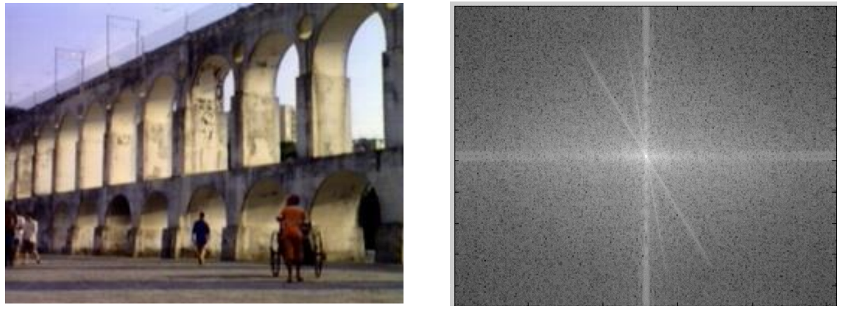
Recap of Filtering

- Linear filtering is dot product at each position
  - Not a matrix multiplication
  - Can smooth, sharpen, translate (among many other uses)

$$\frac{1}{9}\begin{bmatrix}1 & 1 & 1\\ 1 & 1 & 1\\ 1 & 1 & 1\end{bmatrix}$$

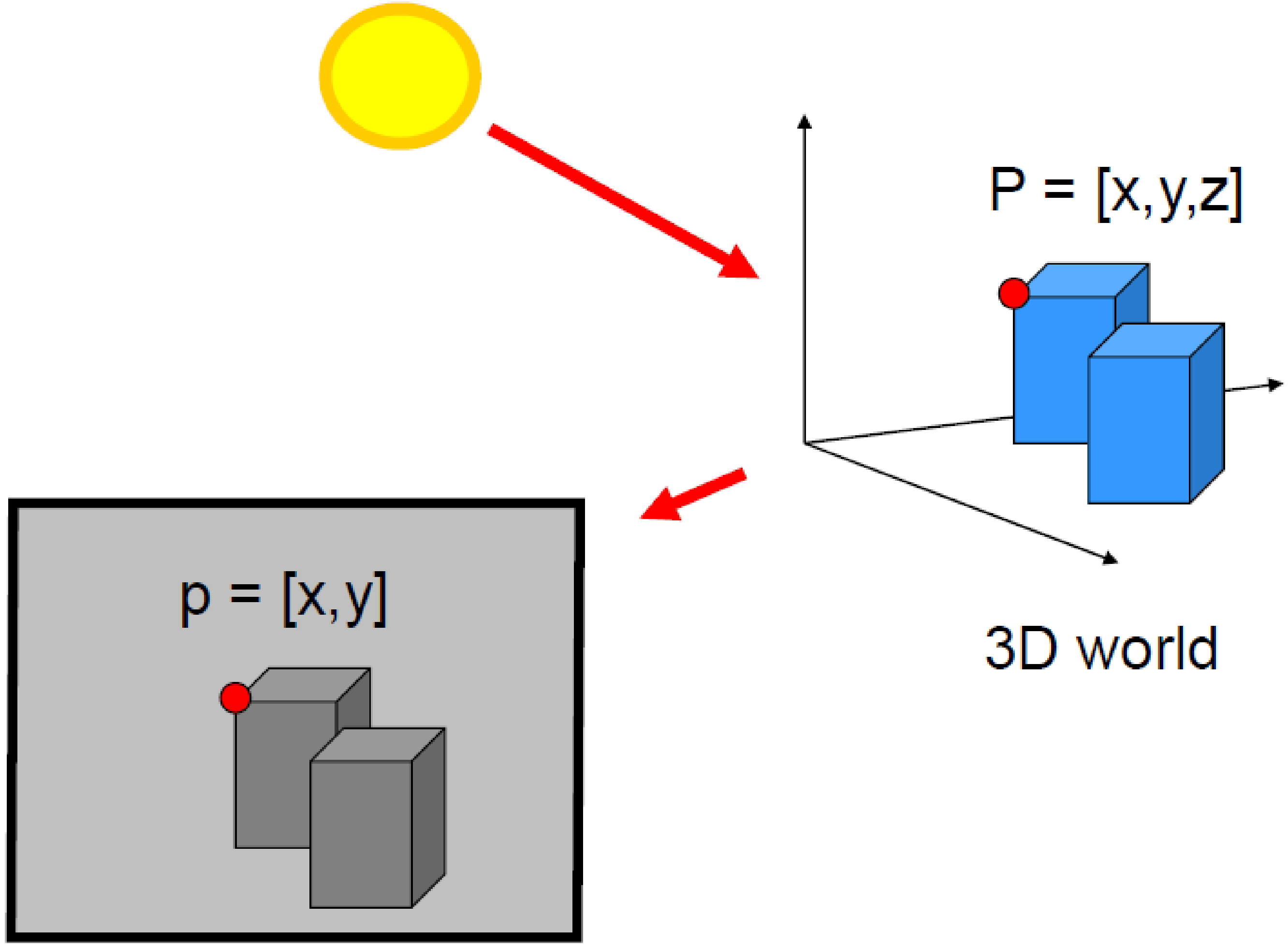
- We can use the Fourier transform to represent images in the frequency domain.
  - Filtering in the spatial domain is multiplication in the frequency domain.



This lecture

- Image Formation
- Biological Vision
- Light and Color

From the 3D to 2D



P = [x,y,z]

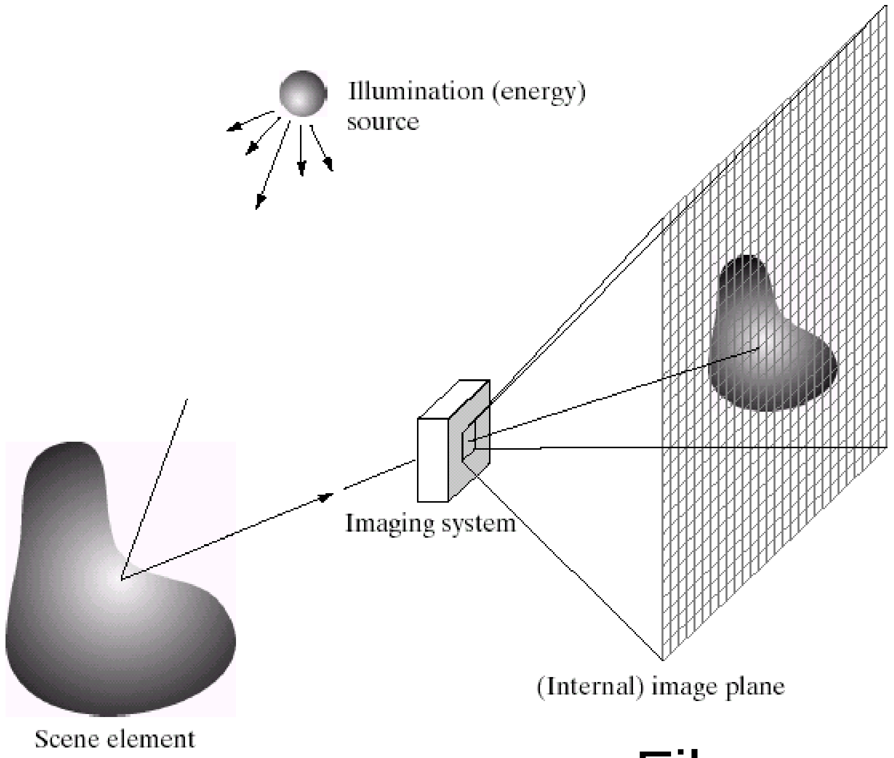
3D world

p = [x,y]

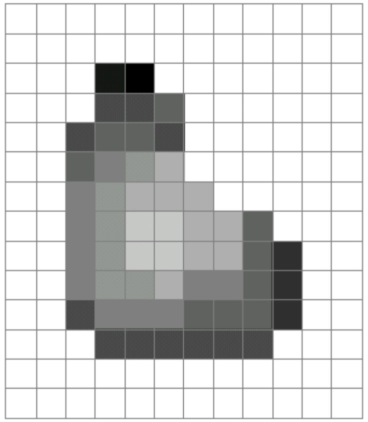
Image

Slide credit Fei Fei Li

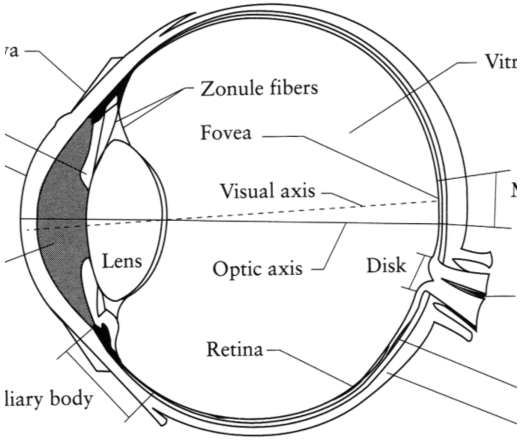
Image Formation



Film



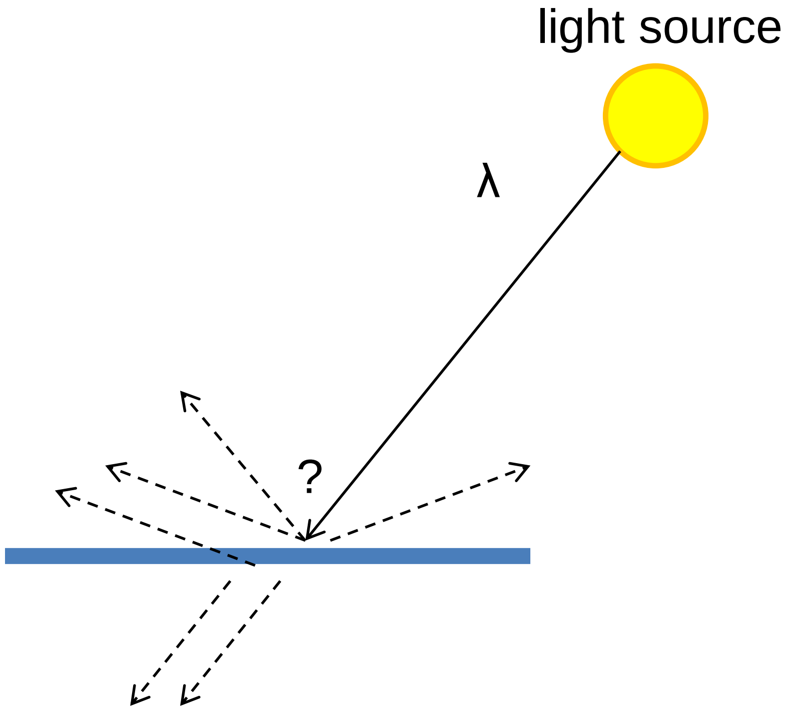
Digital Camera



The Eye

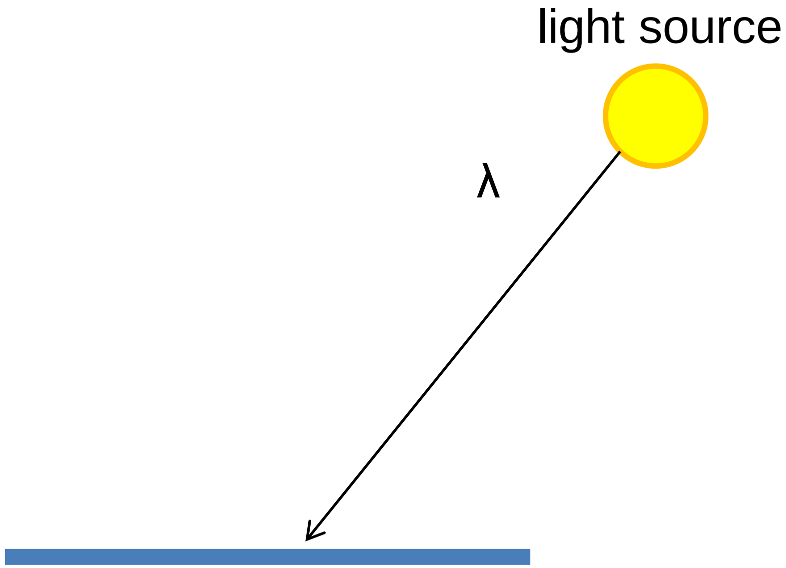
A photon’s life choices

- Absorption
- Diffusion
- Reflection
- Transparency
- Refraction
- Fluorescence
- Subsurface scattering
- Phosphorescence
- Interreflection



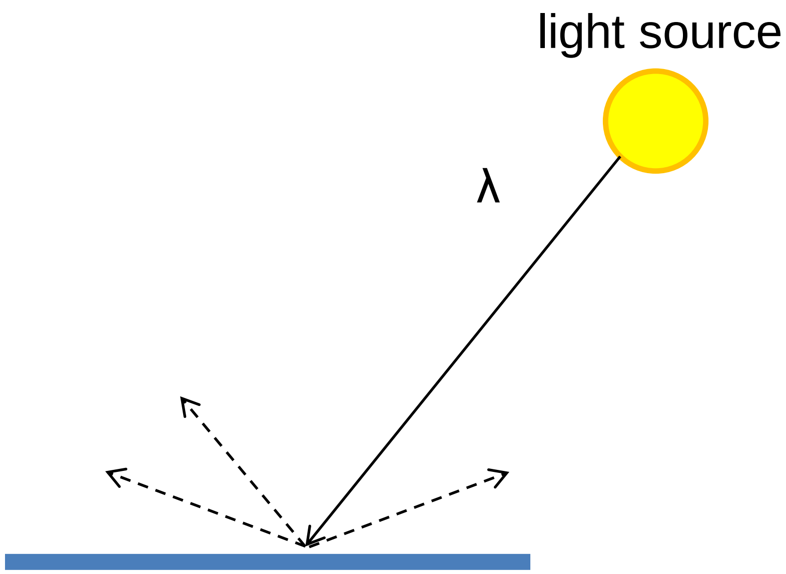
A photon's life choices

- **Absorption**
- Diffusion
- Reflection
- Transparency
- Refraction
- Fluorescence
- Subsurface scattering
- Phosphorescence
- Interreflection



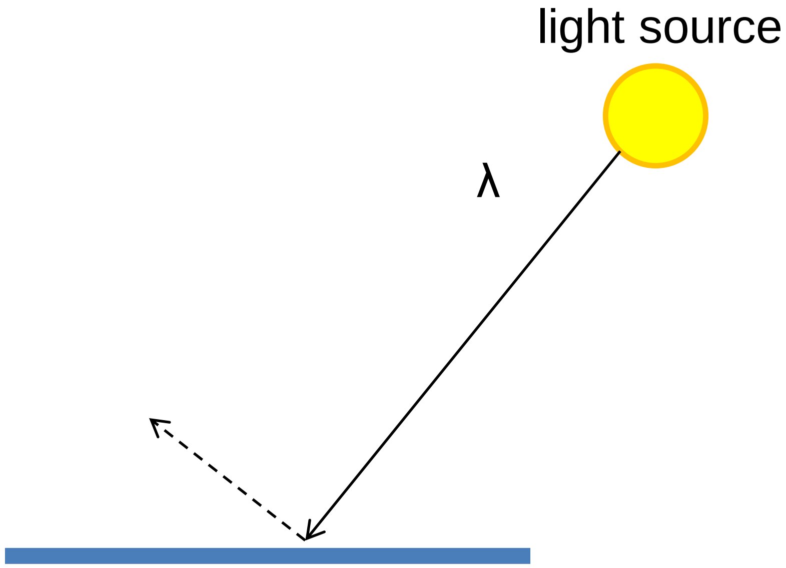
A photon’s life choices

- Absorption
- **Diffuse Reflection**
- Reflection
- Transparency
- Refraction
- Fluorescence
- Subsurface scattering
- Phosphorescence
- Interreflection



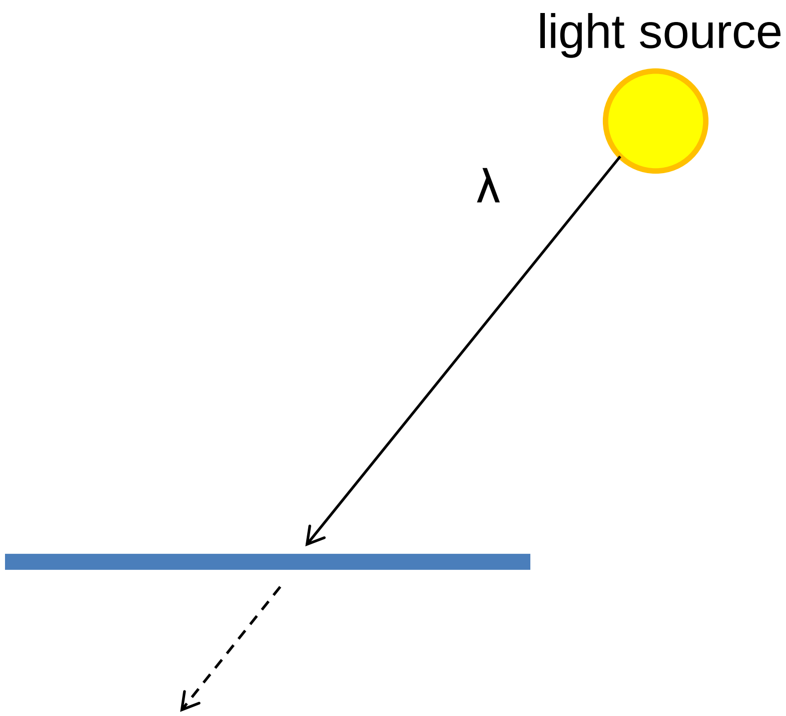
A photon's life choices

- Absorption
- Diffusion
- **Specular Reflection**
- Transparency
- Refraction
- Fluorescence
- Subsurface scattering
- Phosphorescence
- Interreflection



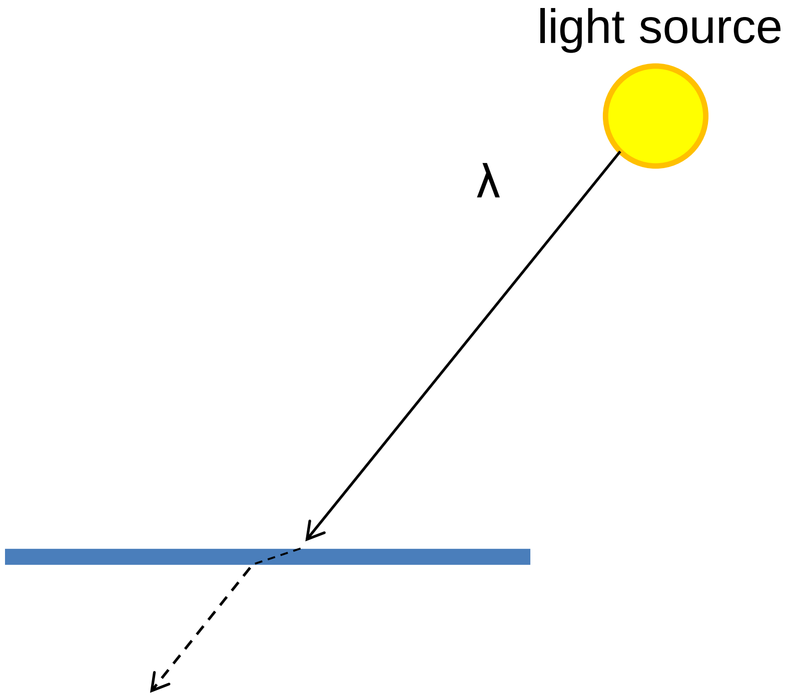
A photon’s life choices

- Absorption
- Diffusion
- Reflection
- **Transparency**
- Refraction
- Fluorescence
- Subsurface scattering
- Phosphorescence
- Interreflection



