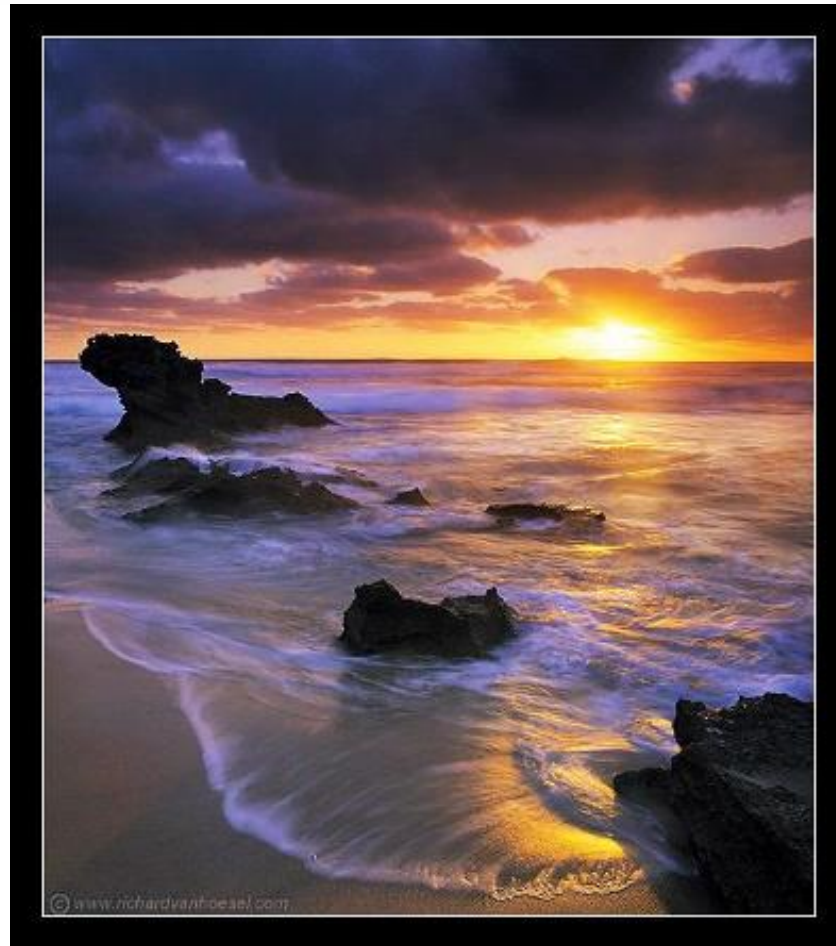


# CS5670: Computer Vision

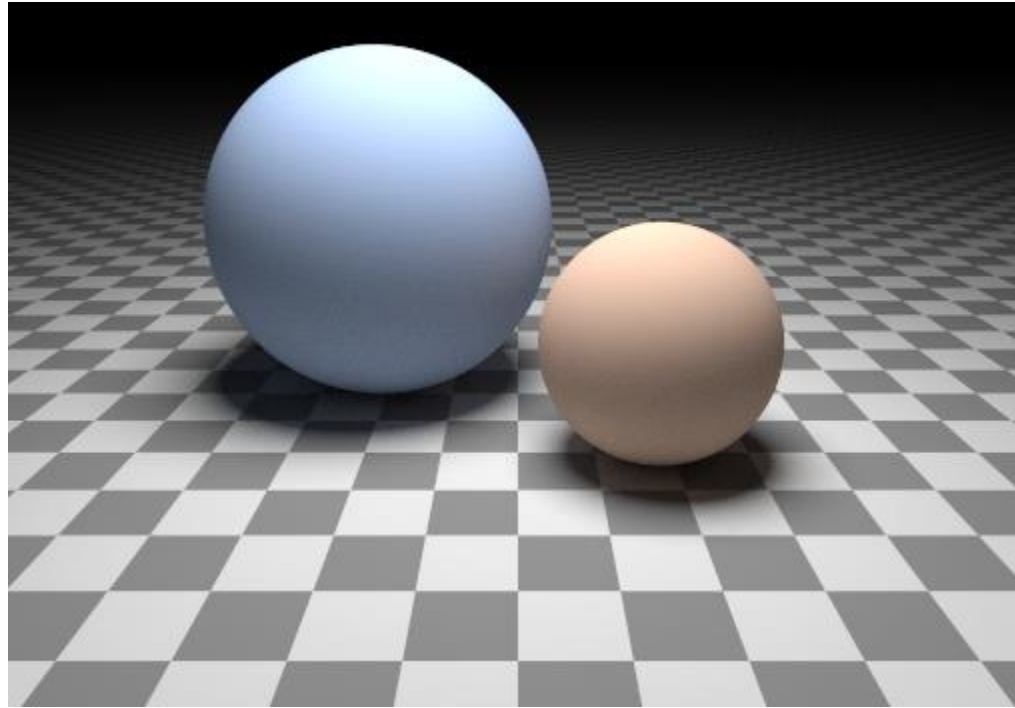
Light & Perception



# Announcements

- Project 3 artifacts (panoramas) due today at 7pm on CMSX
- Project 4 (stereo) to be released this Wednesday, 4/7, due Tuesday, 4/20
- Reminder: Quiz this Wednesday, ends at 3:07pm

# 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 objects

# What we know: Stereo



Key Idea: use feature motion to understand shape

# Next: Photometric Stereo



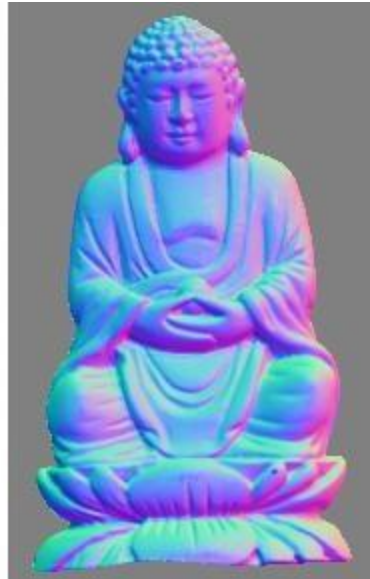
Key Idea: use pixel brightness to understand shape

# Photometric Stereo

What results can you get?



Input  
(1 of 12)



Normals (RGB  
colormap)



Normals (vectors)



