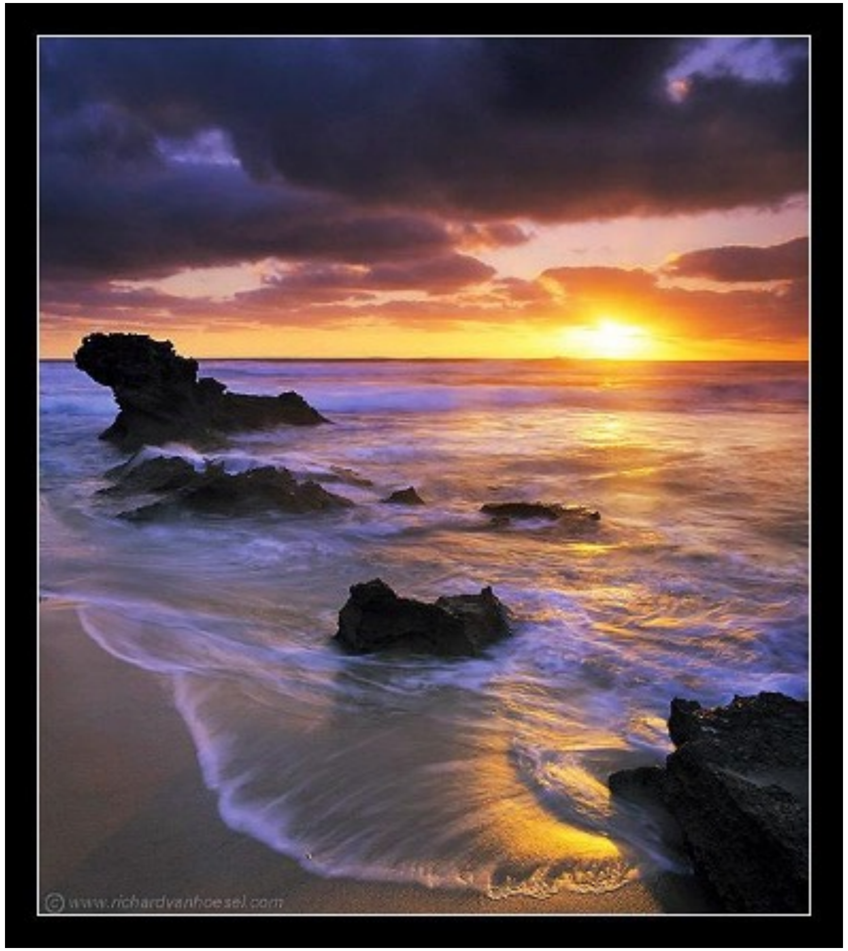
Quiz 5 (on Canvas)
Closed book / closed note

Ends at 1:08pm

CS5670: Computer Vision

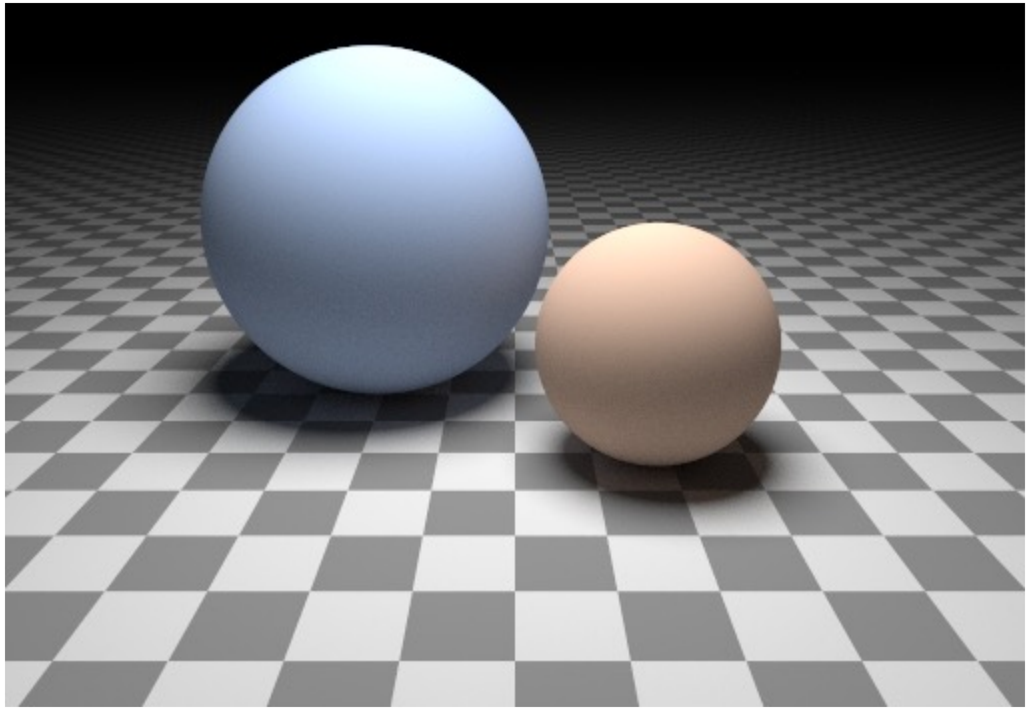
Light & Perception



Announcements

- Project 3 code due **Monday, March 20**, by 8pm to GitHub Classroom
- Project 3 artifact (panorama) due **Tuesday, March 21**, by 8pm to CMSX
- Project 4 to be released on Tuesday, March 21, due Friday, March 31 by 8pm
- Final exam is planned to be in class during the last lecture on Tuesday, May 9

Can we determine shape from lighting?



- Are these spheres?
  - Or just flat discs painted with varying color (albedo)?
  - There is ambiguity between *shading* and *reflectance*
  - But still, as humans we can understand the shapes of these

What we know: Stereo

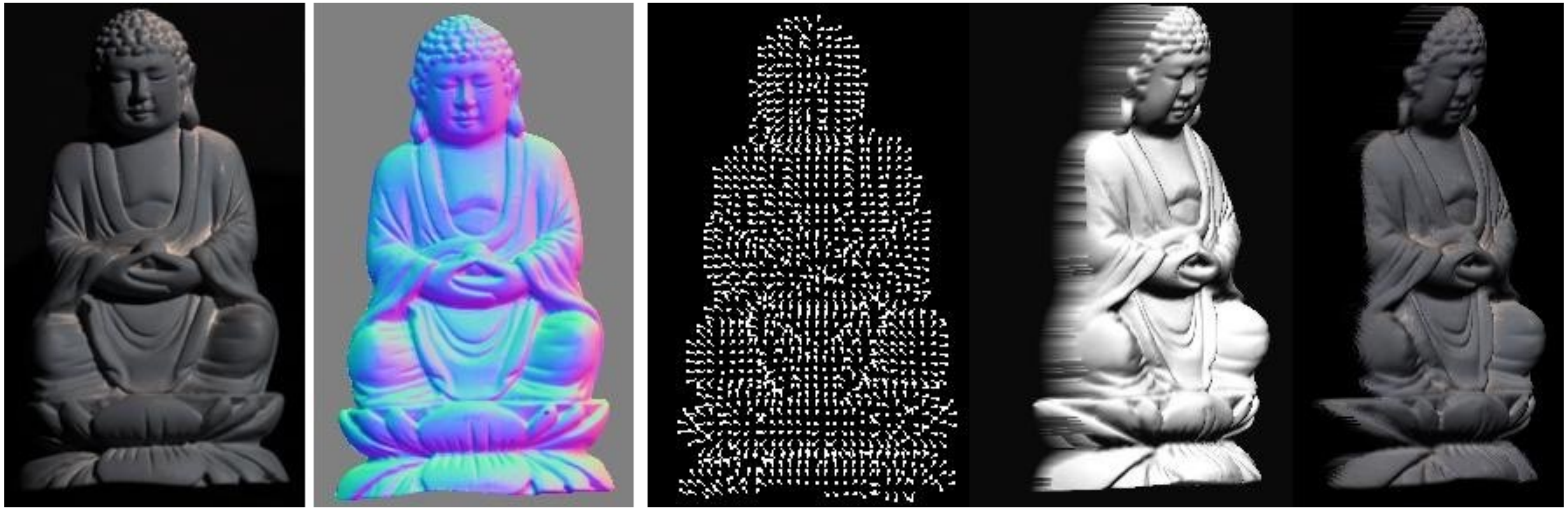
Key Idea: use camera motion to compute shape

Next: Photometric Stereo

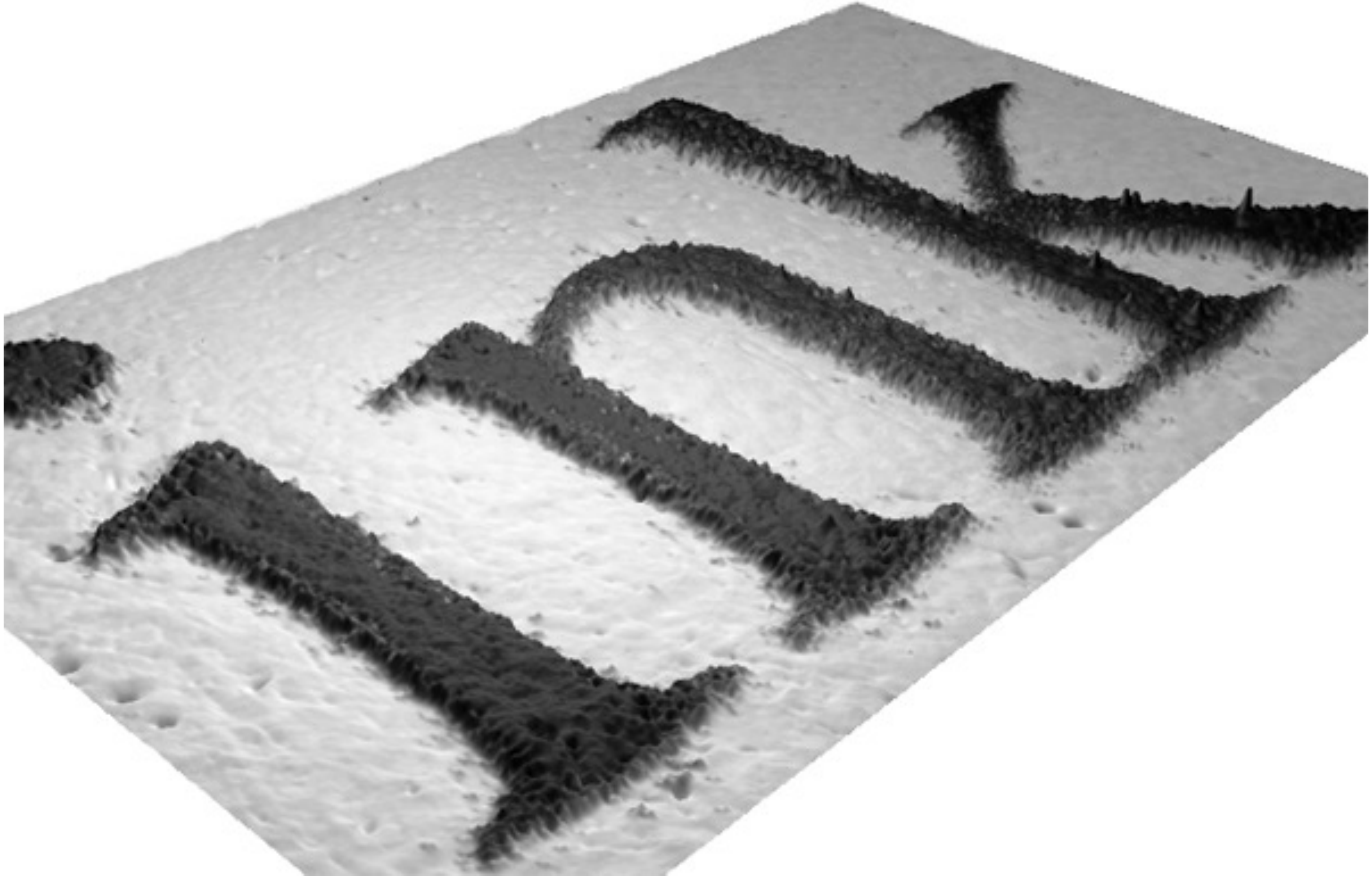
Key Idea: use pixel brightness to understand shape

Photometric Stereo

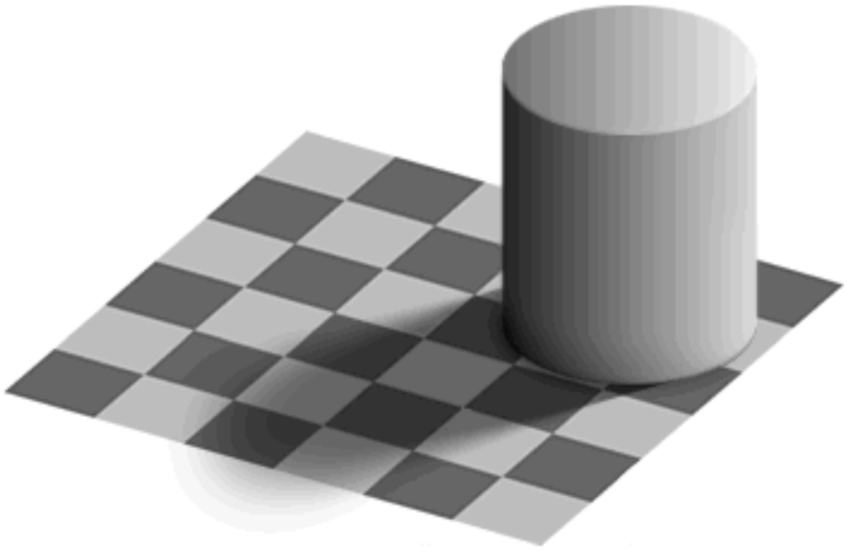
What results can you get?