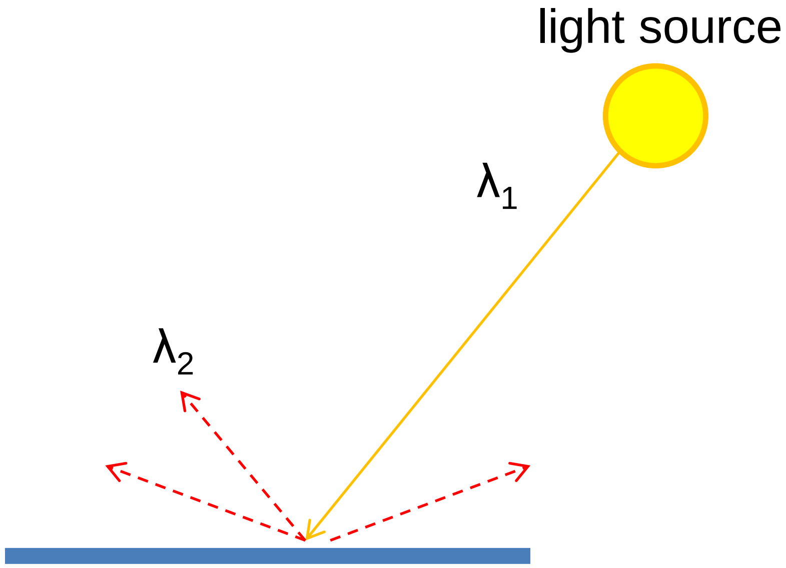
A photon's life choices

- Absorption
- Diffusion
- Reflection
- Transparency
- **Refraction**
- Fluorescence
- Subsurface scattering
- Phosphorescence
- Interreflection



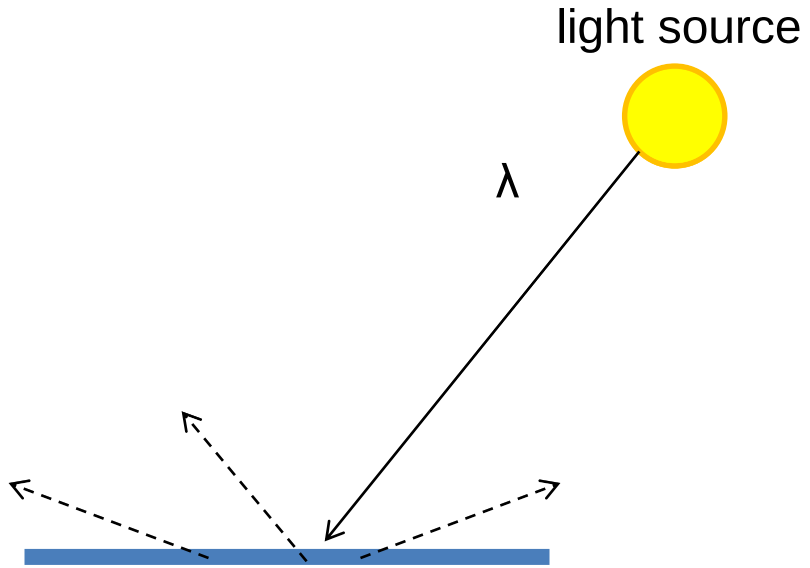
A photon's life choices

- Absorption
- Diffusion
- Reflection
- Transparency
- Refraction
- **Fluorescence**
- Subsurface scattering
- Phosphorescence
- Interreflection



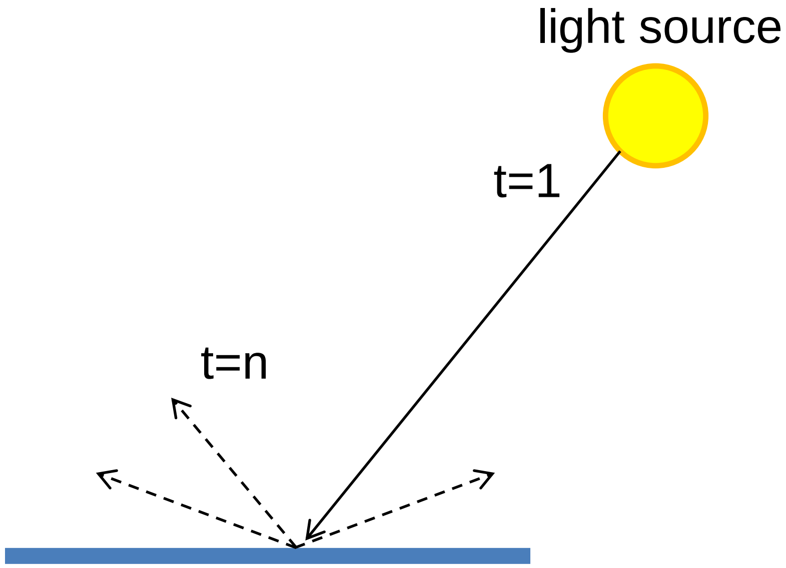
A photon’s life choices

- Absorption
- Diffusion
- Reflection
- Transparency
- Refraction
- Fluorescence
- **Subsurface scattering**
- Phosphorescence
- Interreflection



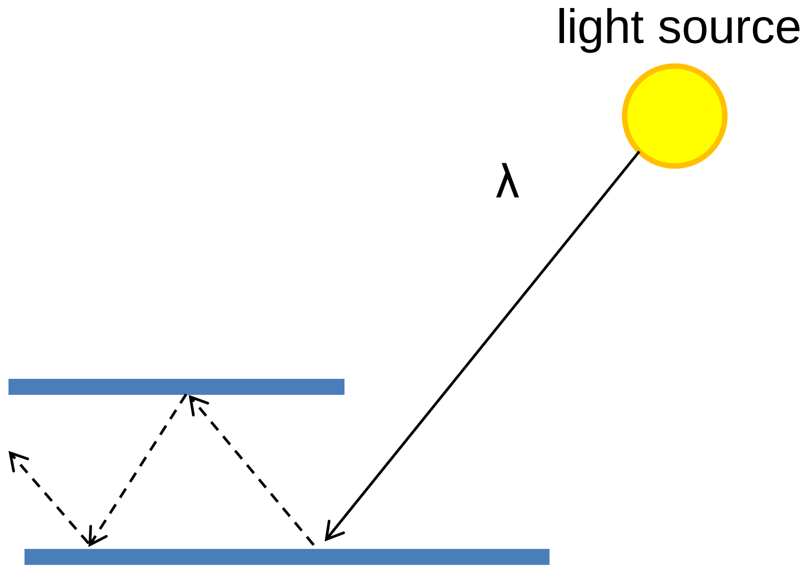
A photon’s life choices

- Absorption
- Diffusion
- Reflection
- Transparency
- Refraction
- Fluorescence
- Subsurface scattering
- **Phosphorescence**
- Interreflection



A photon’s life choices

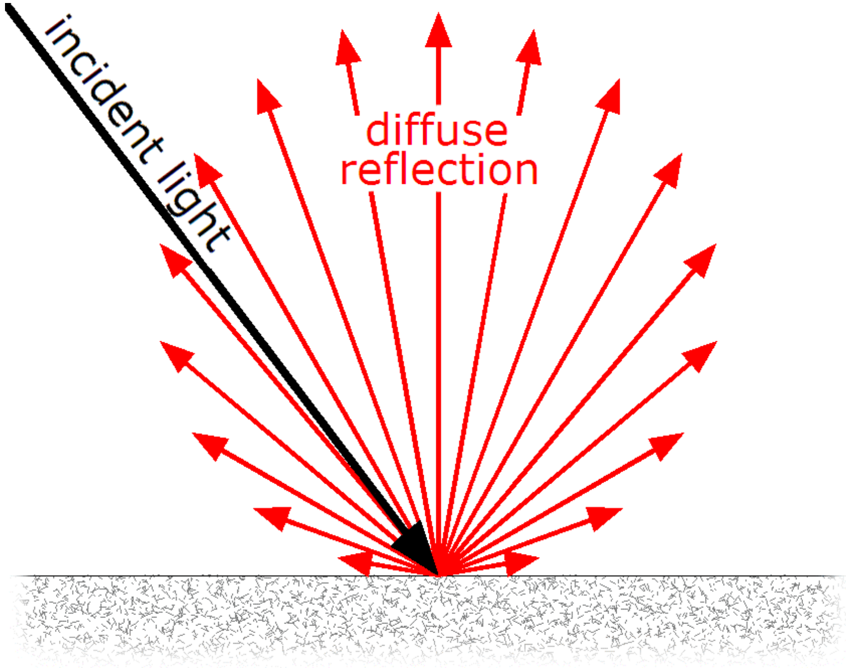
- Absorption
- Diffusion
- Reflection
- Transparency
- Refraction
- Fluorescence
- Subsurface scattering
- Phosphorescence
- **Interreflection**



(Specular Interreflection)

Lambertian Reflectance

- In computer vision, the complexity of light transport is mostly ignored.
- Surfaces are often assumed to be ideal diffuse reflectors with no dependence on viewing direction.



https://en.wikipedia.org/wiki/Lambertian_reflectance

Digital camera

- A digital camera replaces film with a sensor array
  - Each cell in the array is light-sensitive diode that converts photons to electrons
  - Two common types
    - Charge Coupled Device (CCD)
    - CMOS
  - http://electronics.howstuffworks.com/digital-camera.htm

Slide by Steve Seitz

Sensor Array

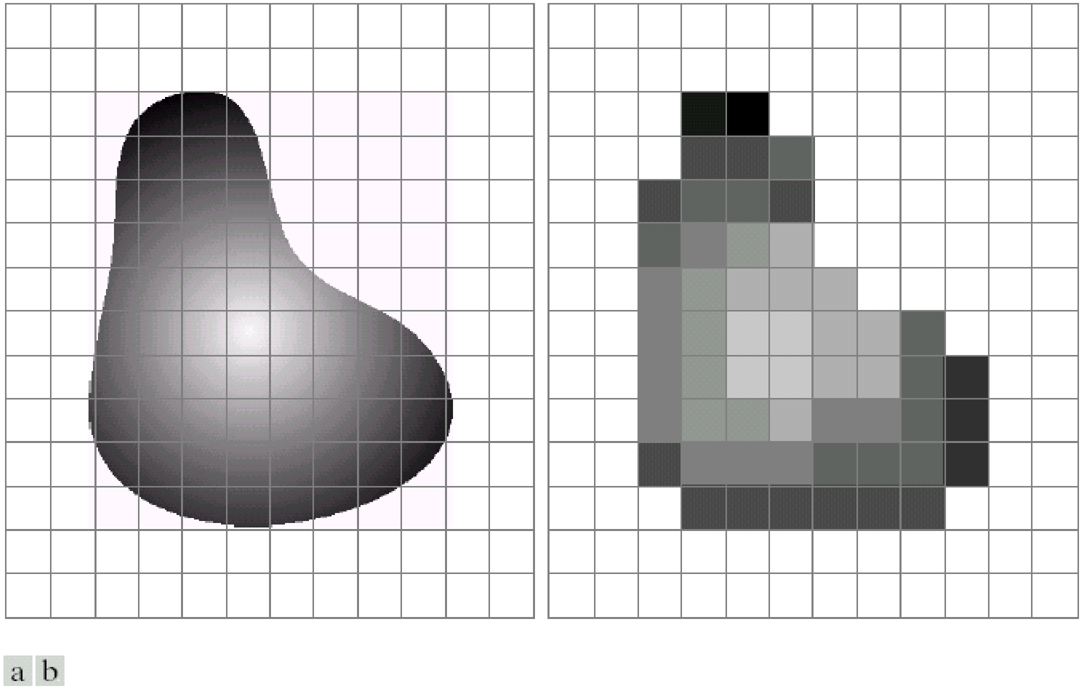
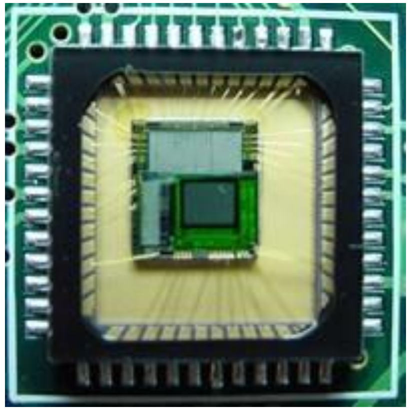
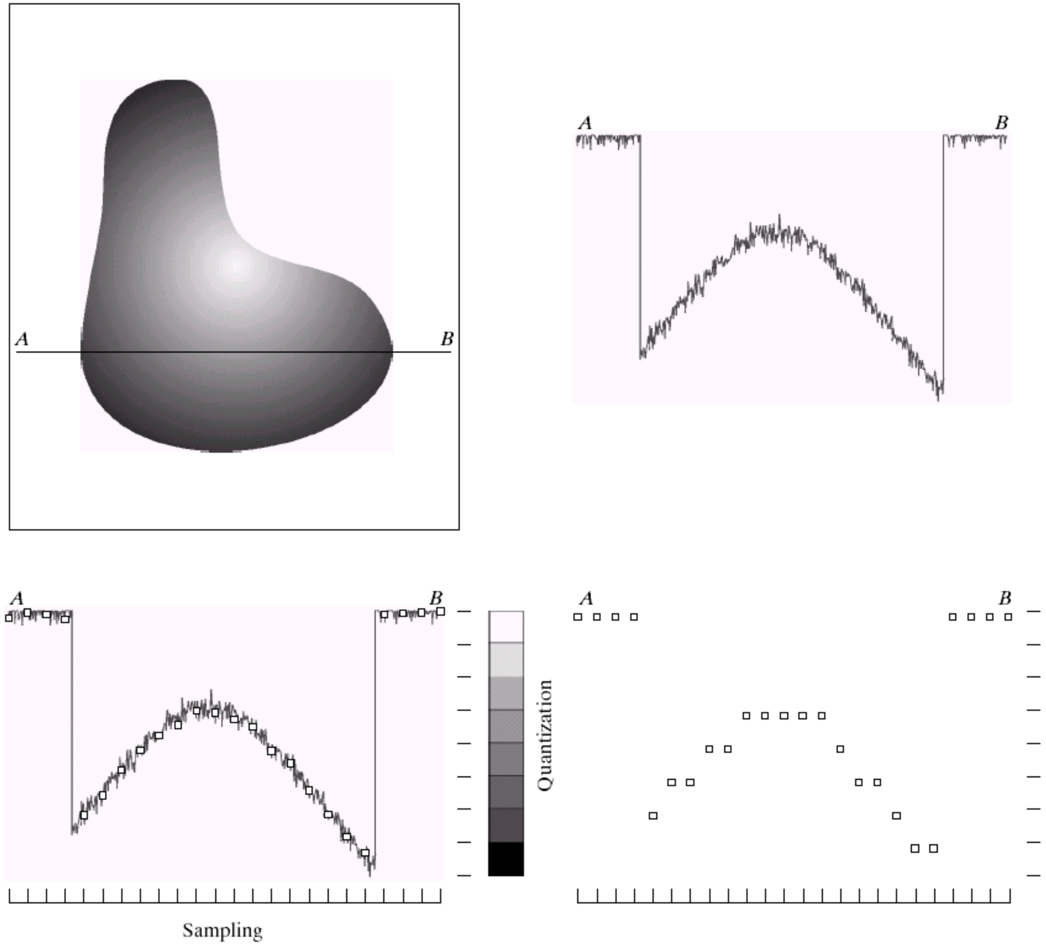


FIGURE 2.17 (a) Continuos image projected onto a sensor array. (b) Result of image sampling and quantization.



CMOS sensor

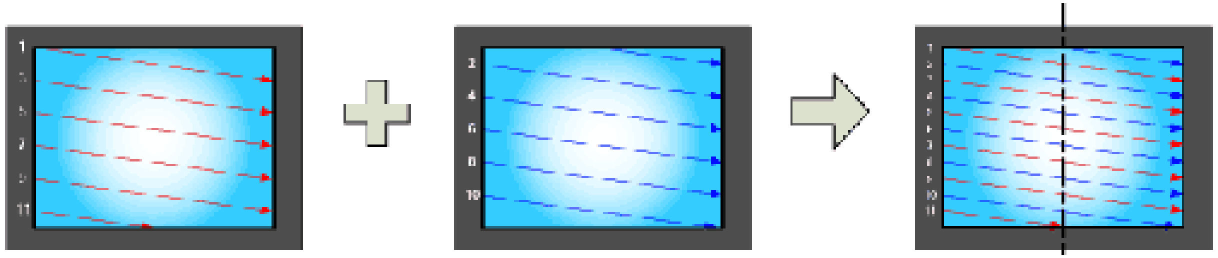
Sampling and Quantization



a b
c d

FIGURE 2.16 Generating a digital image. (a) Continuous image. (b) A scan line from *A* to *B* in the continuous image, used to illustrate the concepts of sampling and quantization. (c) Sampling and quantization. (d) Digital scan line.

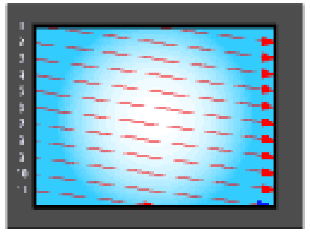
Interlace vs. progressive scan



1st field: Odd field

2nd field: Even field

One complete frame
using interlaced scanning



One complete frame
using progressive scanning

http://www.axis.com/products/video/camera/progressive_scan.htm

Slide by Steve Seitz

Progressive scan or Global shutter

http://www.axis.com/products/video/camera/progressive_scan.htm

Slide by Steve Seitz

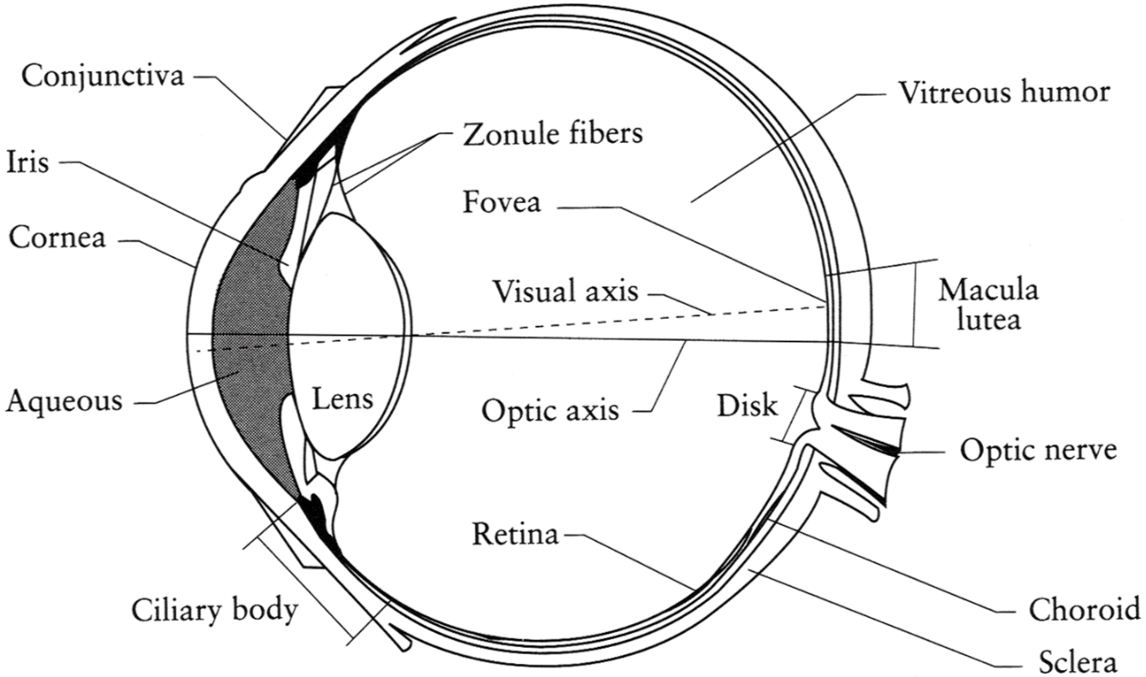
Interlaced

http://www.axis.com/products/video/camera/progressive_scan.htm

Slide by Steve Seitz

Rolling Shutter

The Eye



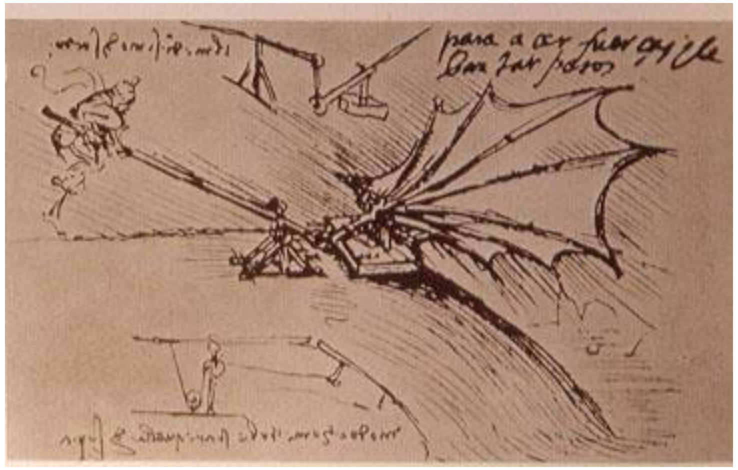
- The human eye is a camera!
  - **Iris** - colored annulus with radial muscles
  - **Pupil** - the hole (aperture) whose size is controlled by the iris
  - What’s the “film”?
    - photoreceptor cells (rods and cones) in the **retina**

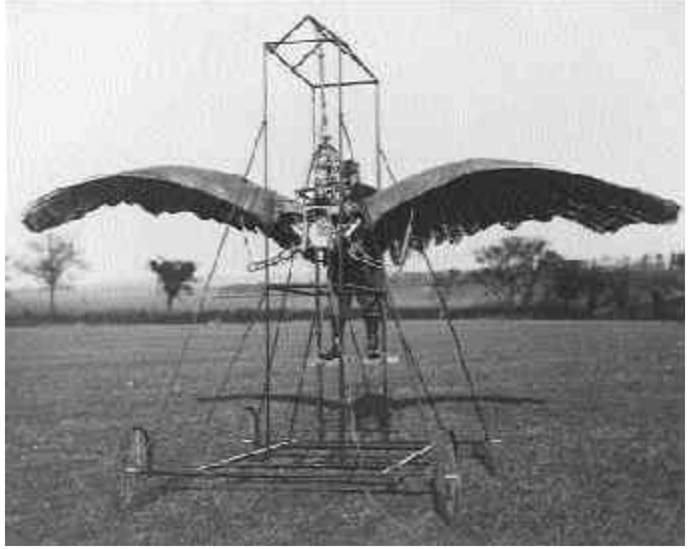
Slide by Steve Seitz

Aside: why do we care about human vision in this class?