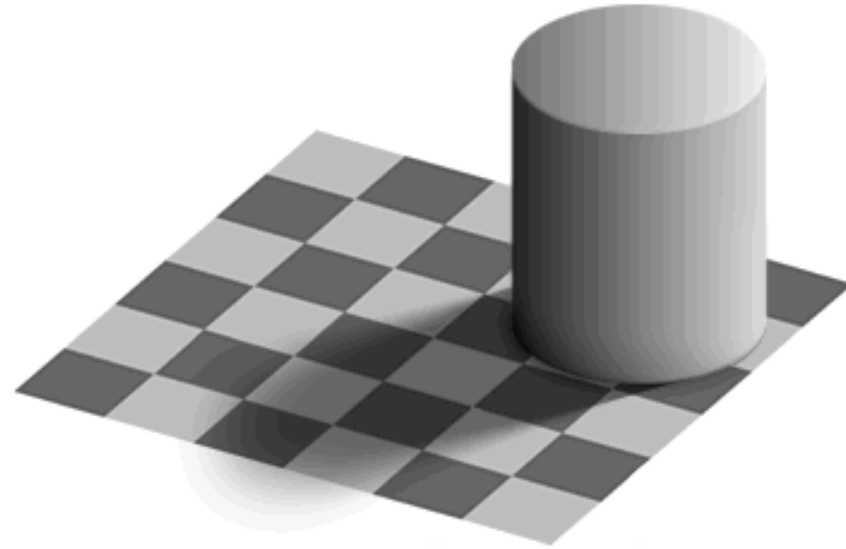
Shaded 3D  
rendering



Textured 3D  
rendering



# Light

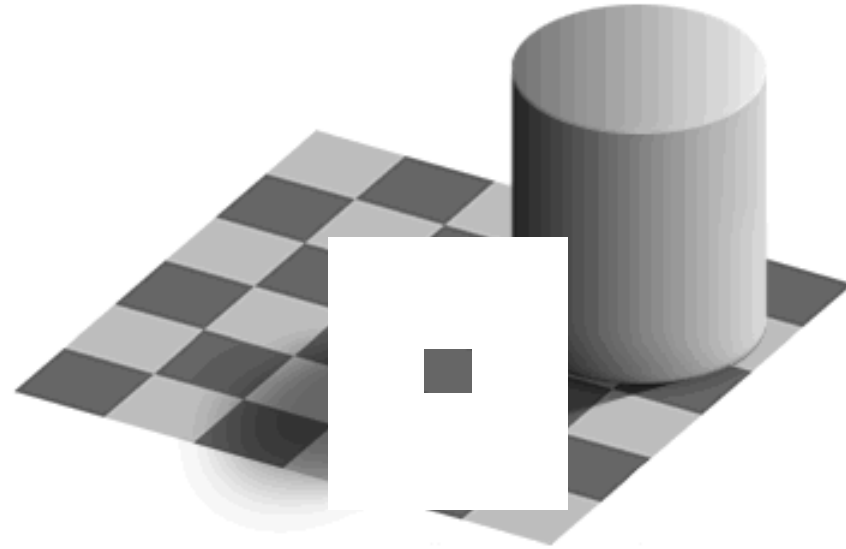


by Ted Adelson

- Readings
  - Szeliski, 2.2, 2.3.2



# Light



by Ted Adelson

## Readings

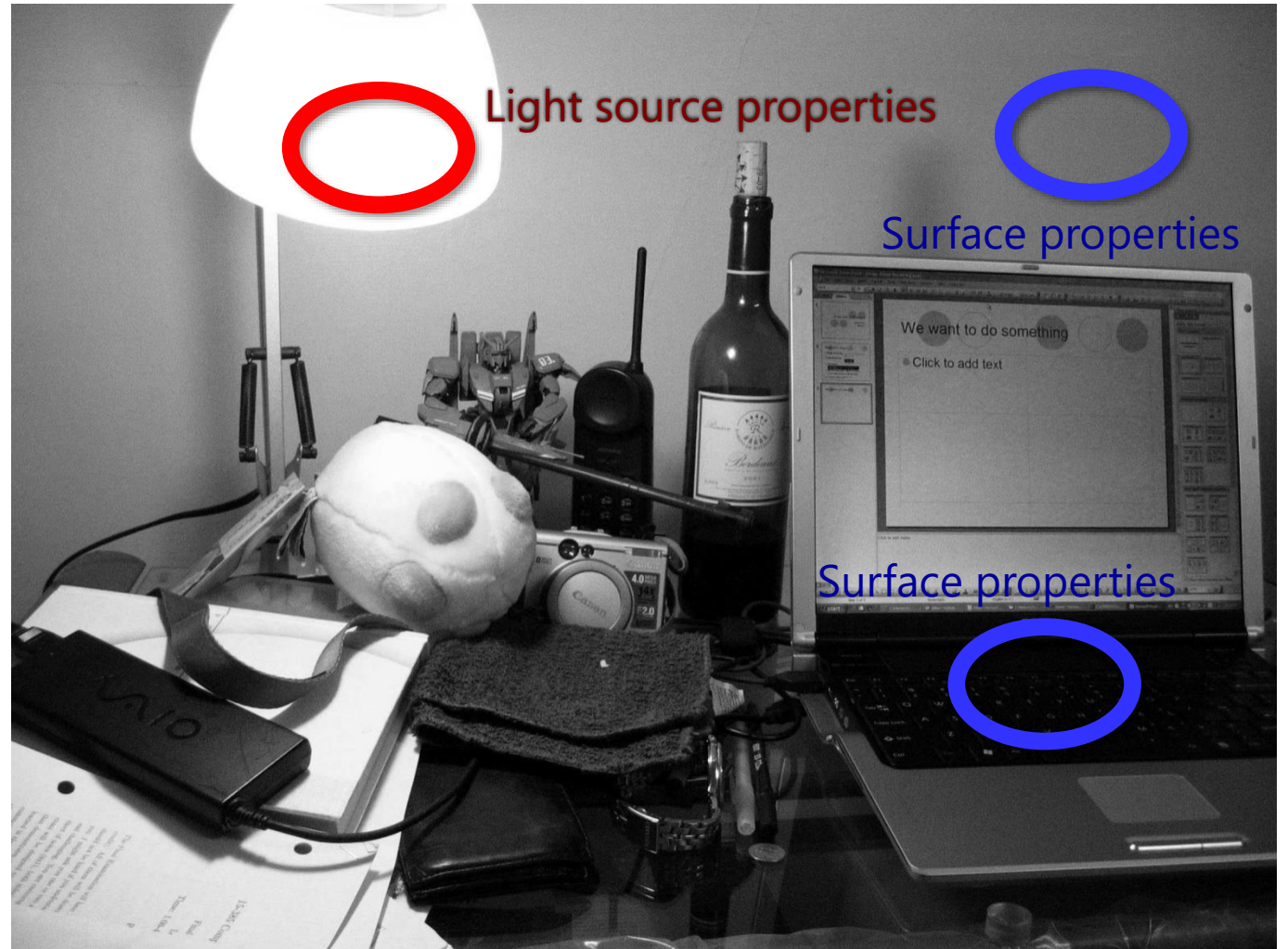
- Szeliski, 2.2, 2.3.2

# 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-/>

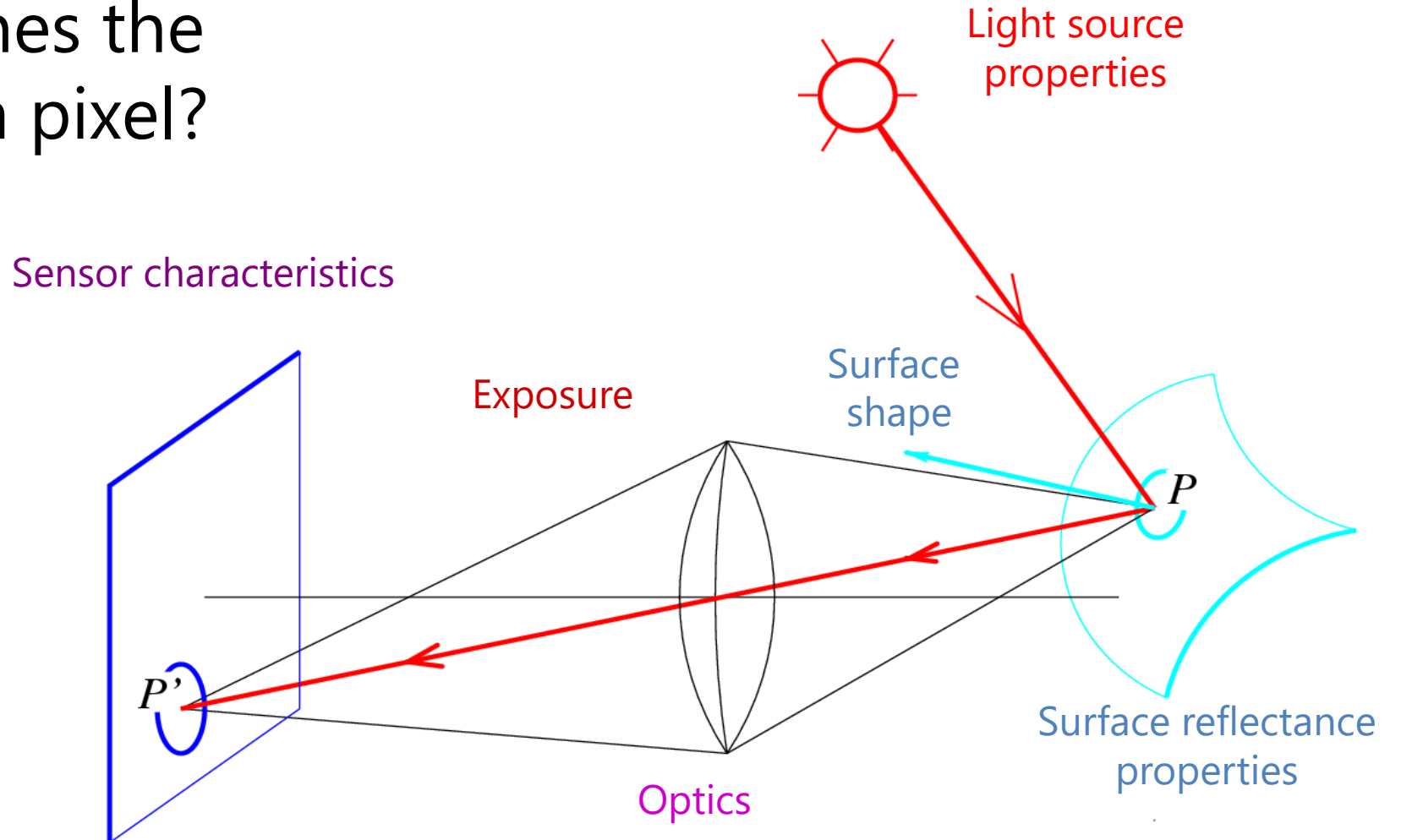
# Radiometry

- What determines the brightness of a pixel?



# Radiometry

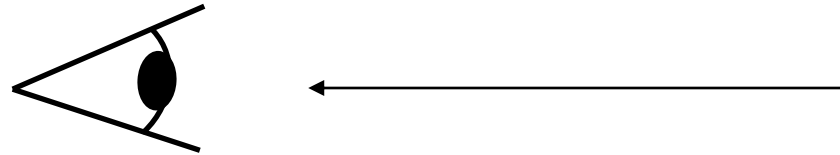
- What determines the brightness of a pixel?