Input (1 of 12) | Normals (RGB colormap) | Normals (vectors) | Shaded 3D rendering | Textured 3D rendering



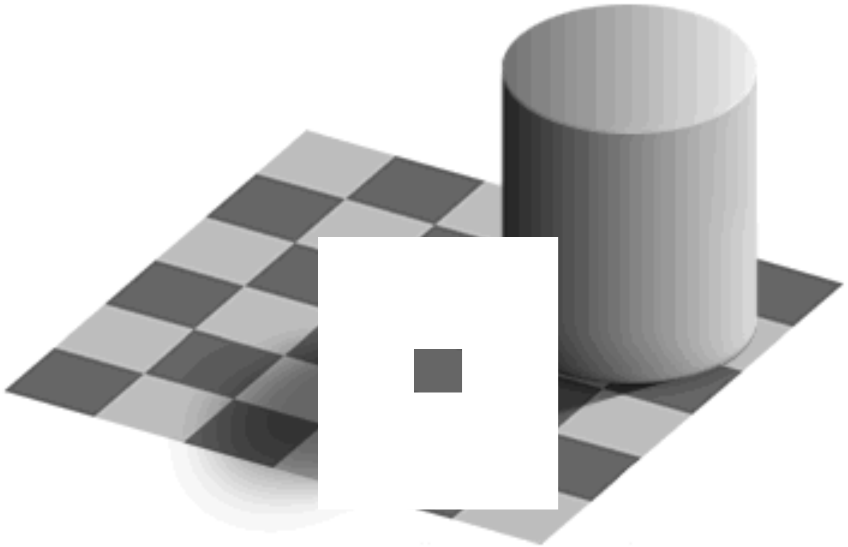
Light



by Ted Adelson

- Readings
  - Szeliski, 2.2, 2.3

Light



by Ted Adelson

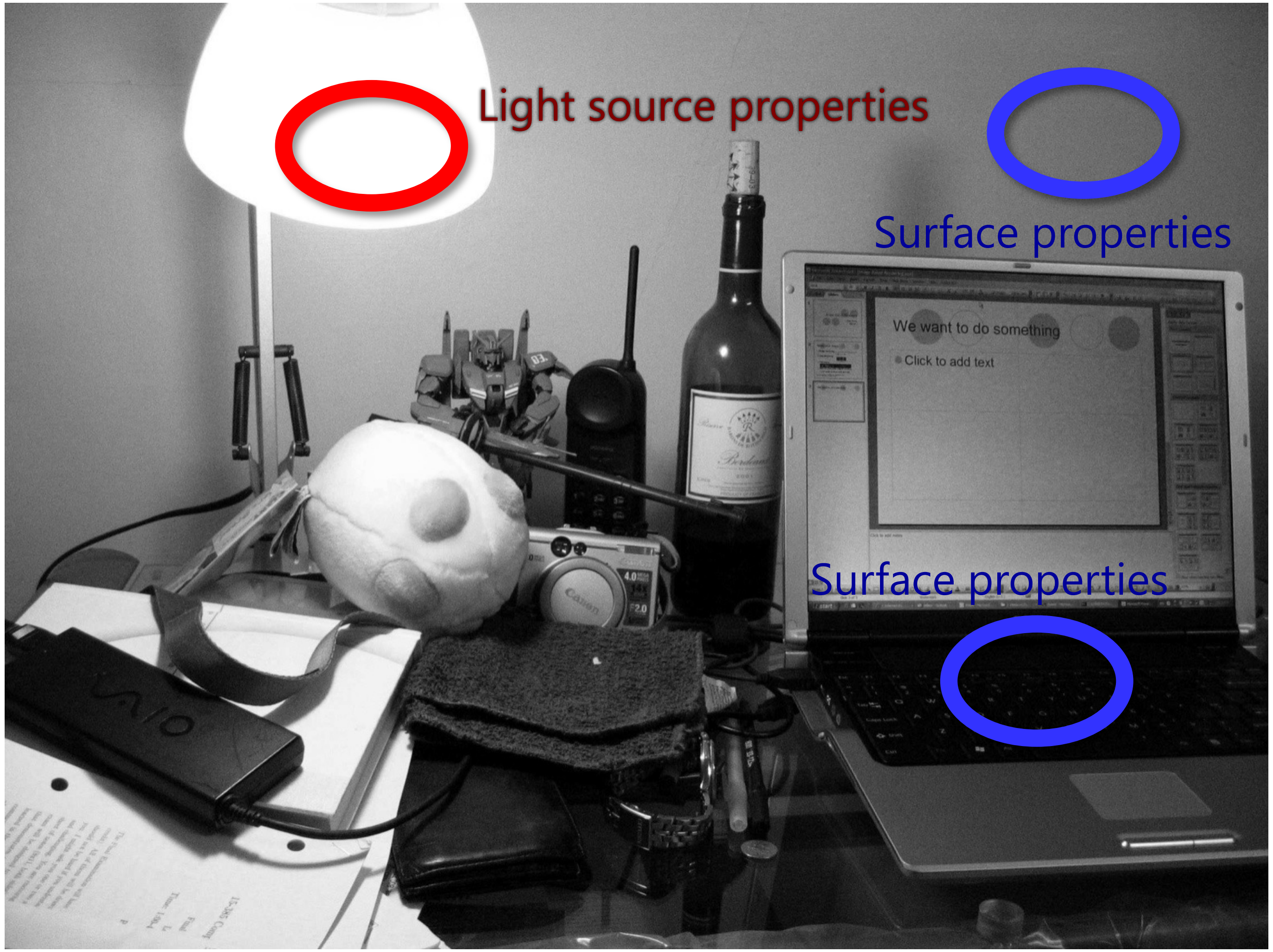
- Readings
  - – Szeliski, 2.2, 2.3

Properties of light

- Today
  - What is light?
  - How do we measure it?
  - How does light propagate?
  - How does light interact with matter?

Radiometry

- What determines the brightness of a pixel?



Radiometry

- What determines the brightness of a pixel?

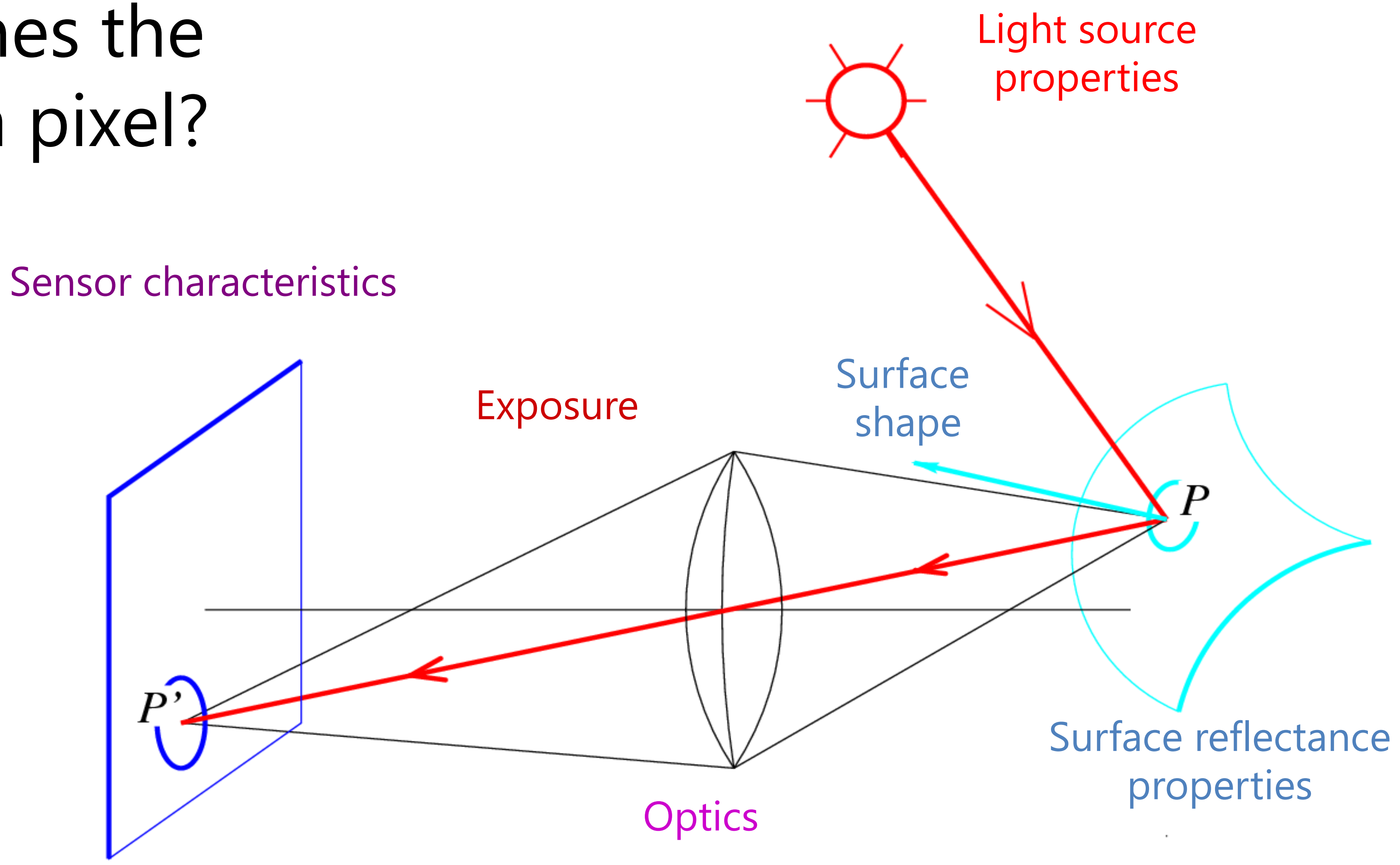
[@robertwestonbreshears](https://www.instagram.com/p/BtgX55ZBhU-/)
https://www.instagram.com/p/BtgX55ZBhU-/

Radiometry

- What determines the brightness of a pixel?

Radiometry

- What determines the brightness of a pixel?

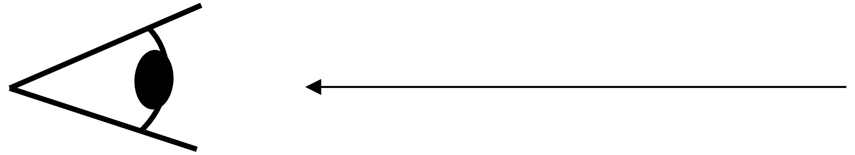


Slide by L. Fei-Fei

What is light?

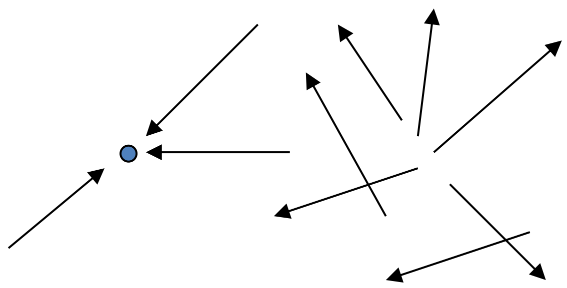
Electromagnetic radiation (EMR) moving along rays in space

- R(λ) is EMR, measured in units of power (watts)
  - λ is wavelength



Light field

- We can describe all of the light in the scene by specifying the radiation (or **"radiance"** along all light rays) arriving at every point in space and from every direction

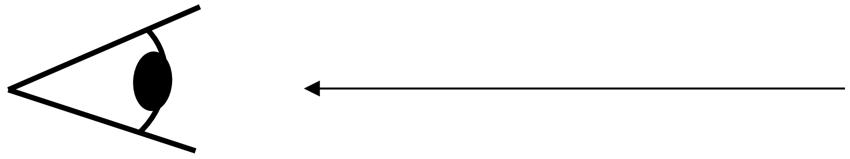


The ***plenoptic function*** describes all of this light: $R(X, Y, Z, \theta, \phi, \lambda, t)$

Color perception

Electromagnetic radiation (EMR) moving along rays in space

- R(λ) is EMR, measured in units of power (watts)
  - λ is wavelength

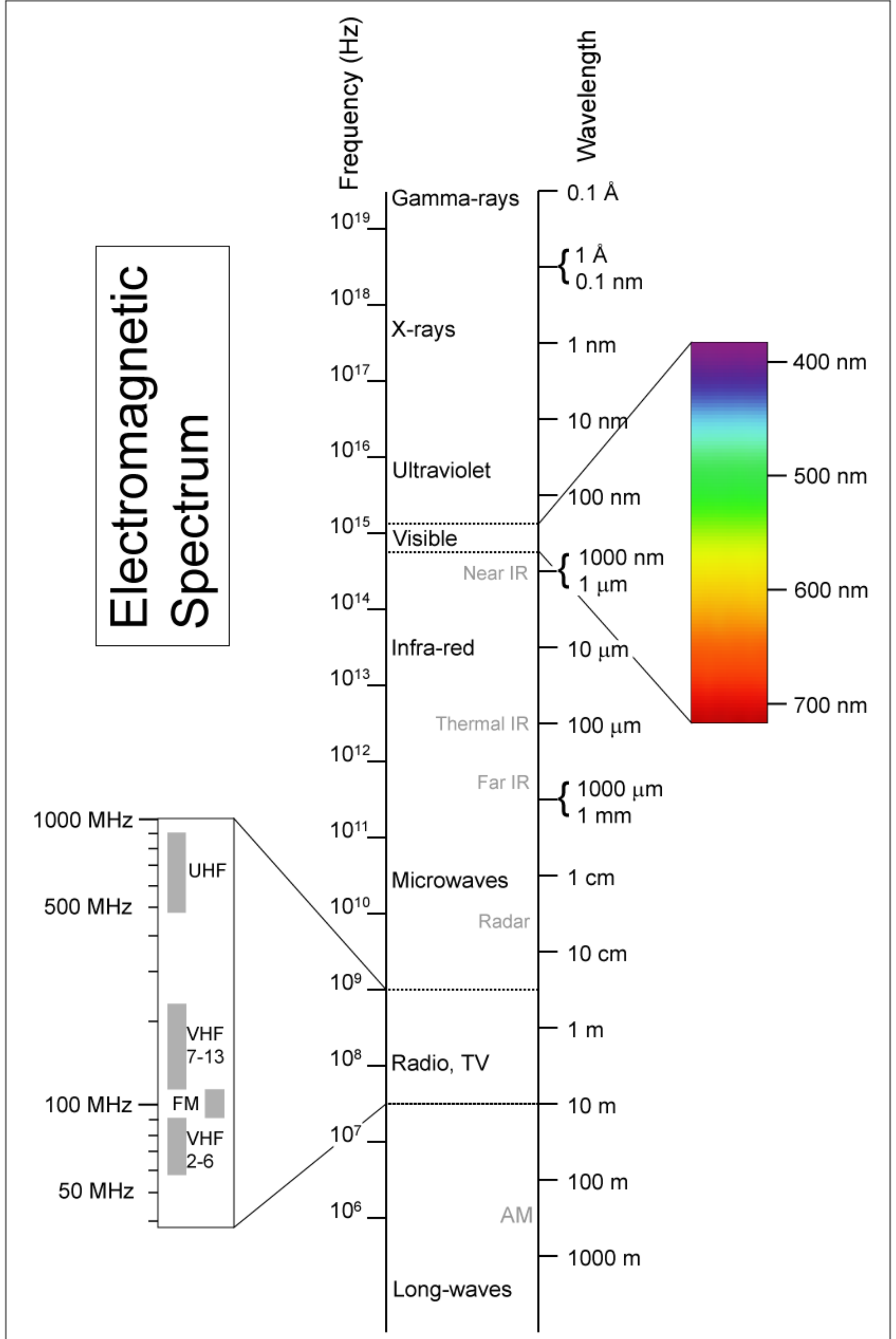


Perceiving light

- How do we convert radiation into “color”?
- What part of the spectrum do we see?