- We don’t, necessarily.

Ornithopters





Why do we care about human vision?

- We don’t, necessarily.
- But cameras necessarily imitate the frequency response of the human eye, so we should know that much.
- Also, computer vision probably wouldn’t get as much scrutiny if biological vision (especially human vision) hadn’t proved that it was possible to make important judgements from 2d images.

Does computer vision “understand” images?

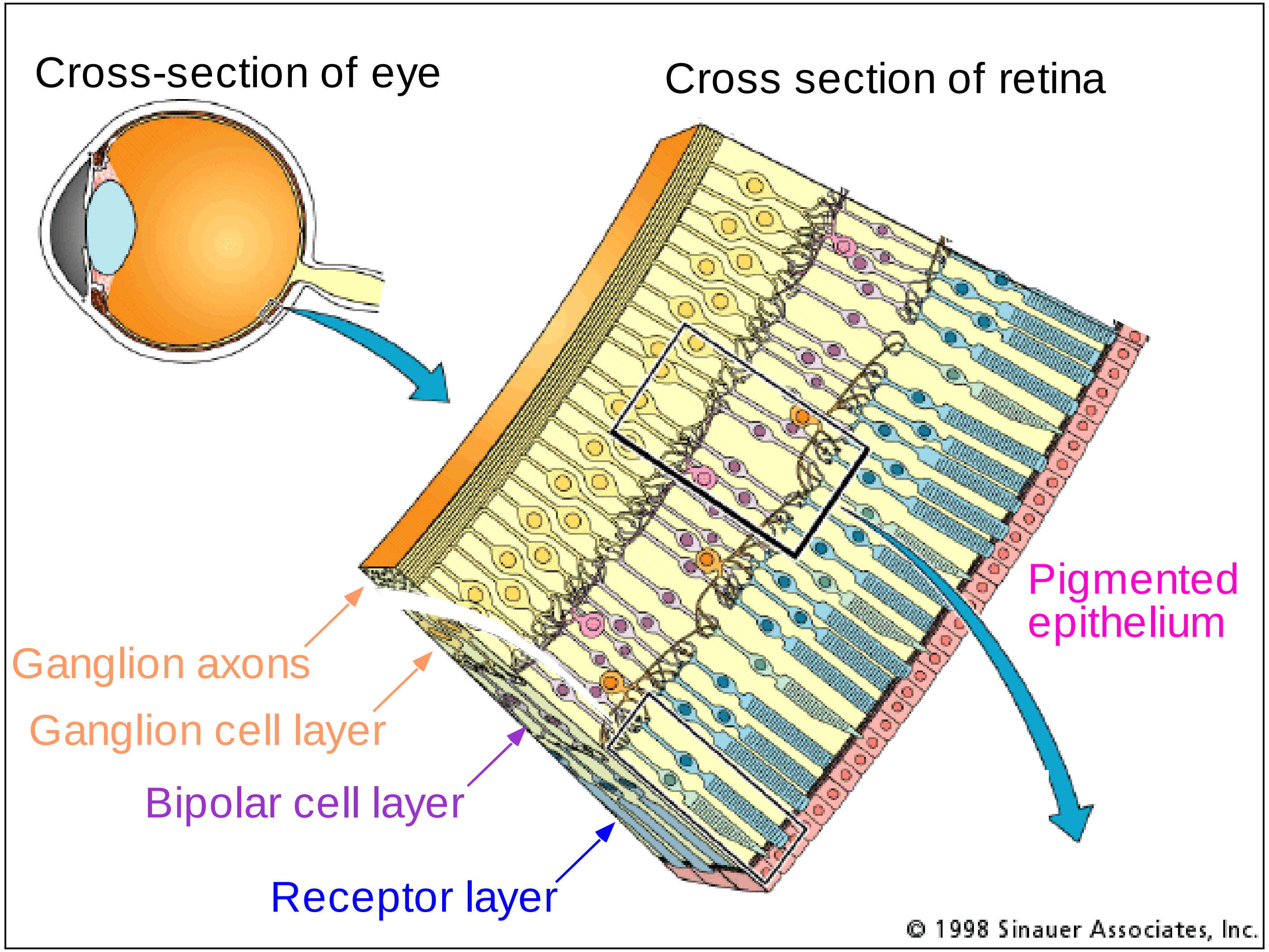
"Can machines fly?" The answer is yes, because airplanes fly.

"Can machines swim?" The answer is no, because submarines don't swim.

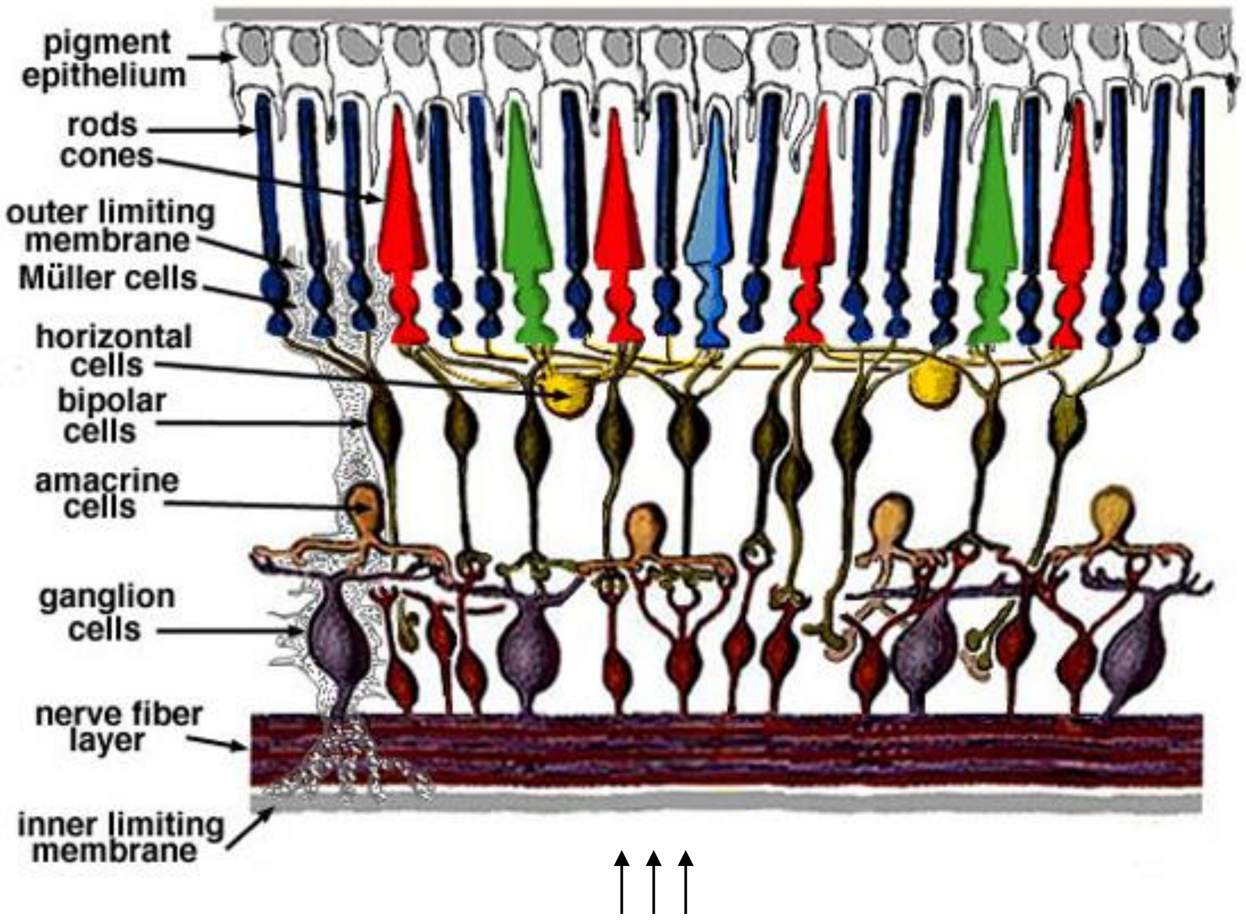
"Can machines think?" Is this question like the first, or like the second?

Source: Norvig

The Retina


Cross-section of eye
Cross section of retina
Pigmented epithelium
Ganglion axons
Ganglion cell layer
Bipolar cell layer
Receptor layer

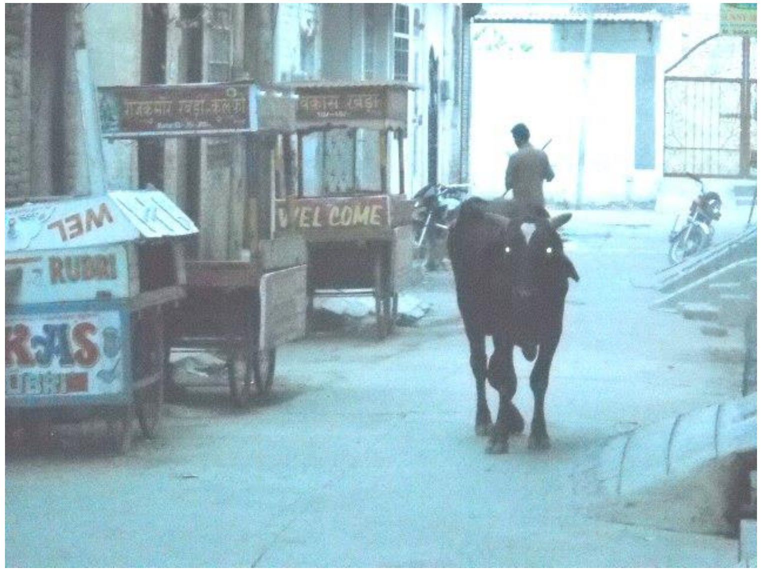
Retina up-close



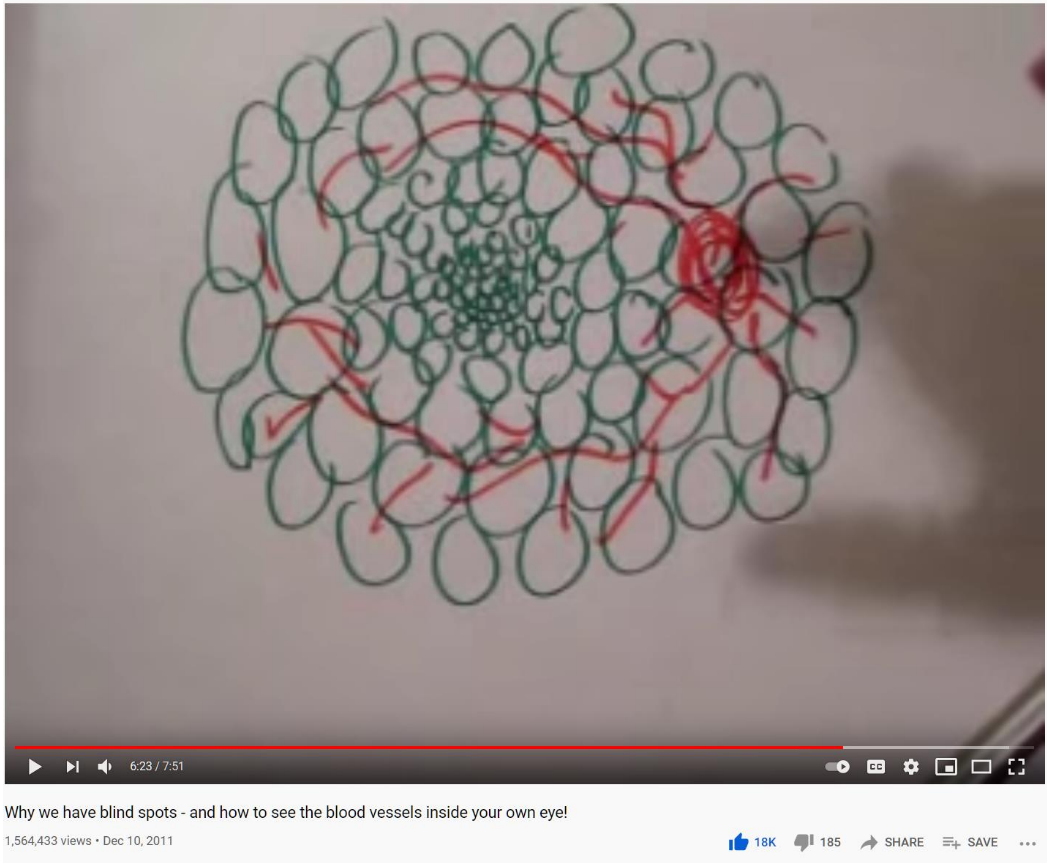
Light

What humans don’t have: tapetum lucidum

Human eyes can reflect a tiny bit and blood in the retina makes this reflection red.



Wait, the blood vessels are in front of the photoreceptors??



Why we have blind spots - and how to see the blood vessels inside your own eye!

1,564,433 views • Dec 10, 2011

https://www.youtube.com/watch?v=L_W-IXqoxHA

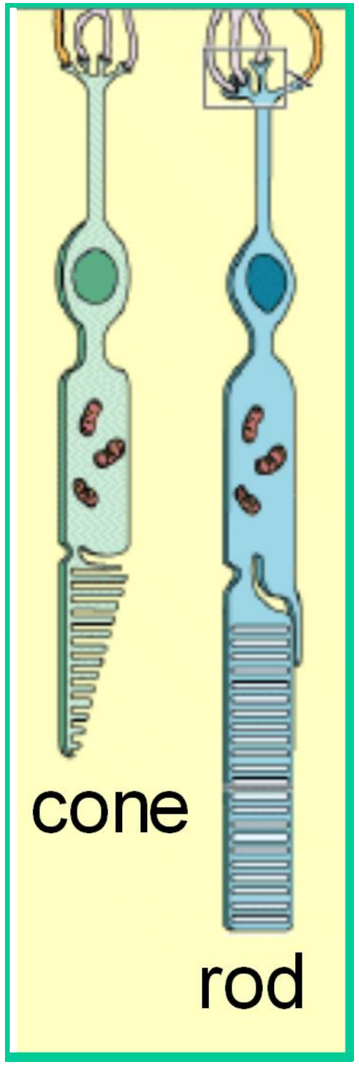
Two types of light-sensitive receptors

Cones

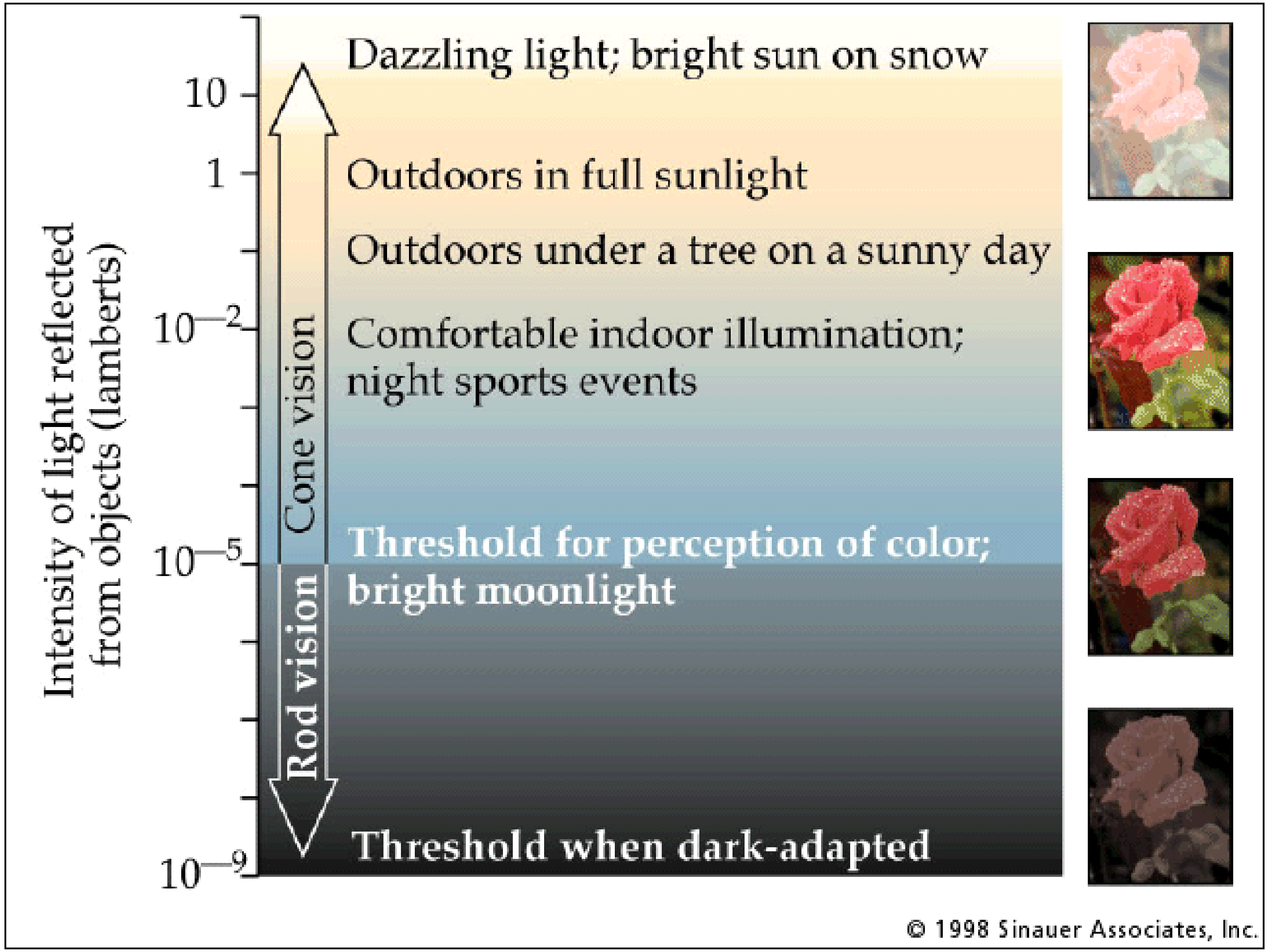
cone-shaped
less sensitive
operate in high light
color vision