# What is light?

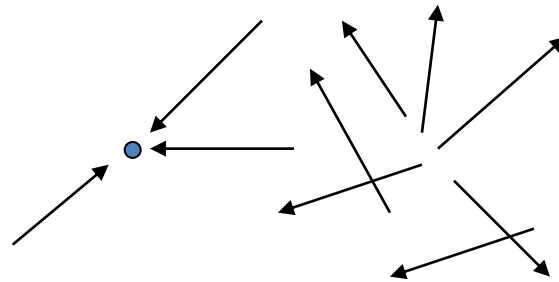
Electromagnetic radiation (EMR) moving along rays in space

- $R(\lambda)$  is EMR, measured in units of power (watts)
  - $\lambda$  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

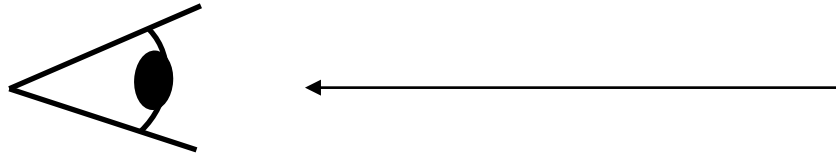


The **plenoptic function** describes all of this light:  $R(X, Y, Z, \theta, \phi, \lambda, t)$

# Color perception

Electromagnetic radiation (EMR) moving along rays in space

- $R(\lambda)$  is EMR, measured in units of power (watts)
  - $\lambda$  is wavelength



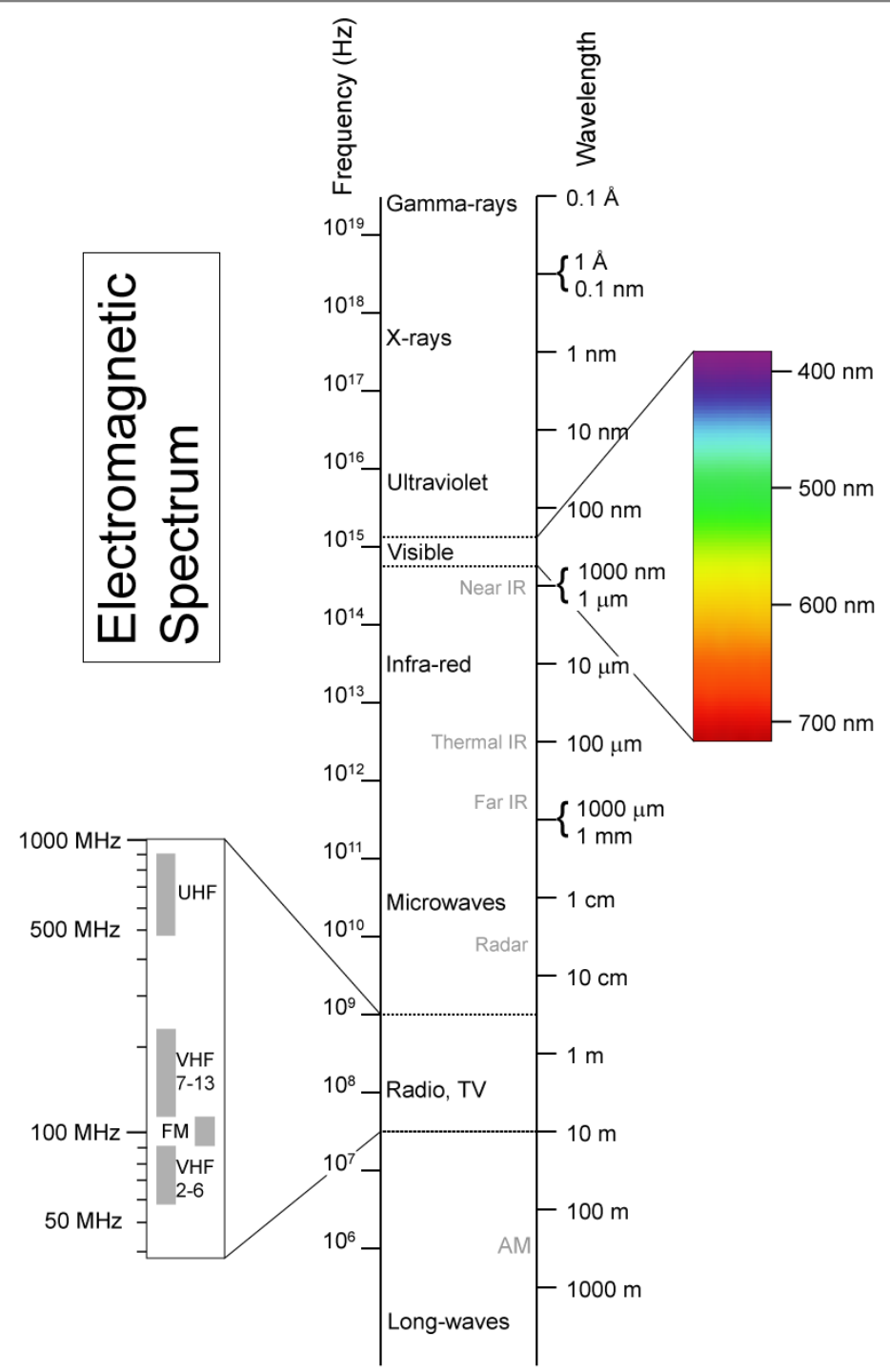
Perceiving light

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



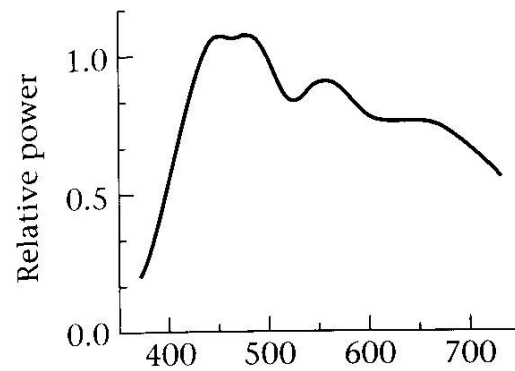
# Visible light

We "see"  
electromagnetic  
radiation in a range of  
wavelengths

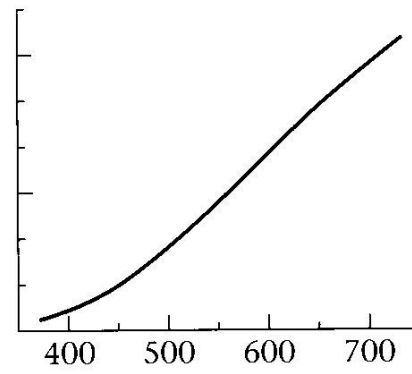


# Light spectrum

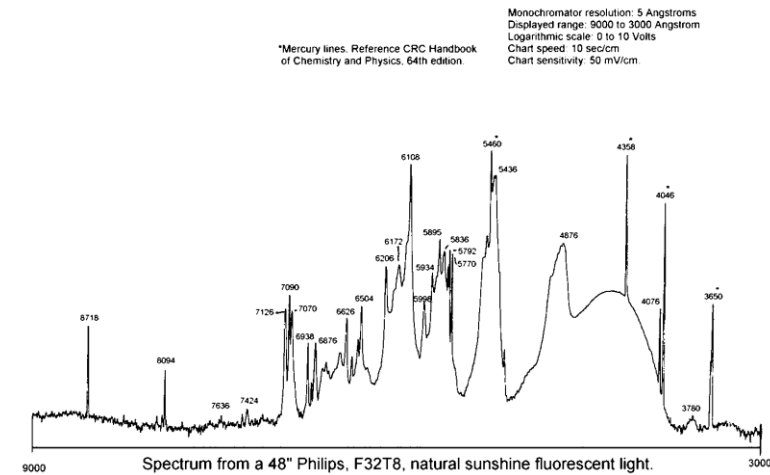
- The appearance of light depends on its power **spectrum**
  - How much power (or energy) at each wavelength



daylight



tungsten bulb



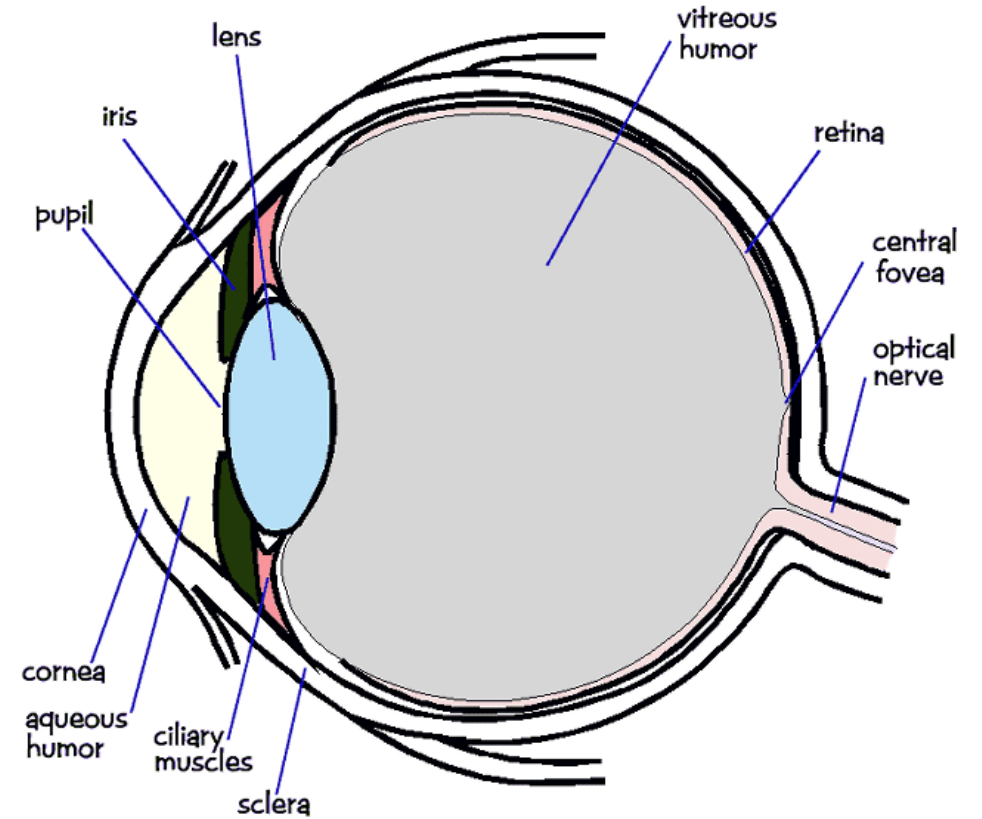
fluorescent bulb

Our visual system converts a light spectrum into "color"