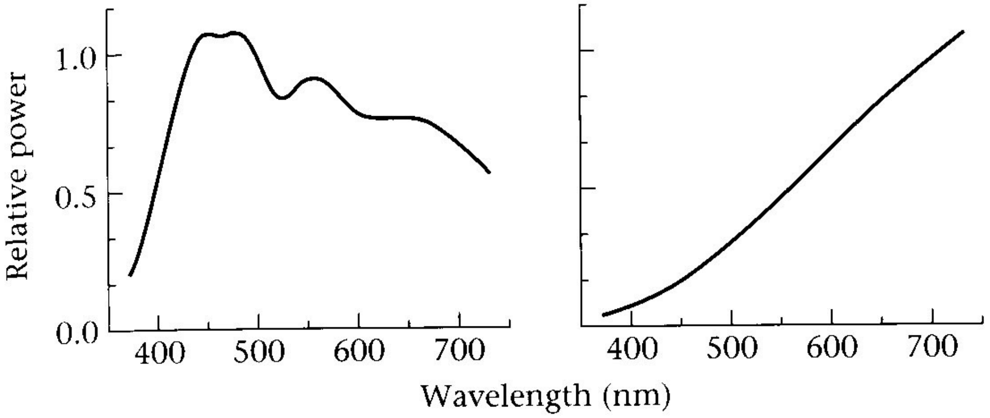
Visible light

We “see” electromagnetic radiation in a range of wavelengths

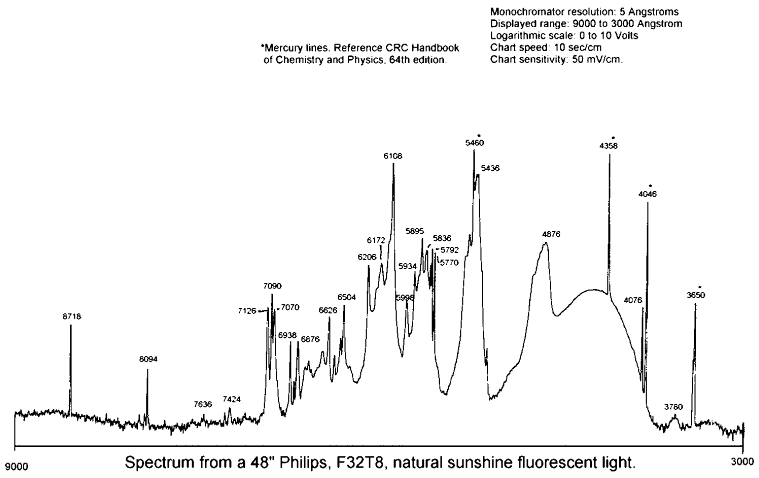


Light spectrum

- The appearance of light depends on its power **spectrum**
  - How much power (or energy) at each wavelength



daylight tungsten bulb



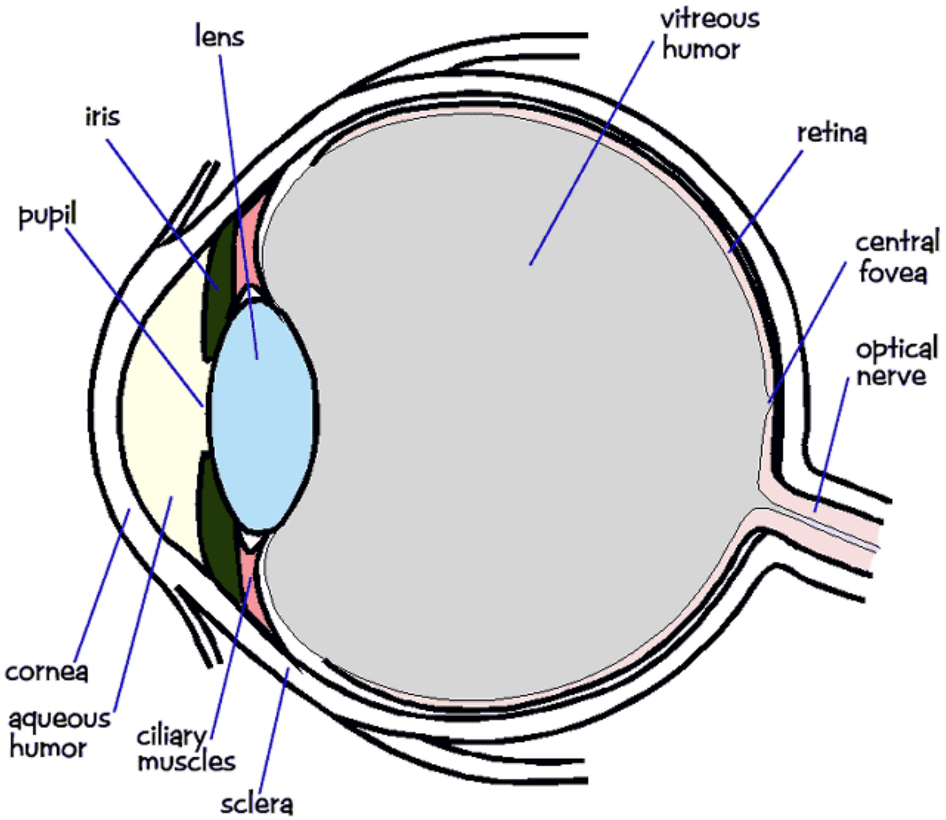
fluorescent bulb

Our visual system converts a light spectrum into “color”

- This is a rather complex transformation

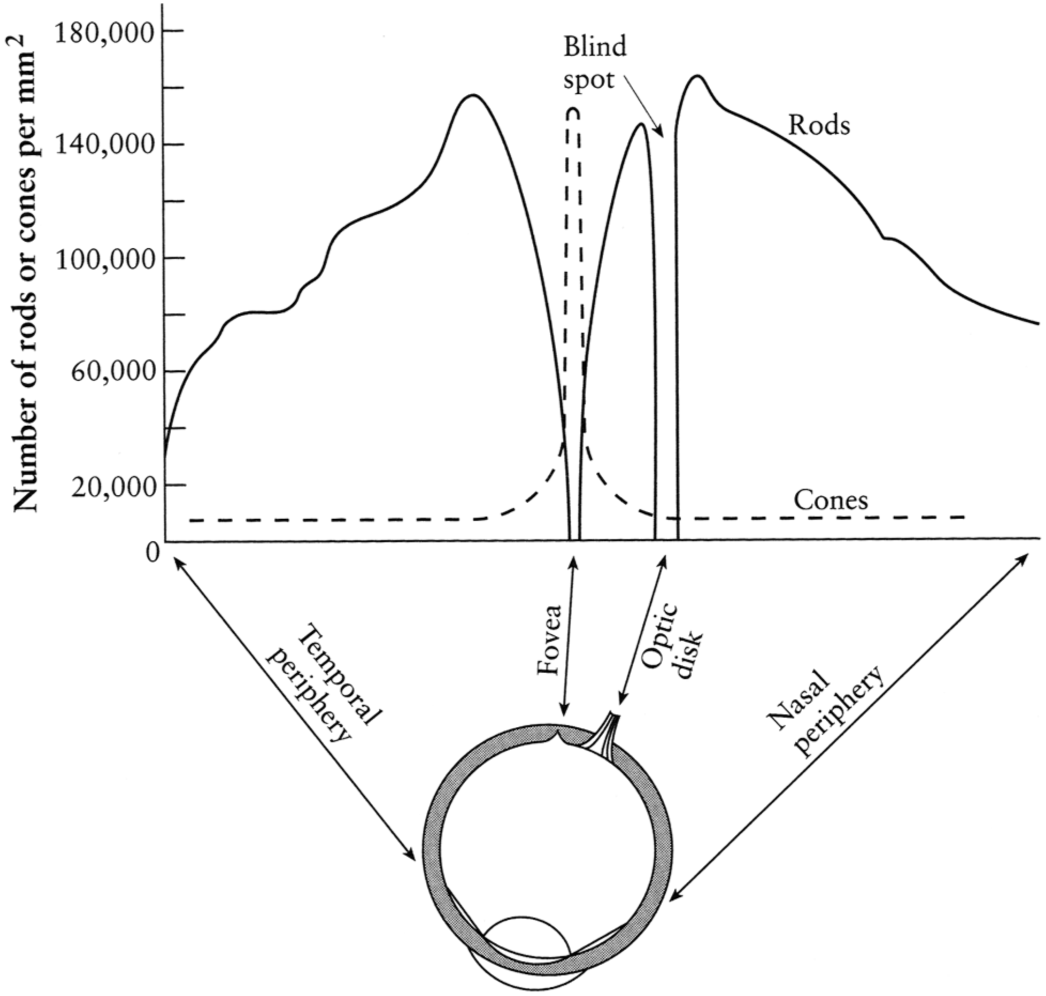
The human visual system

- Color perception
  - Light hits the retina, which contains photosensitive cells
    - rods and cones
  - These cells convert the spectrum into a few discrete values

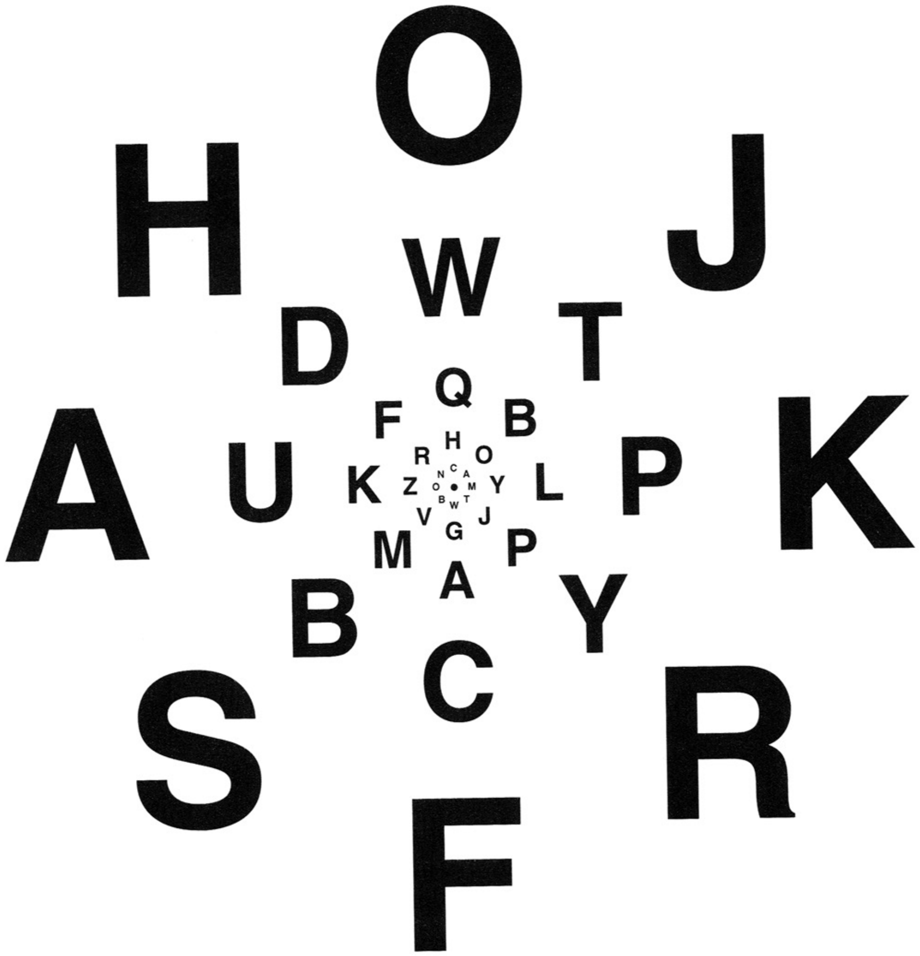


Density of rods and cones

- Rods and cones are *non-uniformly* distributed on the retina
  - Rods responsible for intensity, cones responsible for color
  - **Fovea**: Small region (1 or 2°) at the center of the visual field containing the highest density of cones (and no rods).
  - Less visual acuity in the periphery—many rods wired to the same neuron



Demonstrations of visual acuity



With one eye shut, at the right distance, all of these letters should appear equally legible (Glassner, 1.7).

Demonstrations of visual acuity

With left eye shut, look at the cross on the left. At the right distance, the circle on the right should disappear (Glassner, 1.8).

Brightness contrast and constancy

- The apparent brightness depends on the surrounding region
  - **brightness contrast**: a constant colored region seems lighter or darker depending on the surrounding intensity

  - **brightness constancy**: a surface looks the same under widely varying lighting conditions.

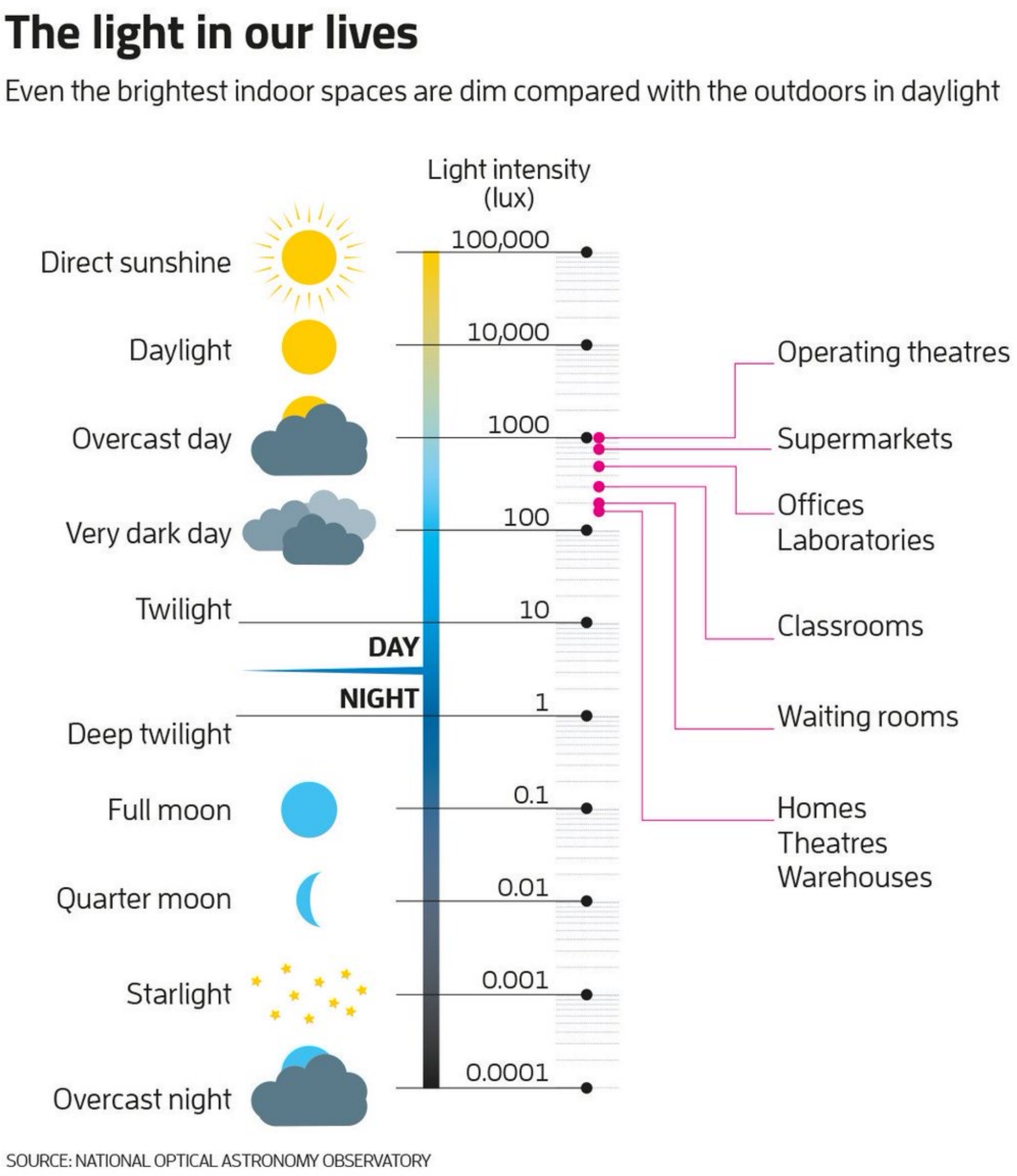
Light response is nonlinear

- Our visual system has a large *dynamic range*
  - We can resolve both light and dark things at the same time
  - One mechanism for achieving this is that we sense light intensity on a *logarithmic scale*
    - an exponential intensity ramp will be seen as a linear ramp
  - Another mechanism is *adaptation*
    - rods and cones adapt to be more sensitive in low light, less sensitive in bright light.

