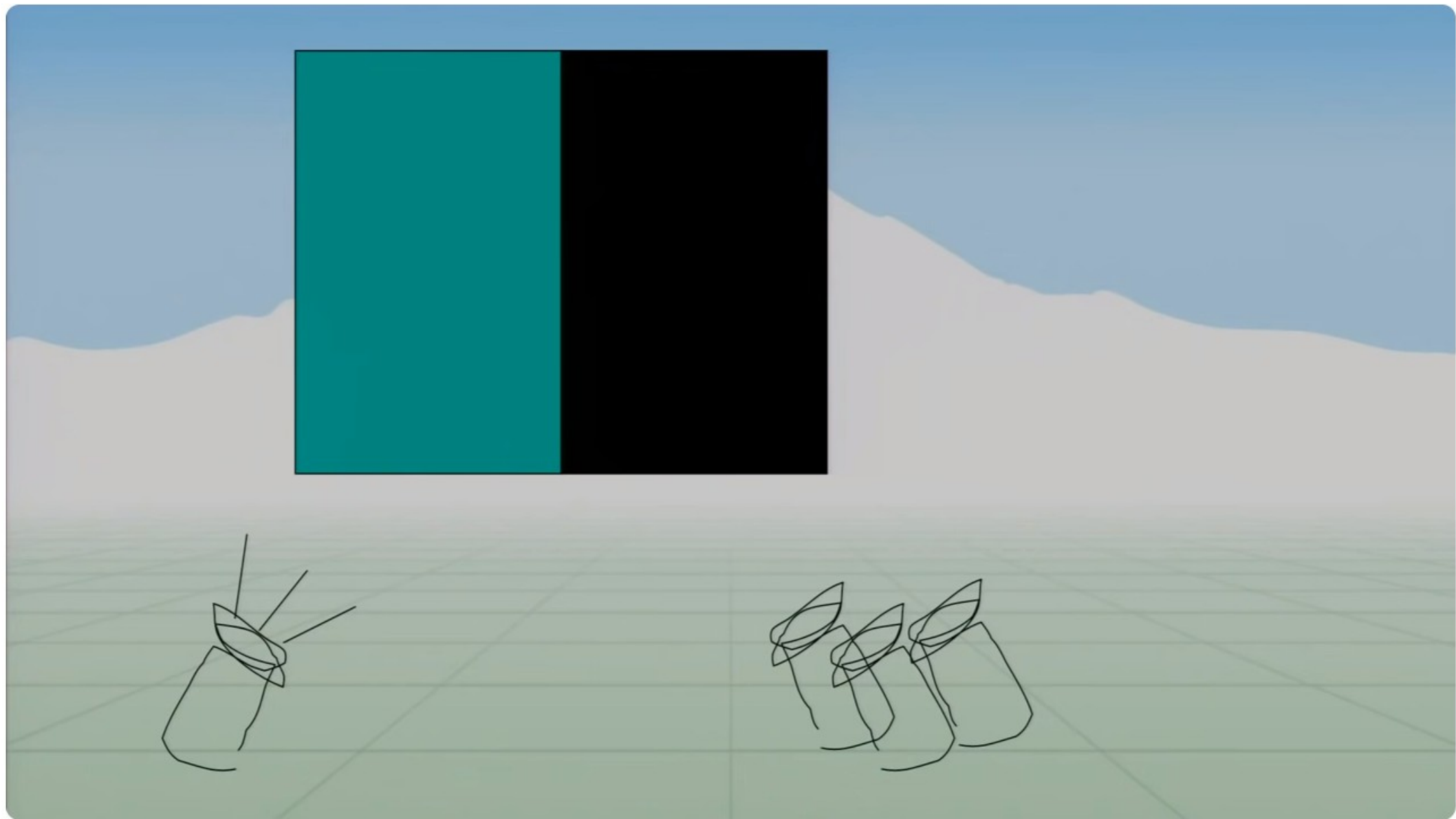


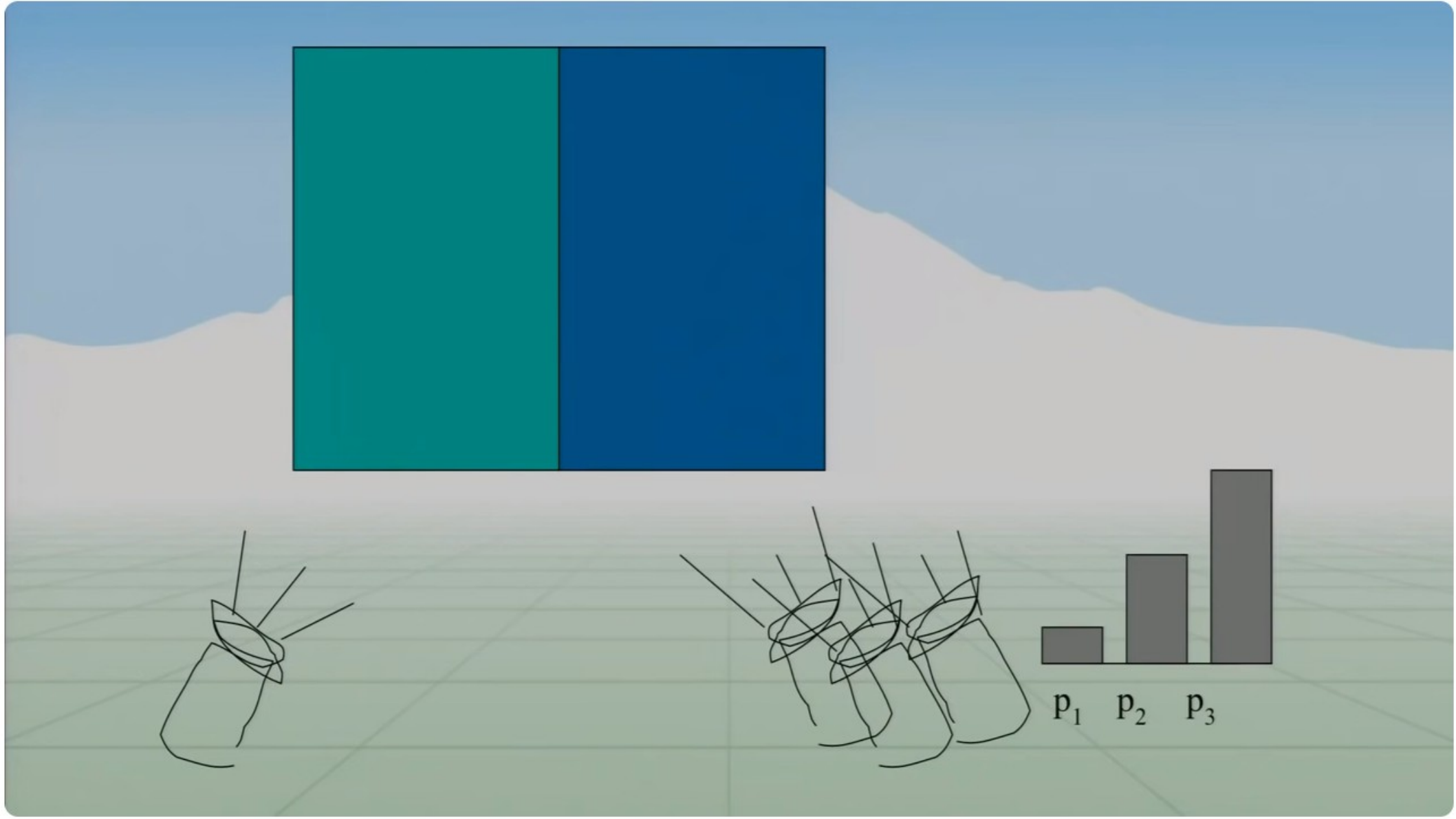
This is hard to read

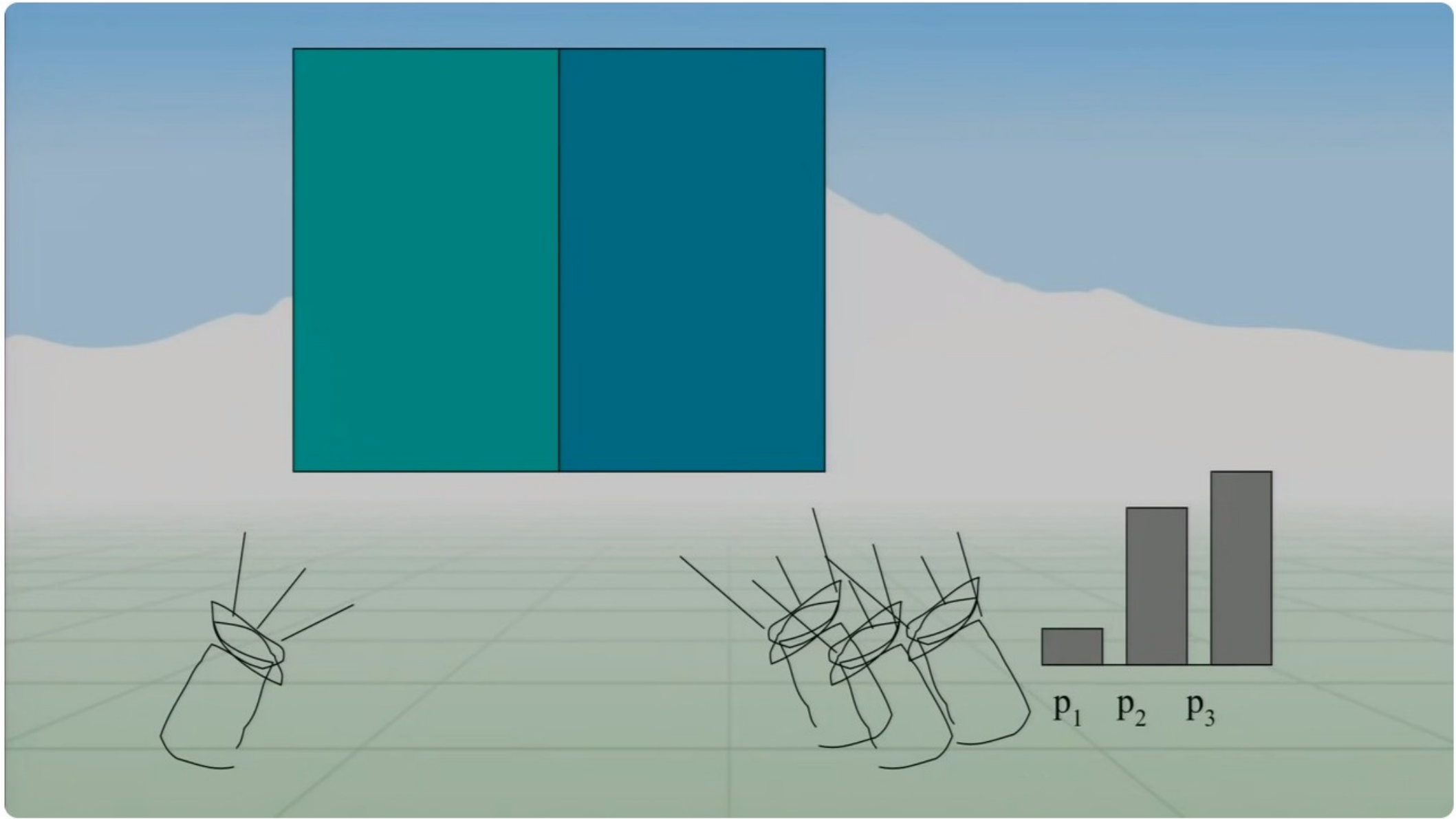
This is easier to read

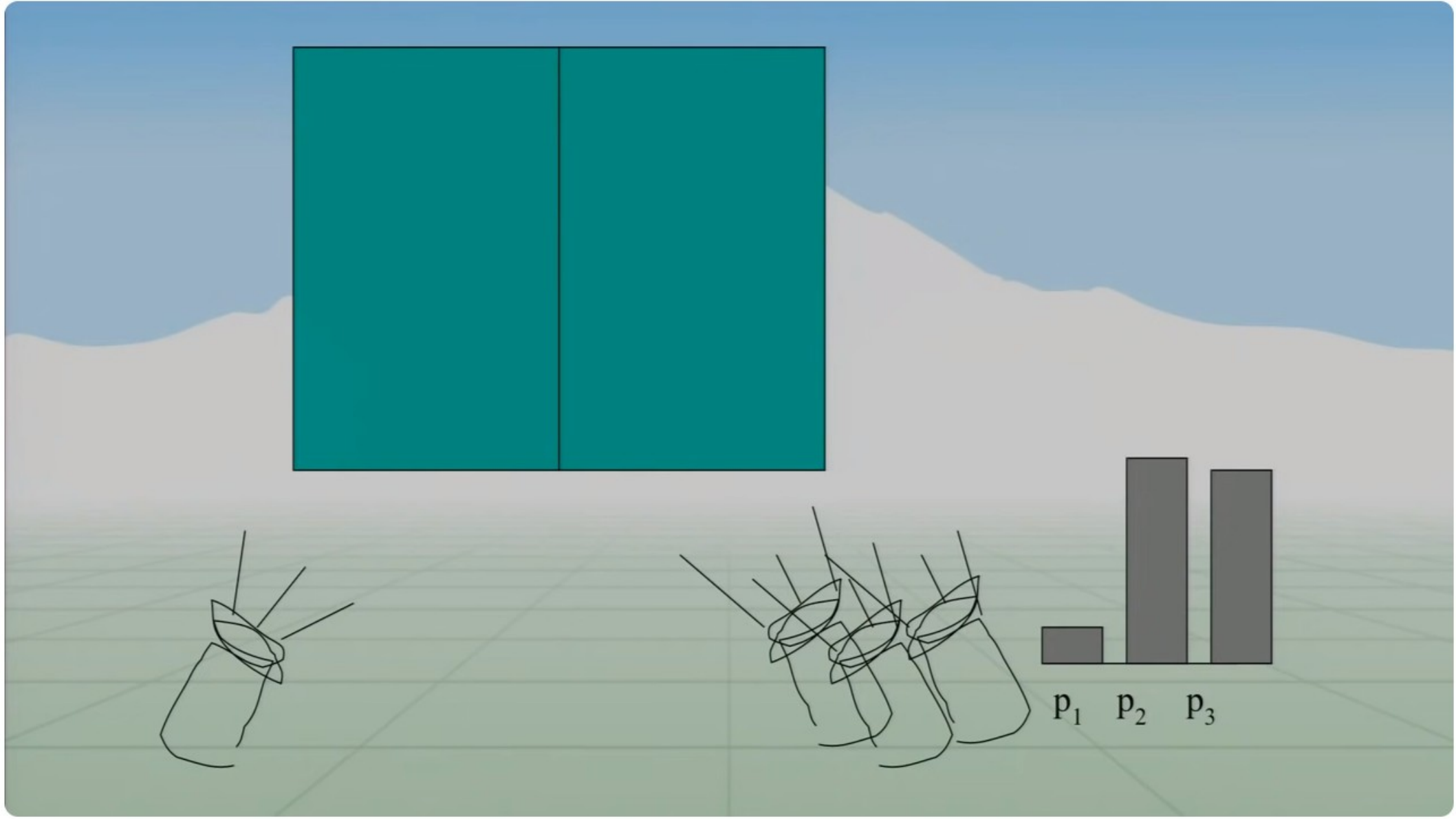
Many variations, what do they see?

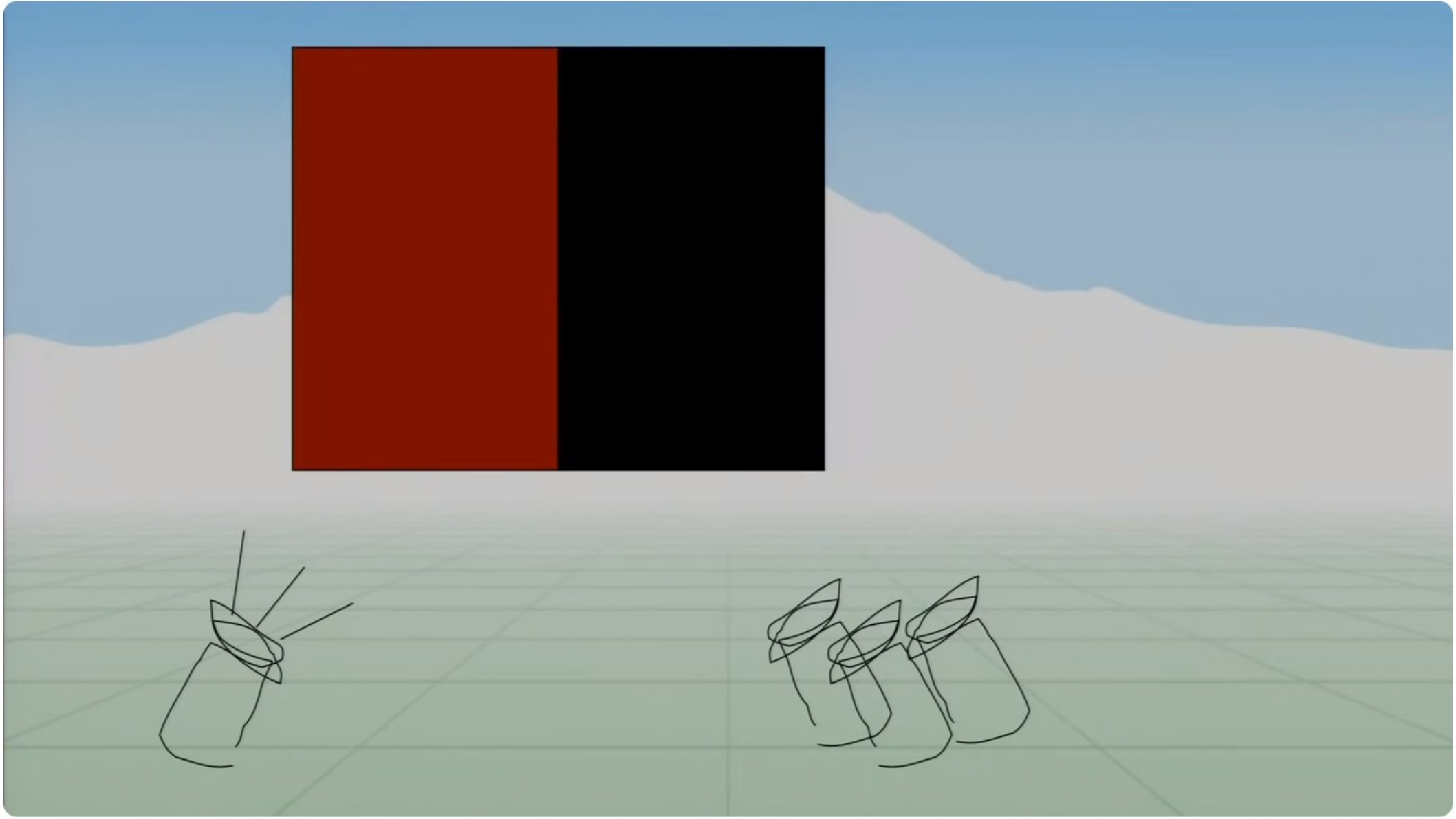
State	Types of cone cells	Approx. number of colors perceived	Carriers
Monochromacy	1	100	marine mammals, owl monkey, Australian sea lion, achromat primates
Dichromacy	2	10,000	most terrestrial non-primate mammals, color blind primates
Trichromacy	3	1 million	most primates, especially great apes (such 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)