Rods

rod-shaped
highly sensitive
operate at night
gray-scale vision



Rod / Cone sensitivity



Camera Gamma Curve

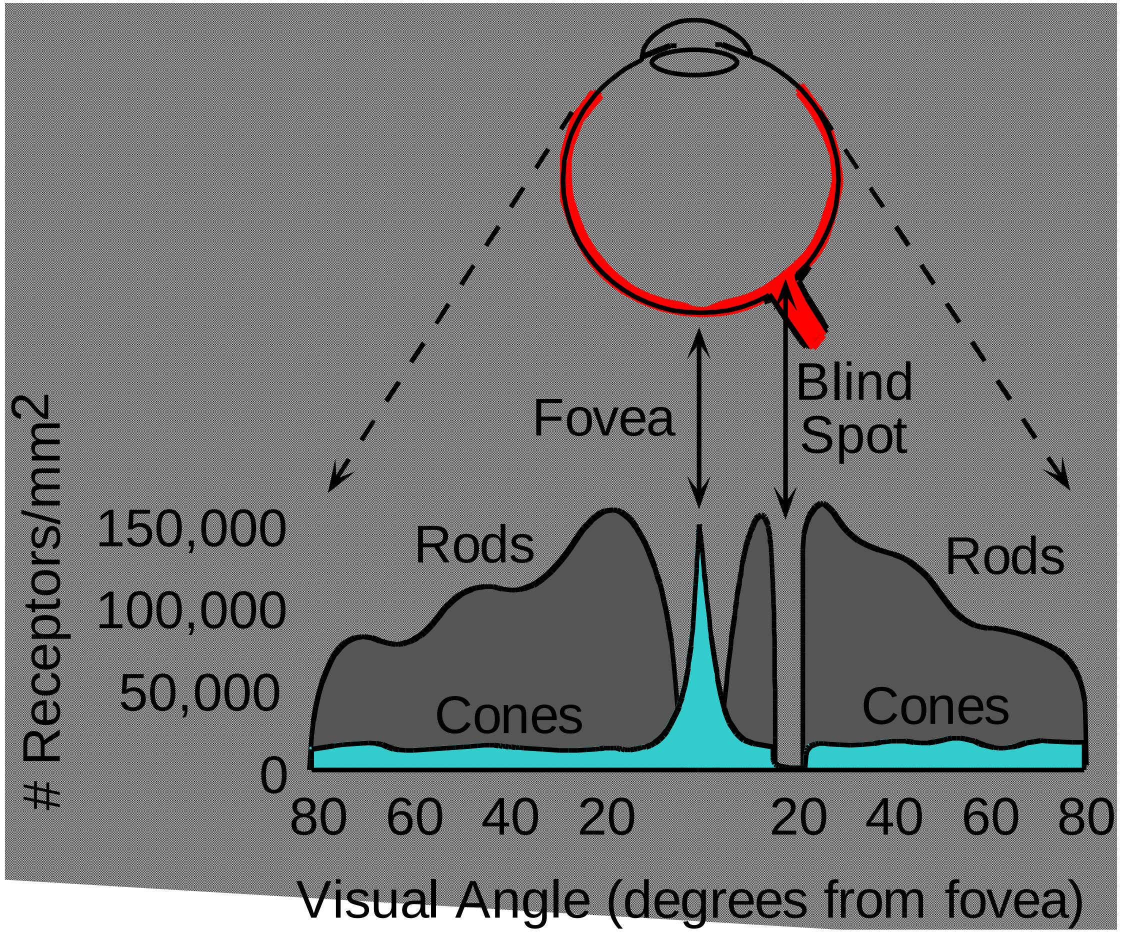
$$encoded\ brightness = measured\ brightness^{\gamma}$$

γ will typically take values less than 1

In this class (e.g. for project 1), you are manipulating *encoded* brightness values. A pixel with value of “100” is not necessarily twice as bright as a pixel with value “50”.

https://en.wikipedia.org/wiki/Gamma_correction

Distribution of Rods and Cones



Night Sky: why are there more stars off-center?

Averted vision: http://en.wikipedia.org/wiki/Averted_vision

Eye Movements

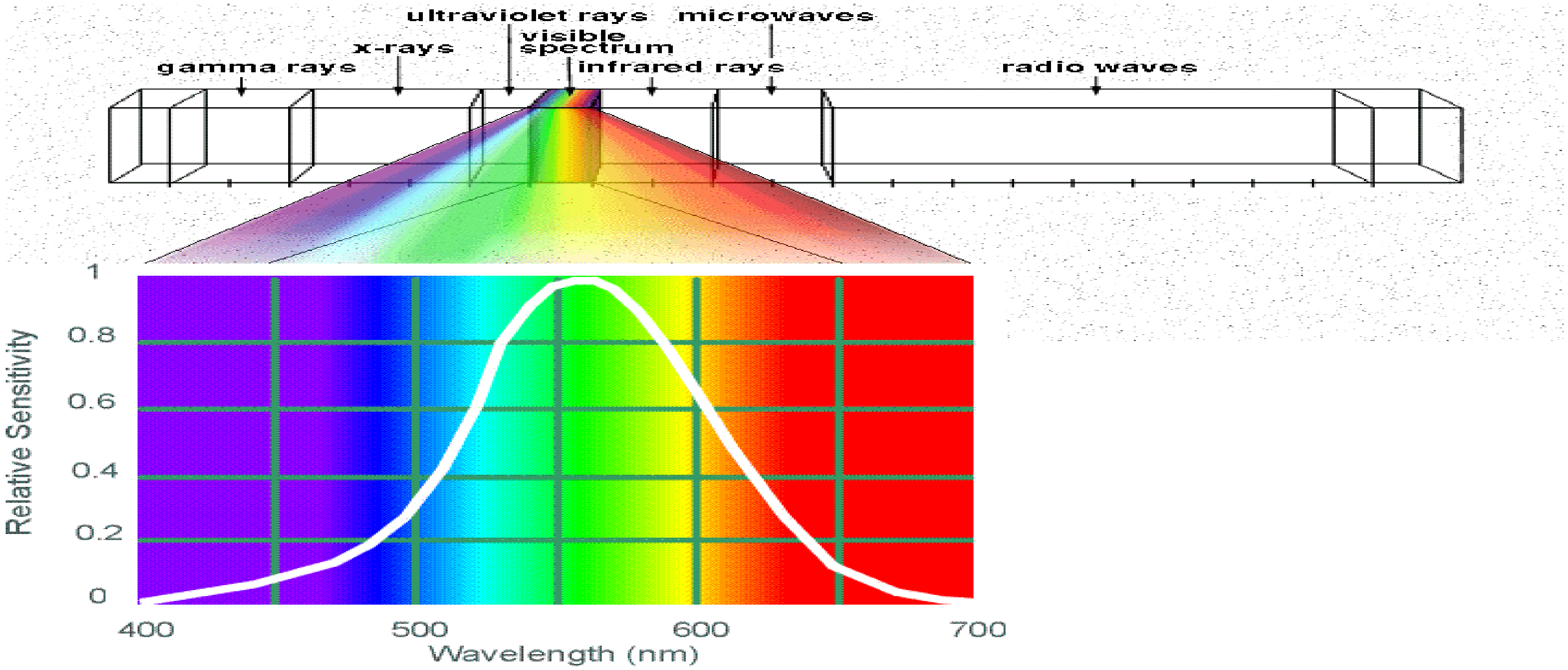
- Saccades
- Can be consciously controlled. Related to perceptual attention.
- 200ms to initiation, 20 to 200ms to carry out. Large amplitude.
- Microsaccades
- Involuntary. Smaller amplitude. Especially evident during prolonged fixation. Function debated.
- Ocular microtremor (OMT)
- Involuntary. high frequency (up to 80Hz), small amplitude.

- Smooth pursuit – tracking an object

Slow mo guys – Saccades and CRTs

- https://youtu.be/Fmg9ZOHESgQ?t=21s
- https://youtu.be/3BJU2drrtCM

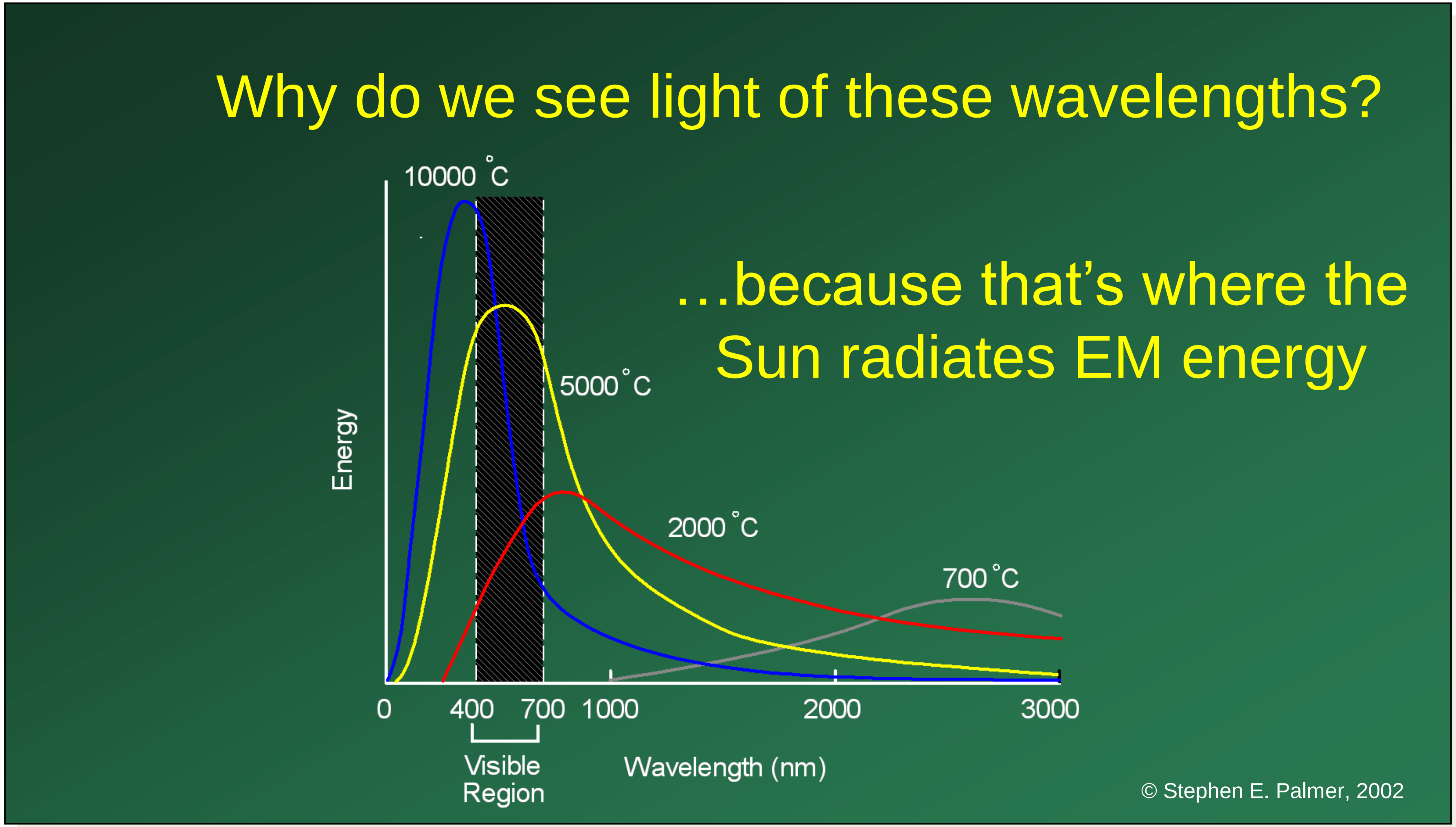
Electromagnetic Spectrum



Human Luminance Sensitivity Function

http://www.yorku.ca/eye/photopik.htm

Visible Light



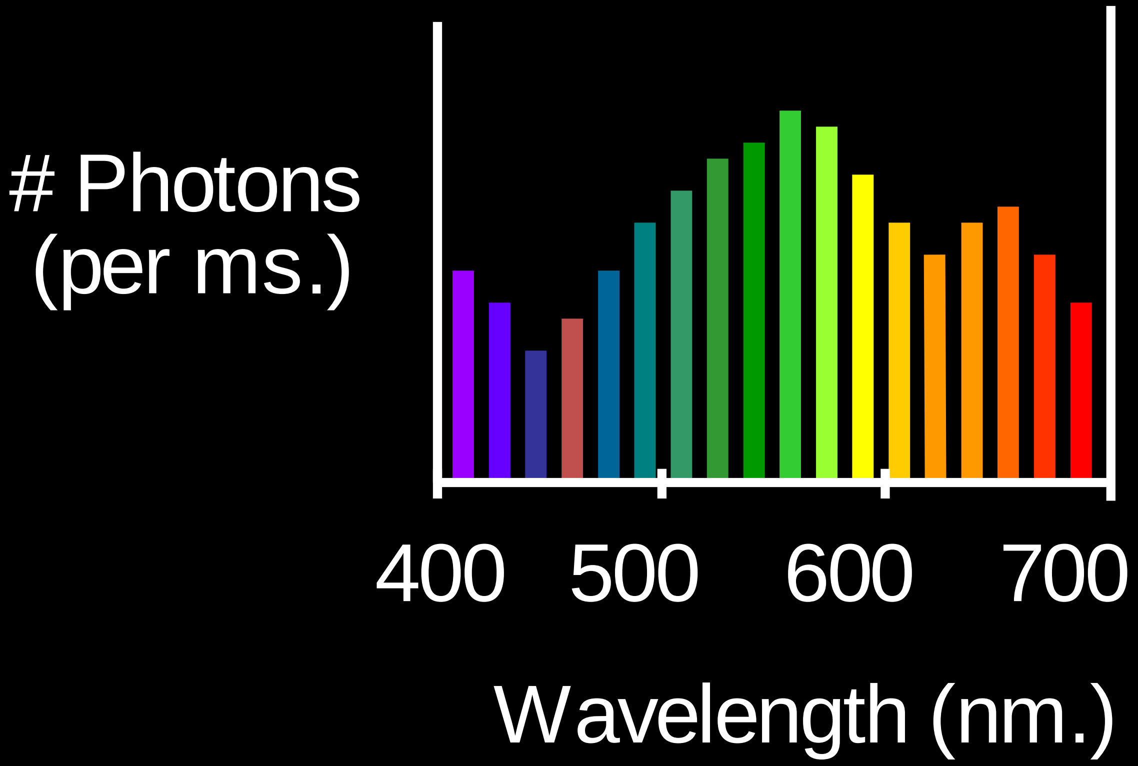
Why do we see light of these wavelengths?

…because that’s where the Sun radiates EM energy

© Stephen E. Palmer, 2002

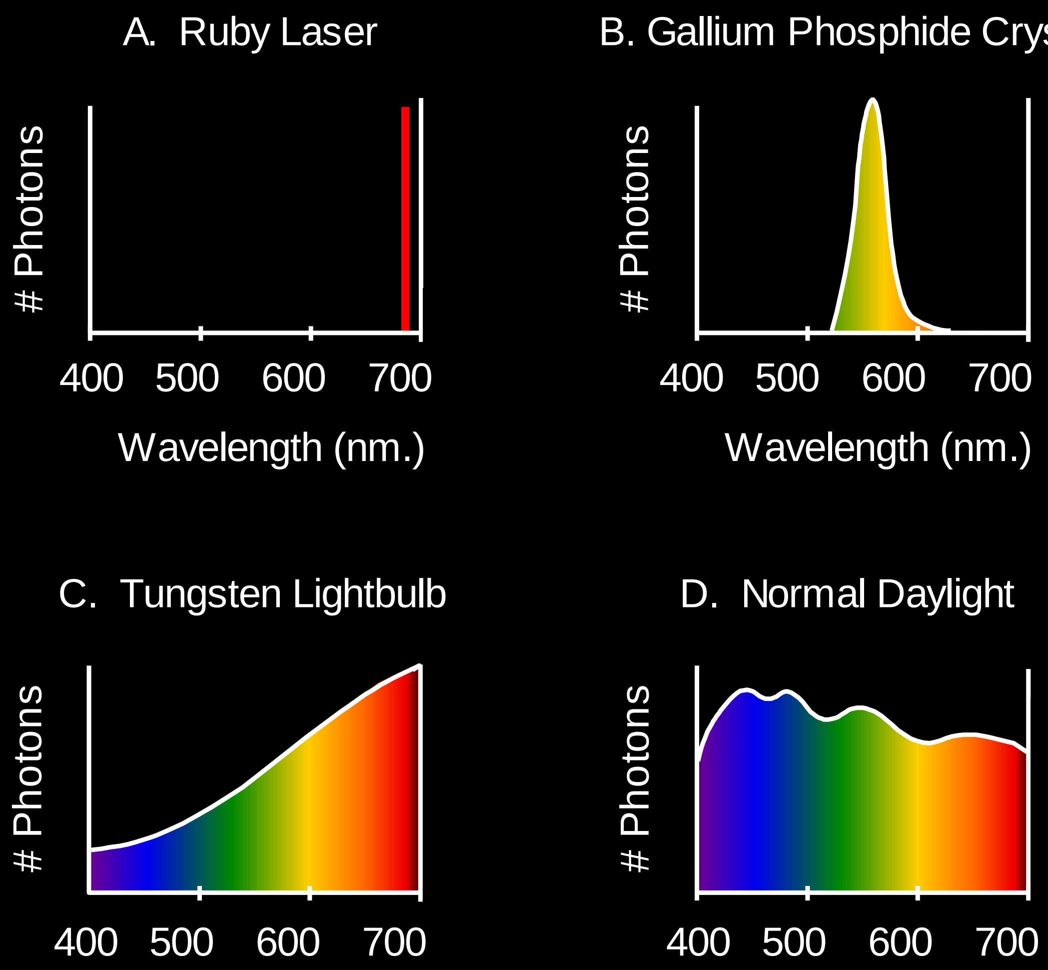
The Physics of Light

Any patch of light can be completely described physically by its spectrum: the number of photons (per time unit) at each wavelength 400 - 700 nm.