Visual dynamic range

A piece of white paper can be 1,000,000,000 times brighter in outdoor sunlight than in a moonless night.

BUT in a given lighting condition, light perception ranges over only about two orders of magnitude.



https://threader.app/thread/1134003178515701762

Learning to See in the Dark

Chen Chen, Qifeng Chen, Jia Xu and Vladlen Koltun

IEEE Conference on Computer Vision and Pattern Recognition (CVPR), 2018

(a) Camera output with ISO 8,000 (b) Camera output with ISO 409,600 (c) Our result from the raw data of (a)

Figure. Extreme low-light imaging by a Sony a7S II camera using ISO 8000, f/5.6, 1/30 second. Dark indoor environment. The illuminance at the camera is <0.1 lux.

http://cchen156.web.engr.illinois.edu/SID.html

Dancing under the stars: video denoising in starlight

CVPR 2022

Kristina Monakhova
UC Berkeley

Stephan Richter
Intel Labs

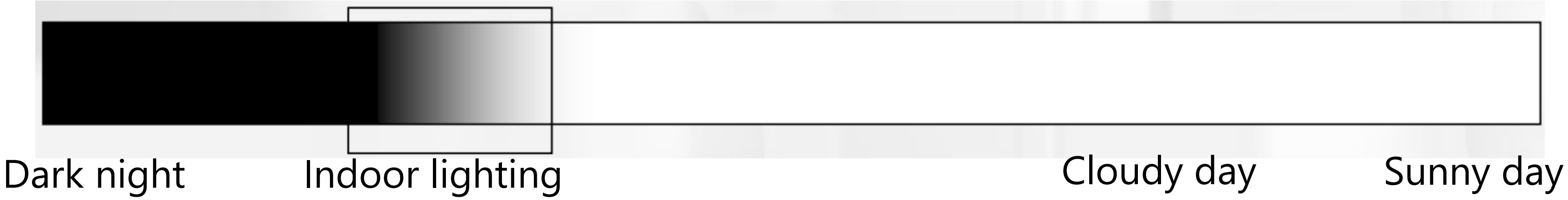
Laura Waller
UC Berkeley

Vladlen Koltun
Intel Labs

Visual dynamic range

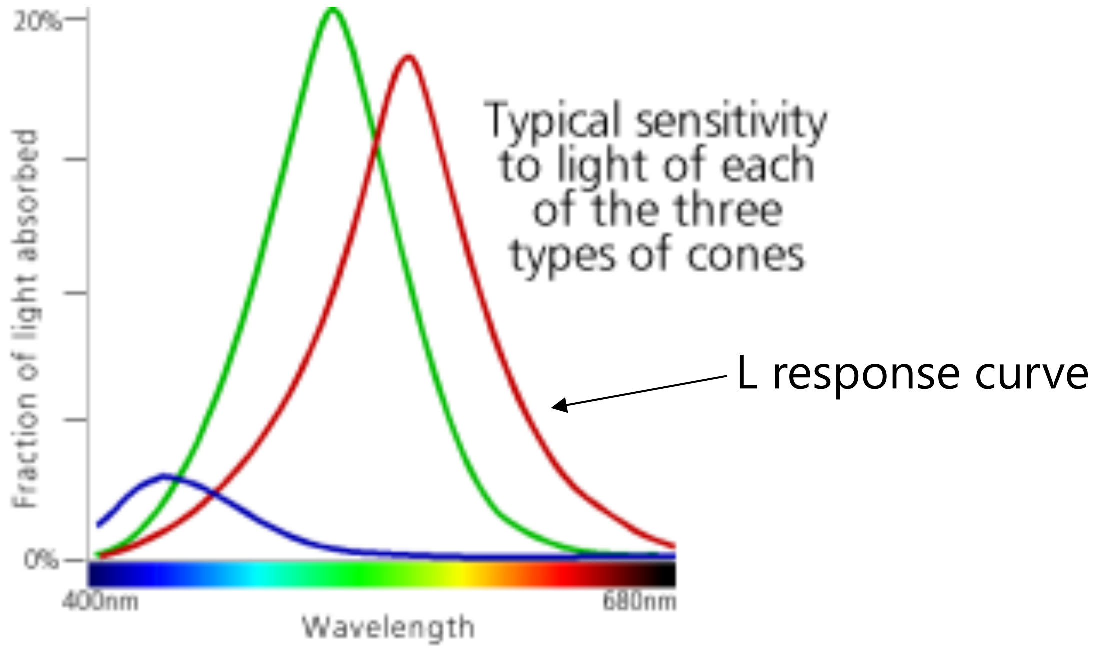
If we were sensitive to this whole range all the time, we wouldn't be able to discriminate lightness levels in a typical scene.

The visual system solves this problem by restricting the 'dynamic range' of its response to match the current overall or 'ambient' light level.

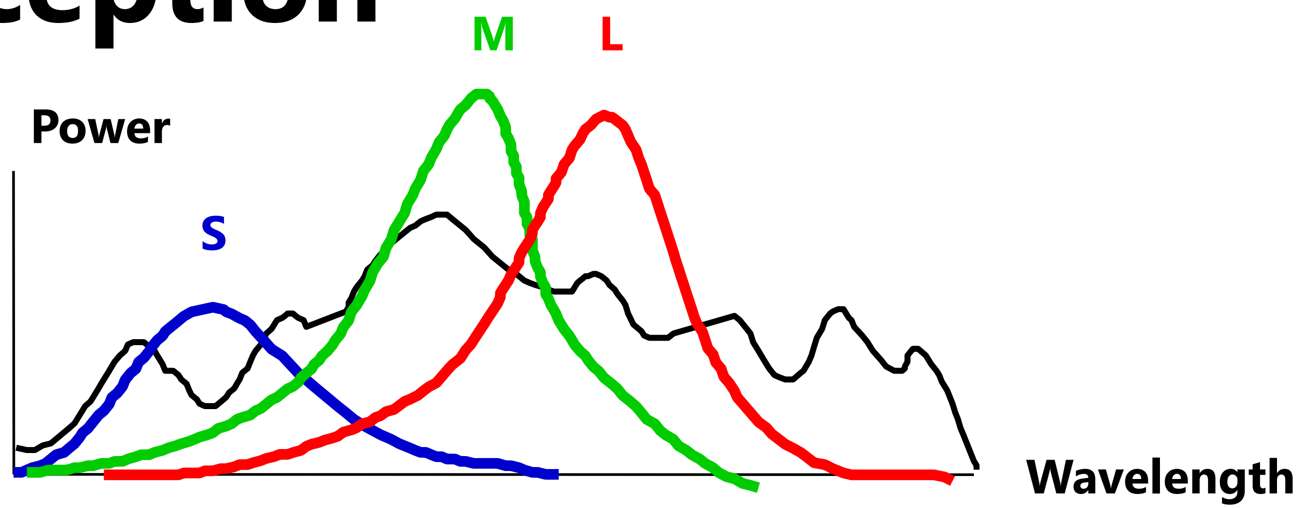


Color perception

- Three types of cones
  - Each is sensitive in a different region of the spectrum
    - but regions overlap
    - Short (S) corresponds to **blue**
    - Medium (M) corresponds to **green**
    - Long (L) corresponds to **red**
  - Different sensitivities: we are more sensitive to green than red
    - varies from person to person (and with age)
  - Colorblindness—deficiency in at least one type of cone



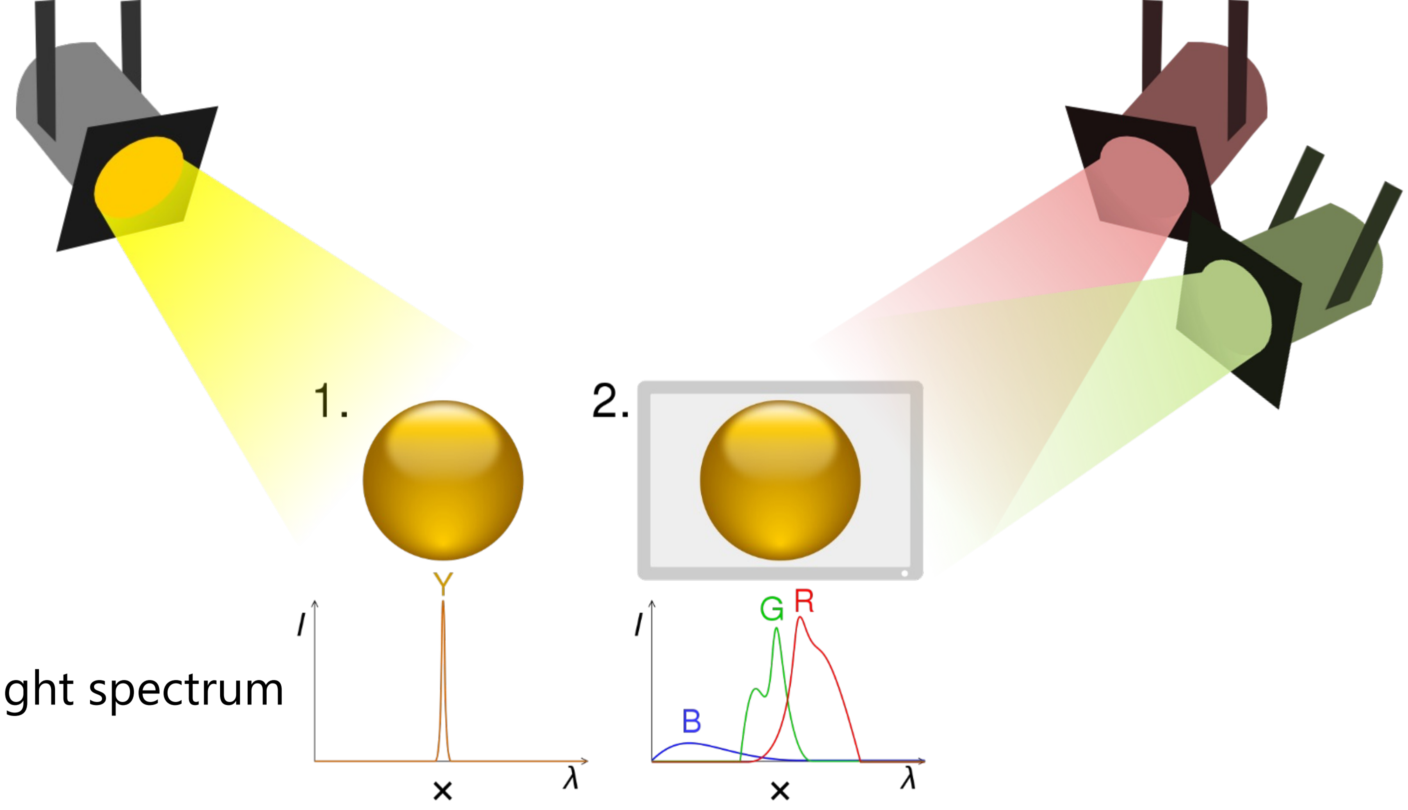
Color perception



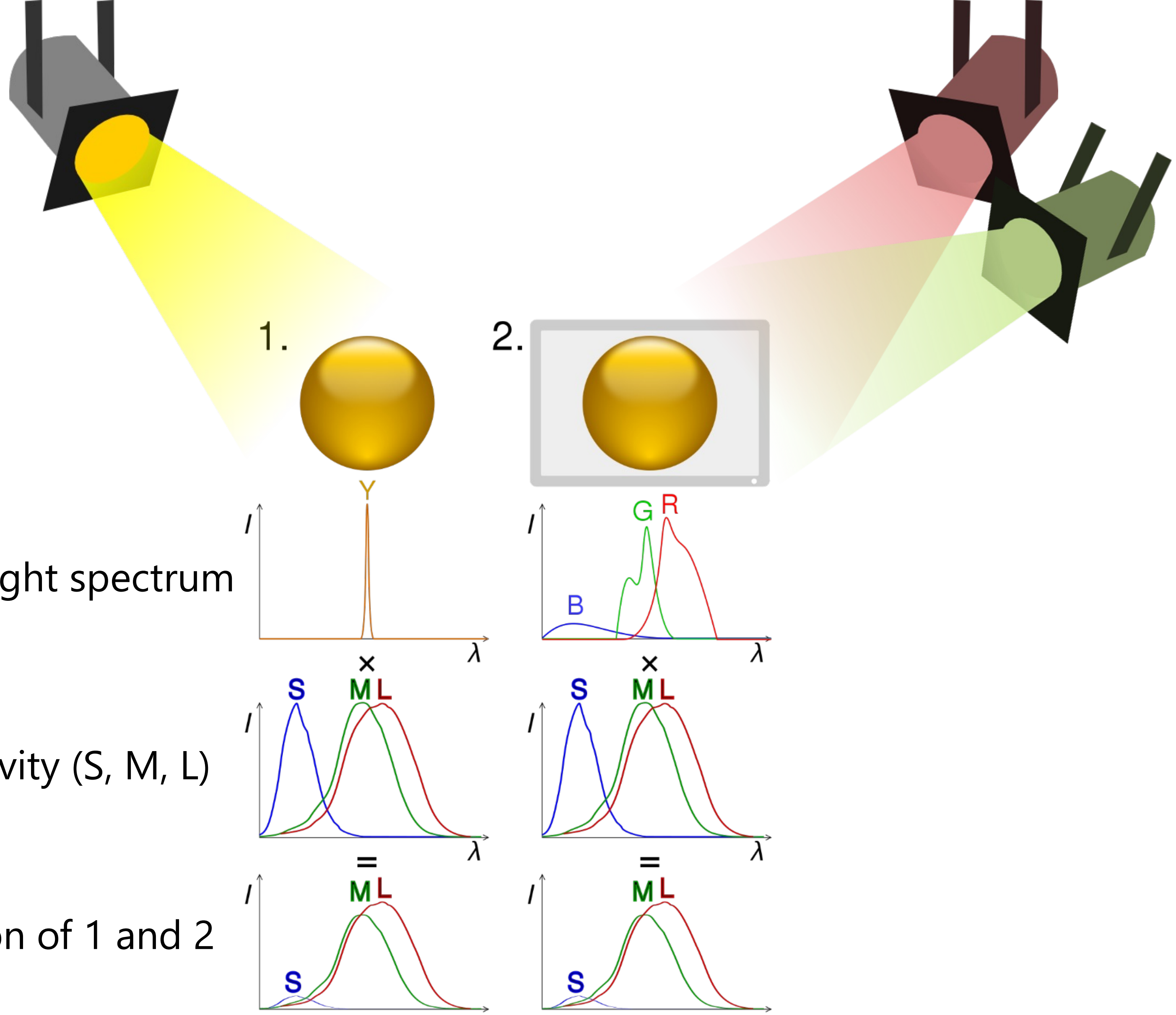
- Rods and cones act as filters on the spectrum
  - To get the output of a filter, multiply its response curve by the spectrum, integrate over all wavelengths
    - Each cone yields one number
  - Q: How can we represent an entire spectrum with 3 numbers?
  - A: We can't! Most of the information is lost
    - As a result, two different spectra may appear indistinguishable
      - such spectra are known as **metamers**