- This is a rather complex transformation

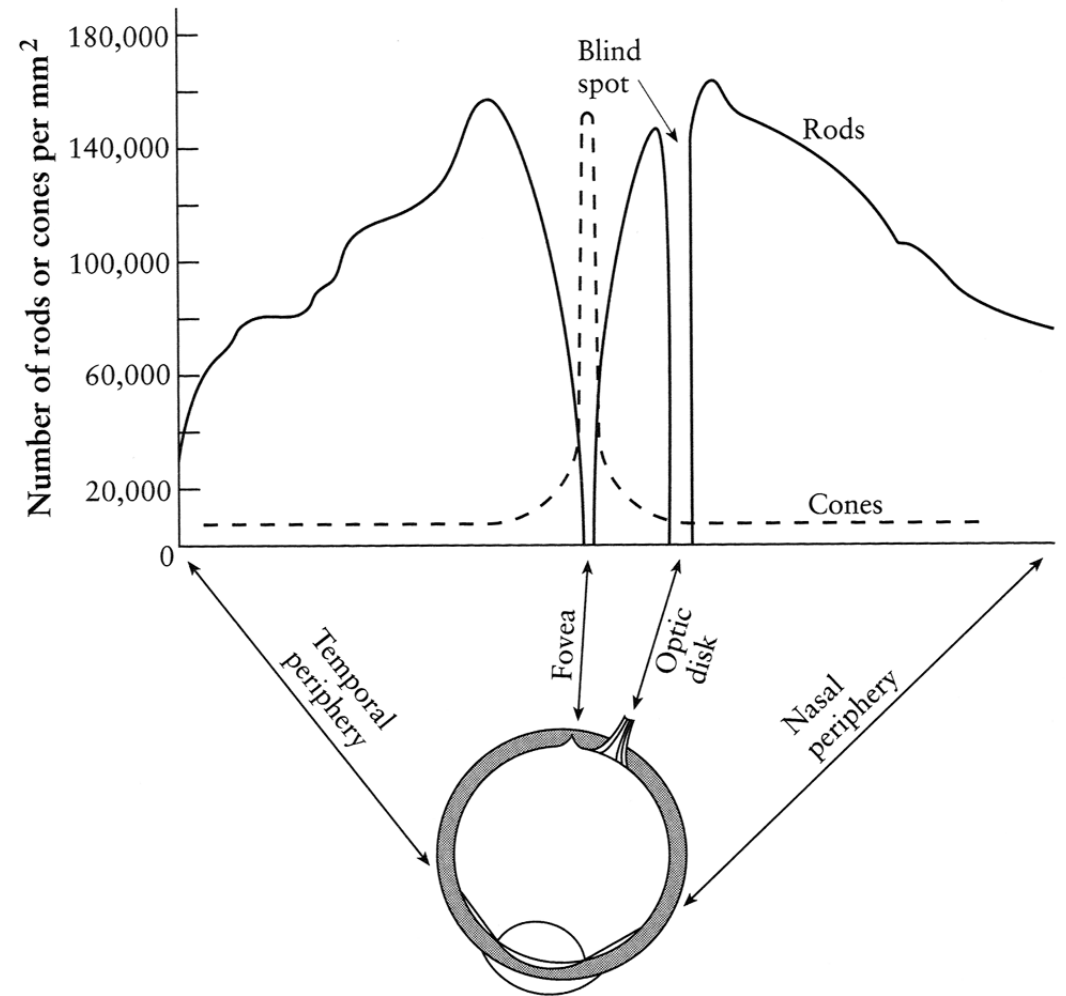
# The human visual system

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

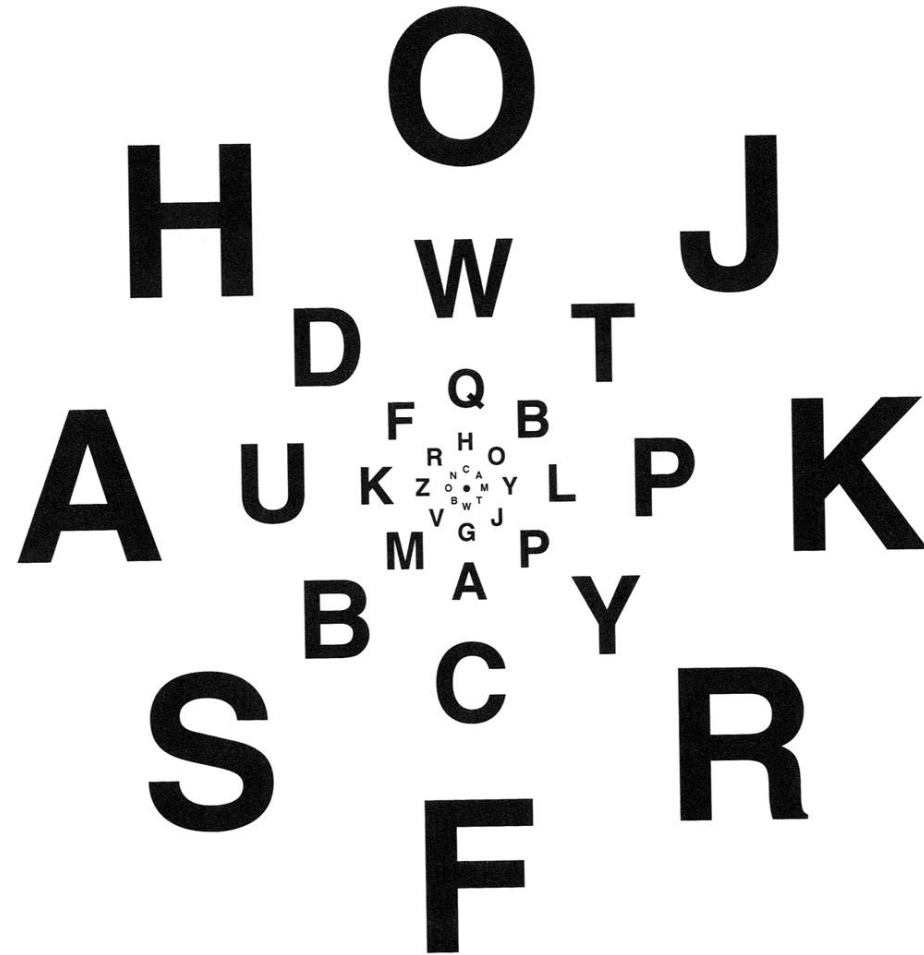


# Density of rods and cones

- 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.

**Start here**



# 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.

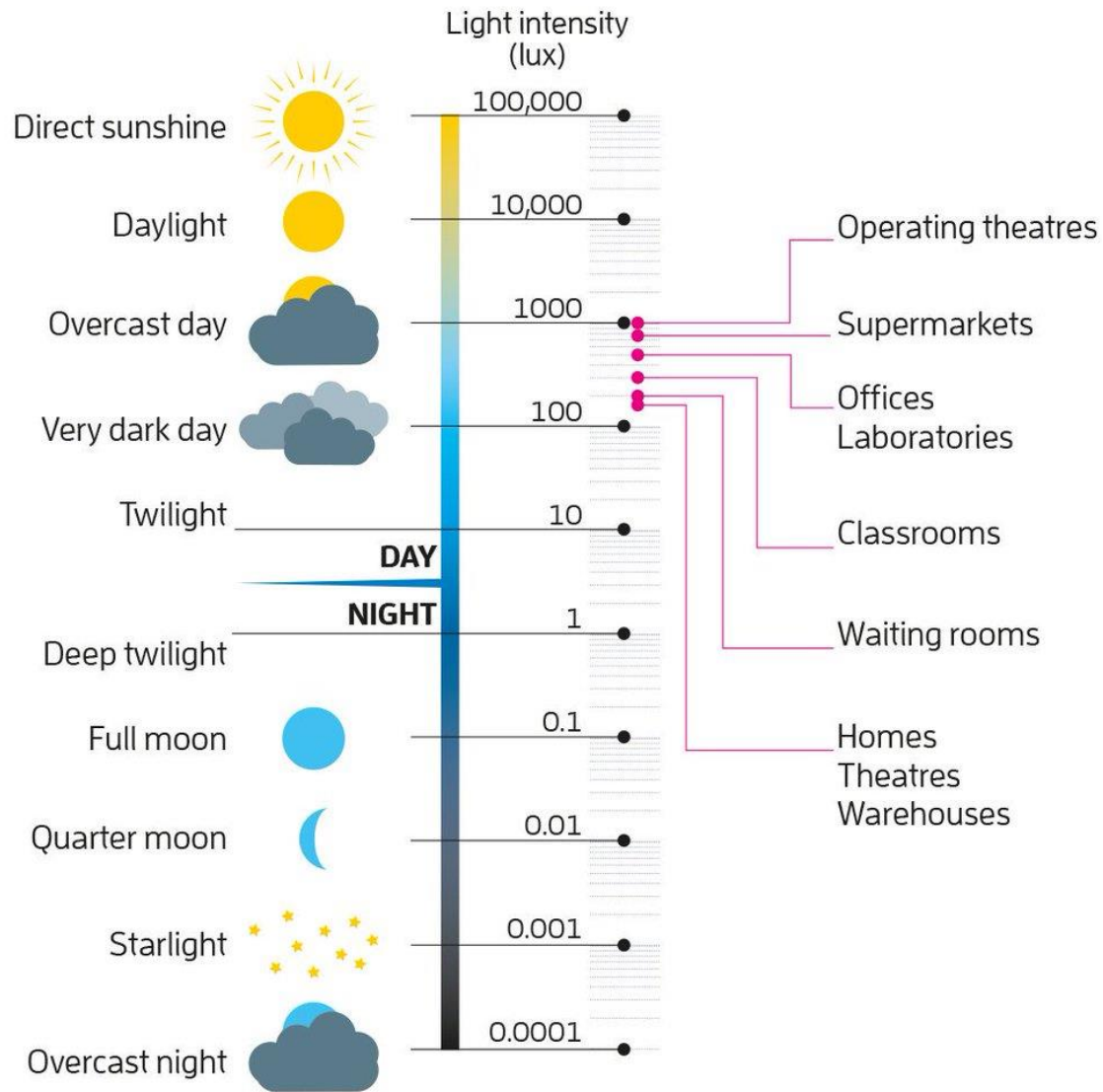
Background	Luminance (candelas per square meter)
Horizon sky	
Moonless overcast night	0.00003
Moonless clear night	0.0003
Moonlit overcast night	0.003
Moonlit clear night	0.03
Deep twilight	0.3
Twilight	3
Very dark day	30
Overcast day	300
Clear day	3,000
Day with sunlit clouds	30,000
Daylight fog	
Dull	300–1,000
Typical	1,000–3,000
Bright	3,000–16,000
Ground	
Overcast day	30–100
Sunny day	300
Snow in full sunlight	16,000