The Physics of Light

Some examples of the spectra of light sources



A. Ruby Laser

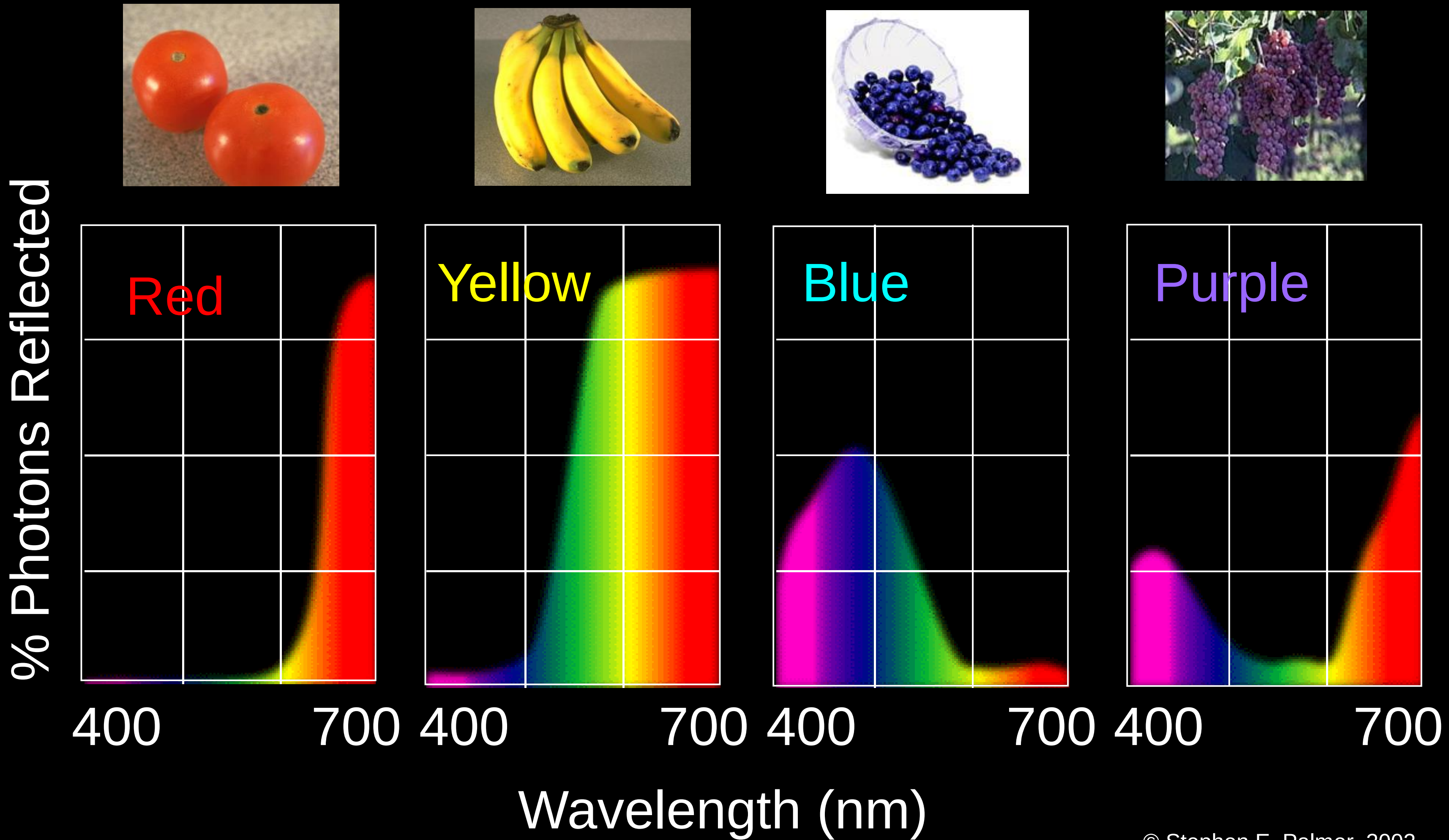
B. Gallium Phosphide Crystal

C. Tungsten Lightbulb

D. Normal Daylight

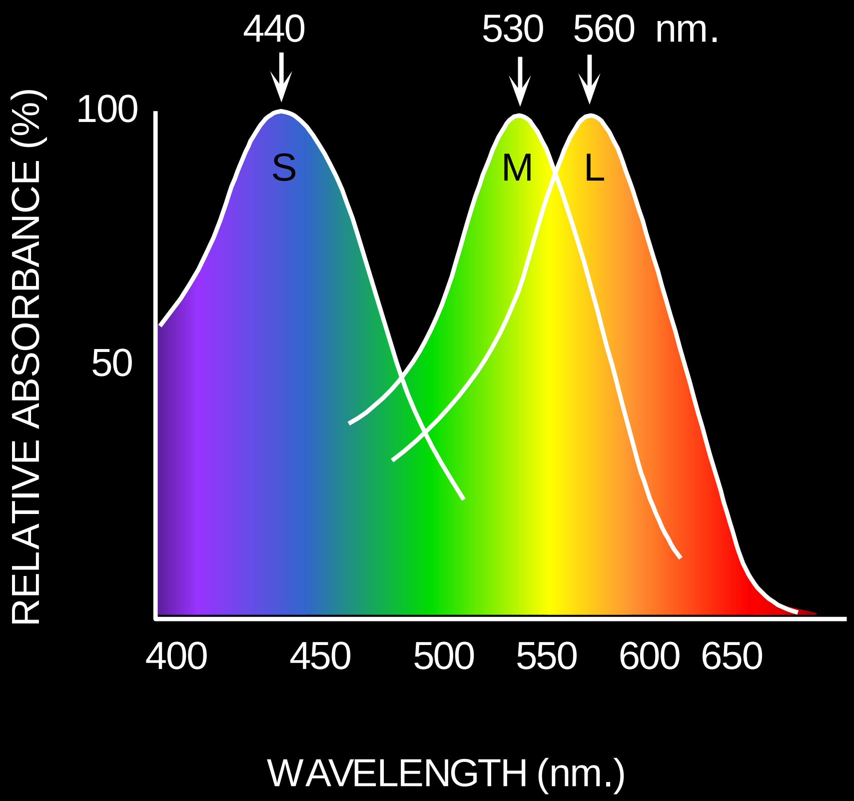
The Physics of Light

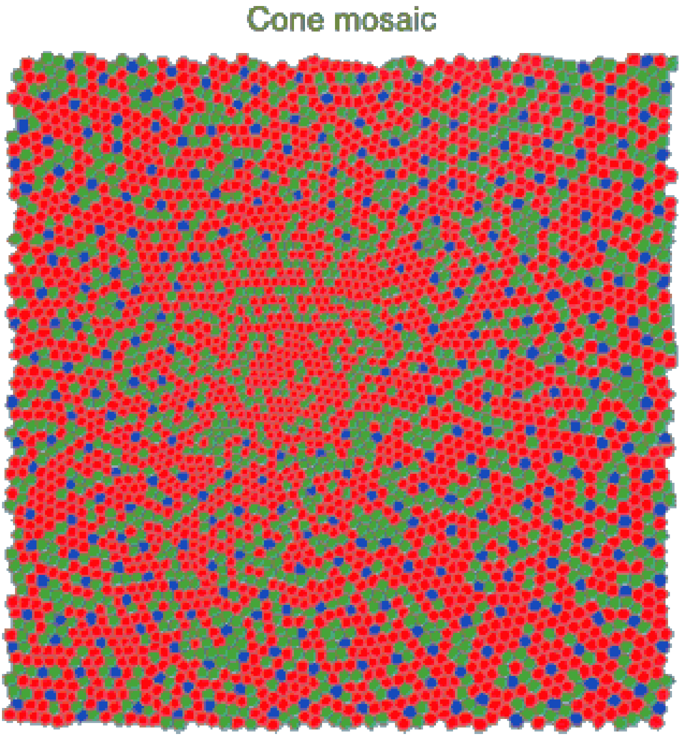
Some examples of the reflectance spectra of surfaces



Physiology of Color Vision

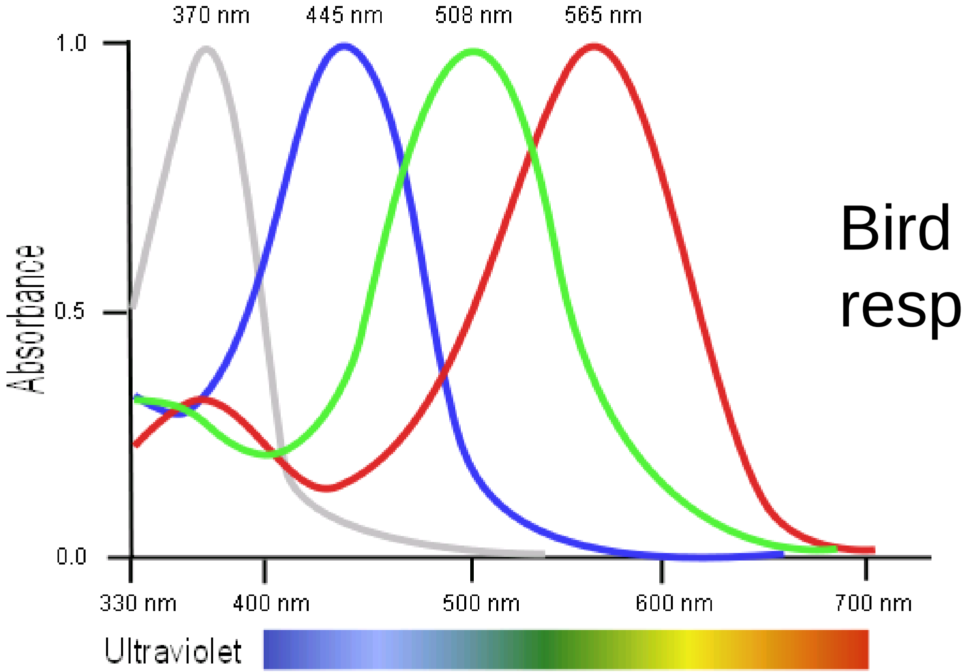
Three kinds of cones:





- Why are M and L cones so close?
- Why are there 3?

Tetrachromacy



Bird cone responses

- Most birds, and many other animals, have cones for ultraviolet light.
- Some humans, mostly female, seem to have slight tetrachromatism.

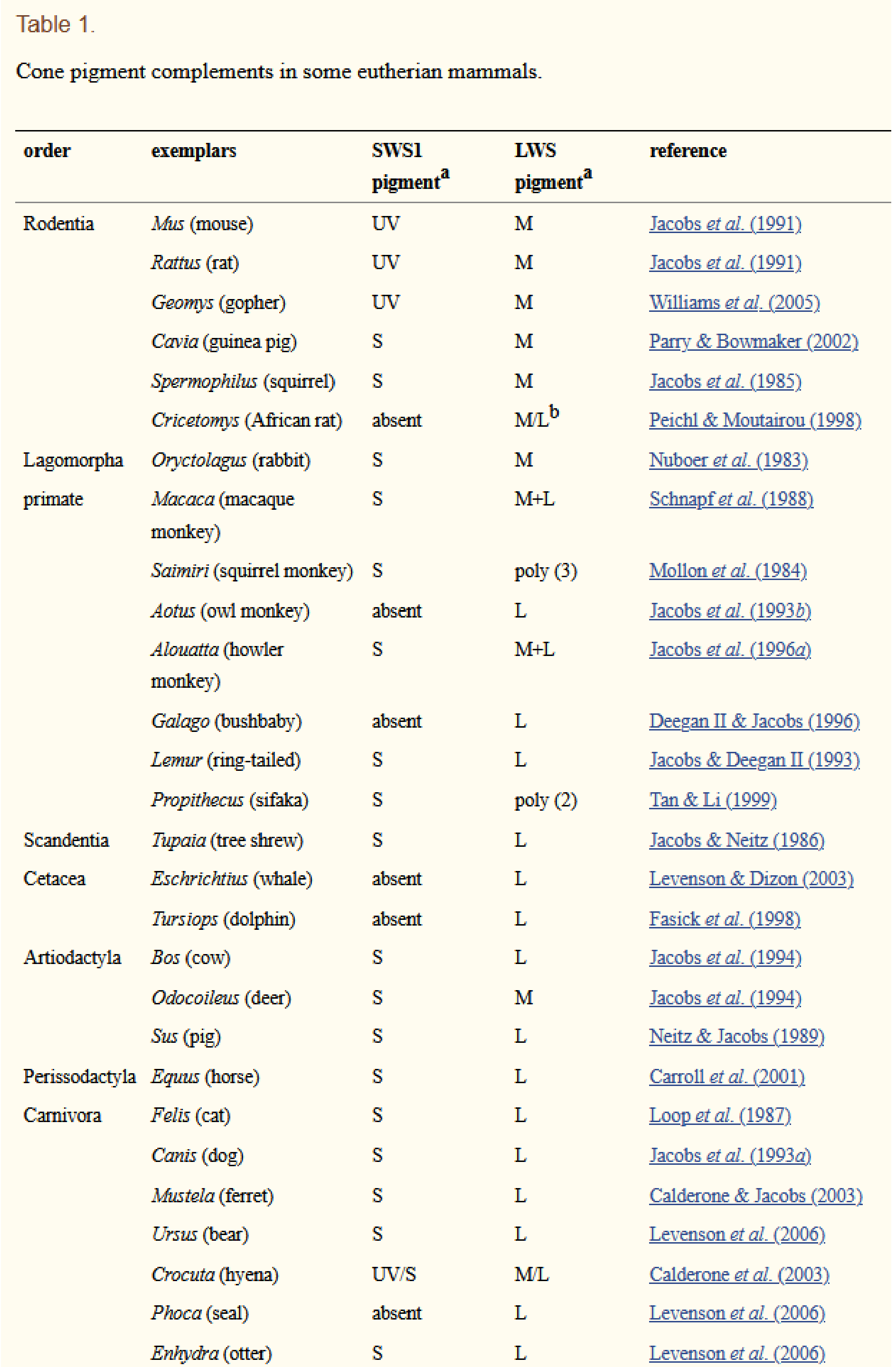
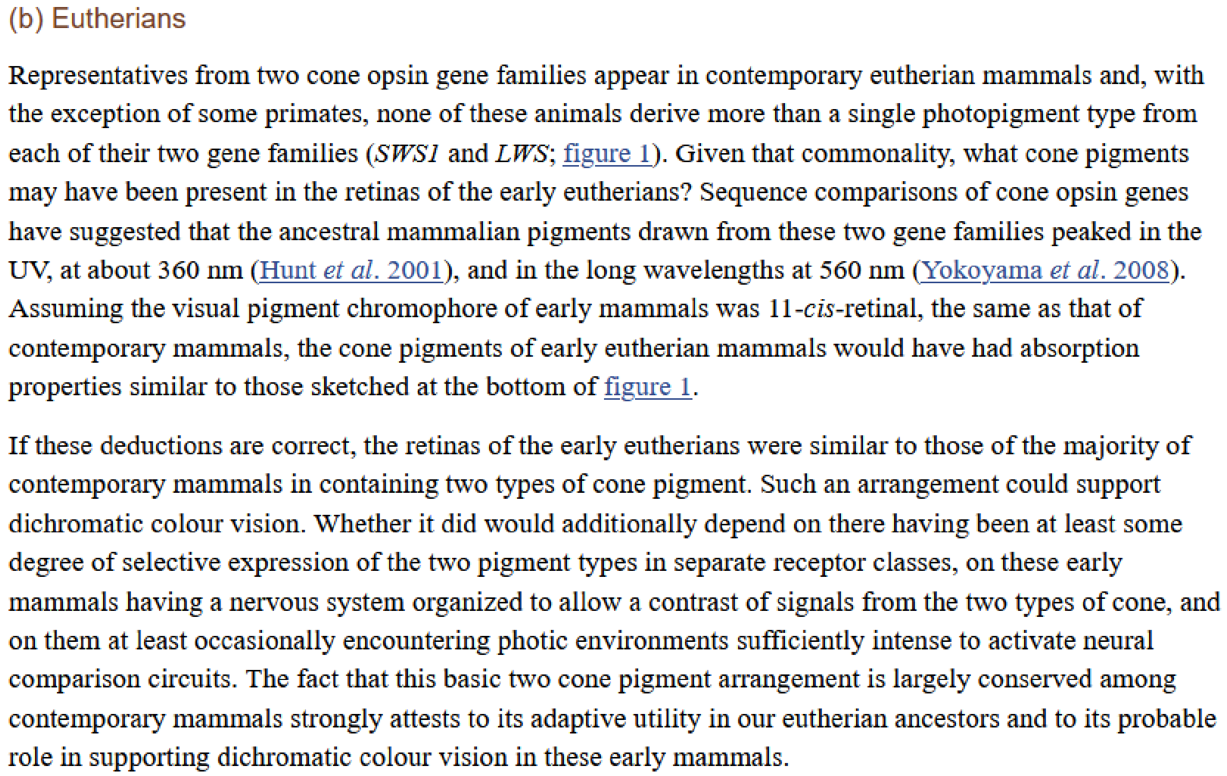


Table 1.

Cone pigment complements in some eutherian mammals.

order	exemplars	SWS1 pigment[a]	LWS pigment[a]	reference
Rodentia	*Mus* (mouse)	UV	M	Jacobs *et al.* (1991)
	Rattus (rat)	UV	M	Jacobs *et al.* (1991)
	Geomys (gopher)	UV	M	Williams *et al.* (2005)
	Cavia (guinea pig)	S	M	Parry & Bowmaker (2002)
	Spermophilus (squirrel)	S	M	Jacobs *et al.* (1985)
	Cricetomys (African rat)	absent	M/L[b]	Peichl & Moutairou (1998)
Lagomorpha	*Oryctolagus* (rabbit)	S	M	Nuboer *et al.* (1983)
primate	*Macaca* (macaque monkey)	S	M+L	Schnapf *et al.* (1988)
	Saimiri (squirrel monkey)	S	poly (3)	Mollon *et al.* (1984)
	Aotus (owl monkey)	absent	L	Jacobs *et al.* (1993*b*)
	Alouatta (howler monkey)	S	M+L	Jacobs *et al.* (1996*a*)
	Galago (bushbaby)	absent	L	Deegan II & Jacobs (1996)
	Lemur (ring-tailed)	S	L	Jacobs & Deegan II (1993)
	Propithecus (sifaka)	S	poly (2)	Tan & Li (1999)
Scandentia	*Tupaia* (tree shrew)	S	L	Jacobs & Neitz (1986)
Cetacea	*Eschrichtius* (whale)	absent	L	Levenson & Dizon (2003)
	Tursiops (dolphin)	absent	L	Fasick *et al.* (1998)
Artiodactyla	*Bos* (cow)	S	L	Jacobs *et al.* (1994)
	Odocoileus (deer)	S	M	Jacobs *et al.* (1994)
	Sus (pig)	S	L	Neitz & Jacobs (1989)
Perissodactyla	*Equus* (horse)	S	L	Carroll *et al.* (2001)
Carnivora	*Felis* (cat)	S	L	Loop *et al.* (1987)
	Canis (dog)	S	L	Jacobs *et al.* (1993*a*)
	Mustela (ferret)	S	L	Calderone & Jacobs (2003)
	Ursus (bear)	S	L	Levenson *et al.* (2006)
	Crocuta (hyena)	UV/S	M/L	Calderone *et al.* (2003)
	Phoca (seal)	absent	L	Levenson *et al.* (2006)
	Enhydra (otter)	S	L	Levenson *et al.* (2006)