Metamers

1. Combined light spectrum



Metamers



1. Combined light spectrum

2. Cone sensitivity (S, M, L)

3. Multiplication of 1 and 2

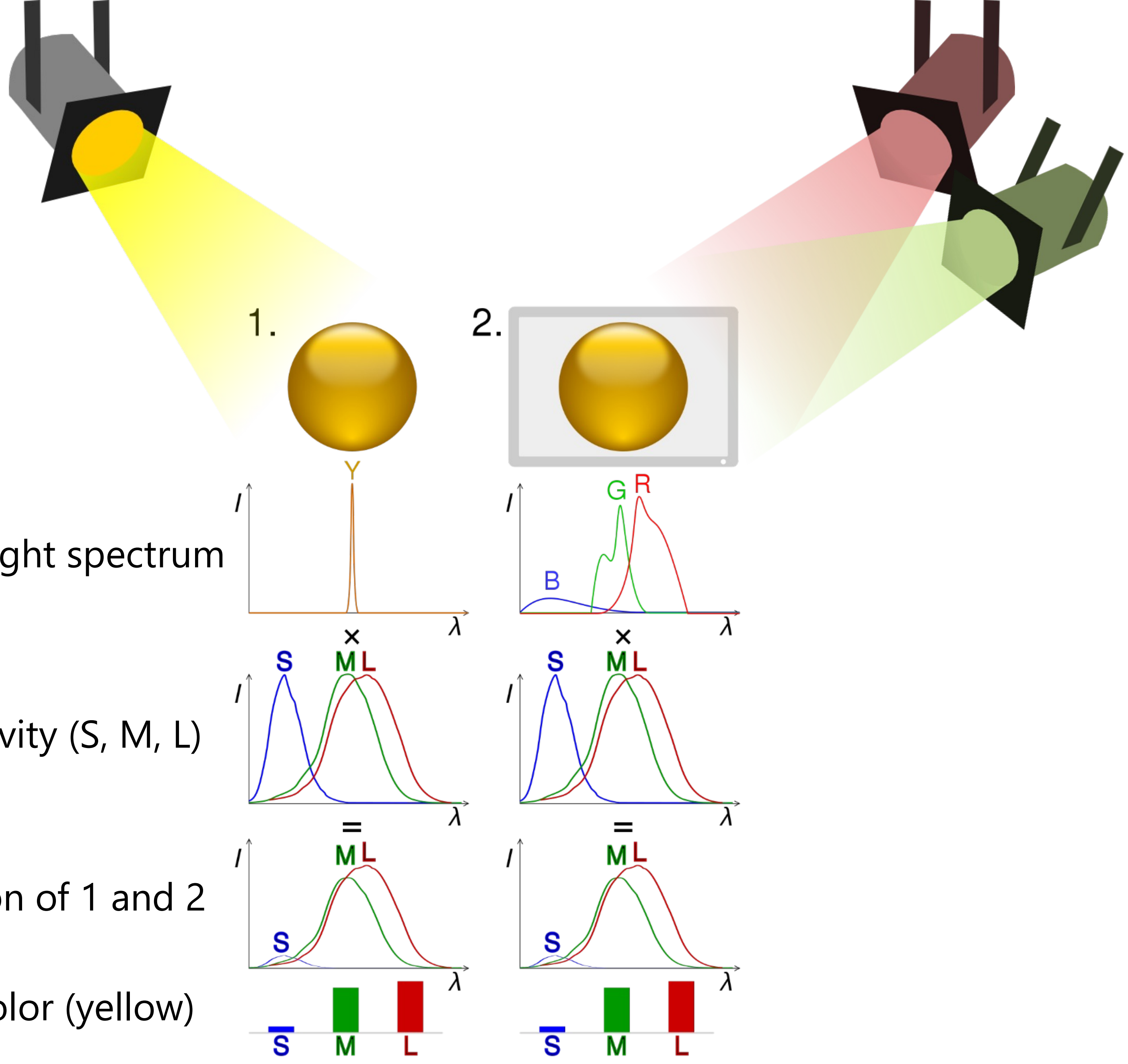
Metamers

1. Combined light spectrum

2. Cone sensitivity (S, M, L)

3. Multiplication of 1 and 2

4. Observed color (yellow)



What kind of bulb is it?

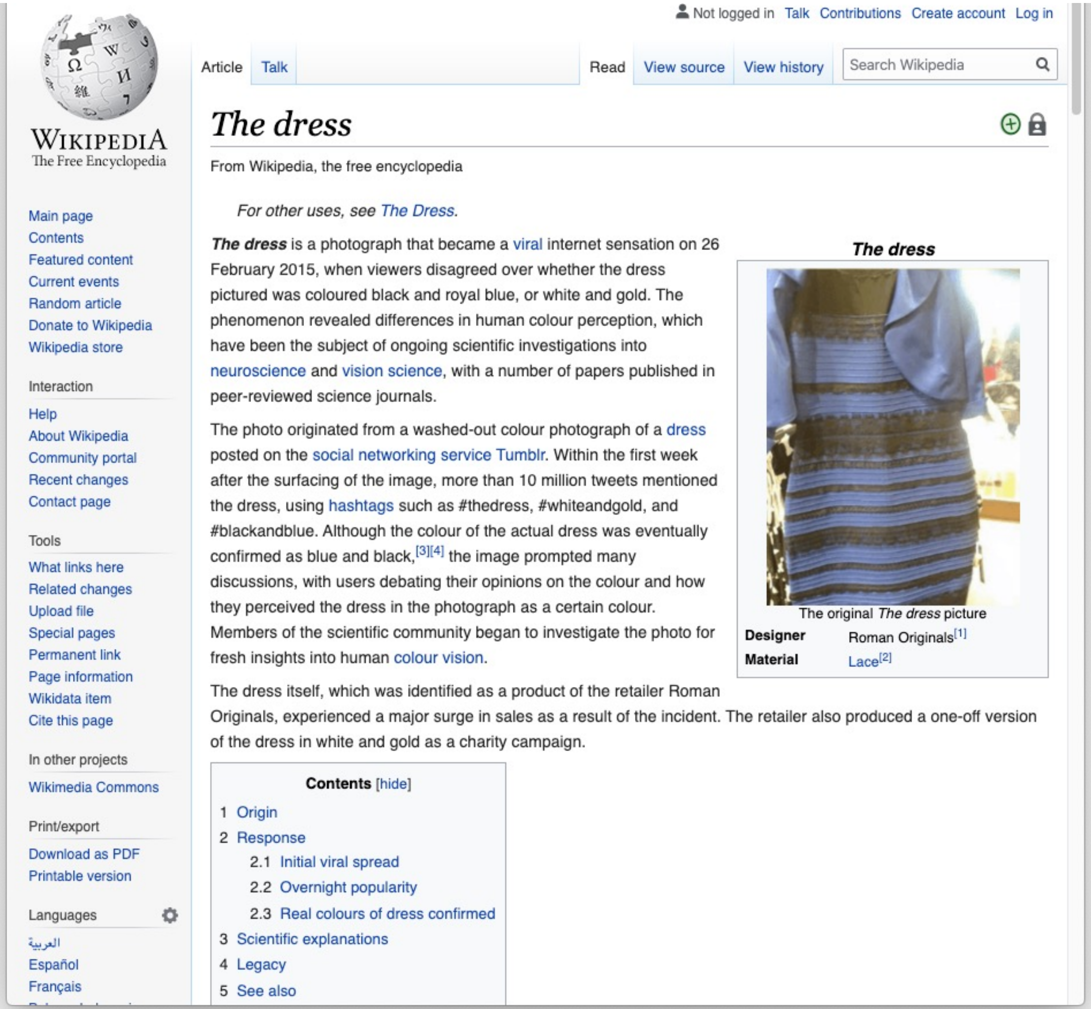



http://www.chemistryland.com/CHM107Lab/Exp7/Spectroscope/Spectroscope.html

What color is the dress?

- White and gold?
- Black and blue?

Reflectance and Illumination In Popular Culture…



Not logged in Talk Contributions Create account Log in

WIKIPEDIA
The Free Encyclopedia

Article Talk | Read View source View history | Search Wikipedia

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 royal 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, with 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 Tumblr. 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 actual dress was eventually confirmed as blue and black,[3][4] the image prompted many discussions, with users debating their opinions on the colour and how they perceived the dress in the photograph as a certain 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.

The dress

The original *The dress* picture

Designer	Roman Originals[1]
Material	Lace[2]

Main page
Contents
Featured content
Current events
Random article
Donate to Wikipedia
Wikipedia store

Interaction
Help
About Wikipedia
Community portal
Recent changes
Contact page

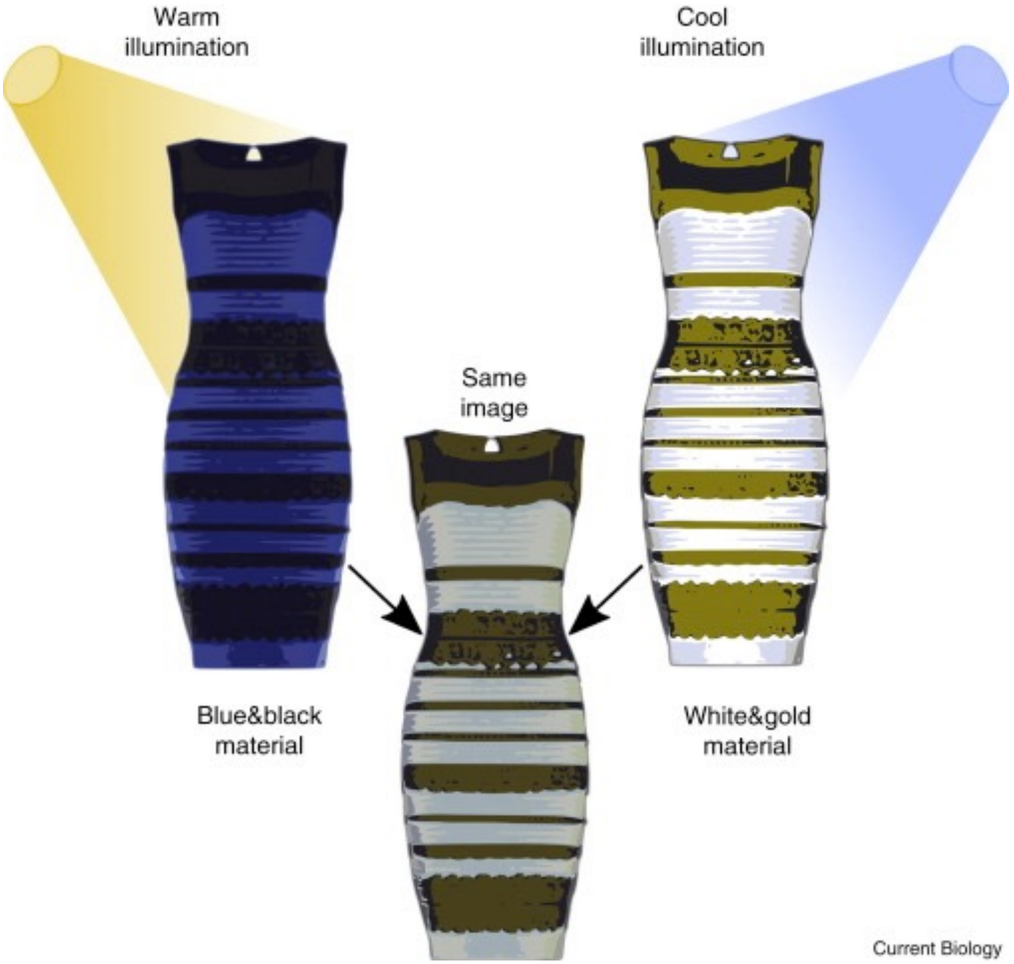
Tools
What links here
Related changes
Upload file
Special pages
Permanent link
Page information
Wikidata item
Cite this page

In other projects
Wikimedia Commons

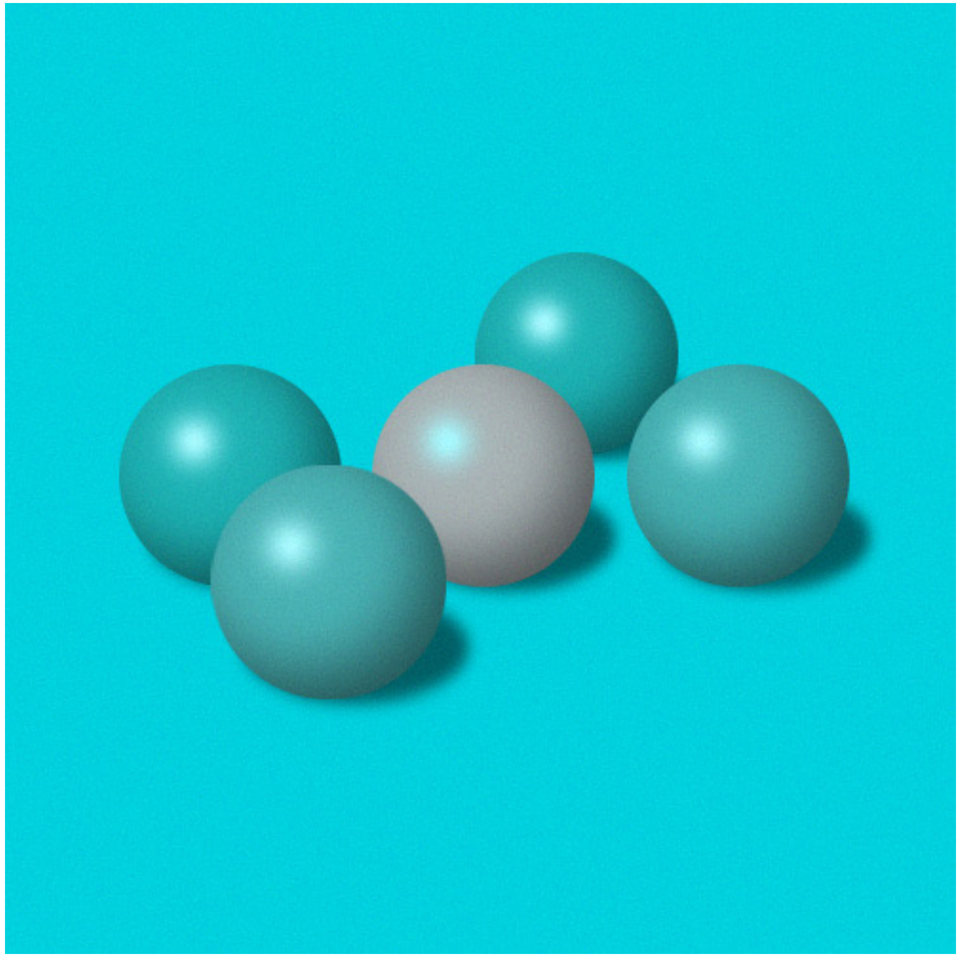
Print/export
Download as PDF
Printable version