**FIGURE 1.13**

Luminance of everyday backgrounds. Source: Data from Rea, ed., *Lighting Handbook 1984 Reference and Application*, fig. 3-44, p. 3-24.

# The light in our lives

Even the brightest indoor spaces are dim compared with the outdoors in daylight



Illuminance	Example
<1 lux	Moonlight, <sup>[3]</sup> clear night sky
0.25 lux	A full Moon, clear night sky <sup>[4][5]</sup>
0.01 lux	A quarter Moon, clear night sky
0.002 lux	Starlight, clear moonless night sky, including airglow <sup>[4]</sup>
0.0002 lux	Starlight, clear moonless night sky, excluding airglow <sup>[4]</sup>
0.00014 lux	Venus at brightest, <sup>[4]</sup> clear night sky
0.0001 lux	Starlight, overcast moonless night sky <sup>[4]</sup>

<https://en.wikipedia.org/wiki/Daylight>

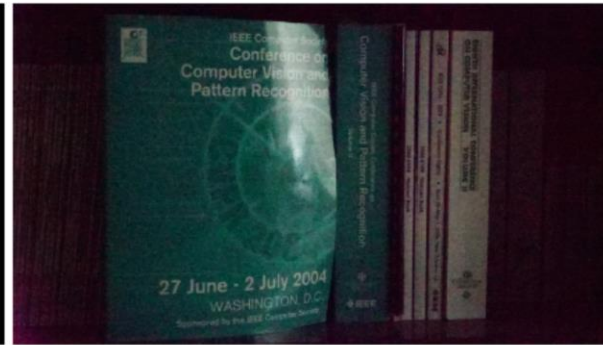
# Learning to See in the Dark

Chen Chen, Qifeng Chen, Jia Xu and Vladlen Koltun

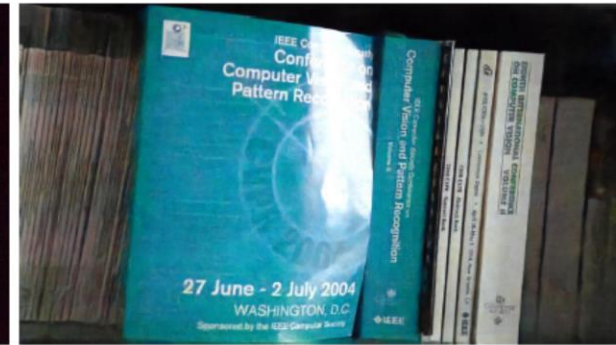
IEEE Conference on Computer Vision and Pattern Recognition (CVPR), 2018



(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.

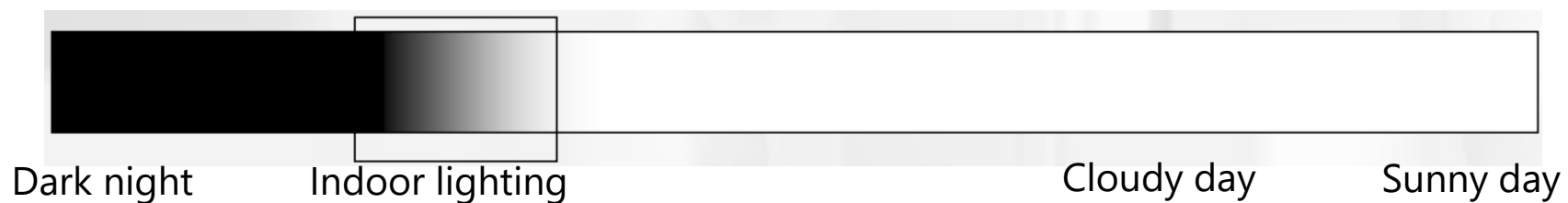
<http://cchen156.web.engr.illinois.edu/SID.html>

# Visual dynamic range



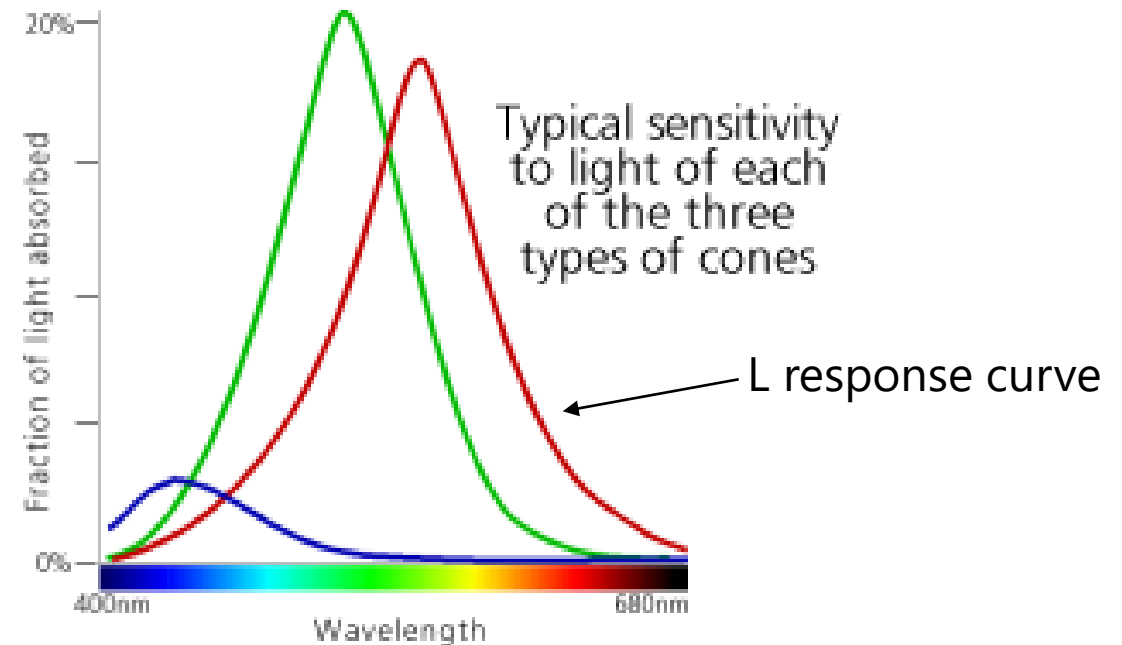
If we were sensitive to this whole range all the time, we wouldn't be able to discriminate lightness levels in a typical scene.