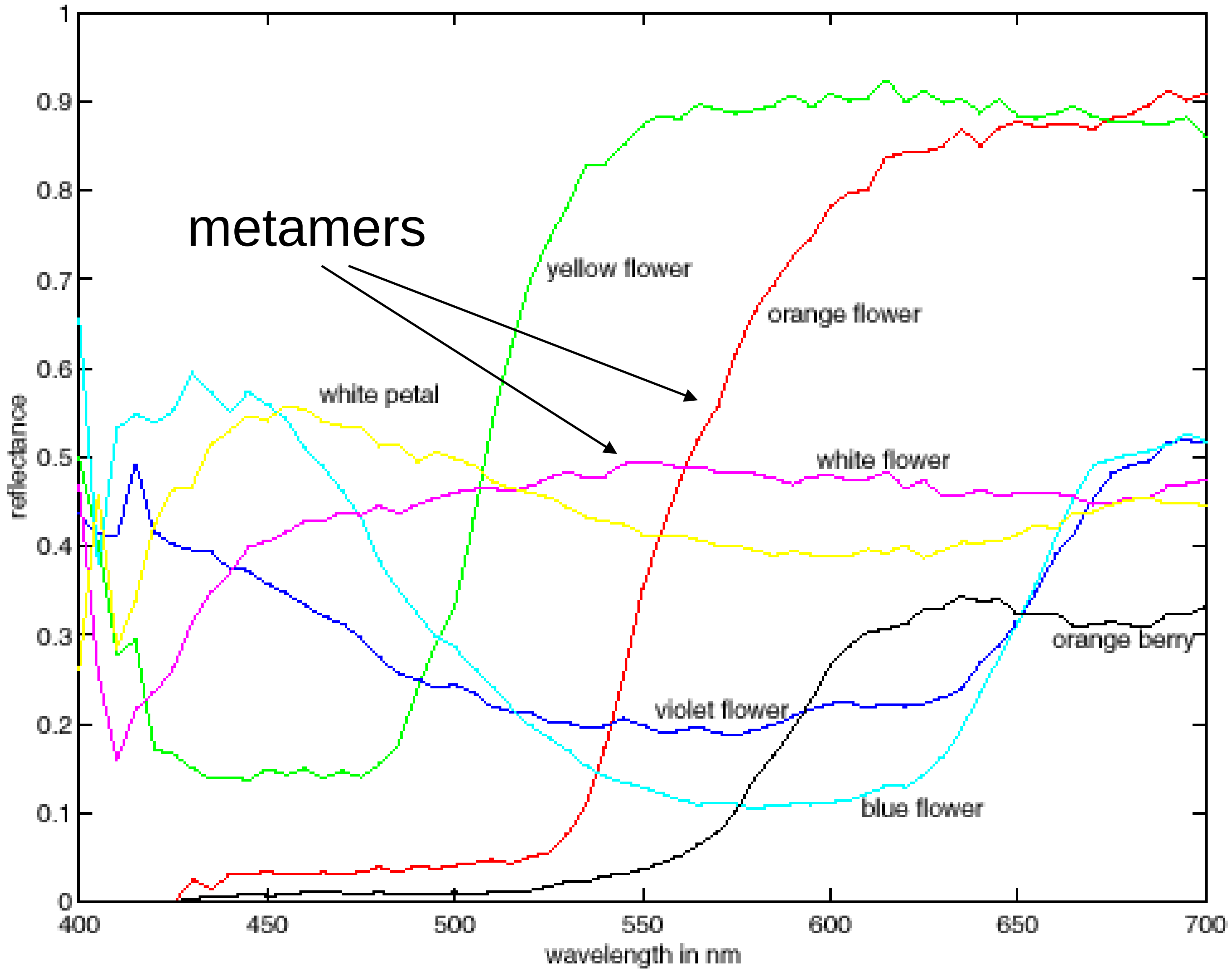
(b) Eutherians

Representatives from two cone opsin gene families appear in contemporary eutherian mammals and, with the exception of some primates, none of these animals derive more than a single photopigment type from each of their two gene families (*SWS1* and *LWS*; figure 1). Given that commonality, what cone pigments may have been present in the retinas of the early eutherians? Sequence comparisons of cone opsin genes have suggested that the ancestral mammalian pigments drawn from these two gene families peaked in the UV, at about 360 nm (Hunt *et al.* 2001), and in the long wavelengths at 560 nm (Yokoyama *et al.* 2008). Assuming the visual pigment chromophore of early mammals was 11-*cis*-retinal, the same as that of contemporary mammals, the cone pigments of early eutherian mammals would have had absorption properties similar to those sketched at the bottom of figure 1.

If these deductions are correct, the retinas of the early eutherians were similar to those of the majority of contemporary mammals in containing two types of cone pigment. Such an arrangement could support dichromatic colour vision. Whether it did would additionally depend on there having been at least some degree of selective expression of the two pigment types in separate receptor classes, on these early mammals having a nervous system organized to allow a contrast of signals from the two types of cone, and on them at least occasionally encountering photic environments sufficiently intense to activate neural comparison circuits. The fact that this basic two cone pigment arrangement is largely conserved among contemporary mammals strongly attests to its adaptive utility in our eutherian ancestors and to its probable role in supporting dichromatic colour vision in these early mammals.

Jacobs GH. Evolution of colour vision in mammals. *Philos Trans R Soc Lond B Biol Sci*. 2009;364(1531):2957-2967. doi:10.1098/rstb.2009.0039

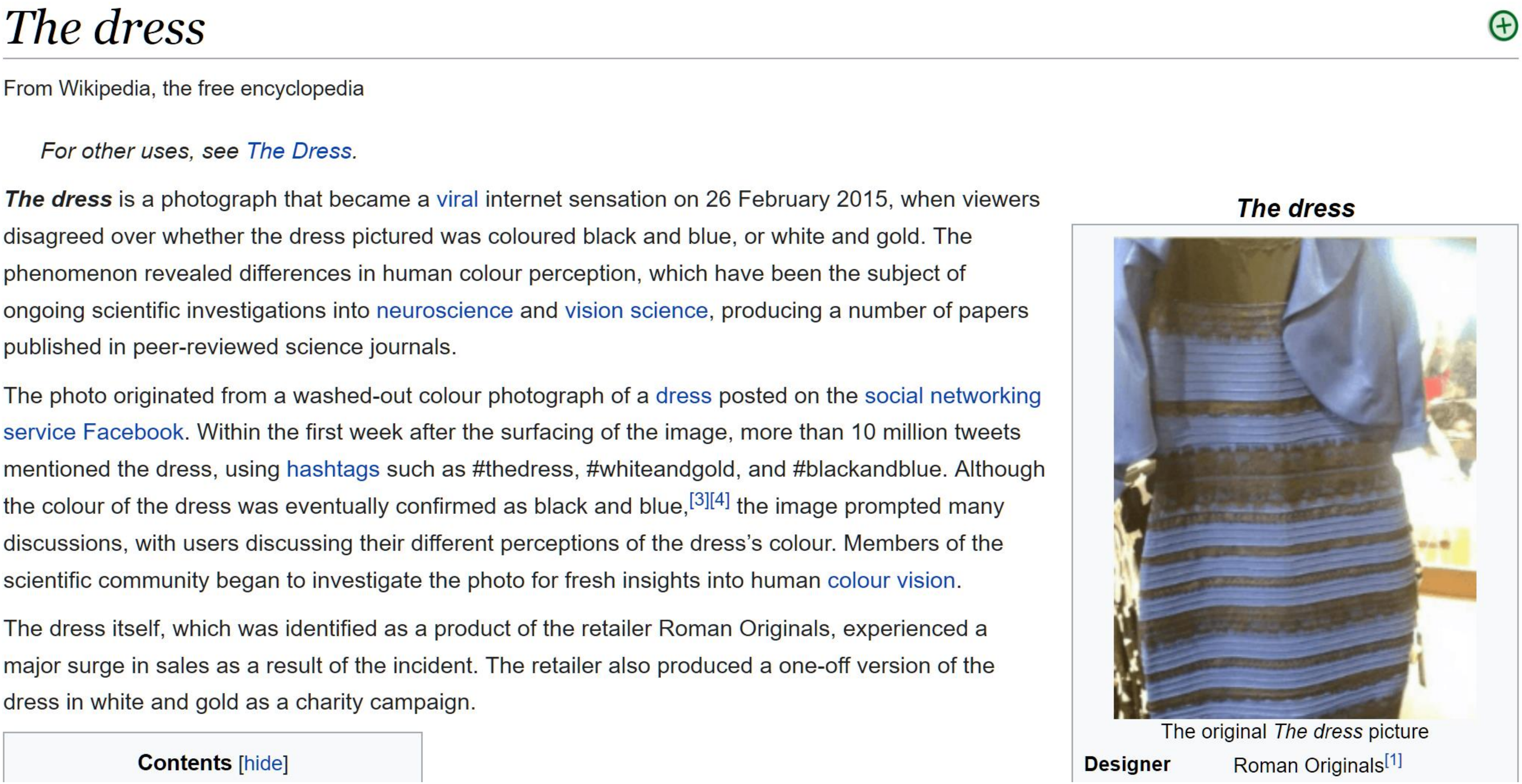
More Spectra



metamers

Color can be ambiguous

Color can be ambiguous



The dress

From Wikipedia, the free encyclopedia

For other uses, see The Dress.

The dress is a photograph that became a viral internet sensation on 26 February 2015, when viewers disagreed over whether the dress pictured was coloured black and blue, or white and gold. The phenomenon revealed differences in human colour perception, which have been the subject of ongoing scientific investigations into neuroscience and vision science, producing a number of papers published in peer-reviewed science journals.

The photo originated from a washed-out colour photograph of a dress posted on the social networking service Facebook. Within the first week after the surfacing of the image, more than 10 million tweets mentioned the dress, using hashtags such as #thedress, #whiteandgold, and #blackandblue. Although the colour of the dress was eventually confirmed as black and blue,[3][4] the image prompted many discussions, with users discussing their different perceptions of the dress's colour. Members of the scientific community began to investigate the photo for fresh insights into human colour vision.

The dress itself, which was identified as a product of the retailer Roman Originals, experienced a major surge in sales as a result of the incident. The retailer also produced a one-off version of the dress in white and gold as a charity campaign.

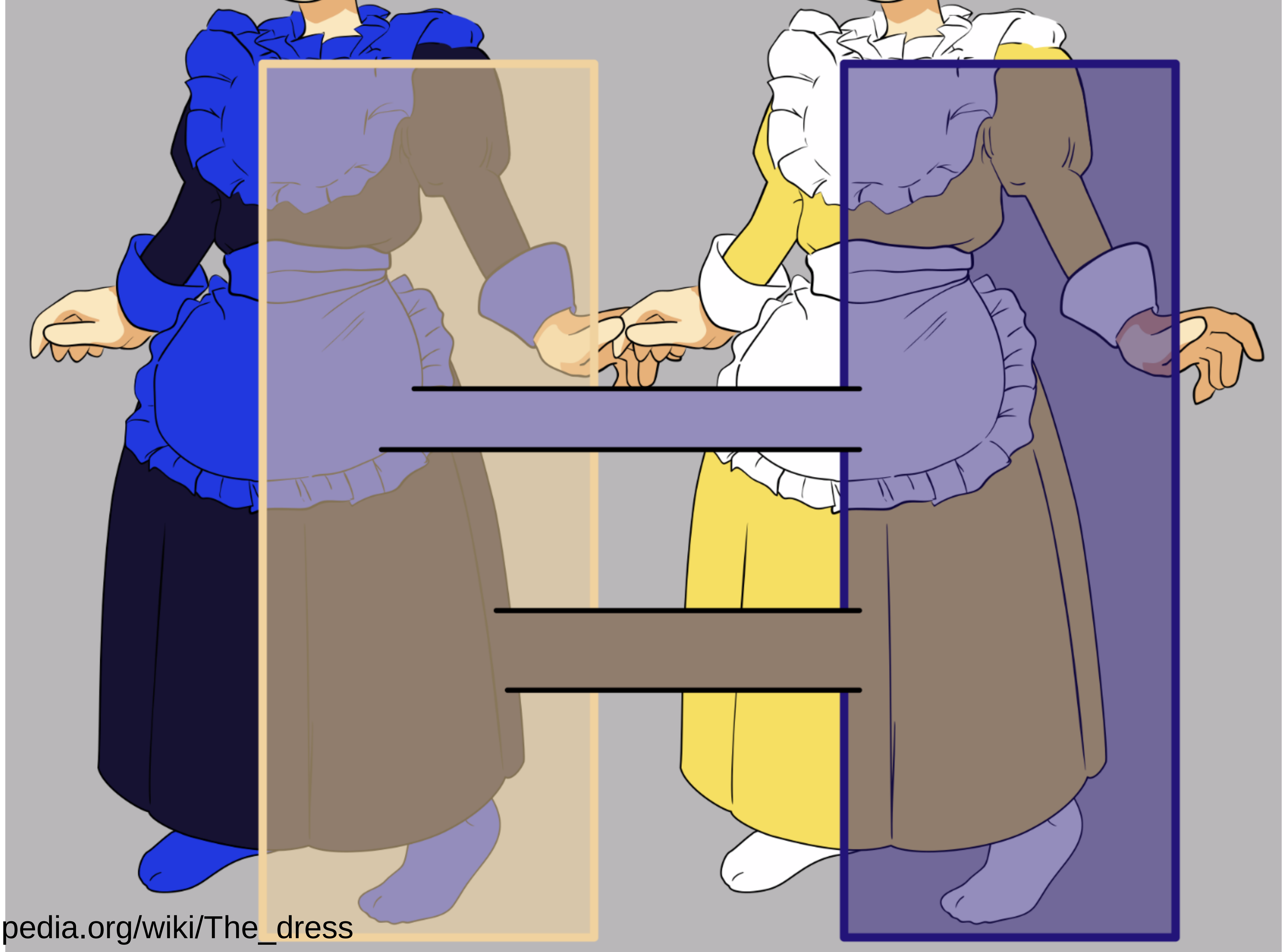
Contents [hide]

The dress

The original *The dress* picture

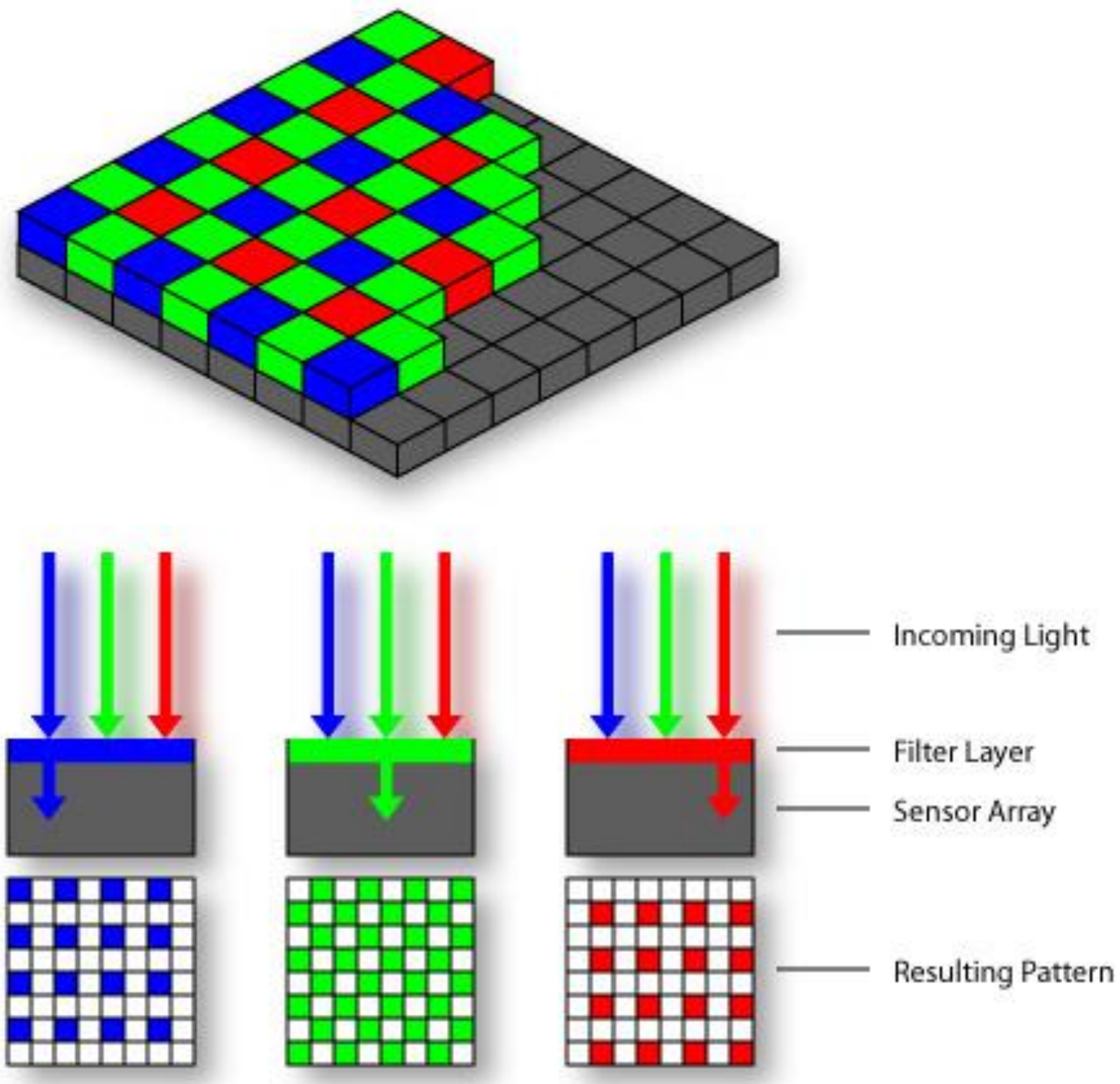
Designer	Roman Originals[1]

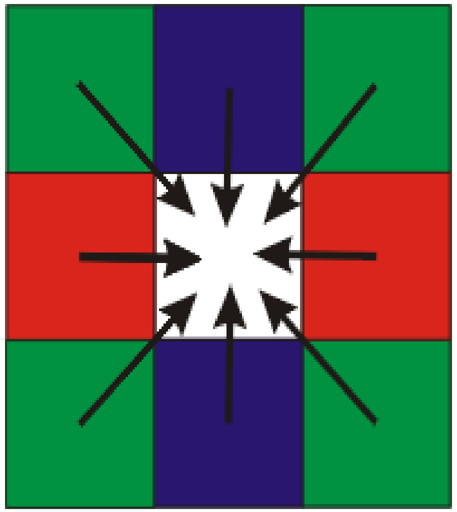
https://en.wikipedia.org/wiki/The_dress



https://en.wikipedia.org/wiki/The_dress

Practical Color Sensing: Bayer Grid





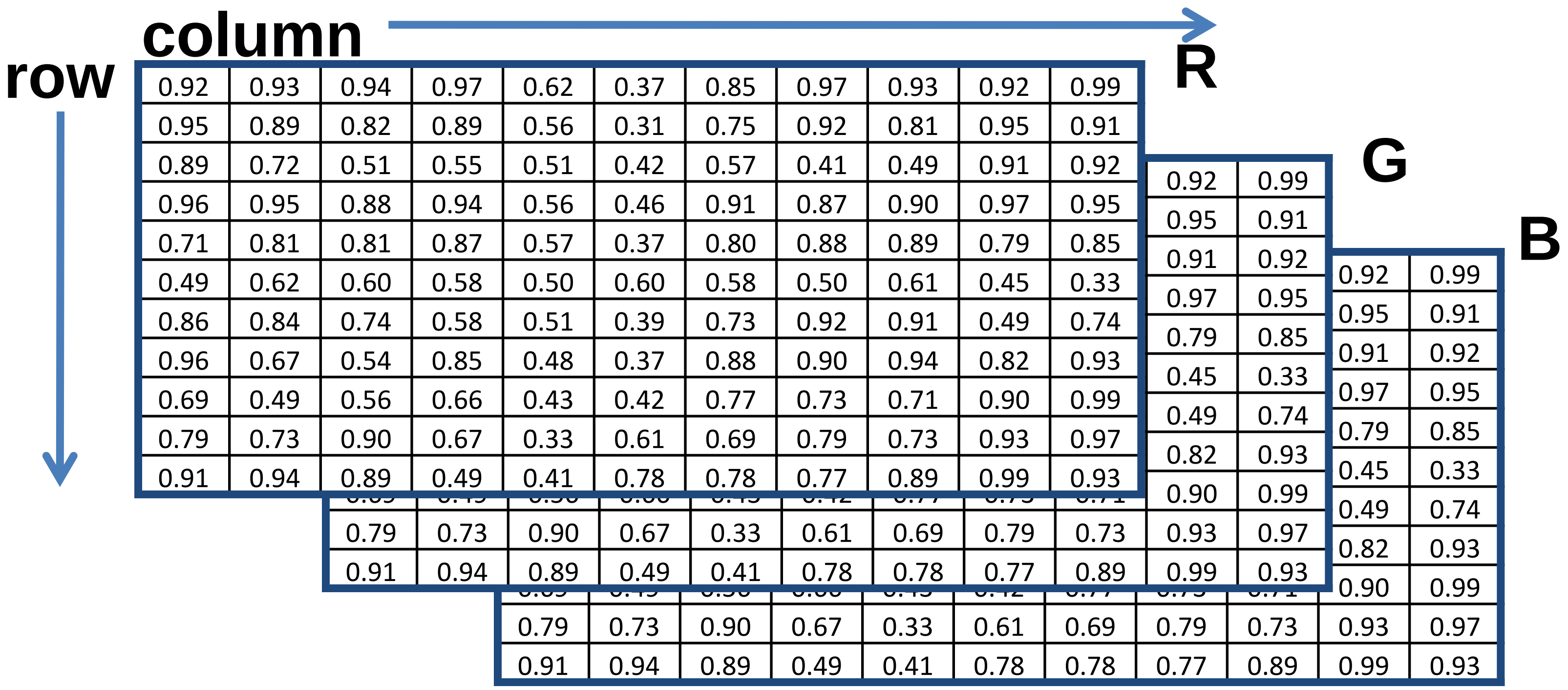
- Estimate RGB at ‘G’ cells from neighboring values