Languages
العربية
Español
Français

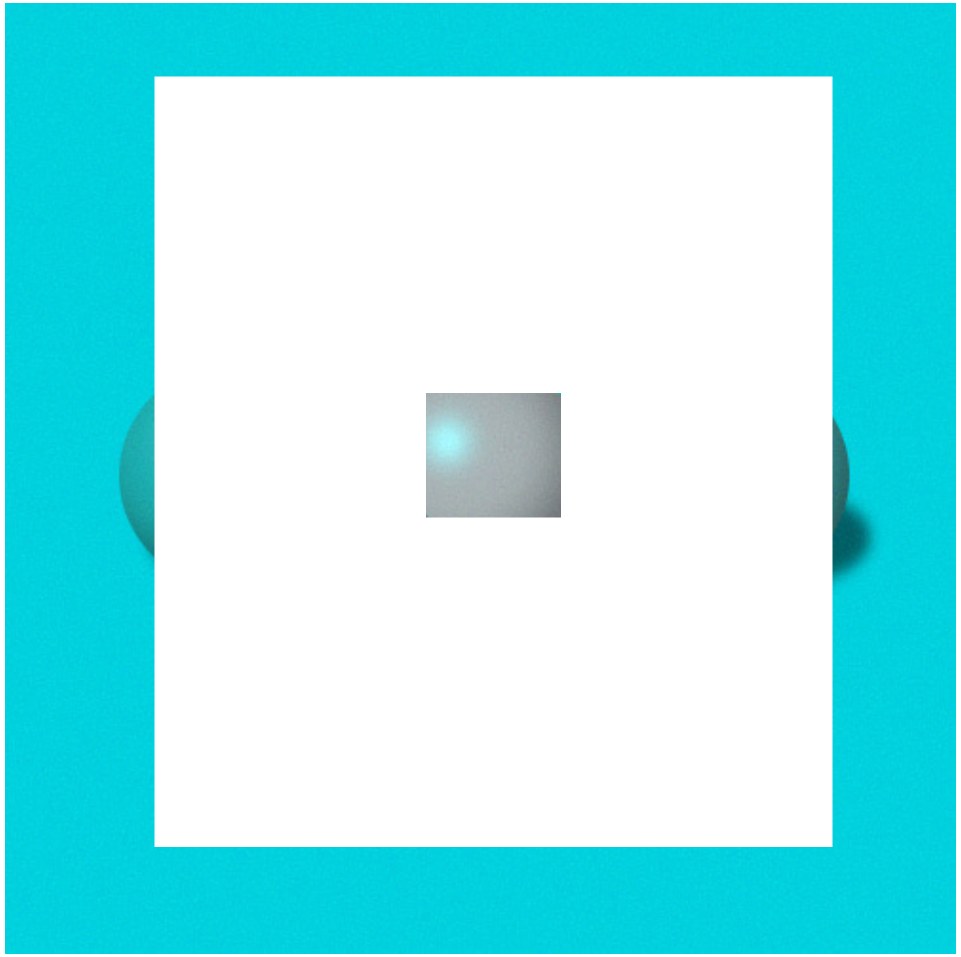
Contents [hide]



What color is the center ball?



What color is the center ball?



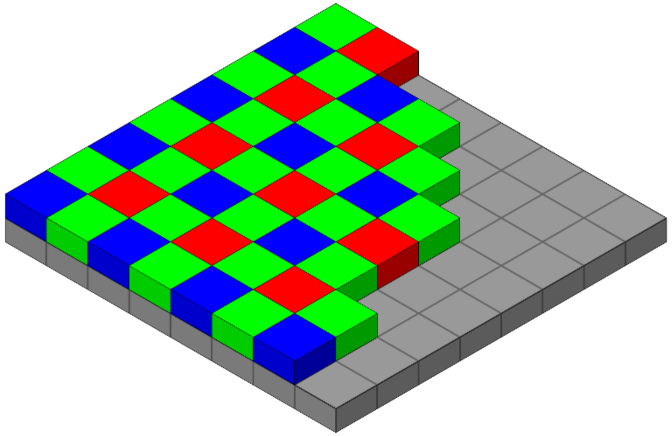
Perception summary

- The mapping from radiance to perceived color is quite complex!
  - We throw away most of the data
  - We apply a logarithm
  - Brightness affected by pupil size and adaptation of rods/cones
  - Brightness contrast and constancy effects

- The same is true for cameras
  - But we have tools to correct for these effects
    - (Computational Photography)

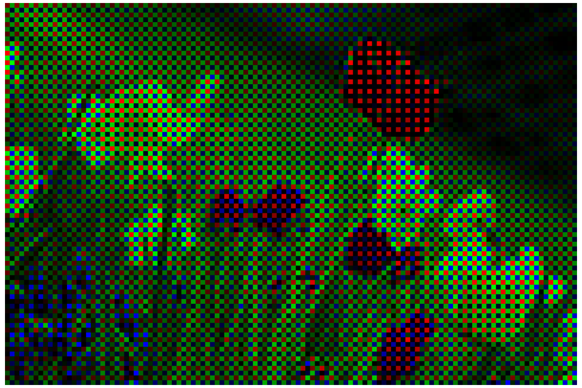
Cameras also see color

- Common technique is to place a mosaic of color filters (a *Bayer filter*) in front of the sensor

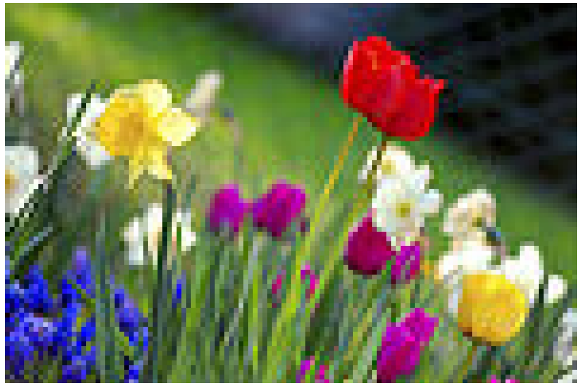


Bayer filter pattern in front of sensor

- Colors are interpolated to create a full-resolution "*demosaicked*" color image



What the camera sees ("raw" image)



Demosaicked image

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

Early color photography

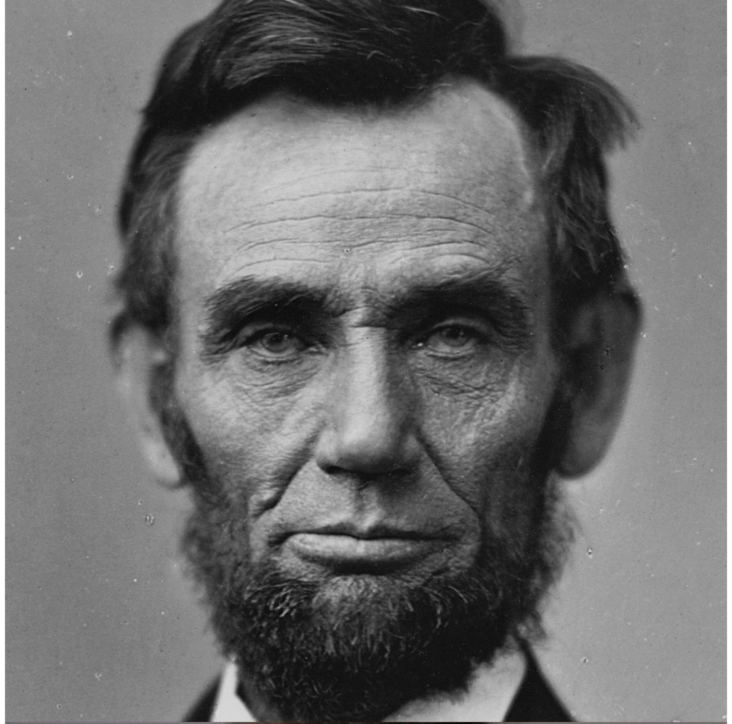
- Prior to the invention of color film, Sergey Prokudin-Gorsky took three separate exposures with three different color filters

Blue, Green, Red exposures

Combined color image (1911)

Film has its own sensitivity

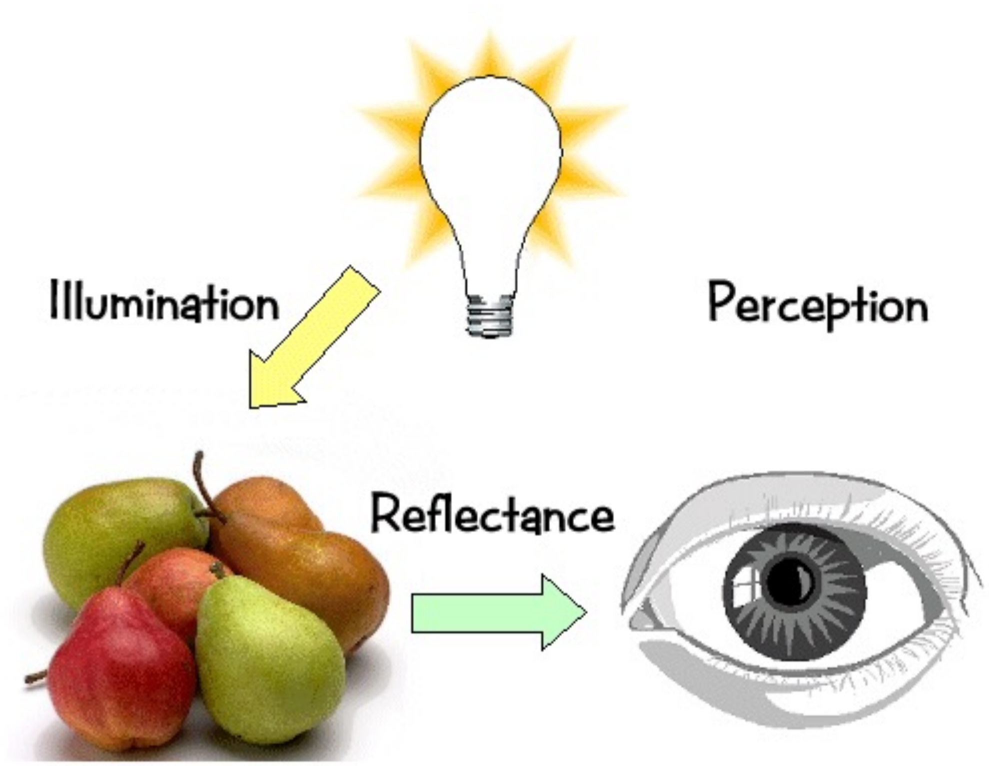
- "… the film of Lincoln's era was sensitive only to blue and UV light, causing cheeks to appear dark, and overly emphasizing wrinkles by filtering out skin subsurface scatter which occurs mostly in the red channel. Hence, the deep lines and sharp creases that we associate with Lincoln's face are likely exaggerated by the photographic process of the time."



Time-Travel Rephotography
Xuan Luo, Xuaner Zhang, Paul Yoo, Ricardo Martin-Brualla, Jason Lawrence, Steven M. Seitz
SIGGRAPH Asia 2021

Questions?

Light transport



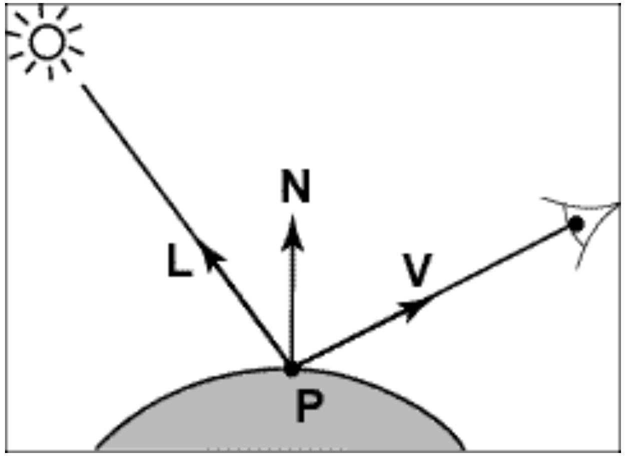
Light sources

- Basic types
  - point source
  - directional source
    - a point source that is infinitely far away
  - area source
    - a union of point sources
- More generally
  - a light field can describe *any* distribution of light sources
- What happens when light hits an object?

Modeling Image Formation

We need to reason about:

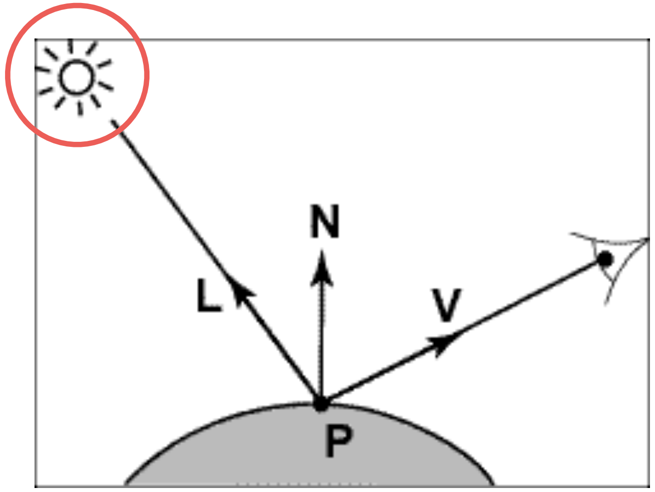
- How light interacts with the scene
- How a pixel value is related to light energy in the world



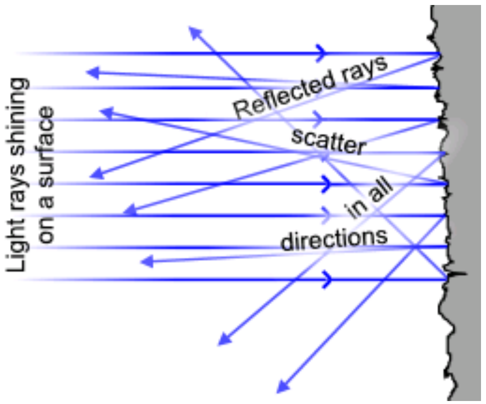
Track a “ray” of light all the way from light source to the sensor

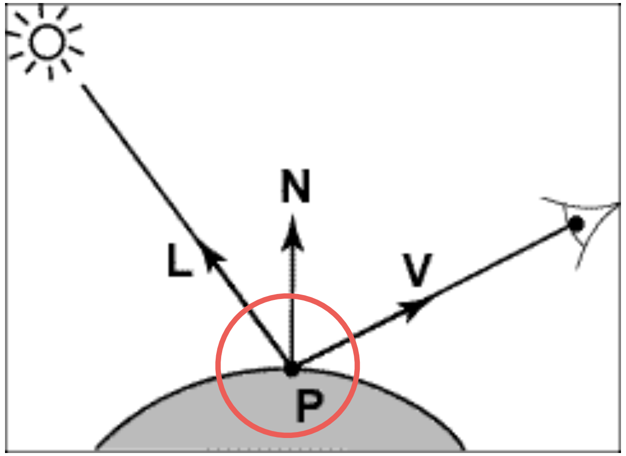
Directional Lighting

- Key property: all rays are parallel
- Equivalent to an infinitely distant point source