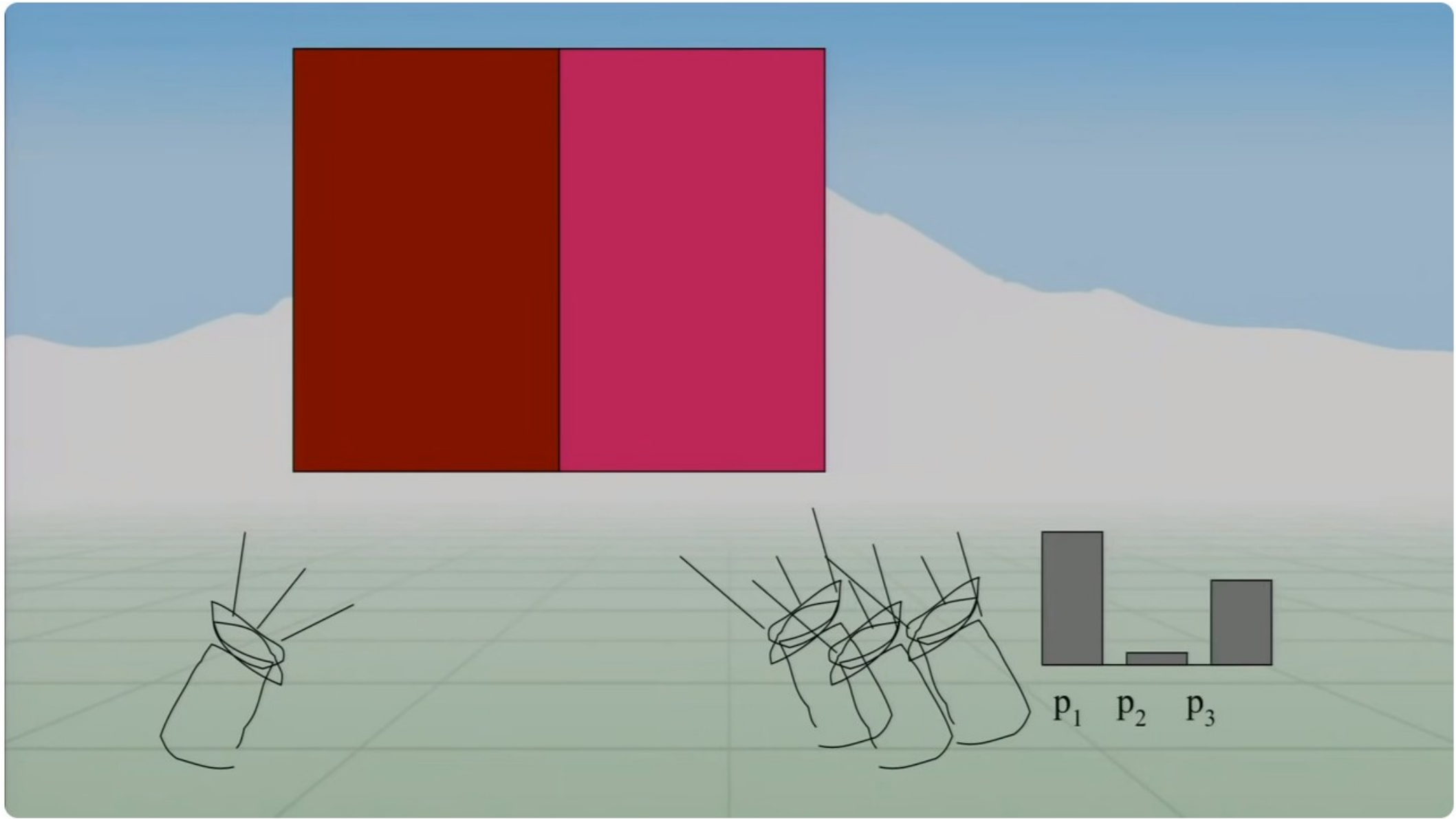



p_1 p_2 p_3


p_1 p_2 p_3


p_1 p_2 p_3

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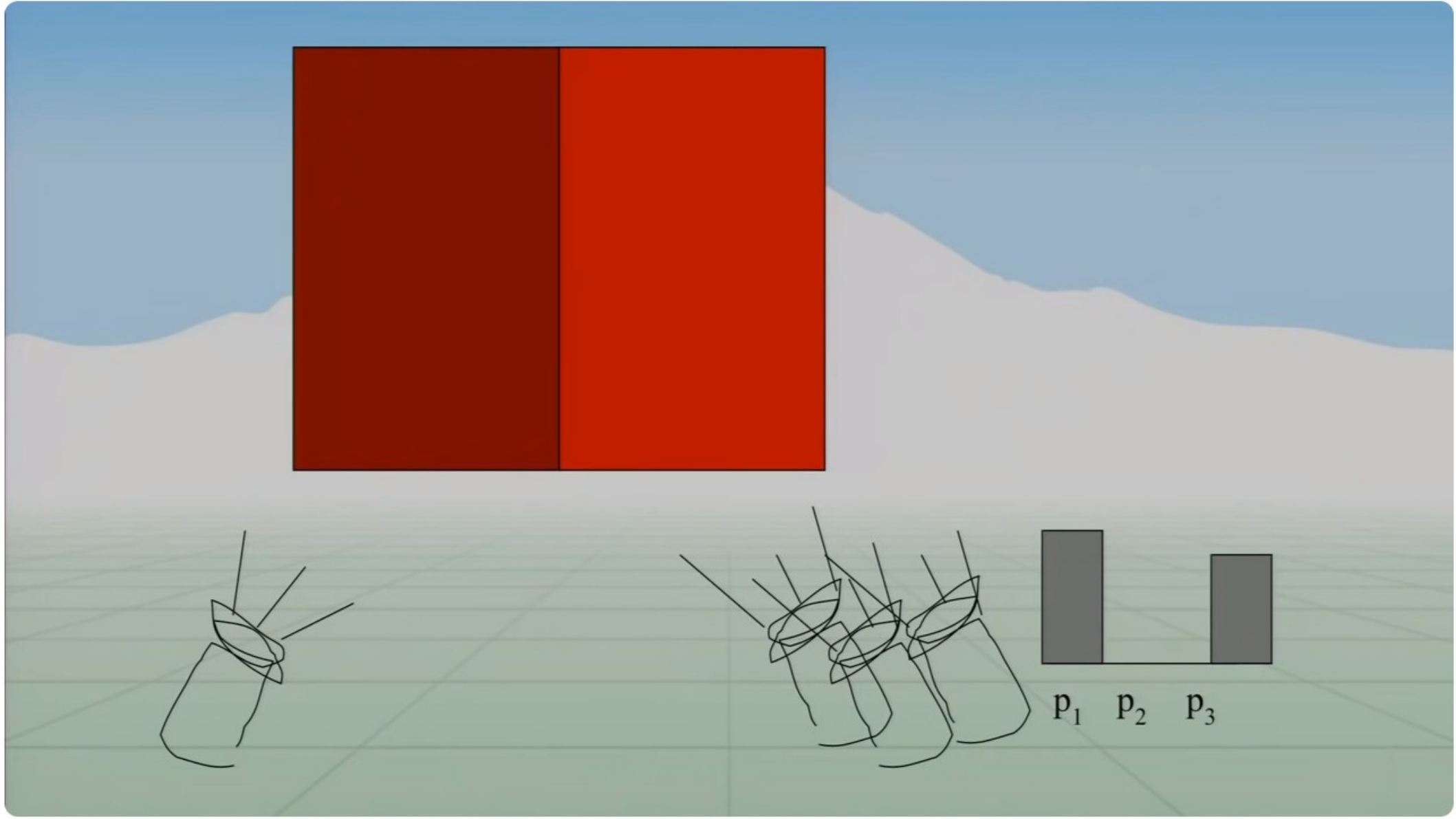
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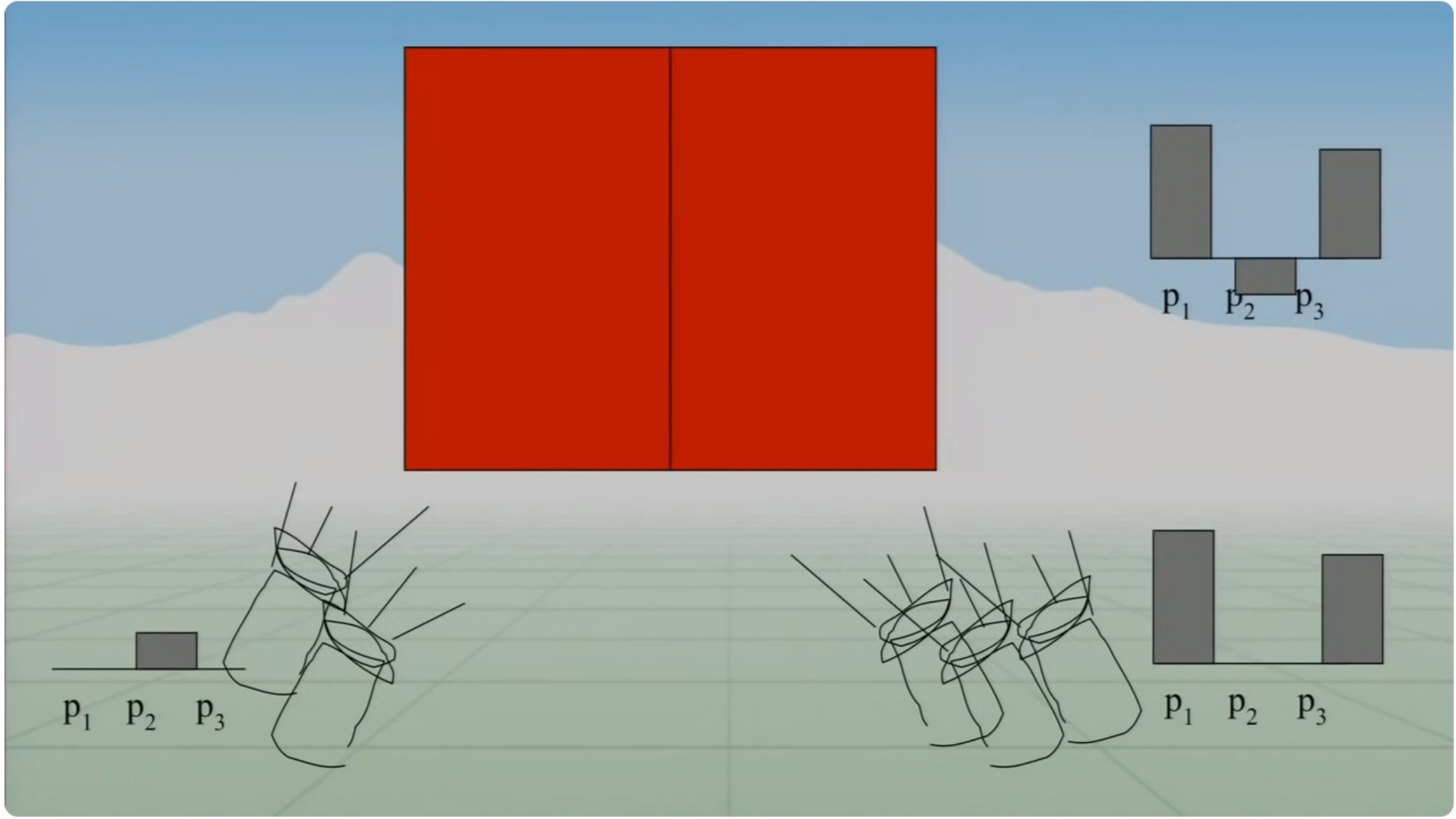
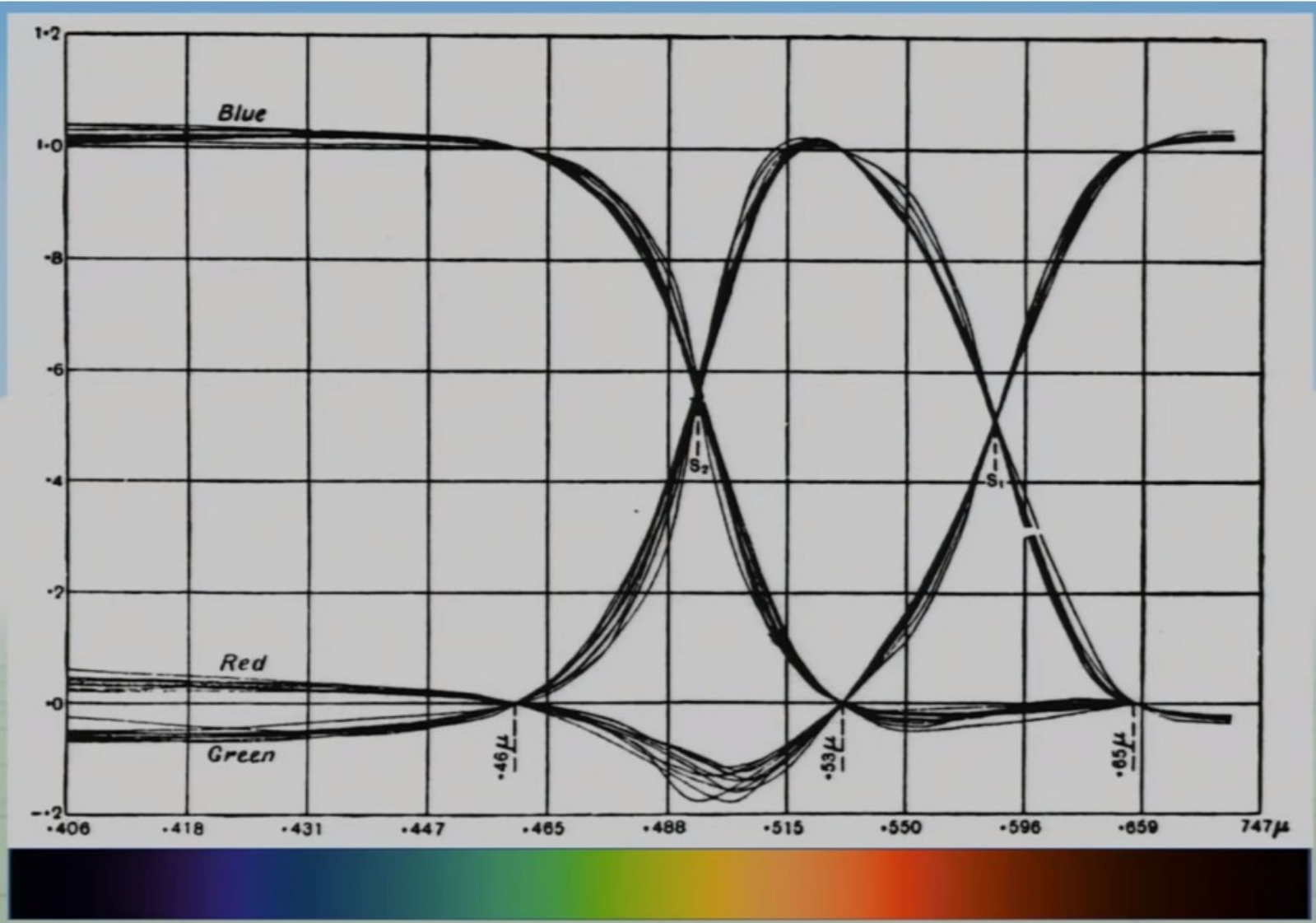