Slide by Steve Seitz

Color Image

Images in Python

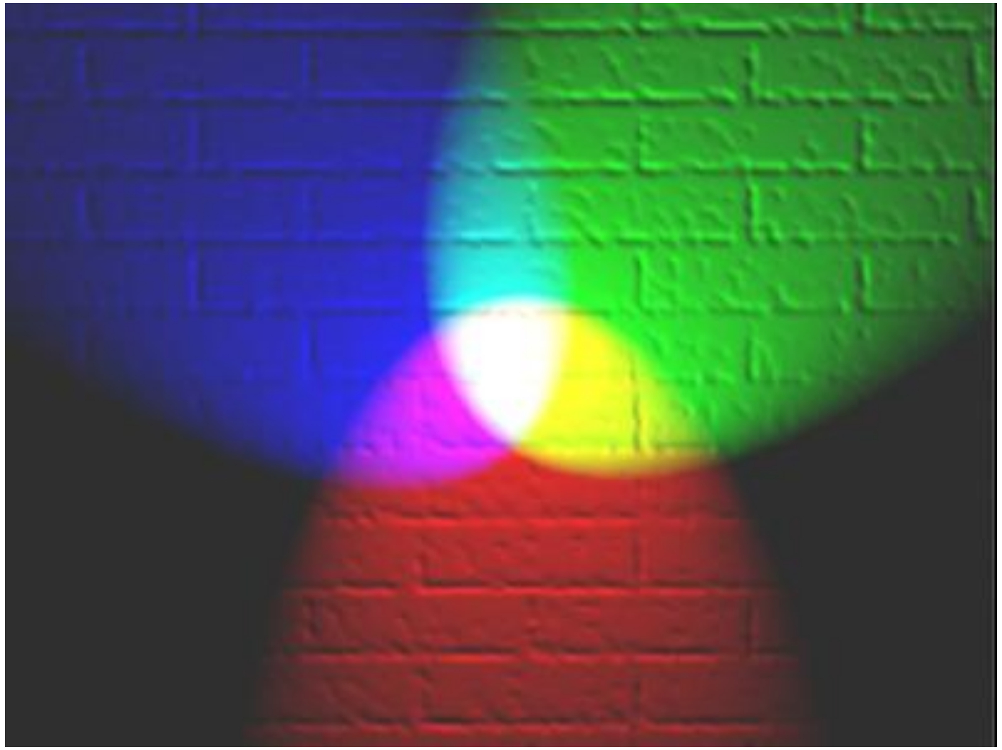
- Images represented as a matrix
- Suppose we have a NxM RGB image called “im”
  - im(0,0,0) = top-left pixel value in R-channel
  - im(y, x, b) = y pixels down, x pixels to right in the bth channel
  - im(N-1, M-1, 2) = bottom-right pixel in B-channel



0.92	0.93	0.94	0.97	0.62	0.37	0.85	0.97	0.93	0.92	0.99
0.95	0.89	0.82	0.89	0.56	0.31	0.75	0.92	0.81	0.95	0.91
0.89	0.72	0.51	0.55	0.51	0.42	0.57	0.41	0.49	0.91	0.92
0.96	0.95	0.88	0.94	0.56	0.46	0.91	0.87	0.90	0.97	0.95
0.71	0.81	0.81	0.87	0.57	0.37	0.80	0.88	0.89	0.79	0.85
0.49	0.62	0.60	0.58	0.50	0.60	0.58	0.50	0.61	0.45	0.33
0.86	0.84	0.74	0.58	0.51	0.39	0.73	0.92	0.91	0.49	0.74
0.96	0.67	0.54	0.85	0.48	0.37	0.88	0.90	0.94	0.82	0.93
0.69	0.49	0.56	0.66	0.43	0.42	0.77	0.73	0.71	0.90	0.99
0.79	0.73	0.90	0.67	0.33	0.61	0.69	0.79	0.73	0.93	0.97
0.91	0.94	0.89	0.49	0.41	0.78	0.78	0.77	0.89	0.99	0.93

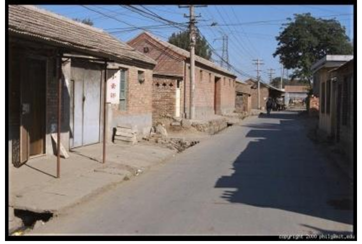
Color spaces

- How can we represent color?

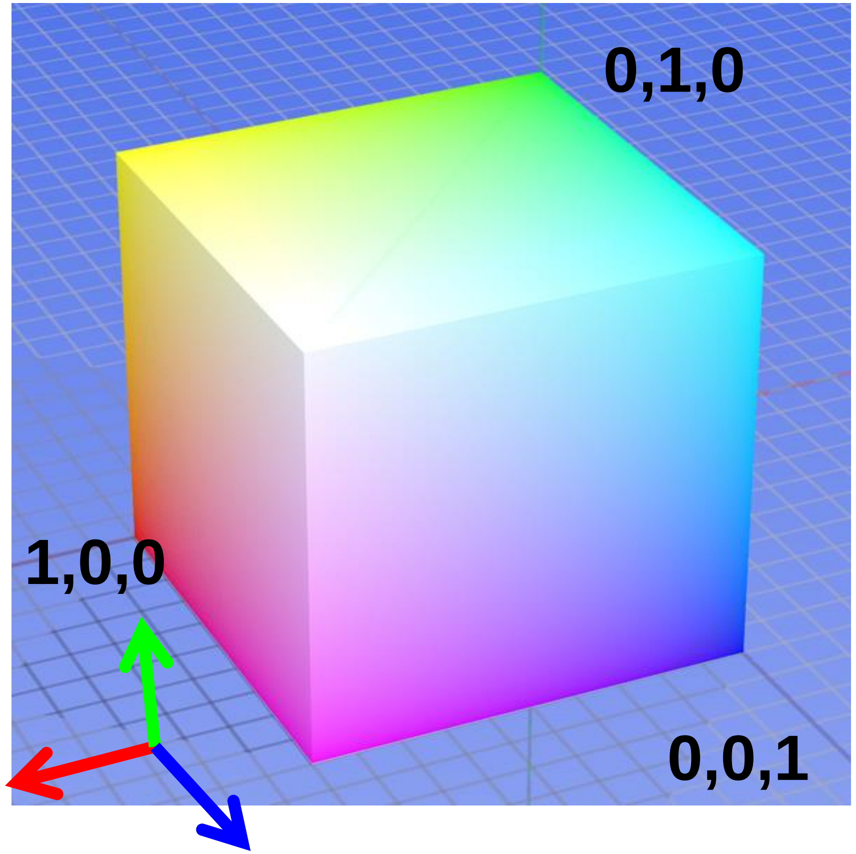


http://en.wikipedia.org/wiki/File:RGB_illumination.jpg

Color spaces: RGB



Default color space



Some drawbacks

- Strongly correlated channels
- Non-perceptual

R

(G=0,B=0)

G

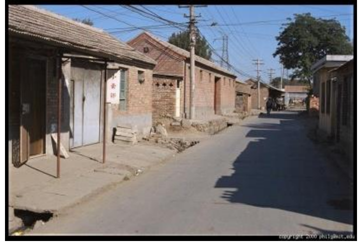
(R=0,B=0)

B

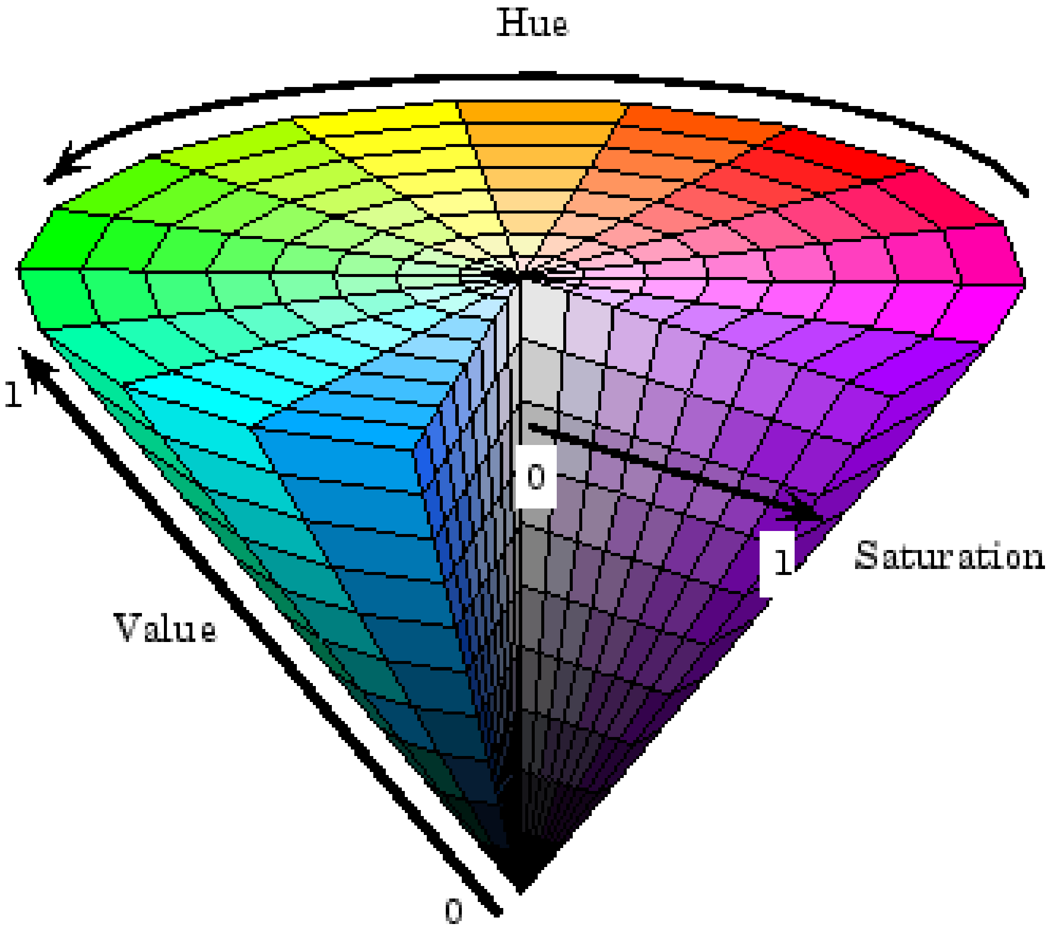
(R=0,G=0)

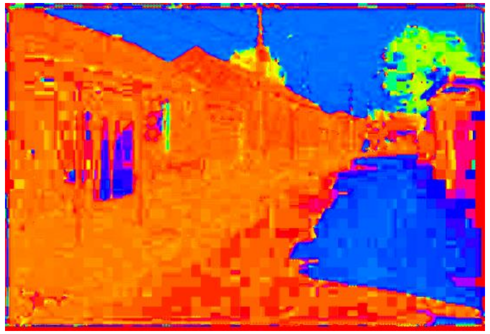
Image from: http://en.wikipedia.org/wiki/File:RGB_color_solid_cube.png

Color spaces: HSV



Intuitive color space





H

(S=1,V=1)

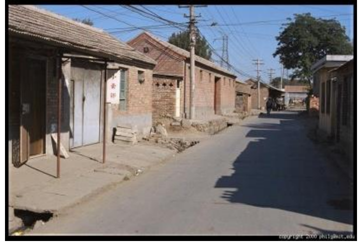
S

(H=1,V=1)

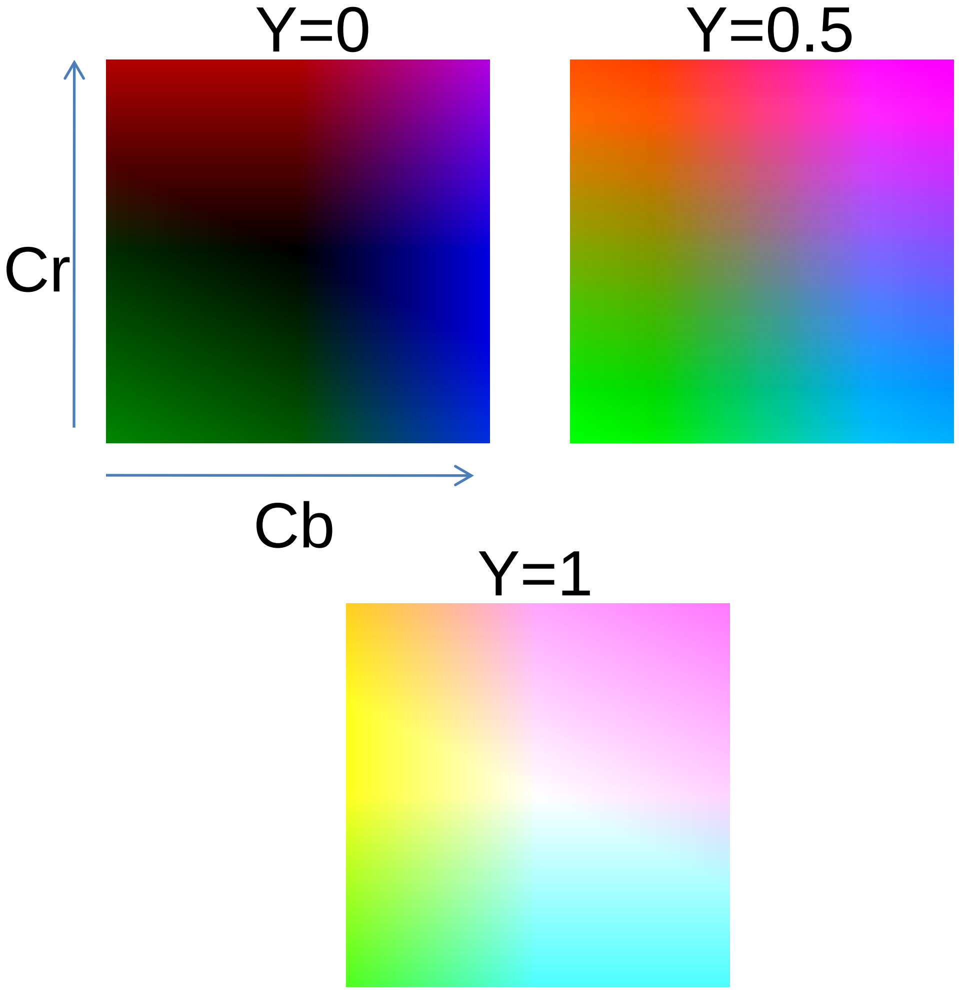
V

(H=1,S=0)

Color spaces: YCbCr



Fast to compute, good for compression, used by TV



Y

(Cb=0.5,Cr=0.5)

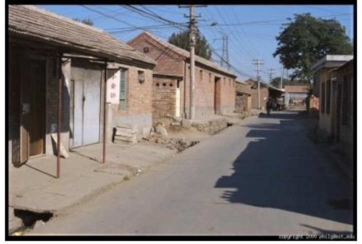
Cb

(Y=0.5,Cr=0.5)

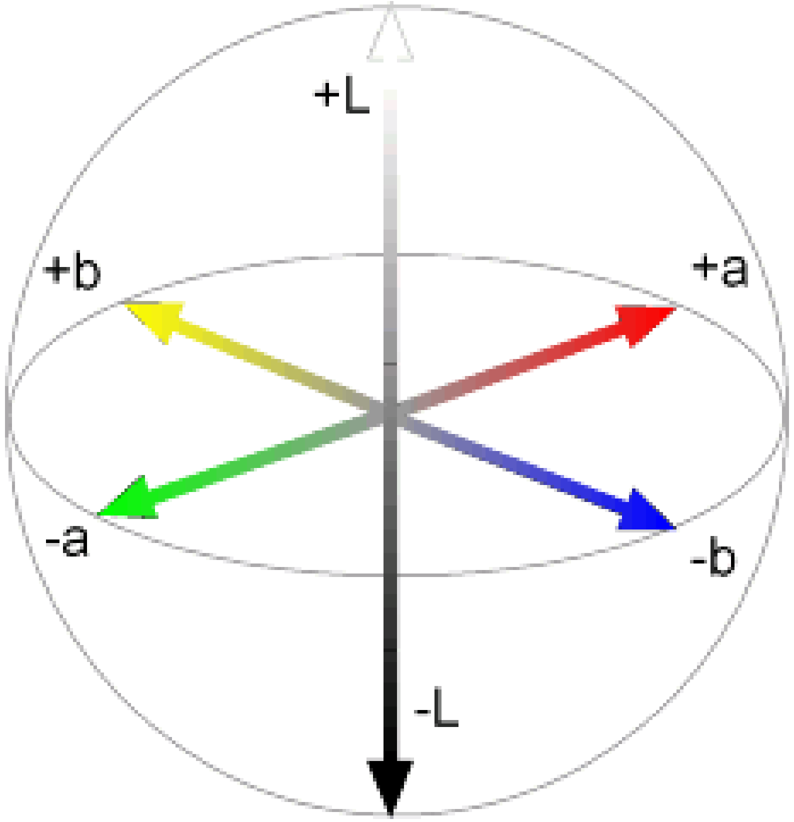
Cr

(Y=0.5,Cb=05)

Color spaces: L*a*b*



“Perceptually uniform”* color space



L
(a=0,b=0)

a
(L=65,b=0)

b
(L=65,a=0)

If you had to choose, would you rather go without luminance or chrominance?

If you had to choose, would you rather go without **luminance** or chrominance?