Lambertian Reflectance



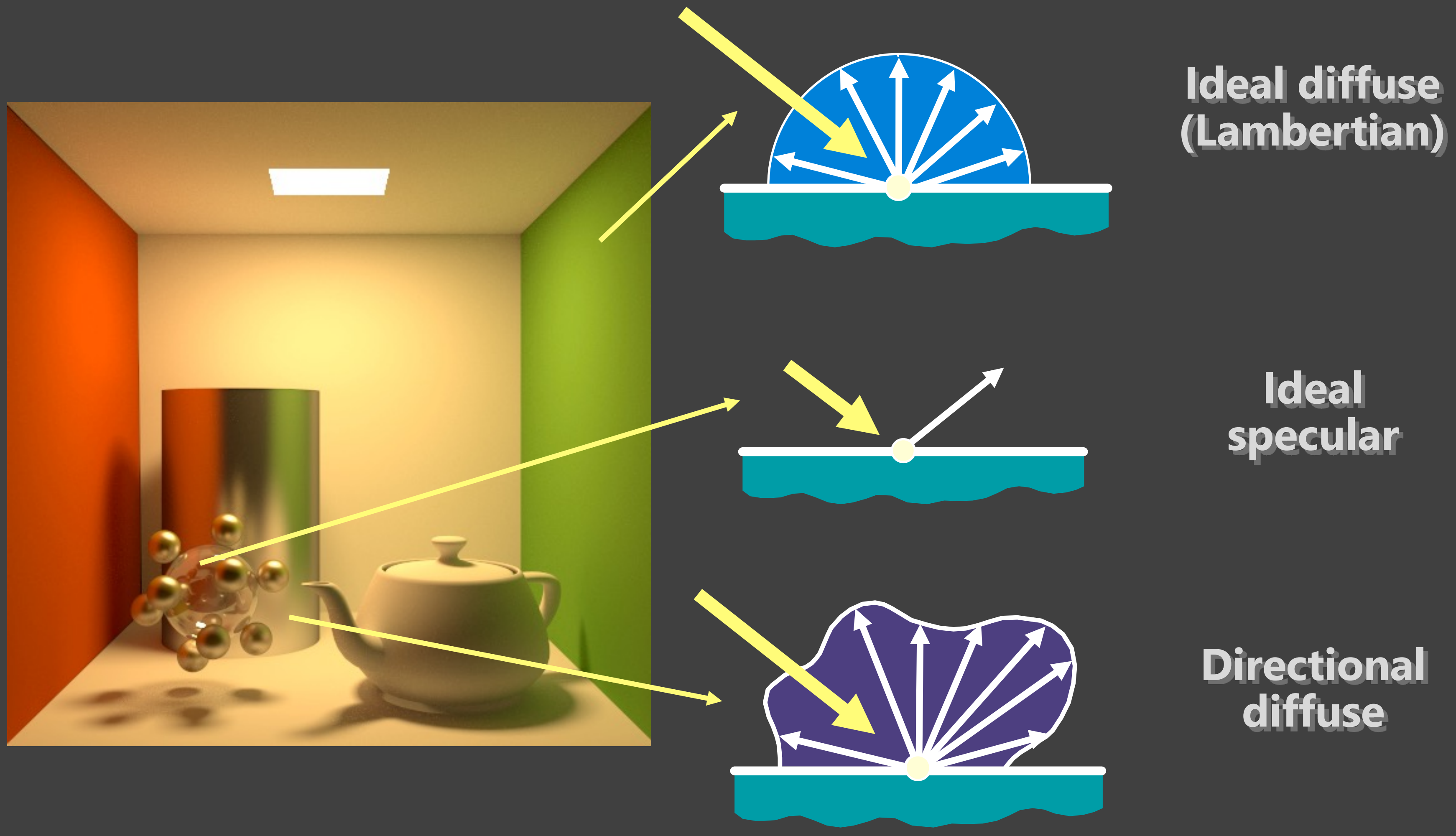


$$I = N \cdot L$$

Image intensity = Surface normal • Light direction

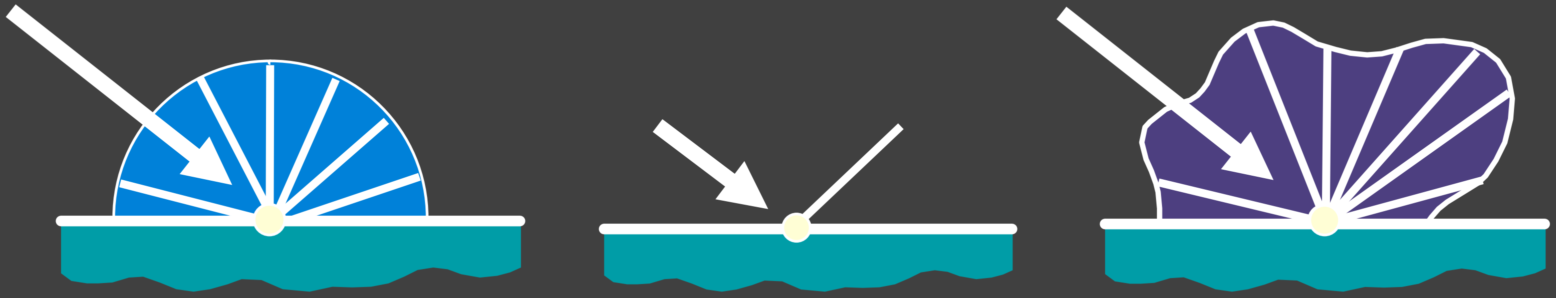
Image intensity $\propto$ cos(angle between N and L)

Materials - Three Forms



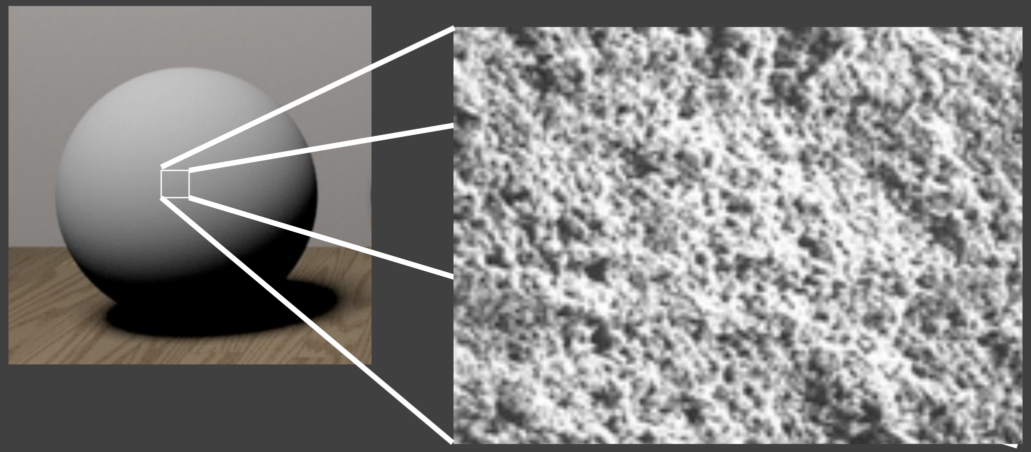
Refle

Ideal diffuse
(Lambertian)
Ideal
specular
Directional
diffuse

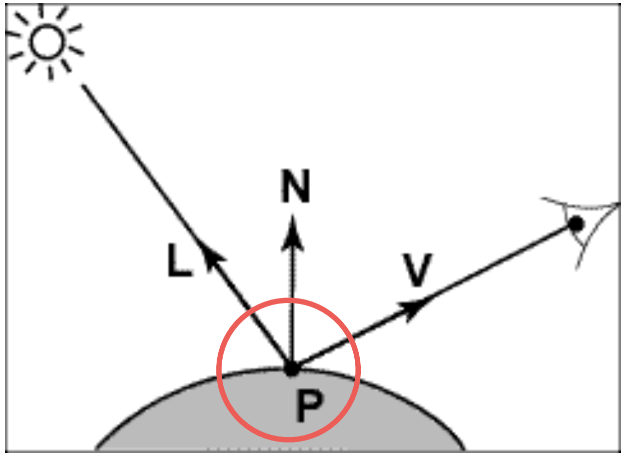


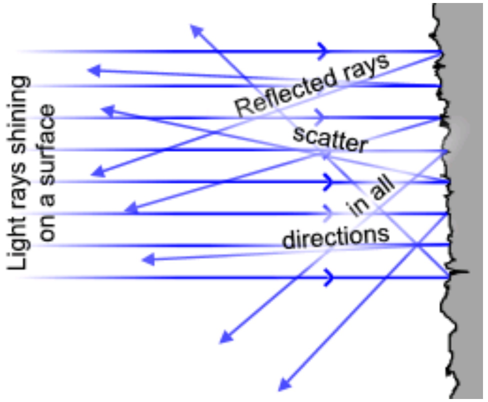
Ideal Diffuse Reflection

- Characteristic of multiple scattering materials
- An idealization but reasonable for matte surfaces



Lambertian Reflectance





1. Reflected energy is proportional to cosine of angle between L and N **(incoming)**

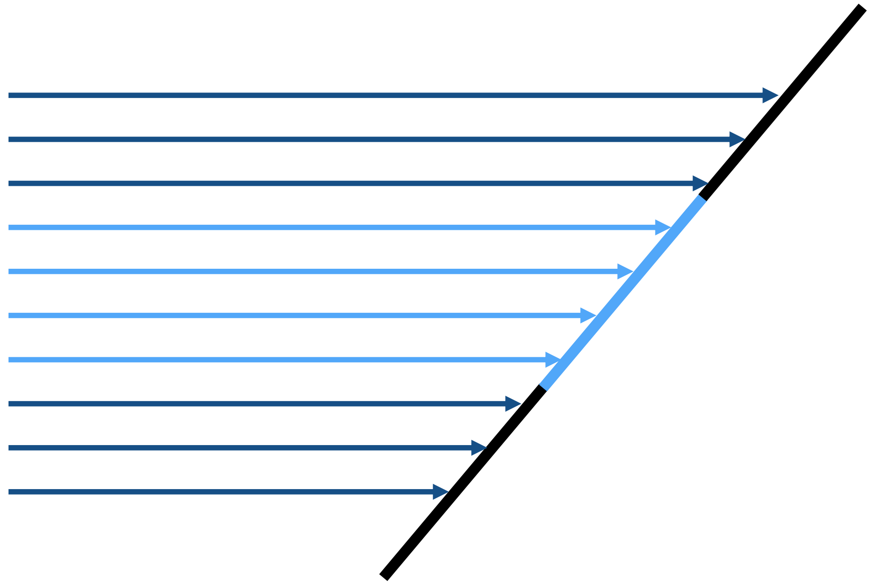
2. Measured intensity is viewpoint-independent **(outgoing)**

Lambertian Reflectance: Incoming

- Reflected energy is proportional to cosine of angle between L and N

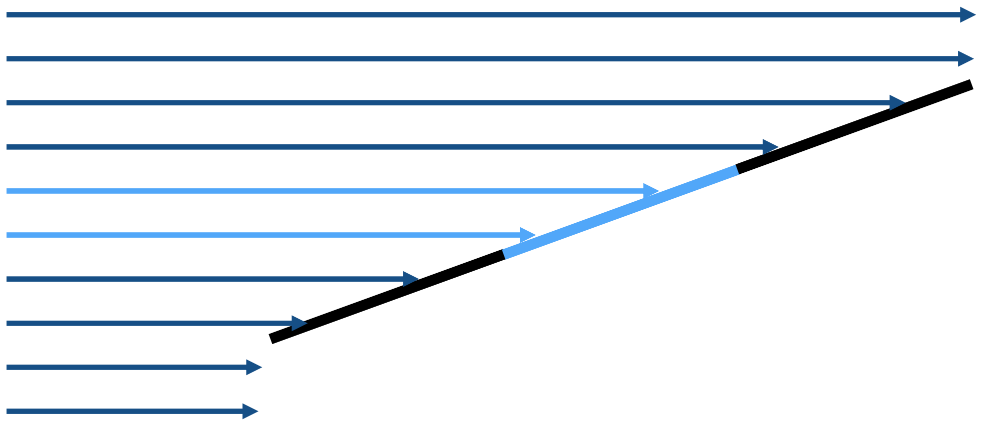
Lambertian Reflectance: Incoming

- Reflected energy is proportional to cosine of angle between L and N



Lambertian Reflectance: Incoming

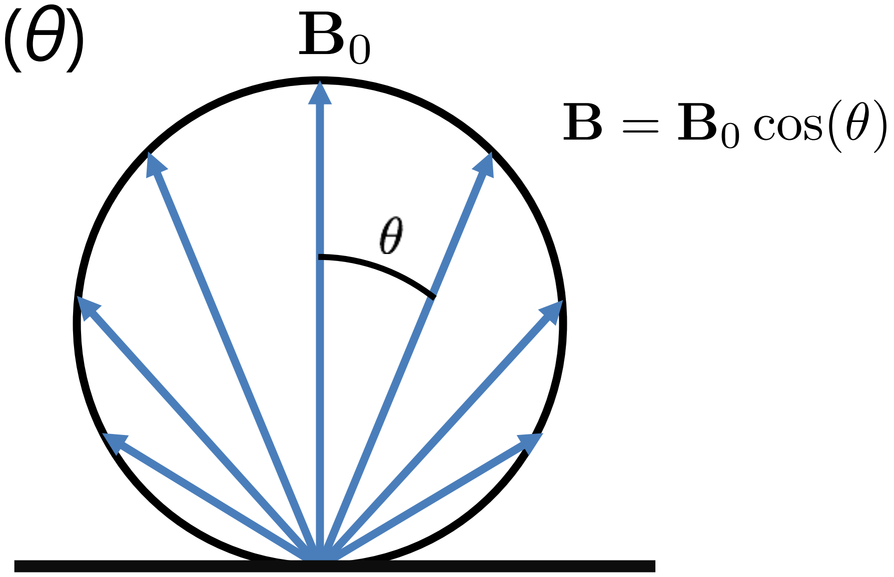
- Reflected energy is proportional to cosine of angle between L and N



Light hitting surface is proportional to the **cosine**

Lambertian appearance is view-independent

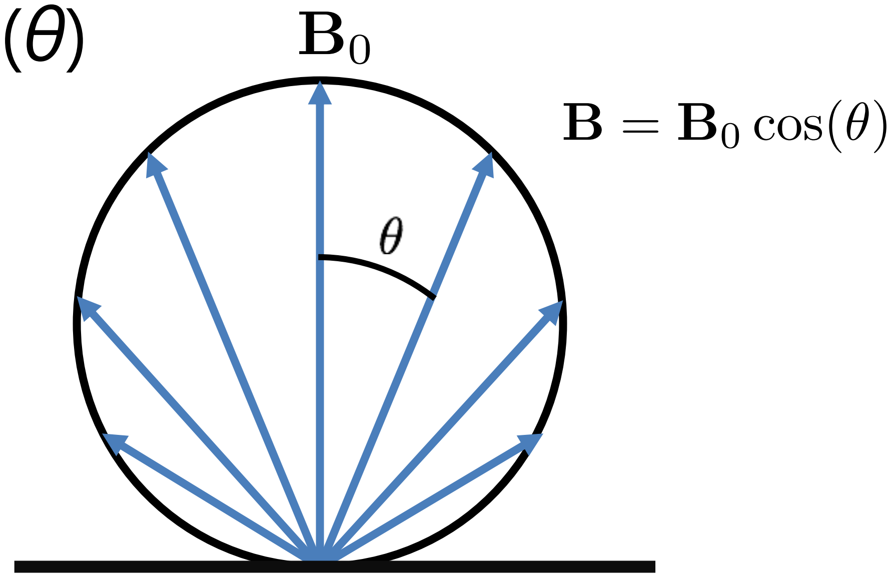
- Number of photons reflected to a given angle θ is proportional to $\cos(\theta)$