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

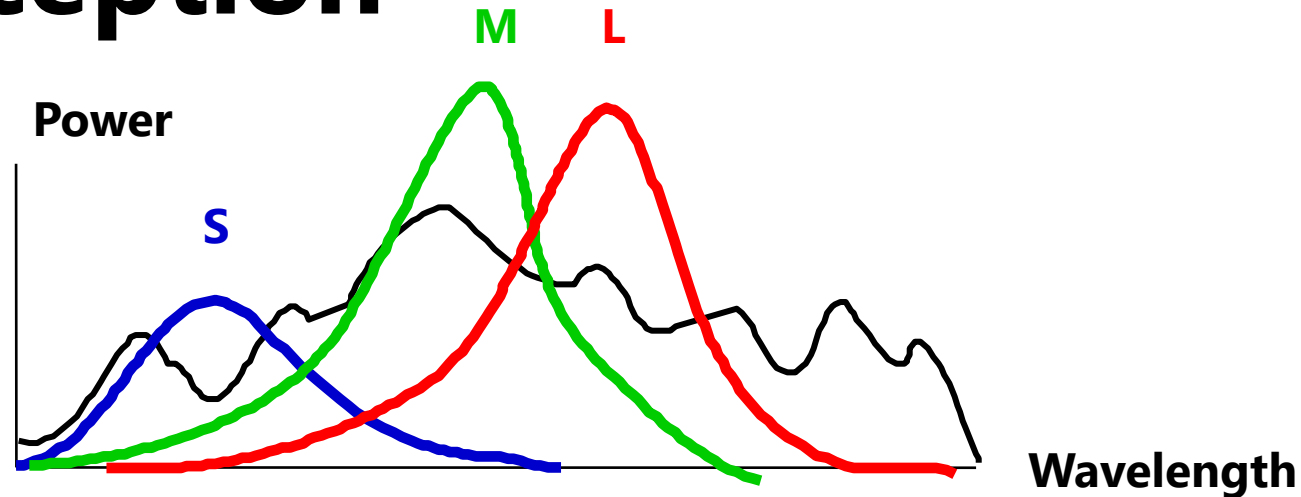


# Color perception

- 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

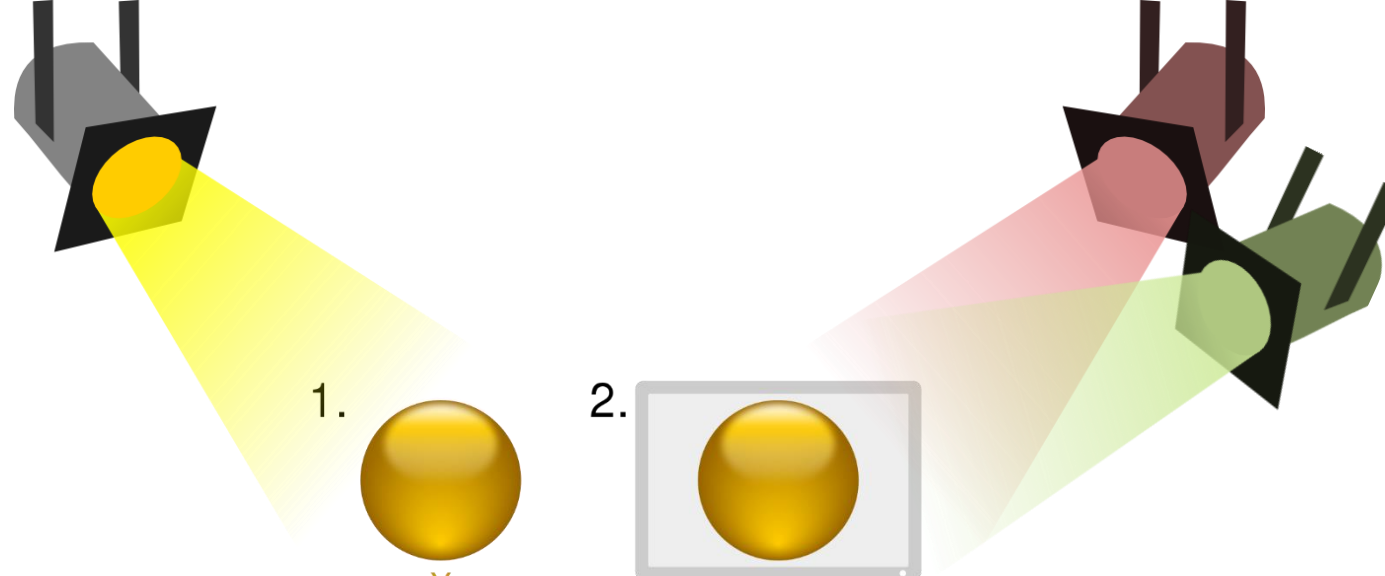


# Color perception

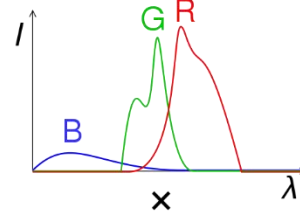
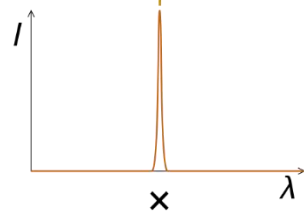


- Rods and cones act as filters on the spectrum
  - To get the output of a filter, multiply its response curve by the spectrum, integrate over all wavelengths
    - Each cone yields one number
  - Q: How can we represent an entire spectrum with 3 numbers?
  - A: We can't! Most of the information is lost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

# Metamers

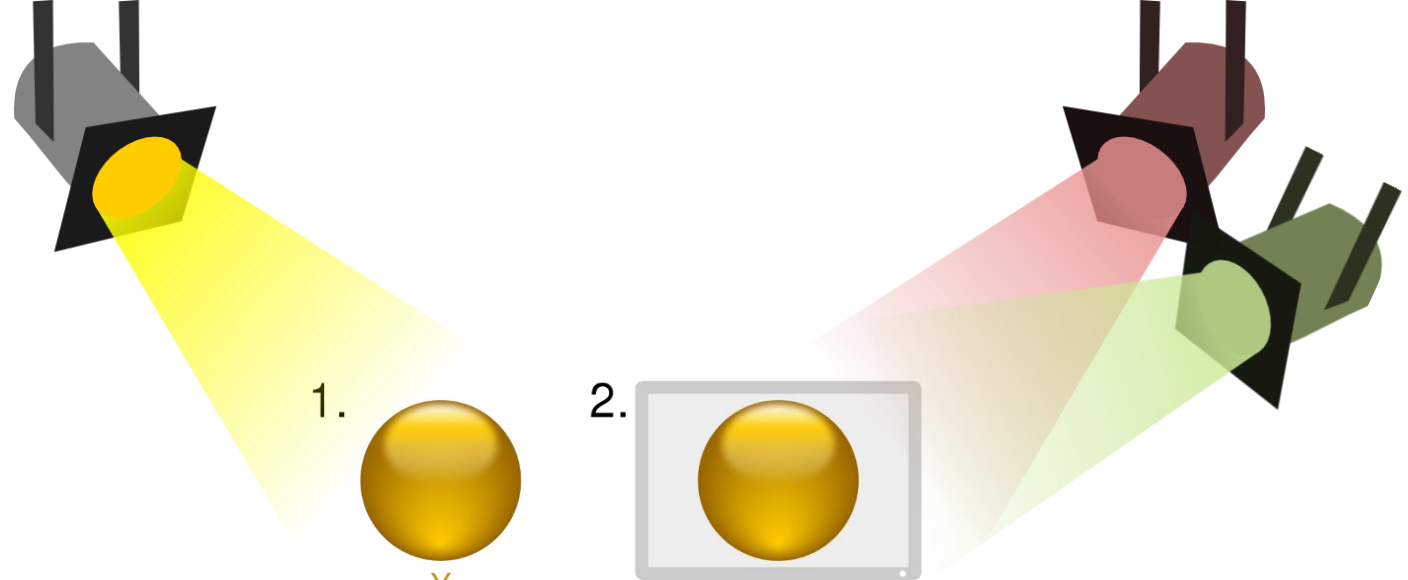


1. Combined light spectrum

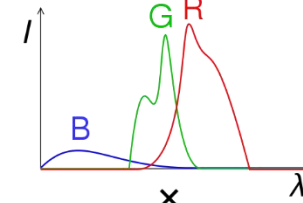
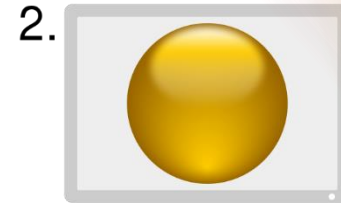
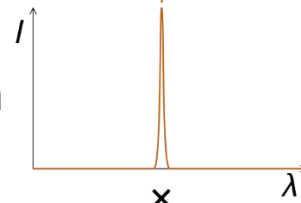




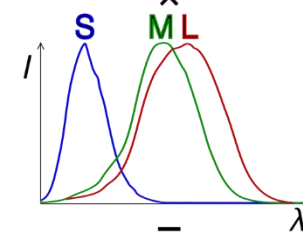
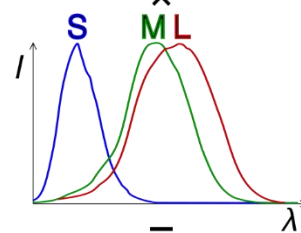
# Metamers



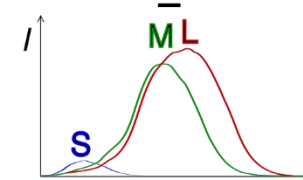
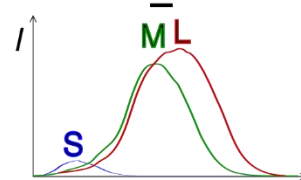
1. Combined light spectrum