p1 p2 p3
p1 p2 p3
p1 p2 p3


1·2
1·0
·8
·6
·4
·2
·0
-·2
Blue
Red
Green
S2
S1
·46μ
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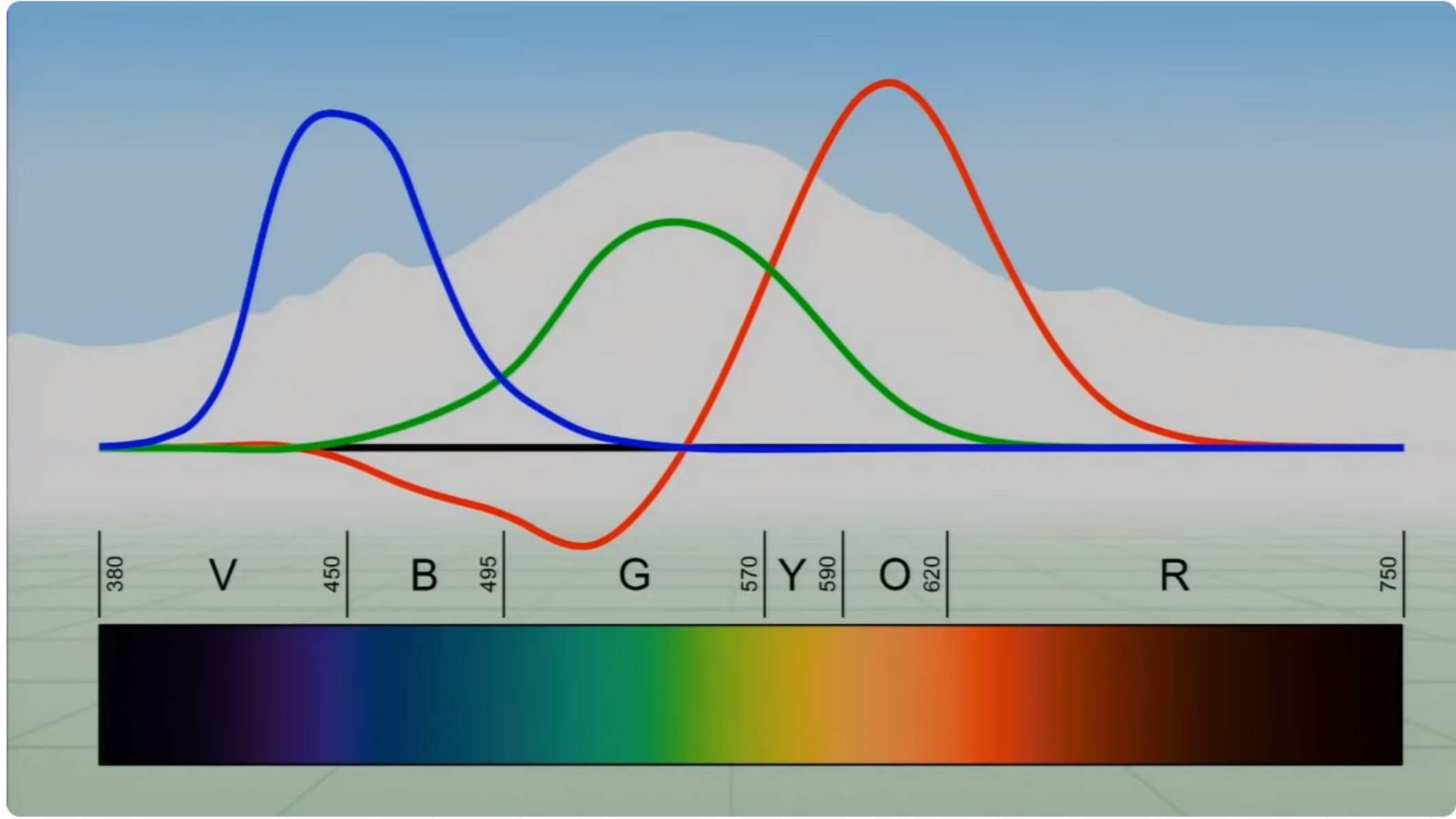
·65μ
·406
·418
·431
·447
·465
·488
·515
·550
·596
·659
747μ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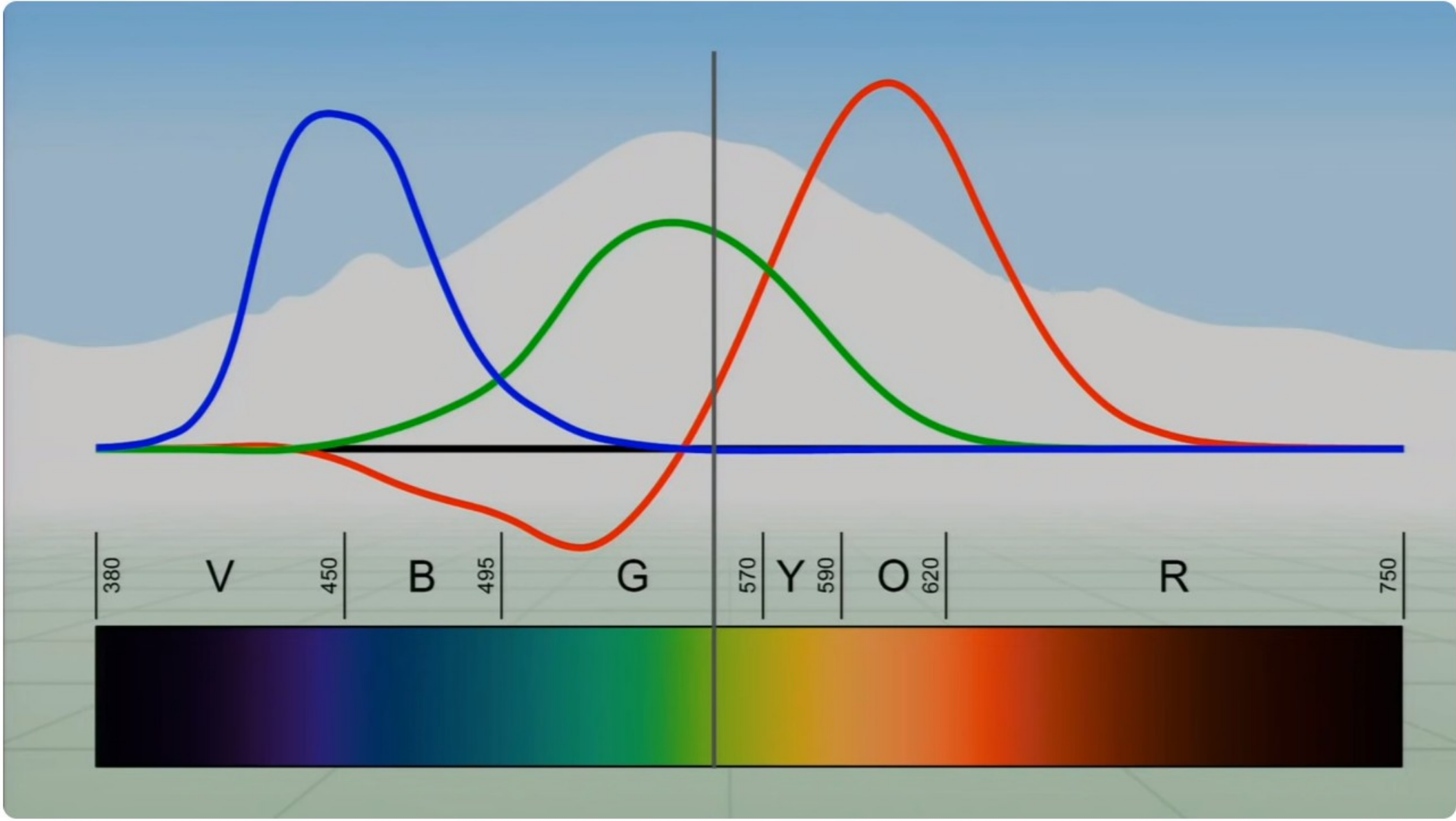
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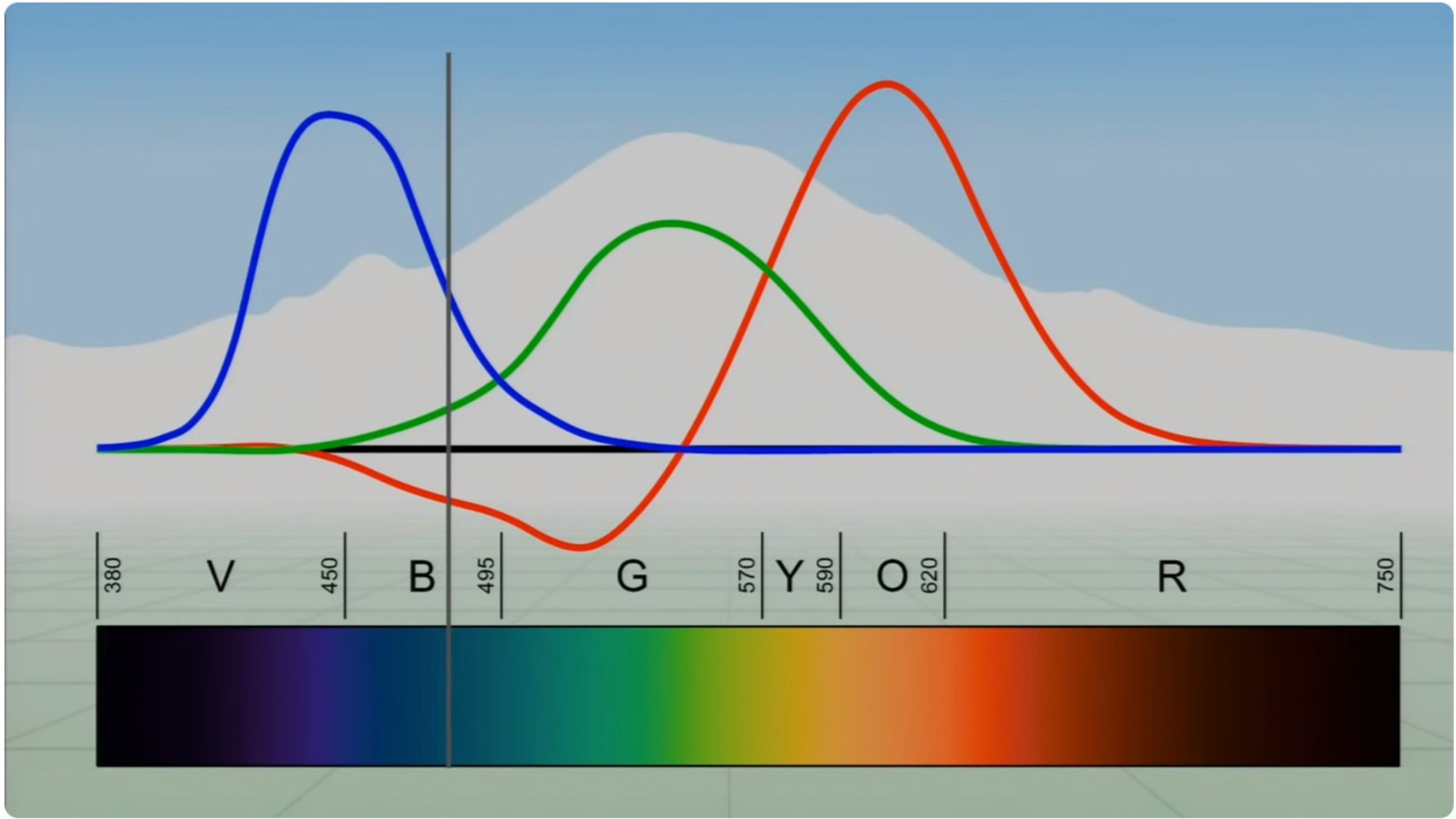
380
V
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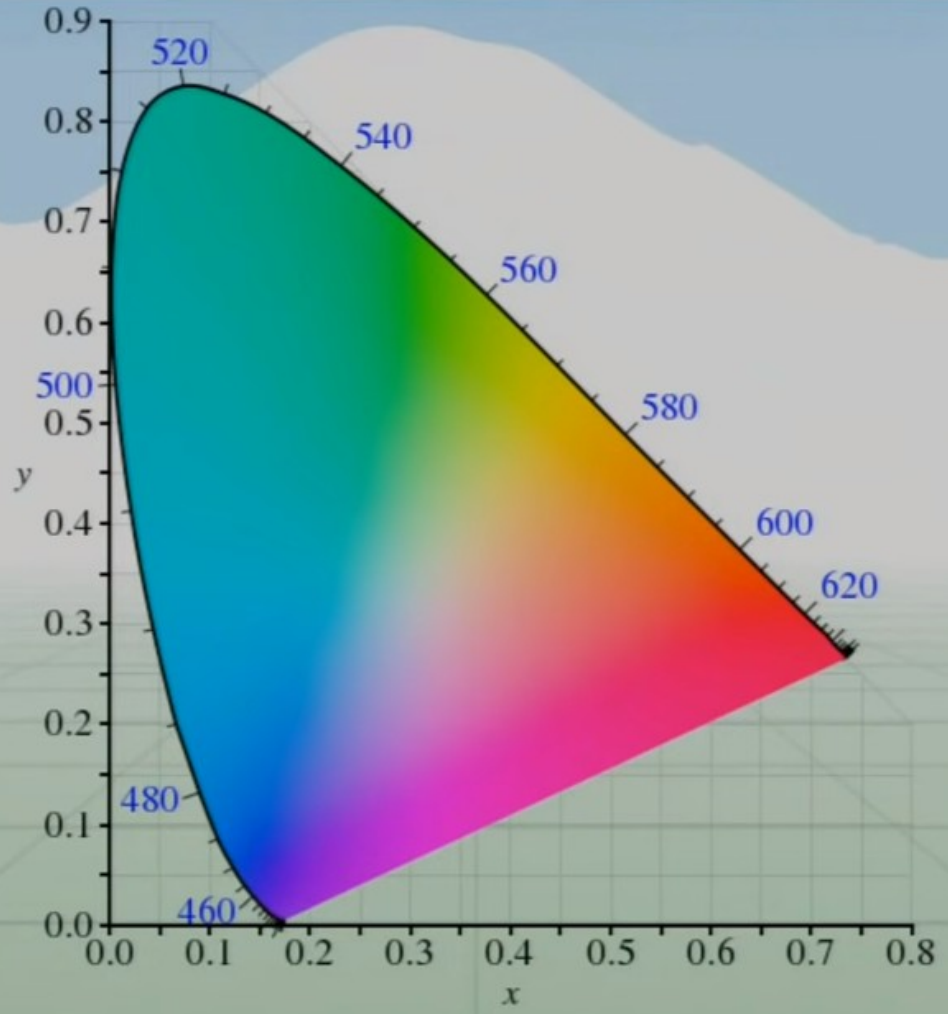
G
570
Y
590
O
620
R
750

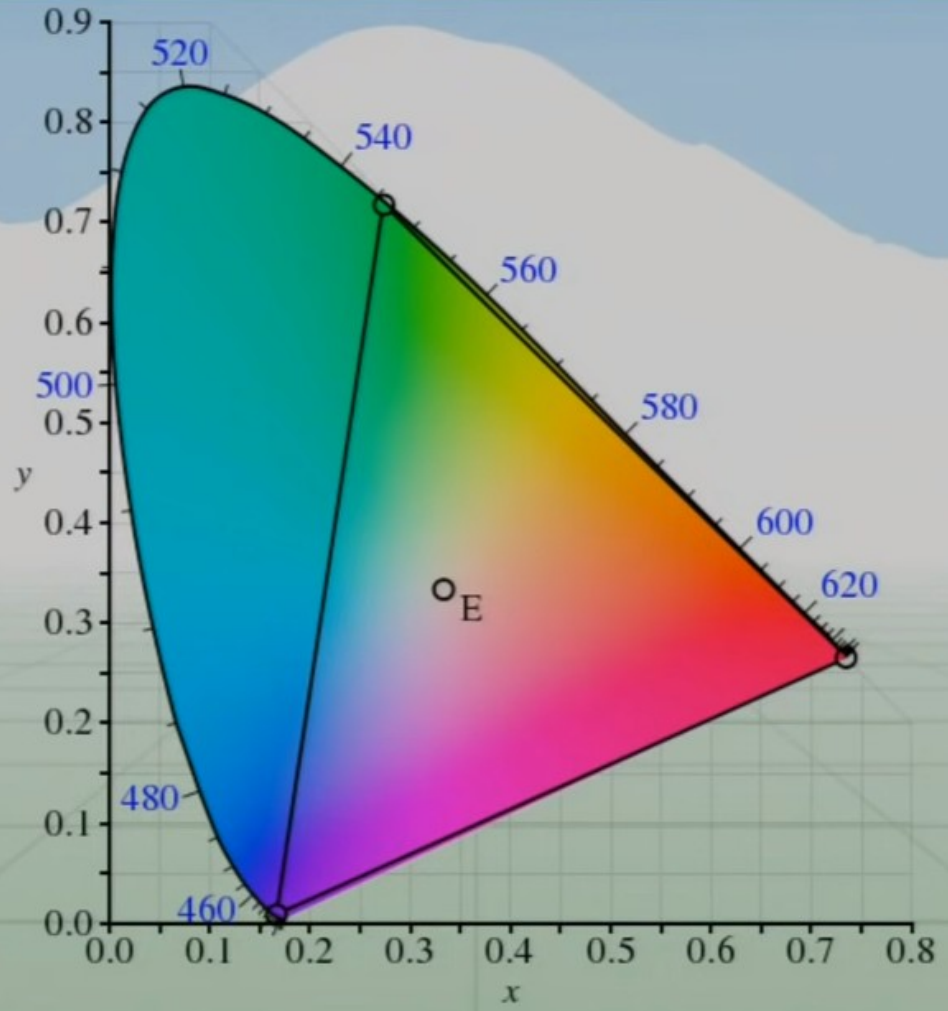
Results:

- 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

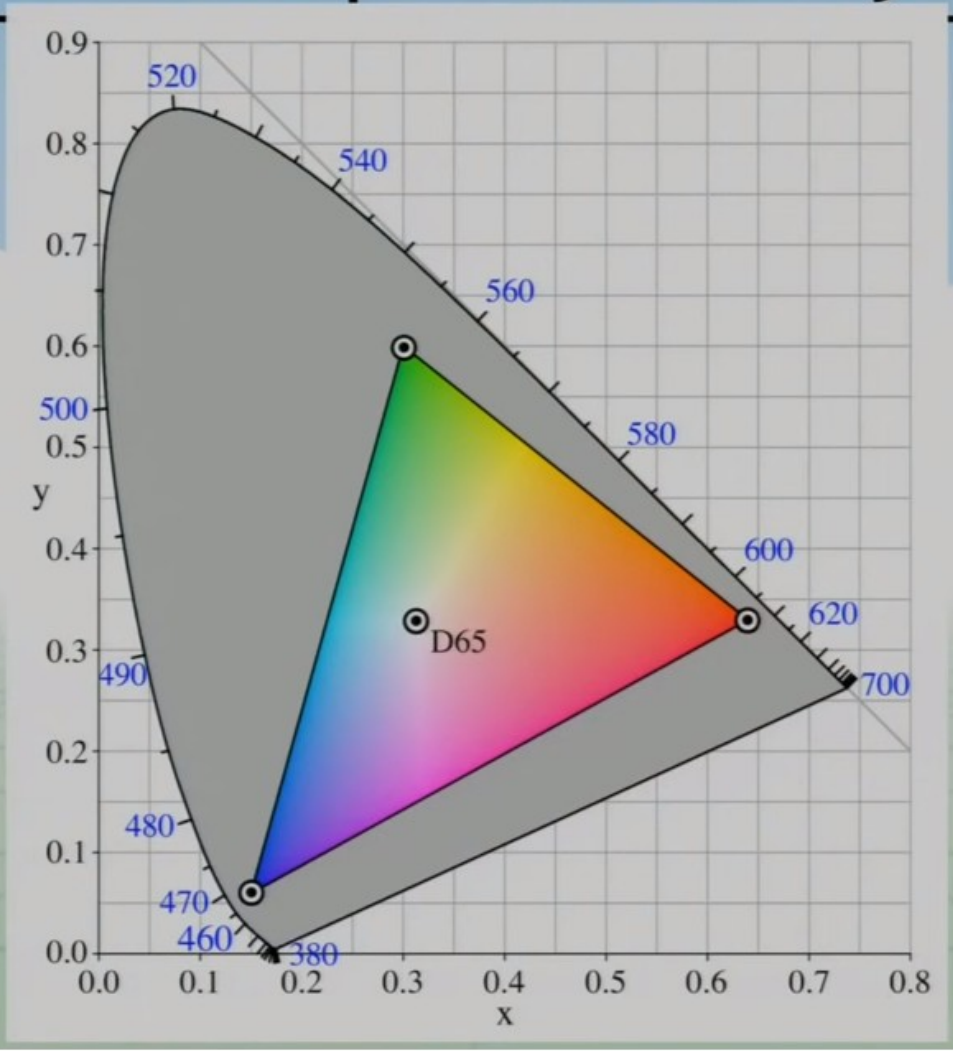
Now we can make a map of color



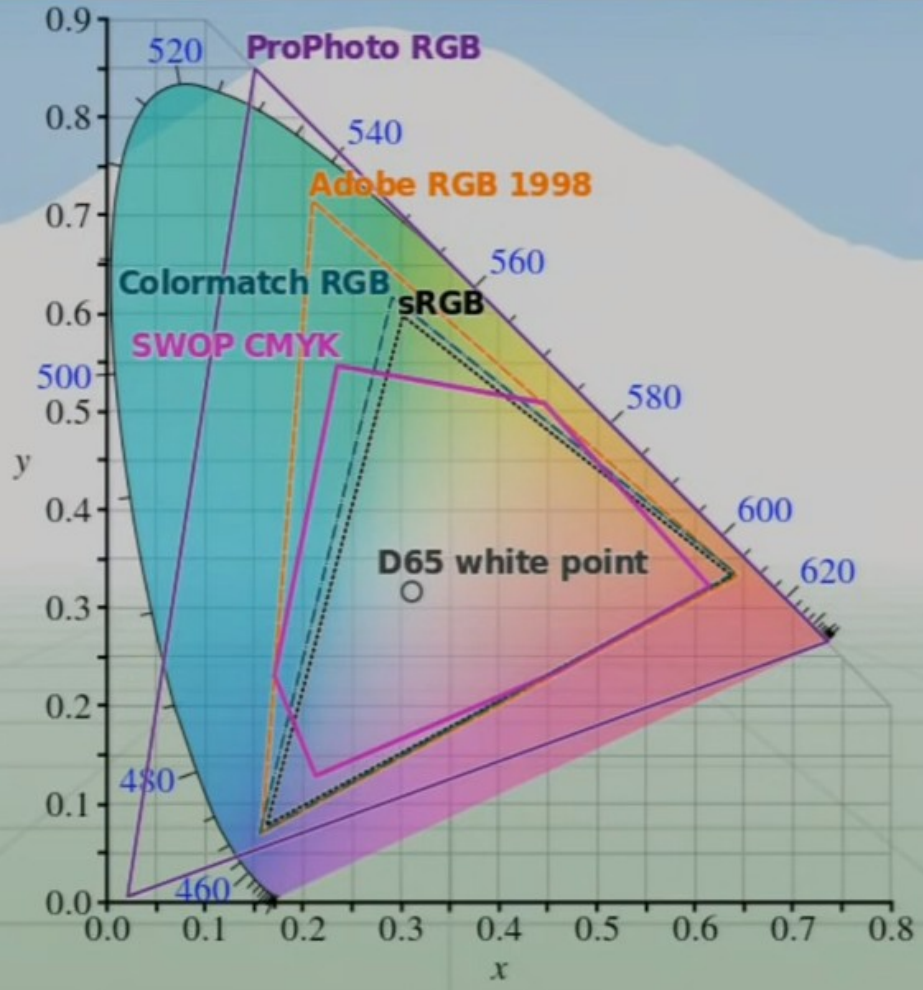
“Theoretical” CIE RGB primaries



Practical sRGB primaries, MSFT 1996



MANY different colorspaces

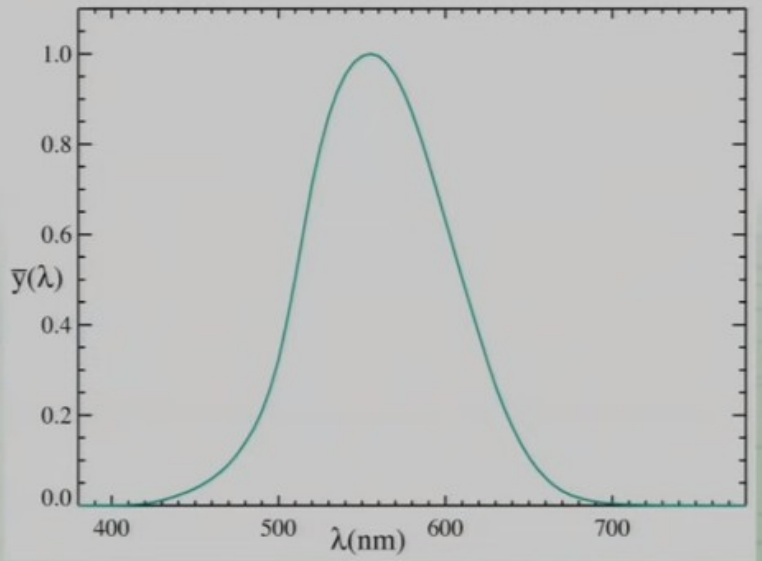


What does this mean for computers?

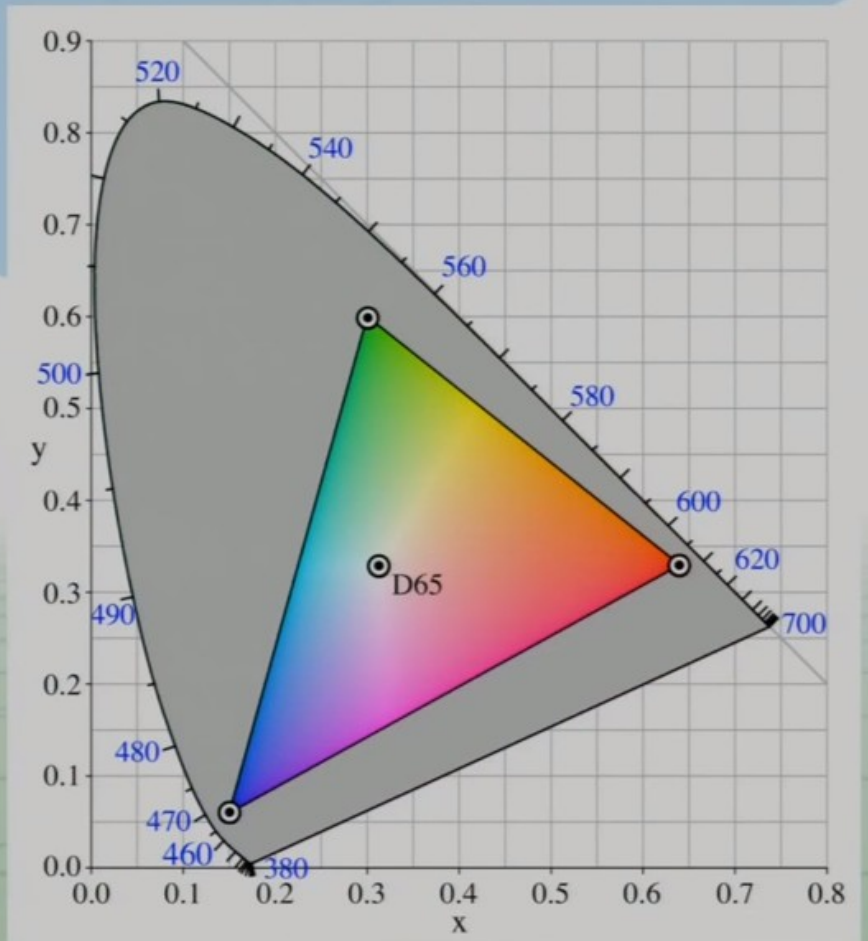
- We represent images as grids of pixels
- Each pixel has a color, 3 components: RGB
- Not every color can be represented in RGB!
  - Have to go out in the real world sometimes
- RGB is made to trick humans, not be accurate
- sRGB is not actually linear, gamma compressed
  - Humans see differences between 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….