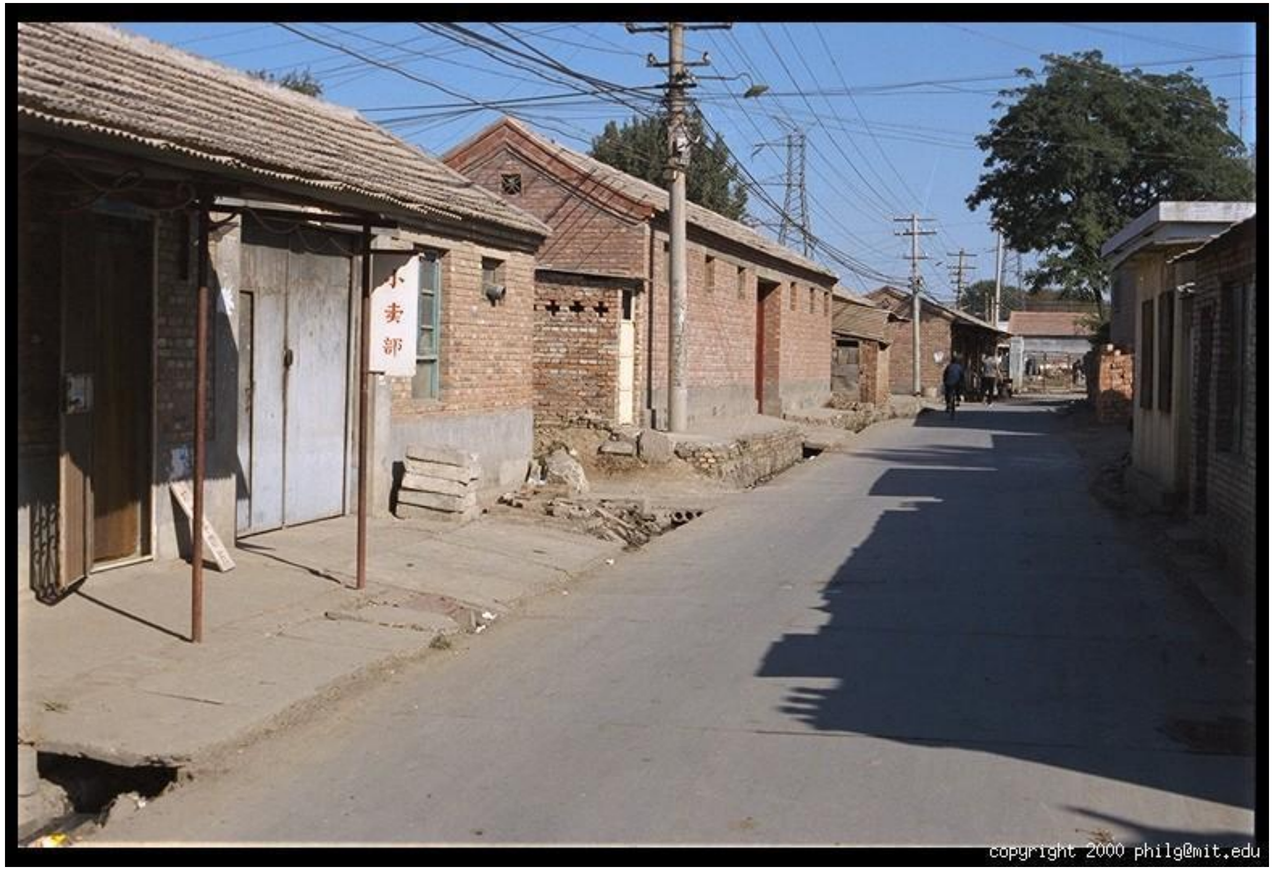
Most information in intensity

Only color shown – constant intensity

Most information in intensity

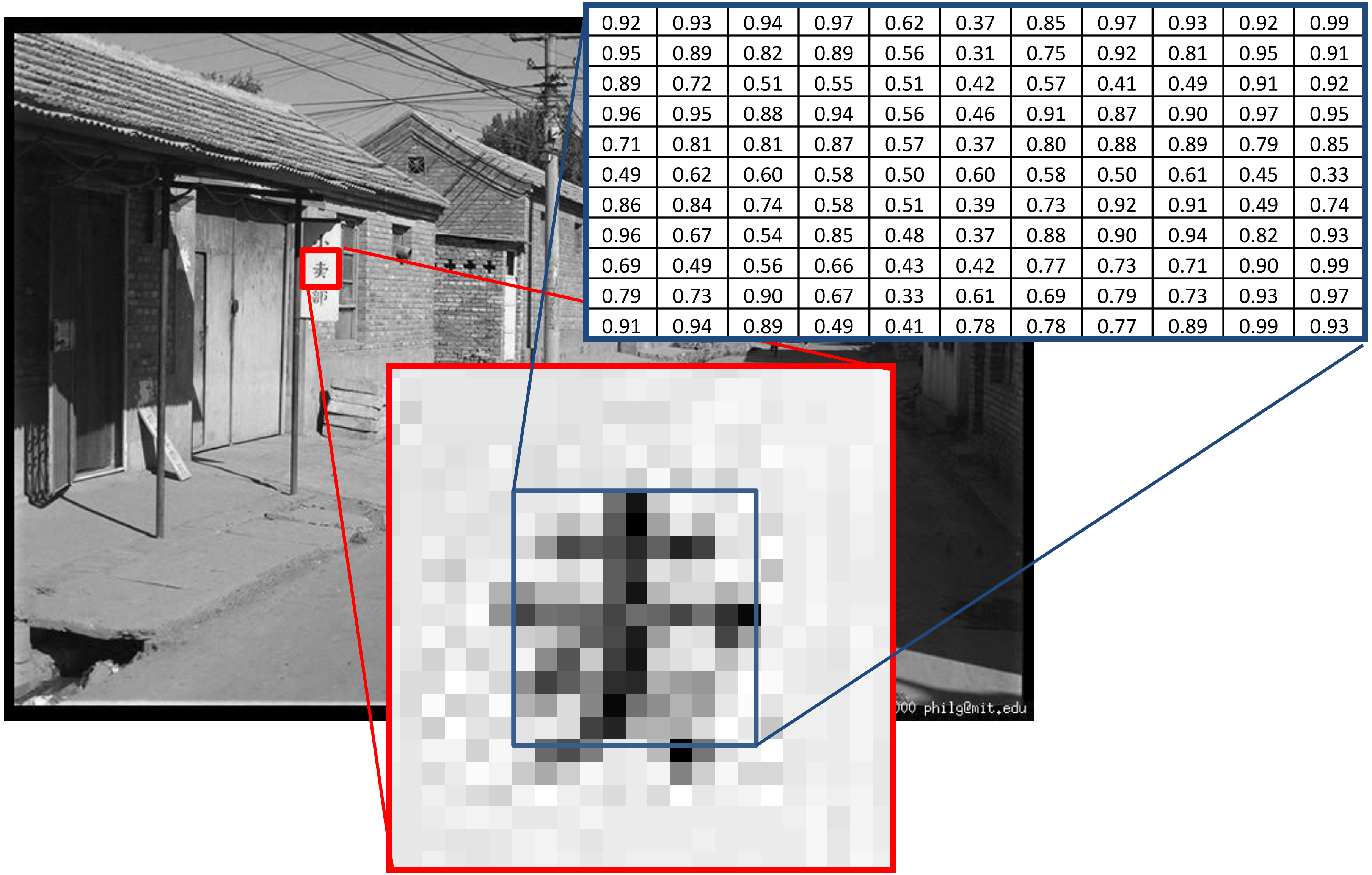
Only intensity shown – constant color

Most information in intensity



Original image

Back to grayscale intensity



0.92	0.93	0.94	0.97	0.62	0.37	0.85	0.97	0.93	0.92	0.99
0.95	0.89	0.82	0.89	0.56	0.31	0.75	0.92	0.81	0.95	0.91
0.89	0.72	0.51	0.55	0.51	0.42	0.57	0.41	0.49	0.91	0.92
0.96	0.95	0.88	0.94	0.56	0.46	0.91	0.87	0.90	0.97	0.95
0.71	0.81	0.81	0.87	0.57	0.37	0.80	0.88	0.89	0.79	0.85
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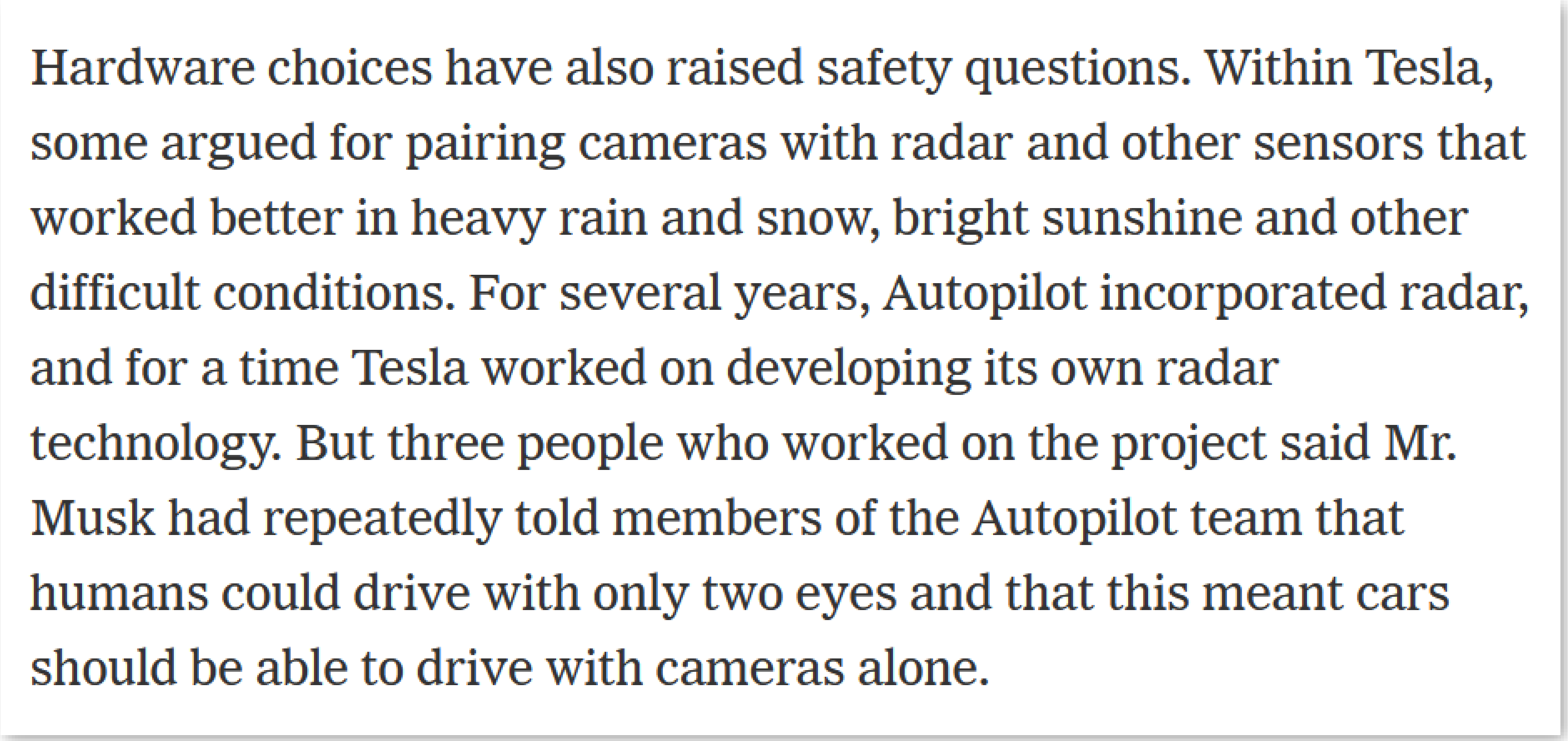
0.79	0.73	0.90	0.67	0.33	0.61	0.69	0.79	0.73	0.93	0.97
0.91	0.94	0.89	0.49	0.41	0.78	0.78	0.77	0.89	0.99	0.93

Wrap up: Why do we care about cameras and eyes?

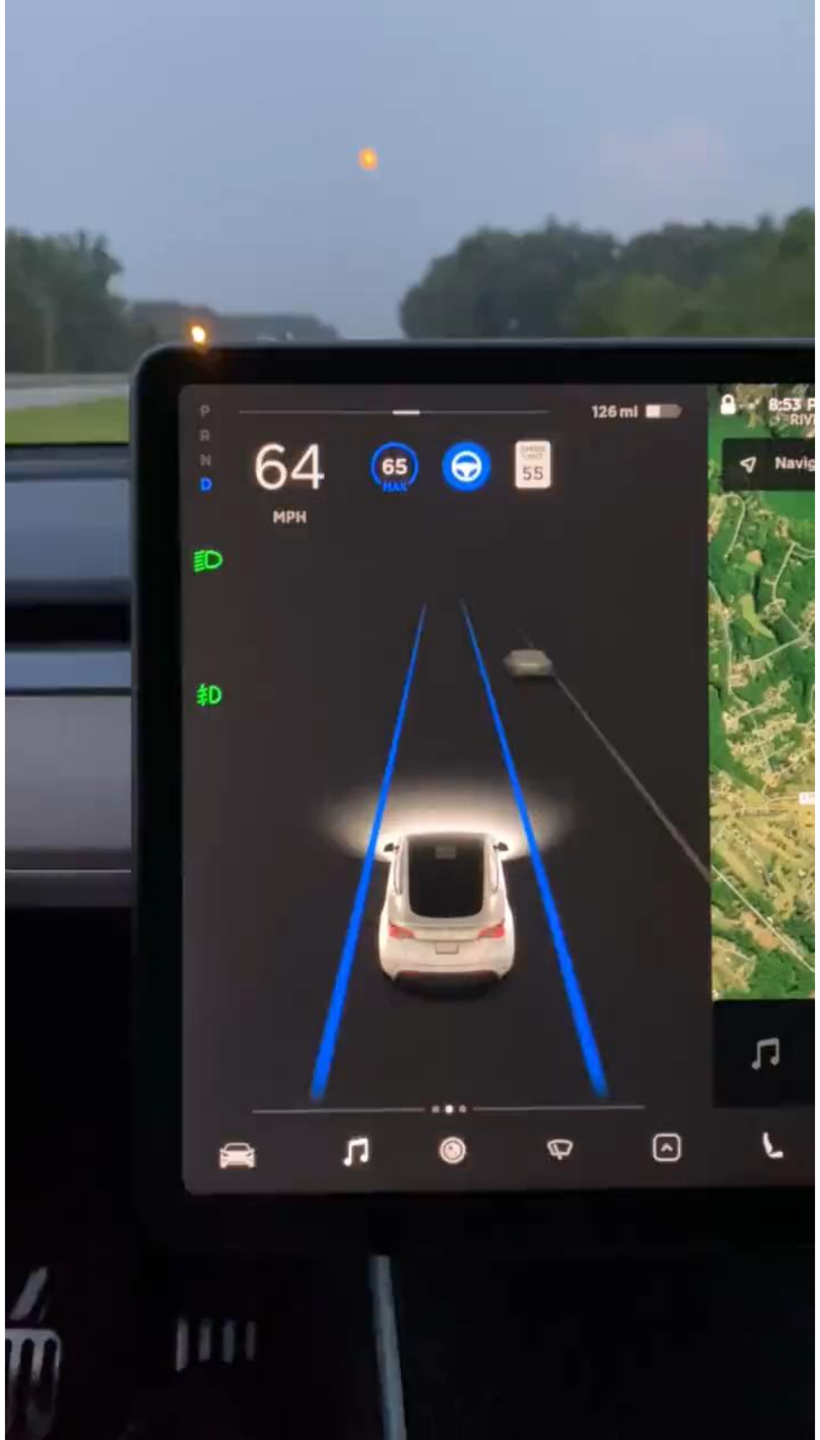
Inside Tesla as Elon Musk Pushed an Unflinching Vision for Self-Driving Cars

The automaker may have undermined safety in designing its Autopilot driver-assistance system to fit its chief executive's vision, former employees say.



Hardware choices have also raised safety questions. Within Tesla, some argued for pairing cameras with radar and other sensors that worked better in heavy rain and snow, bright sunshine and other difficult conditions. For several years, Autopilot incorporated radar, and for a time Tesla worked on developing its own radar technology. But three people who worked on the project said Mr. Musk had repeatedly told members of the Autopilot team that humans could drive with only two eyes and that this meant cars should be able to drive with cameras alone.

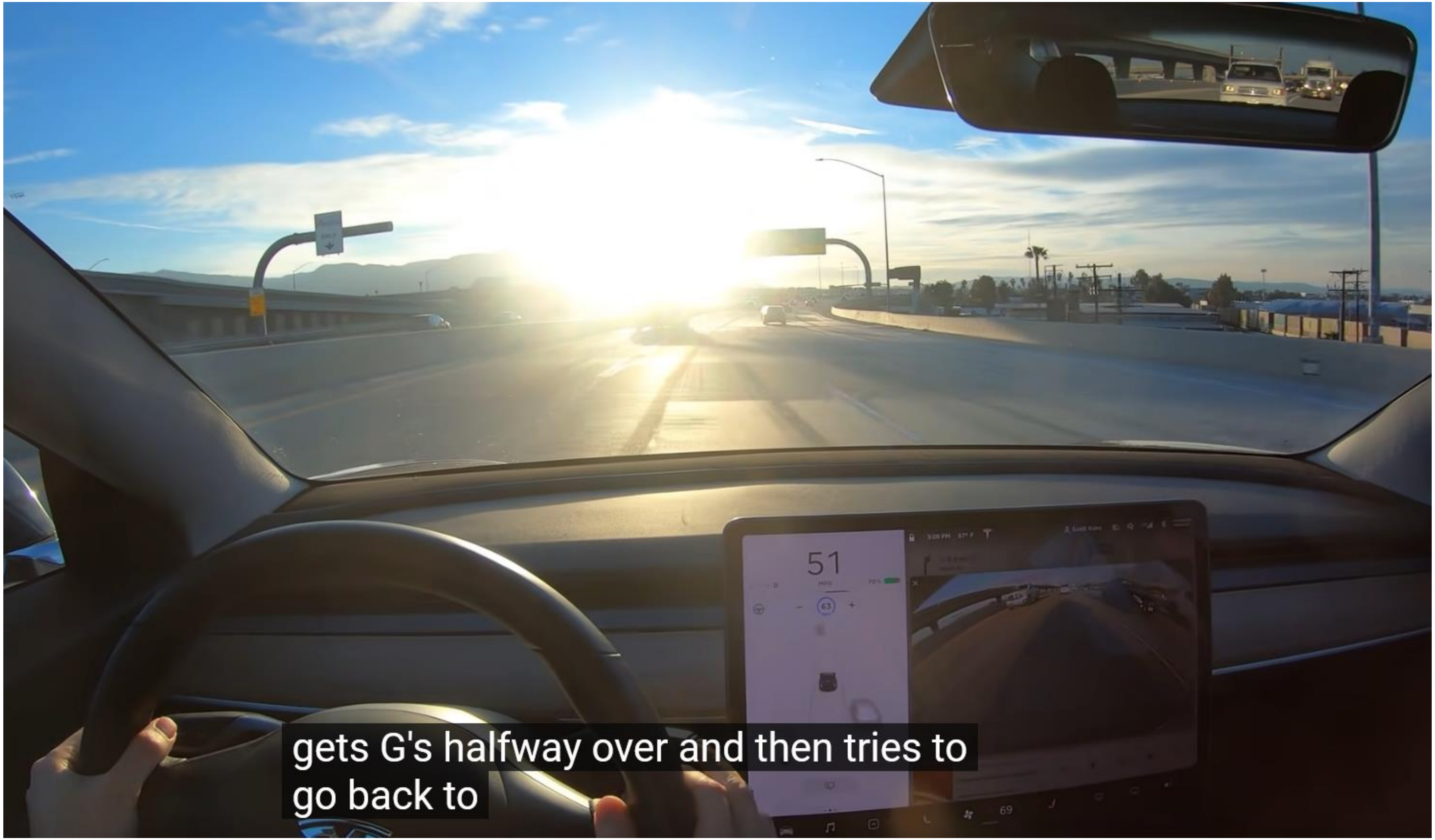
Another driving system with human level eyesight



https://twitter.com/JordanTeslaTech/status/1418413307862585344

https://www.reddit.com/r/teslamotors/comments/nrs8kf/you_think_ice_cream_truck_stop_signs_are_a_problem/

- On the whole, cameras *are* a reasonable analogy for eyes. They do capture sufficient information for safe driving 99.9% of the time.



gets G's halfway over and then tries to
go back to

https://www.youtube.com/watch?v=s1eTBMYEs-Y

- On the whole, cameras *are* a reasonable analogy for eyes. They do capture sufficient information for safe driving 99.9% of the time.
  - Imagine remote controlling a vehicle based on a camera feed.
- *But* the computer vision and machine learning methods that interpret the camera images *are not* yet a reasonable analogy for the human brain.

Next: Interest points and corners

Slides: Hoiem, Efros, and others