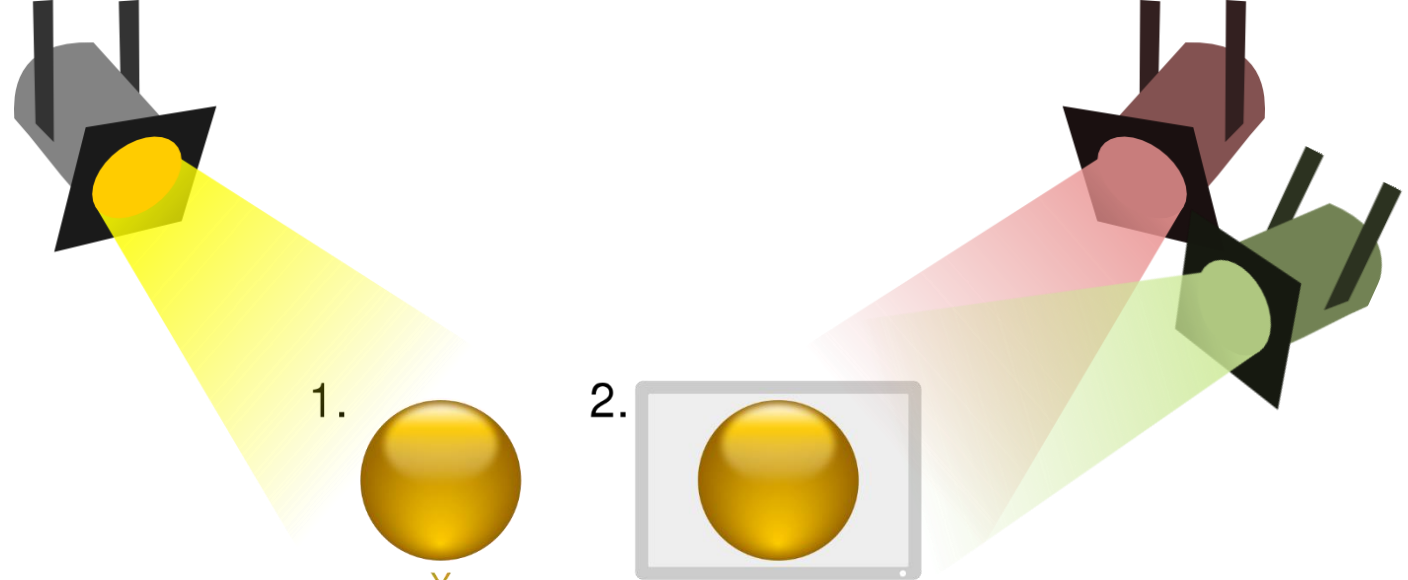
2. Cone sensitivity (S, M, L)



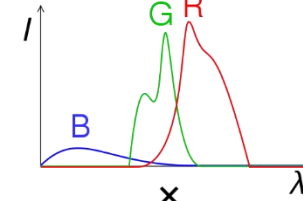
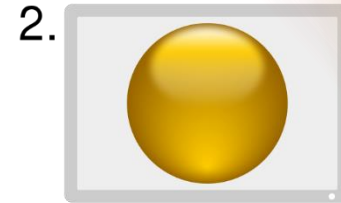
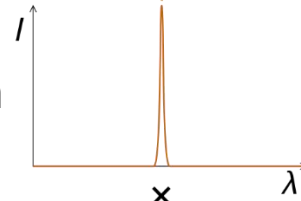
3. Multiplication of 1 and 2



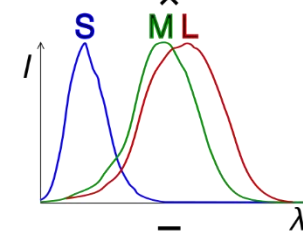
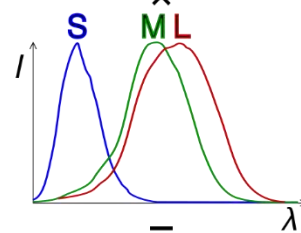
# Metamers



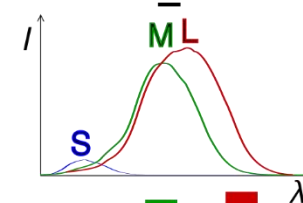
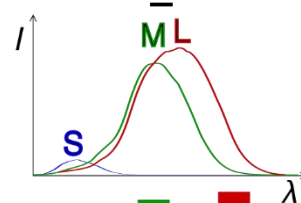
1. Combined light spectrum



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?

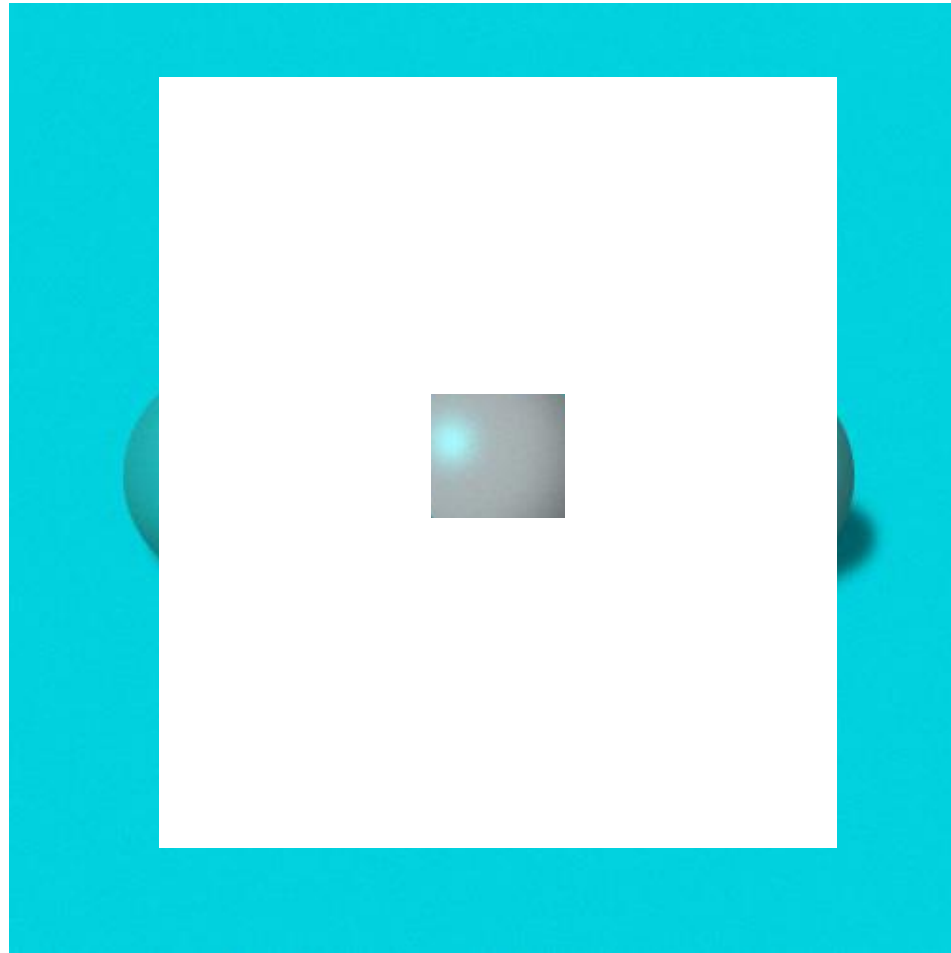
- White and gold?
- Black and blue?



**What color is the center ball?**



**What color is the center ball?**



# Reflectance and Illumination In Popular Culture...

WIKIPEDIA  
The Free Encyclopedia

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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,<sup>[3][4]</sup> 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.

**Contents** [hide]

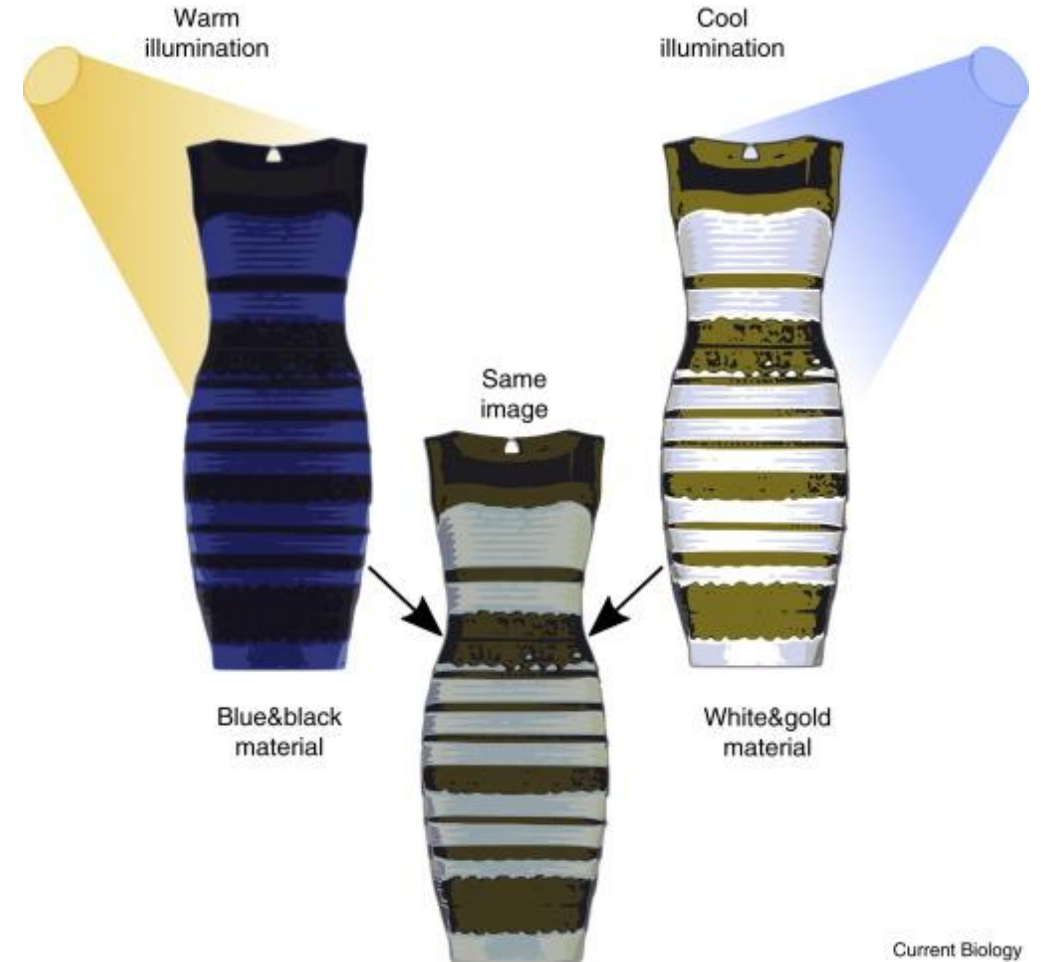
- Origin
- Response
  - Initial viral spread
  - Overnight popularity
  - Real colours of dress confirmed
- Scientific explanations
- Legacy
- See also