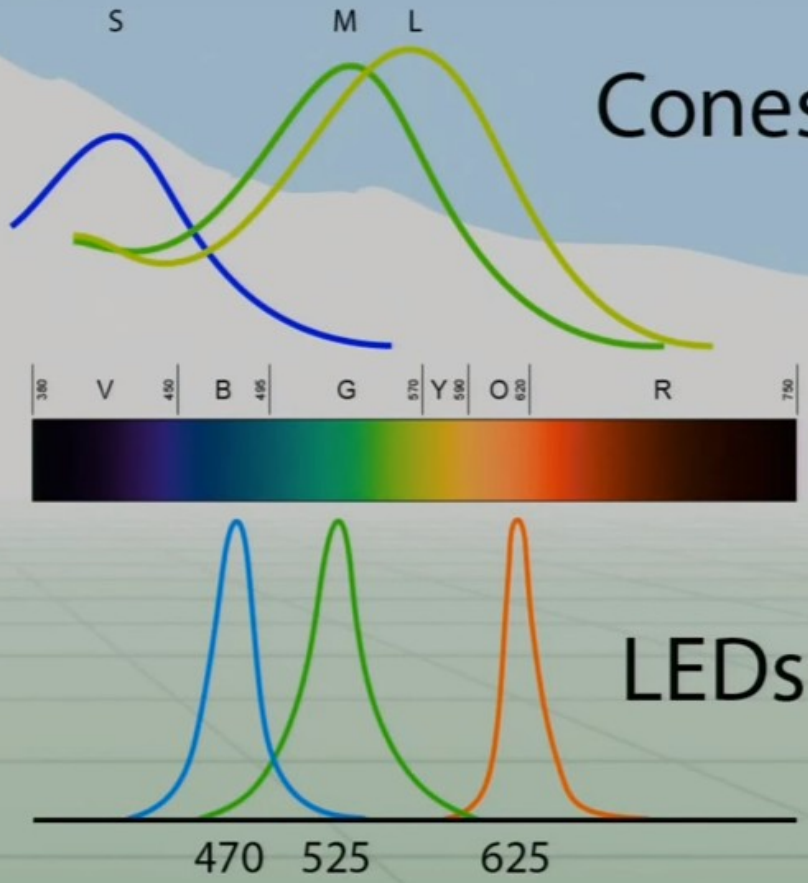
Grayscale - making color images not

- 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

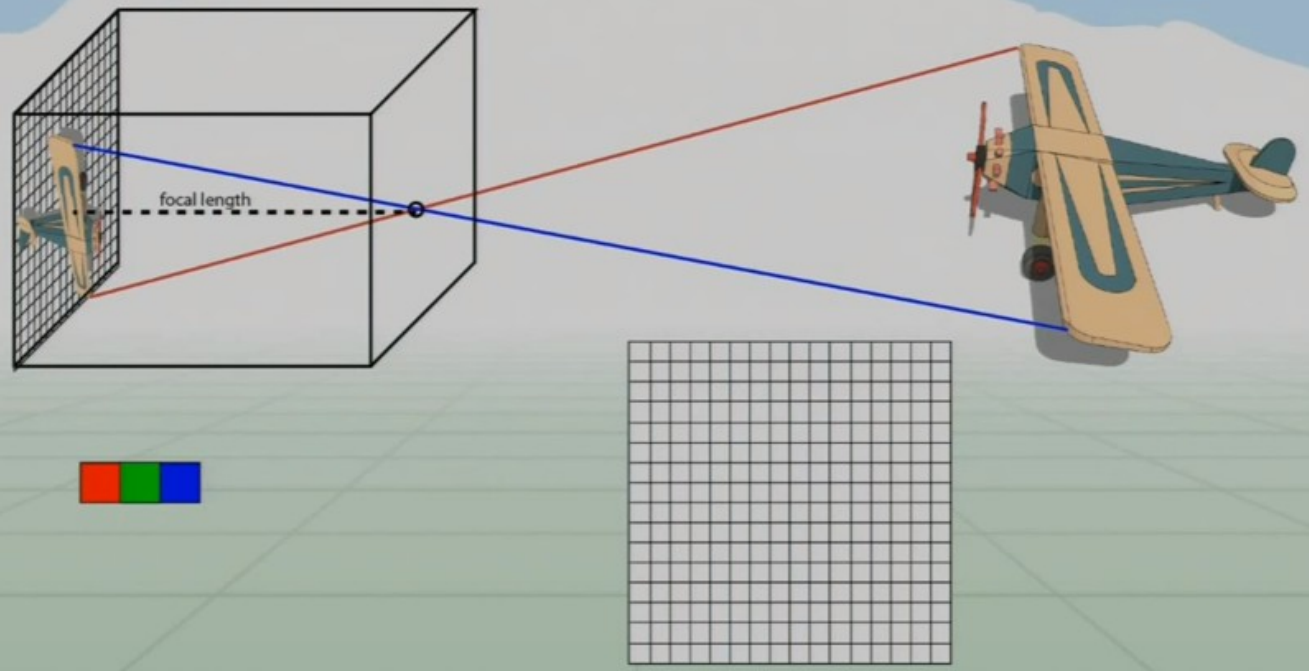


sRGB: most widely used colorspace

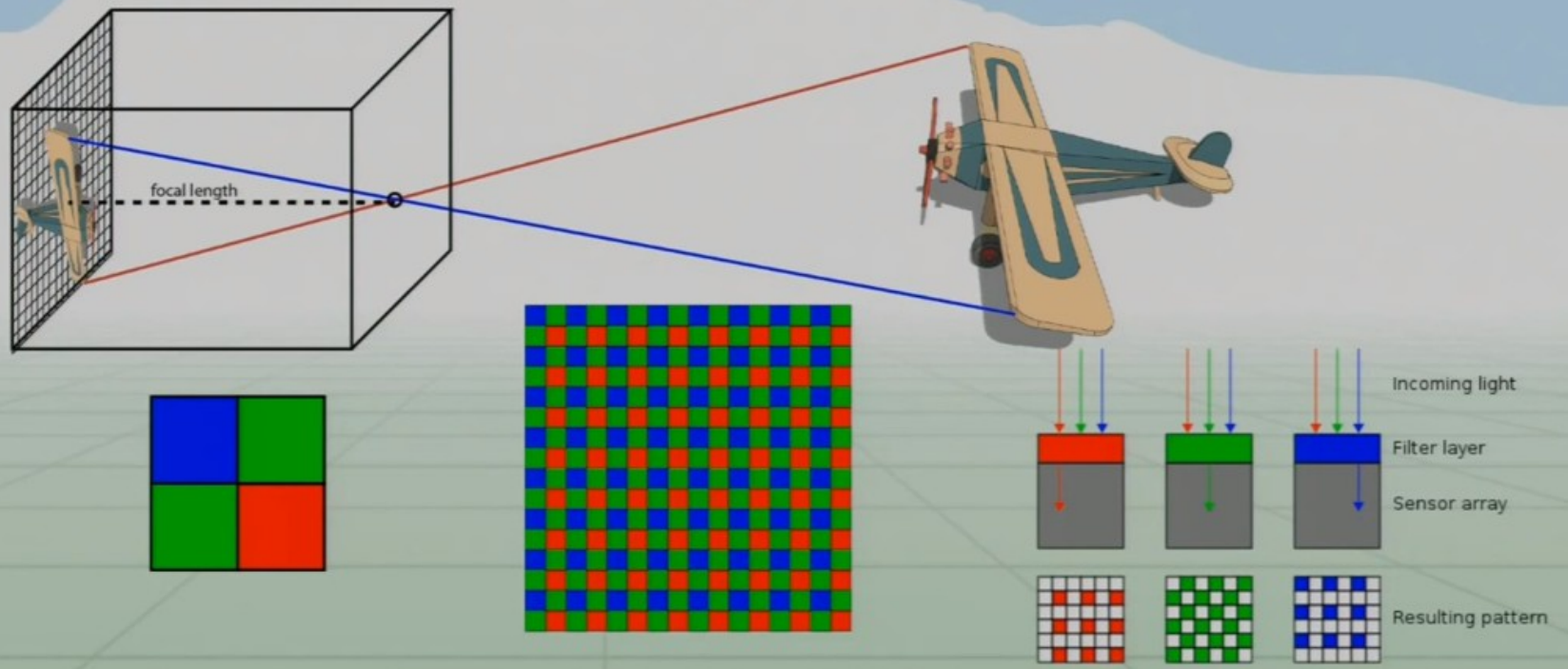




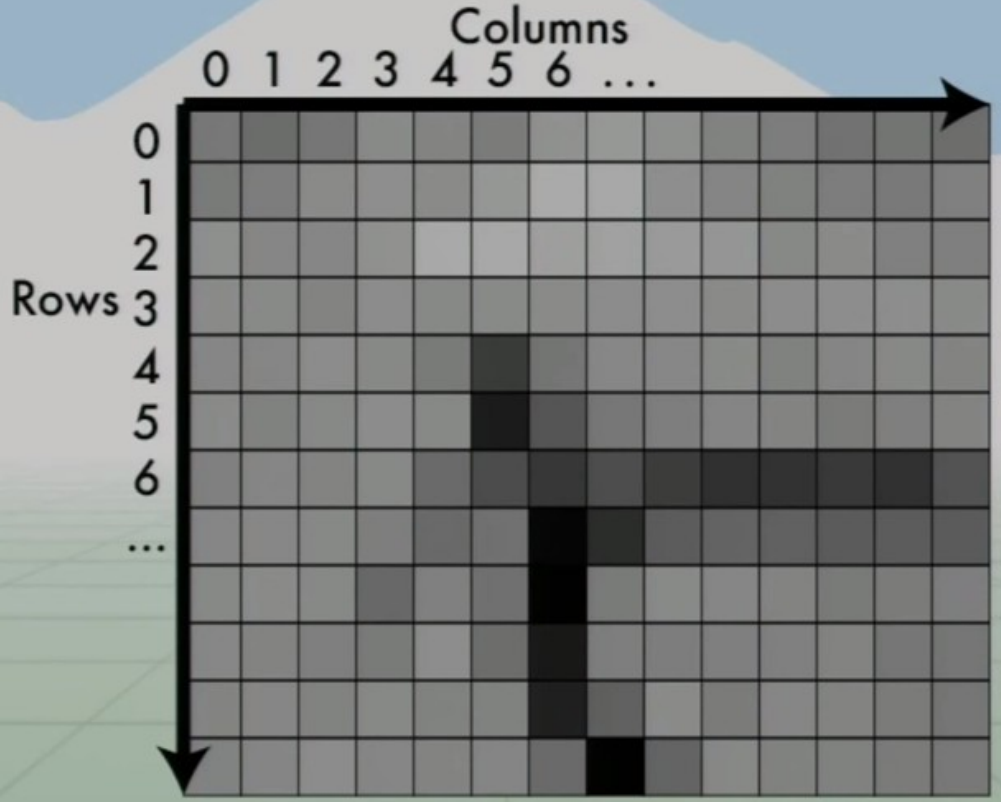
How do we record color?