Lambert's cosine law: $\mathbf{B} = \mathbf{B}_0 \cos(\theta)$

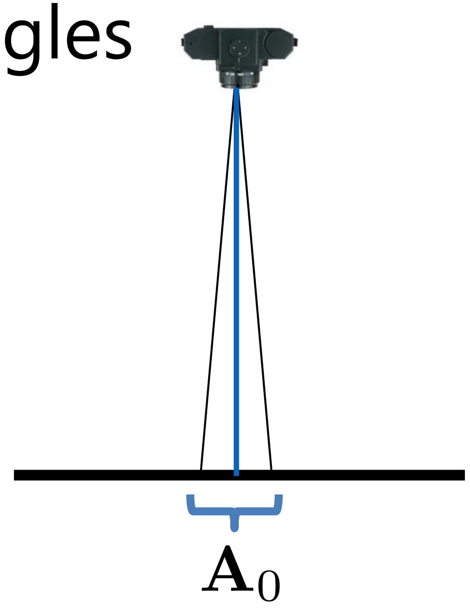
Lambertian appearance is view-independent

- Number of photons reflected to a given angle θ is proportional to $\cos(\theta)$



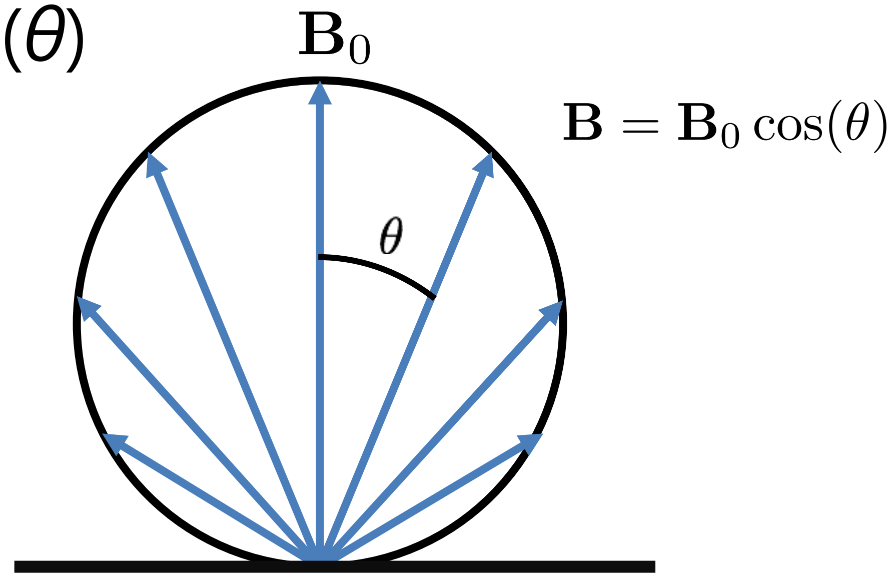
Lambert's cosine law: $\mathbf{B} = \mathbf{B}_0 \cos(\theta)$

- But appearance is the same from every angle due to larger pixel footprint at larger angles



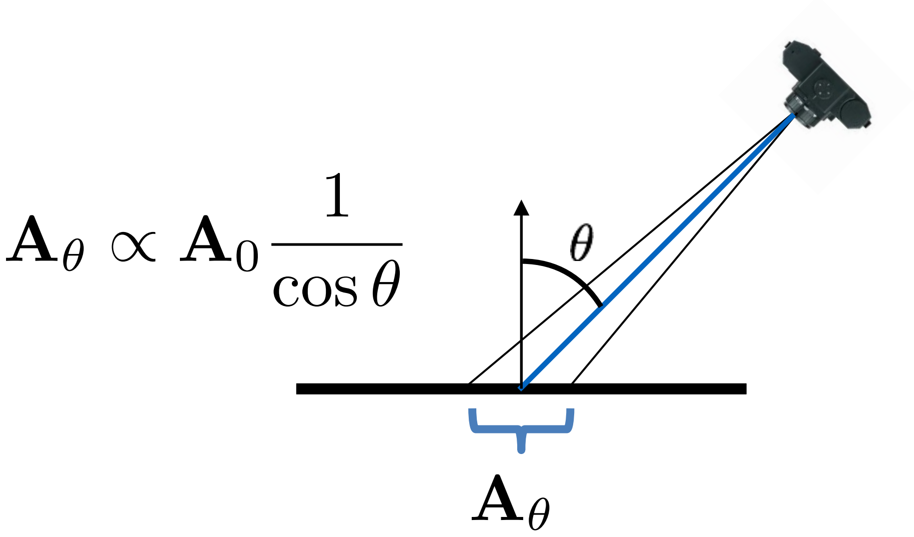
Lambertian appearance is view-independent

- Number of photons reflected to a given angle θ is proportional to cos(θ)



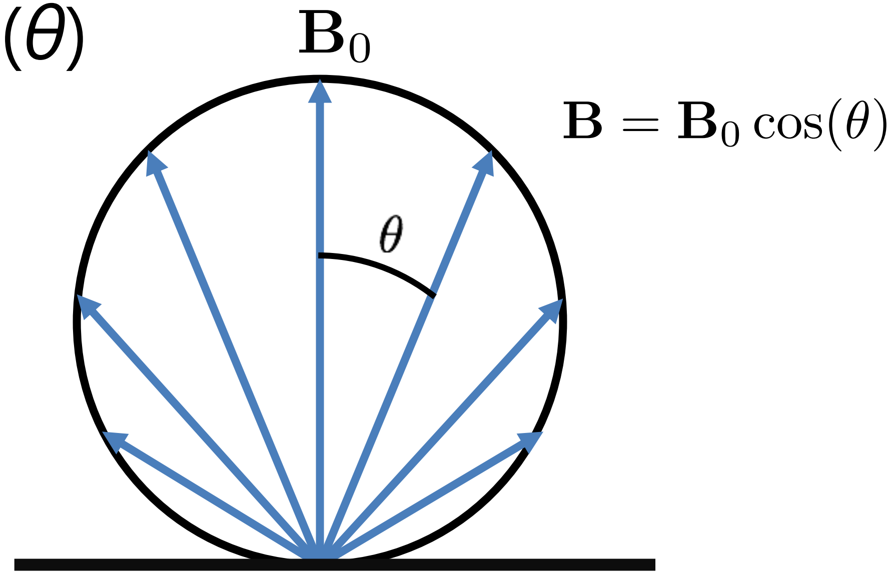
Lambert's cosine law: $\mathbf{B} = \mathbf{B}_0 \cos(\theta)$

- But appearance is the same from every angle due to larger pixel footprint at larger angles



Lambertian appearance is view-independent

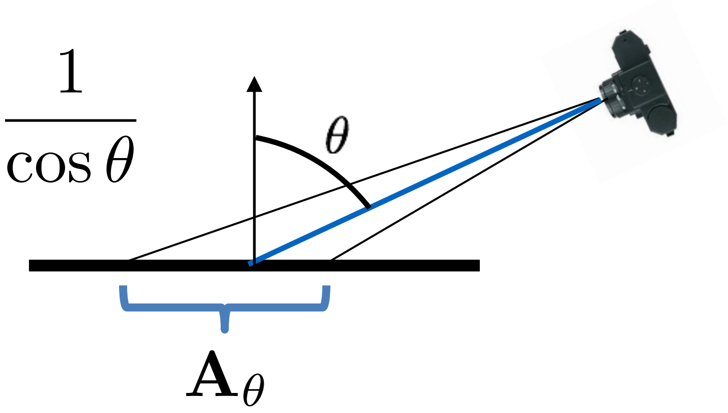
- Number of photons reflected to a given angle θ is proportional to $\cos(\theta)$



Lambert's cosine law: $\mathbf{B} = \mathbf{B}_0 \cos(\theta)$

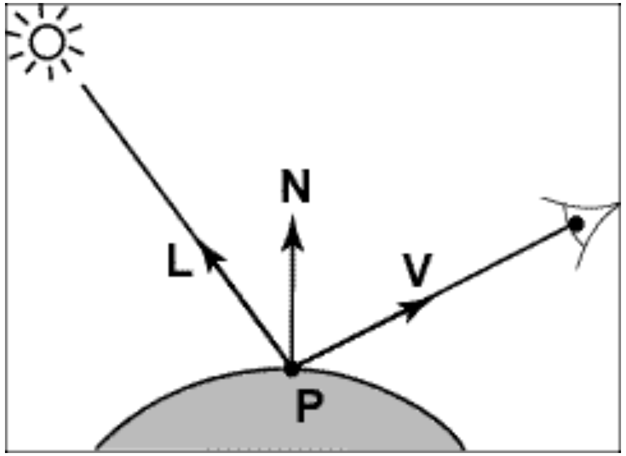
- But appearance is the same from every angle due to larger pixel footprint at larger angles

$$\mathbf{A}_\theta \propto \mathbf{A}_0 \frac{1}{\cos\theta}$$

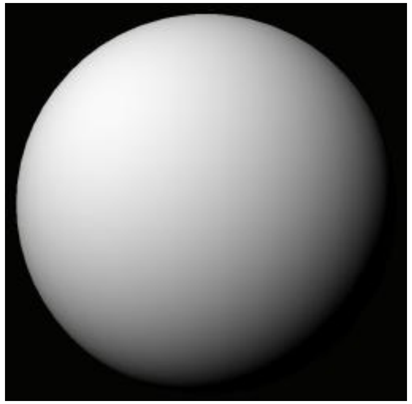


Radiance (what eye sees) $\propto \mathbf{B}_0 \mathbf{A}_0 \cancel{\cos(\theta)} \frac{1}{\cancel{\cos(\theta)}}$

Final Lambertian image formation model



$$I = k_d \mathbf{N} \cdot \mathbf{L}$$

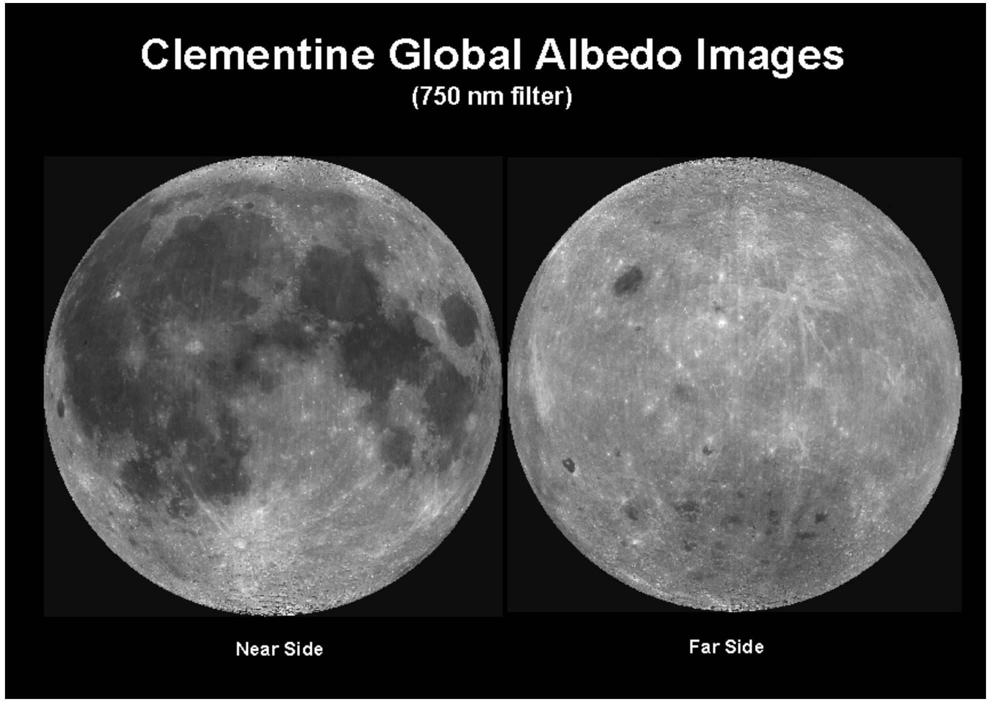


1. Diffuse **albedo**: what fraction of incoming light is reflected?
   - Introduce scale factor k_d
2. Light intensity: how much light is arriving?
   - Compensate with camera exposure (global scale factor)
3. Camera response function
   - Assume pixel value is linearly proportional to incoming energy (perform radiometric calibration if not)

Albedo

Sample albedos

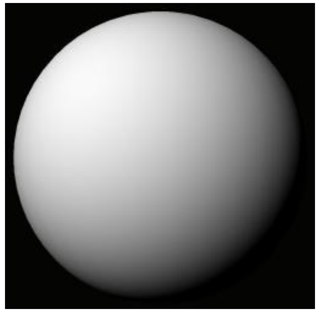
Surface	Typical albedo
Fresh asphalt	0.04[4]
Open ocean	0.06[5]
Worn asphalt	0.12[4]
Conifer forest (Summer)	0.08,[6] 0.09 to 0.15[7]
Deciduous trees	0.15 to 0.18[7]
Bare soil	0.17[8]
Green grass	0.25[8]
Desert sand	0.40[9]
New concrete	0.55[8]
Ocean ice	0.5–0.7[8]
Fresh snow	0.80–0.90[8]

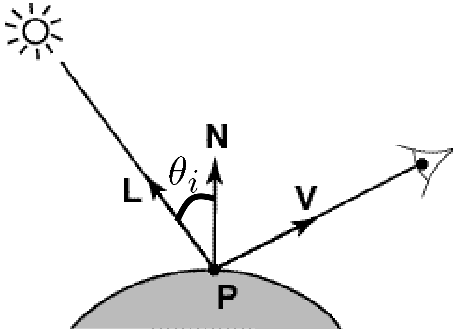


Objects can have varying albedo and albedo varies with wavelength

Source: https://en.wikipedia.org/wiki/Albedo

A Single Image: Shape from shading





Suppose (for now) $k_d = 1$

$$\begin{aligned} I &= k_d \mathbf{N} \cdot \mathbf{L} \\ &= \mathbf{N} \cdot \mathbf{L} \\ &= cos\ \theta_i \end{aligned}$$

You can directly measure angle between normal and light source

- Not quite enough information to compute surface shape
- But can be if you add some additional info, for example
  - assume a few of the normals are known (e.g., along silhouette)
  - constraints on neighboring normals—“integrability”
  - smoothness
- Hard to get it to work well in practice
  - plus, how many real objects have constant albedo?
  - But, deep learning can help

https://www.good.is/optical-illusion-plates-and-bowls-upside-down-or-not

Application: Detecting composite photos

Fake photo

Real photo

Questions?