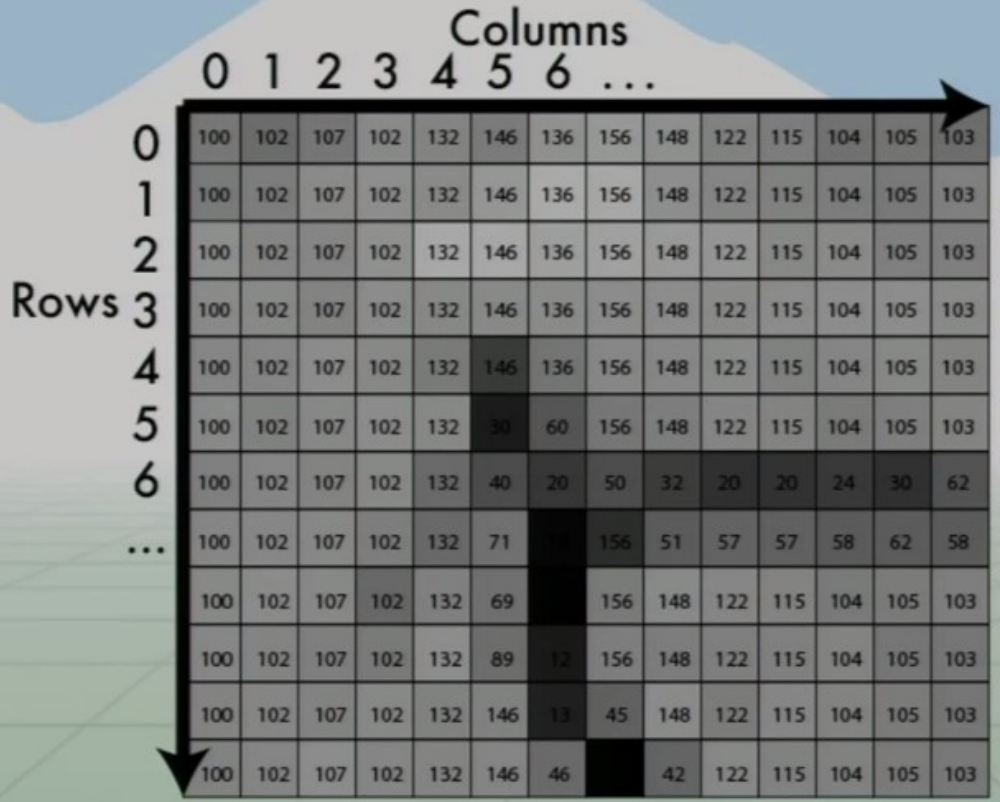
Bayer pattern for CMOS sensors



An image is a matrix of light

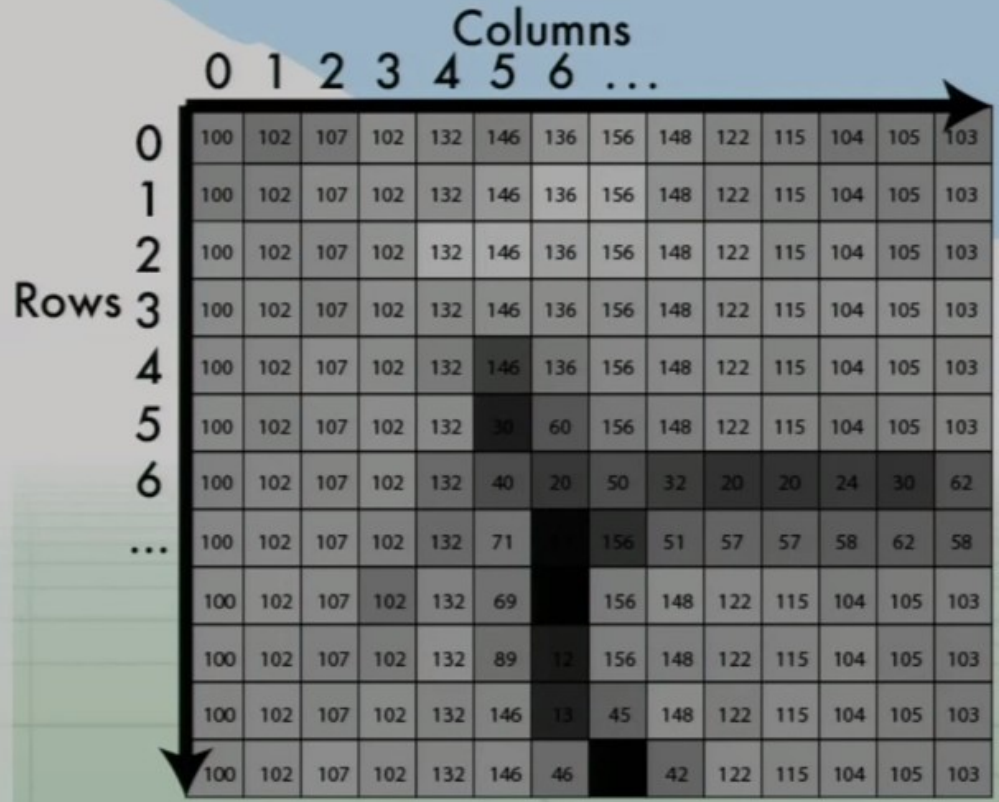


Values in matrix = how much light

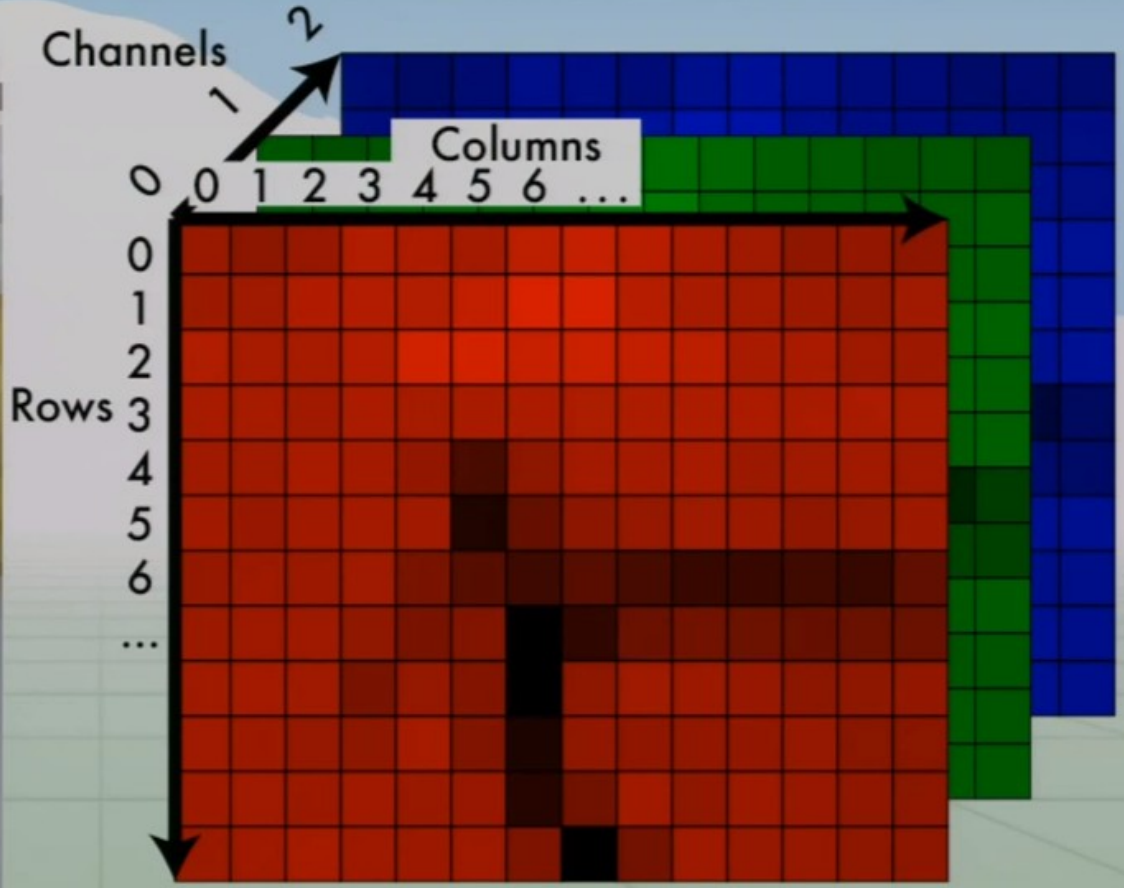


Values in matrix = how much light

- Higher = more light
- Lower = less light
- Bounded
  - No light = 0
  - Sensor/device limit = max
  - Typical ranges:
    - [0-255], fit into byte
    - [0-1], floating point
- Called pixels



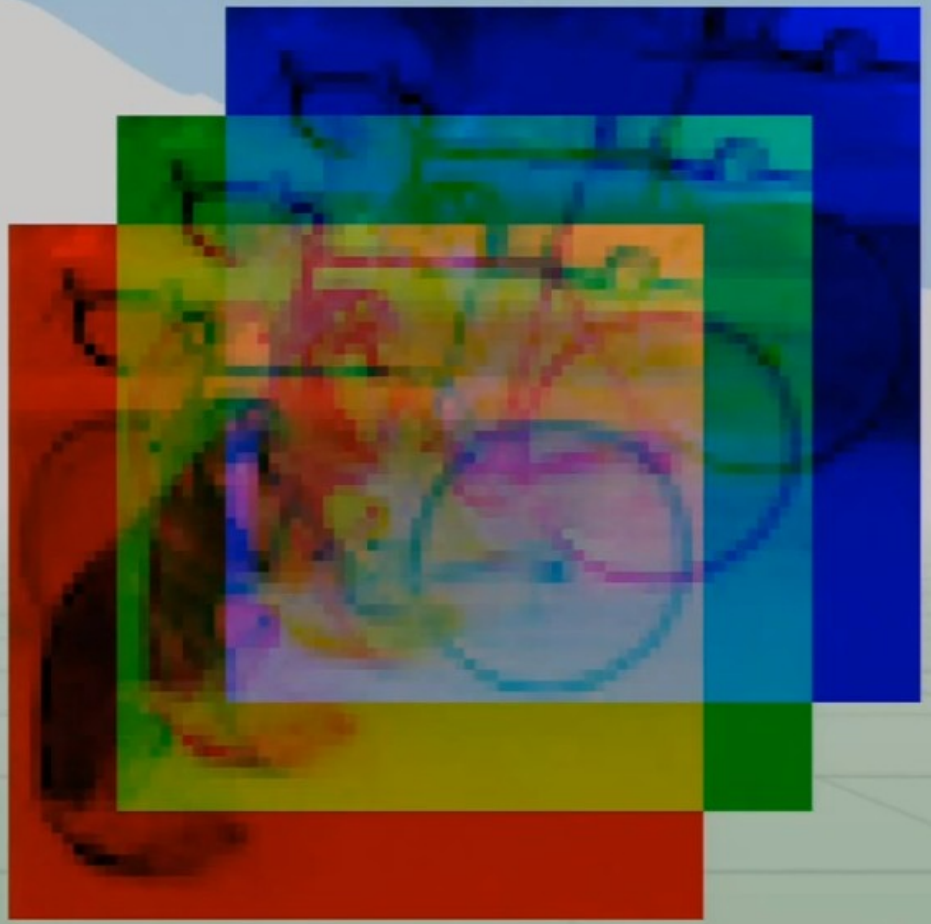
Color image: 3d tensor in colorspace



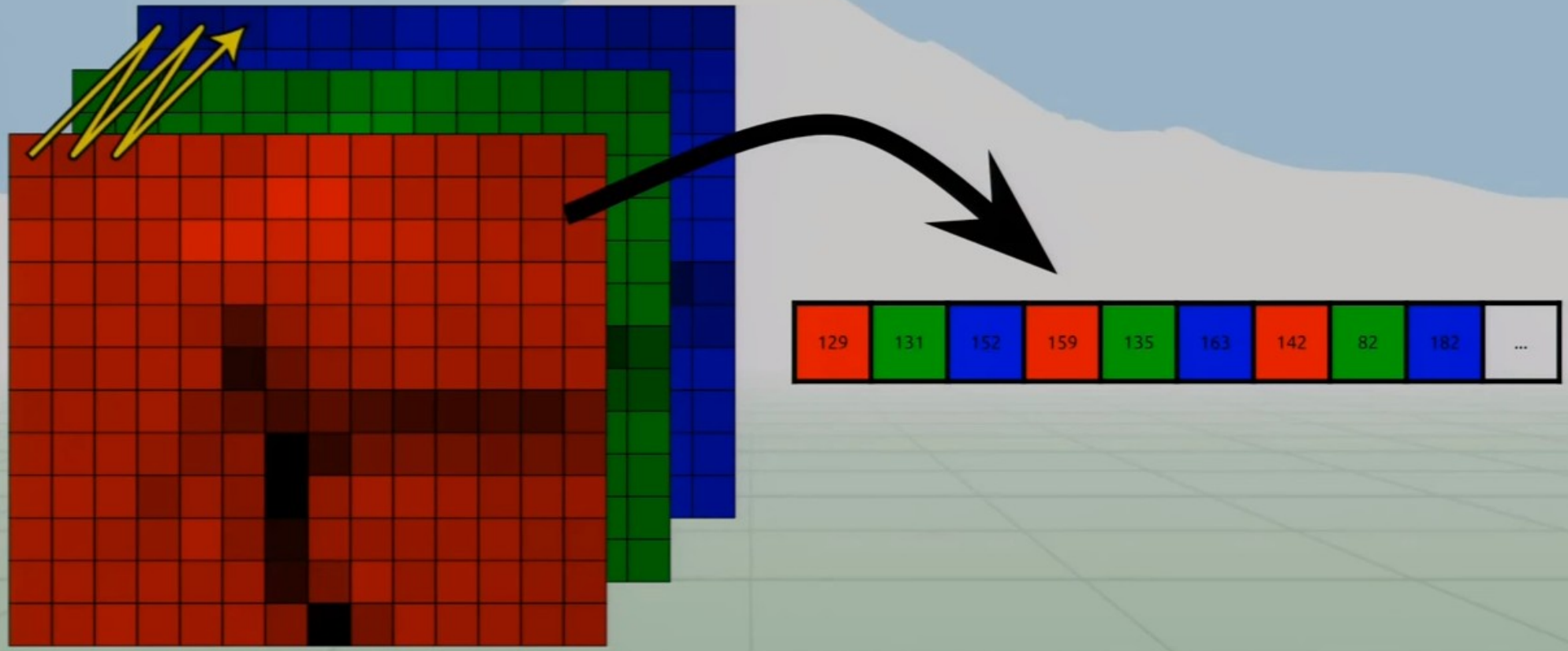
RGB information in separate “channels”

Remember: we can match “real” colors using a mix of primaries.

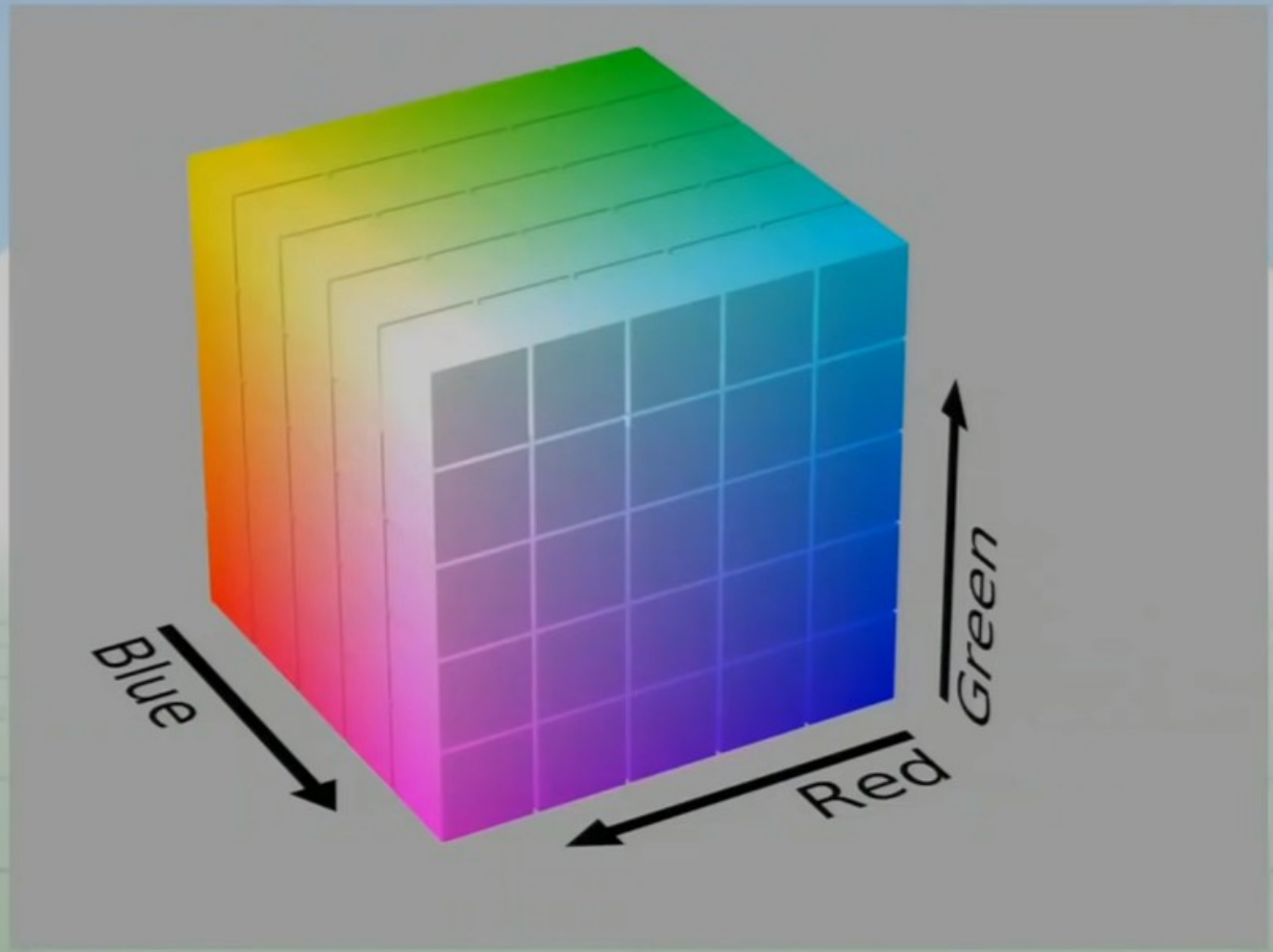
Each channel encodes one primary. Adding the light produced from each primary mimics the original color.



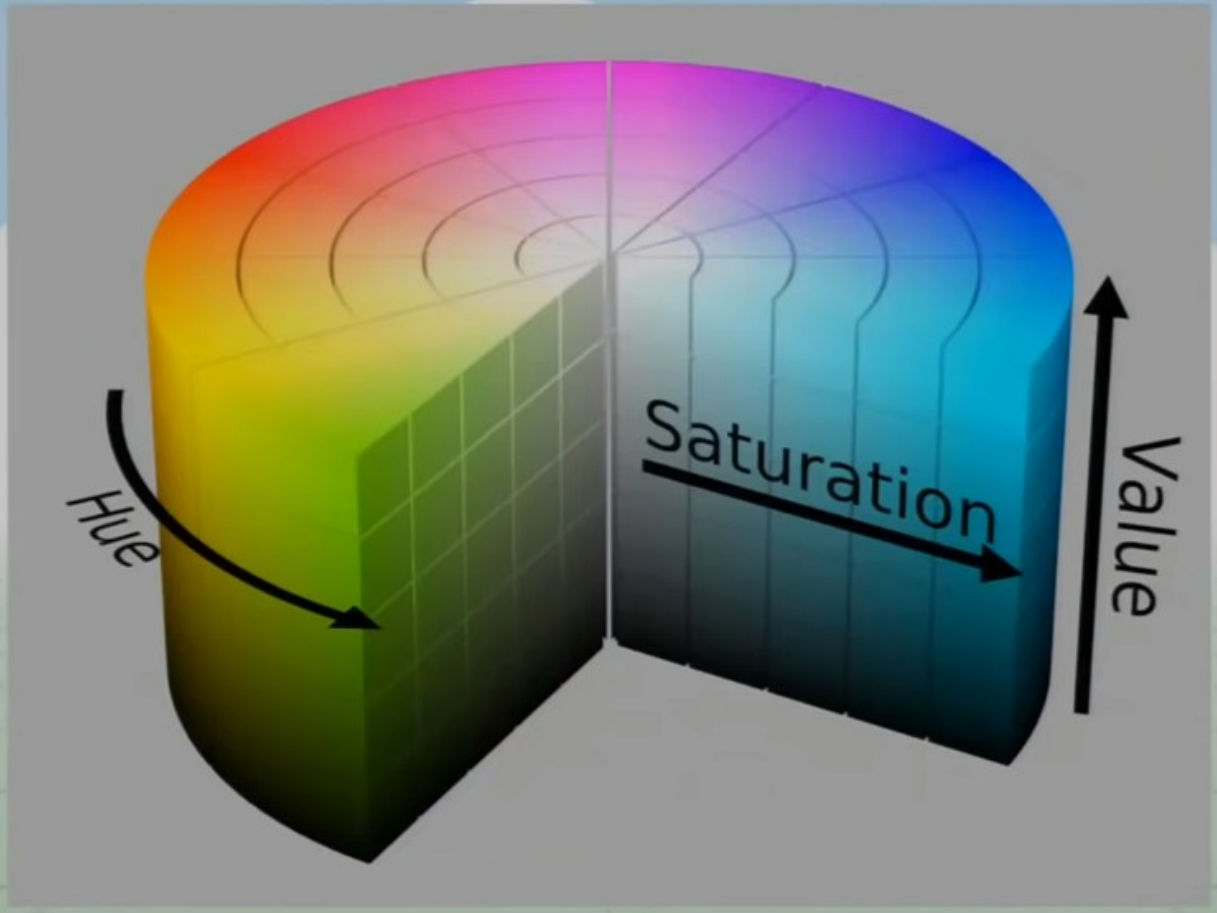
HWC: channels interleaved



RGB is a cube...

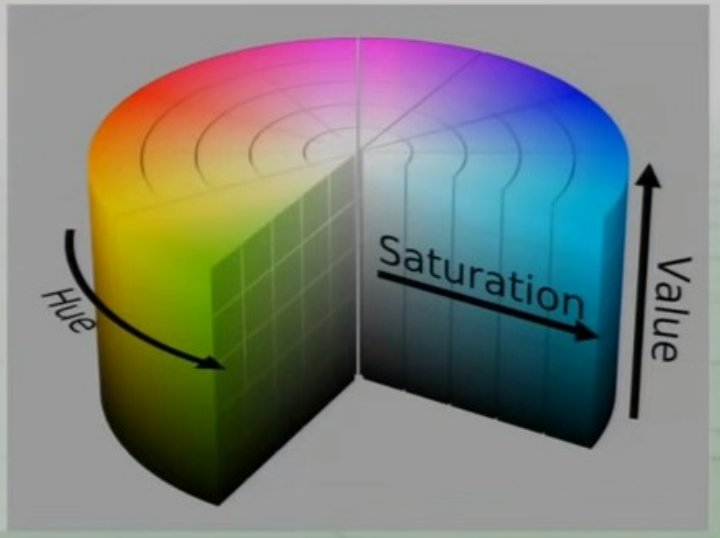


Hue, Saturation, Value: cylinder!

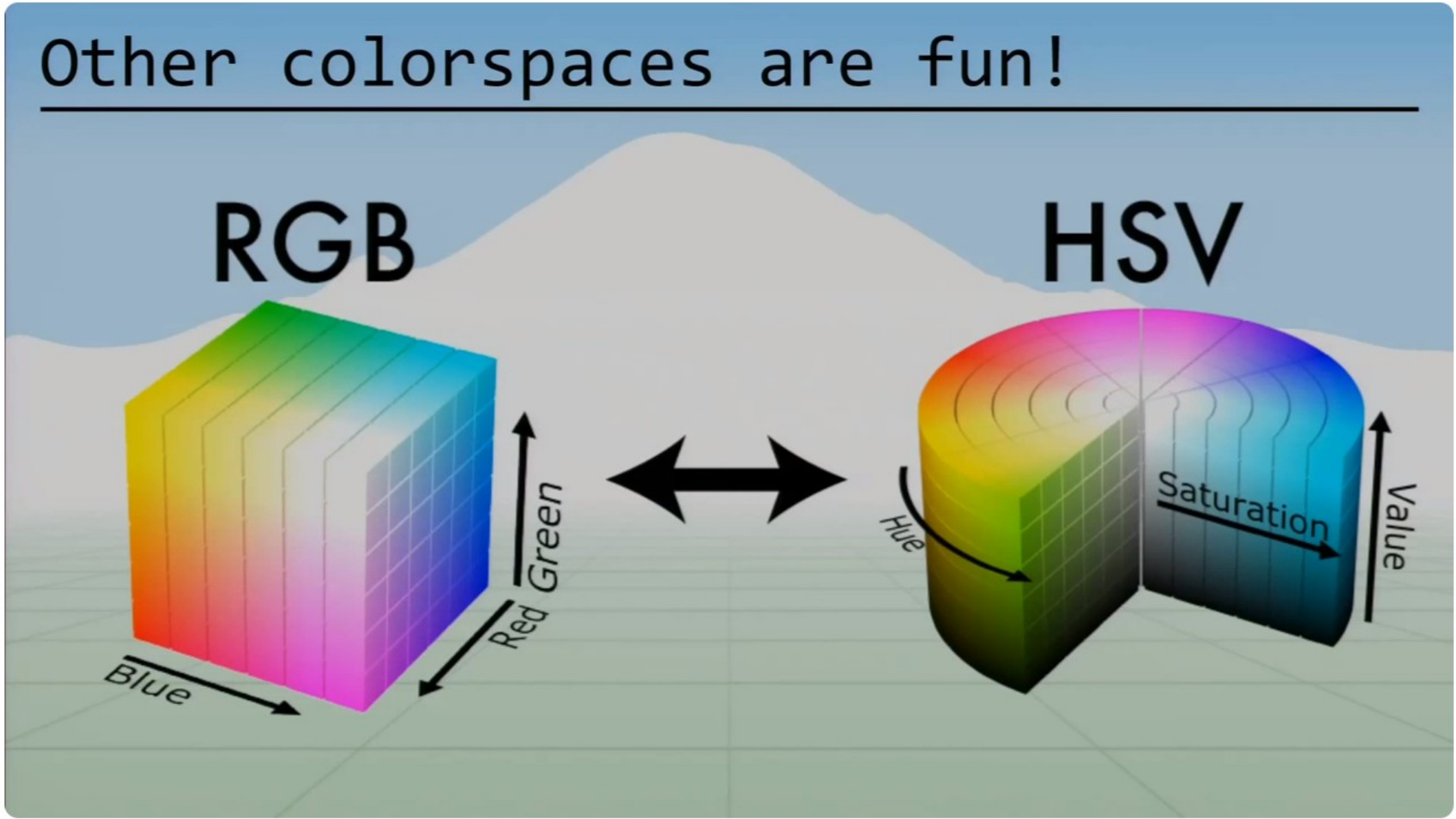


Hue, Saturation, Value

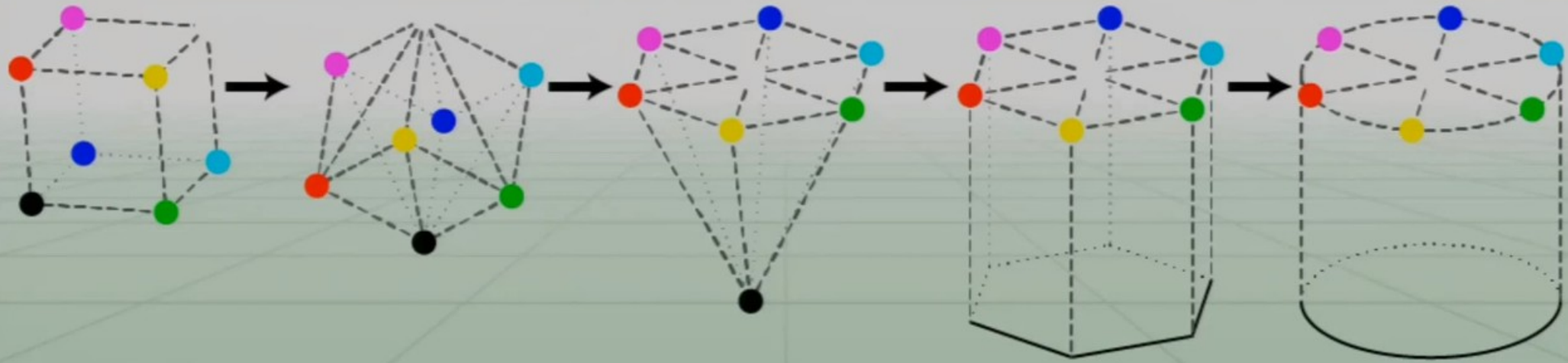
- Different model based on perception of light
- Hue: what color
- Saturation: how much color
- Value: how bright
- Allows easy image transforms
  - Shift the hue
  - Increase saturation



Other colorspaces are fun!



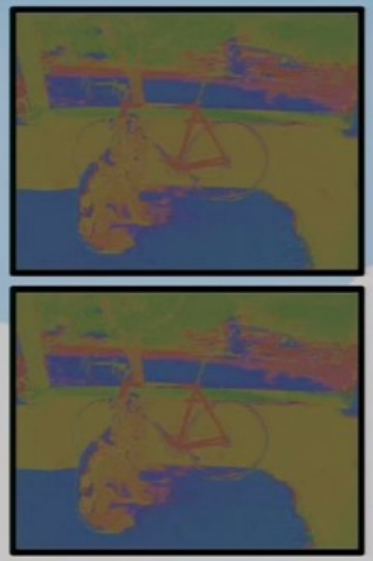
Geometric HSV to RGB:



Still 3d tensor, different info

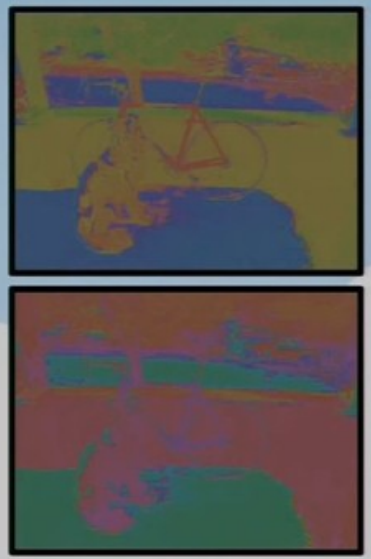
Hue Saturation Value

More saturation = intense colors



2x

Shift hue = shift colors



-.2