**The dress**



The original *The Dress* picture

<b>Designer</b>	<a href="#">Roman Originals</a> <sup>[1]</sup>
<b>Material</b>	<a href="#">Lace</a> <sup>[2]</sup>



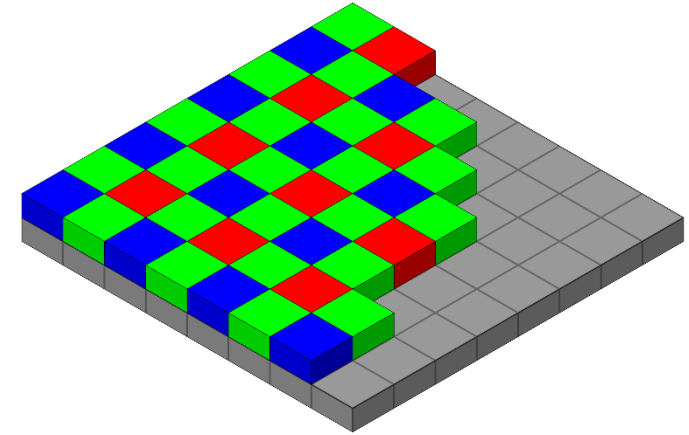
# Perception summary

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

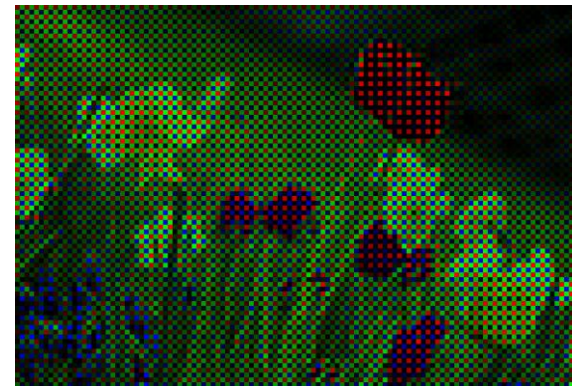


# Cameras also see color

- Common technique is to place a mosaic of color filters (a *Bayer filter*) in front of the sensor
- Colors are interpolated to create a full-resolution "*demosaicked*" color image



Bayer filter pattern in front of sensor



What the camera sees  
("raw" image)



Demosaicked image

# Early color photography

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



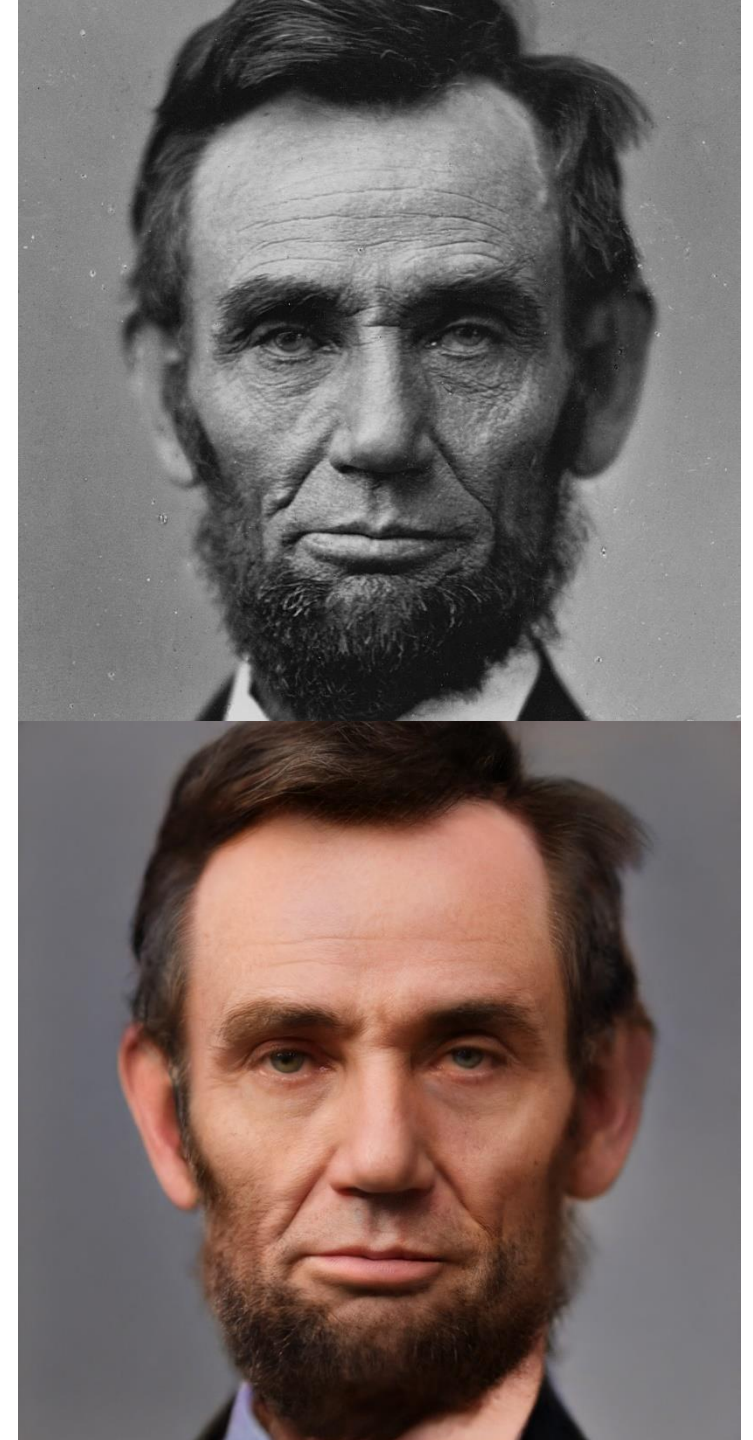
Blue, Green, Red exposures



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**

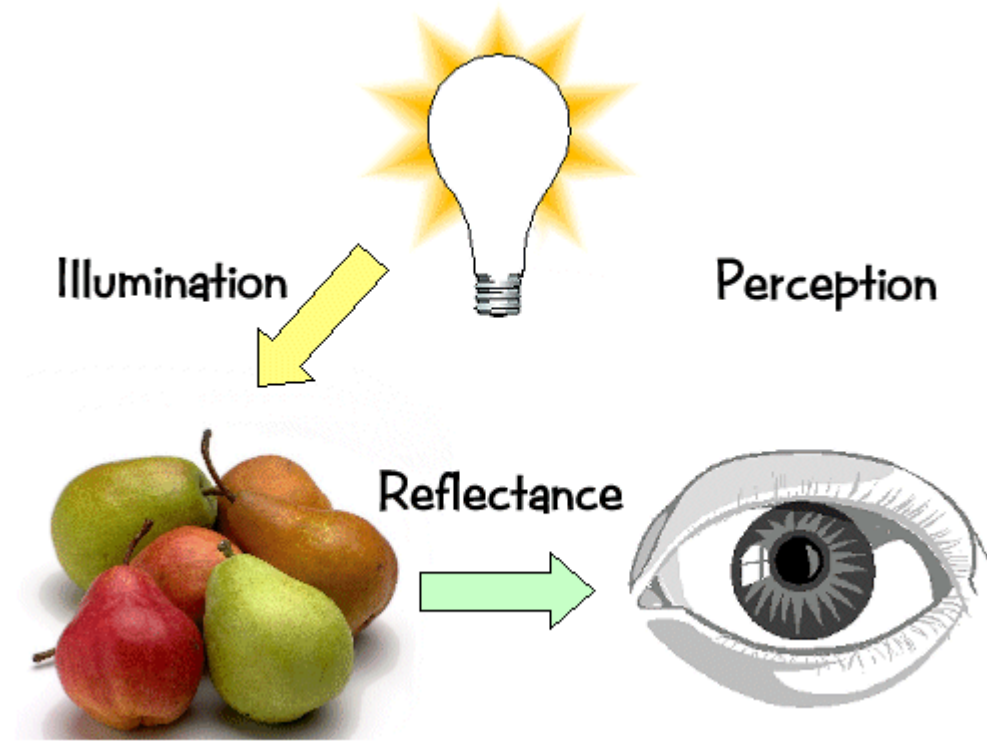
[Xuan Luo](#), [Xuaner Zhang](#), [Paul Yoo](#), [Ricardo Martin-Brualla](#), [Jason Lawrence](#), [Steven M. Seitz](#)

arXiv 2020

**Questions?**



# Light transport



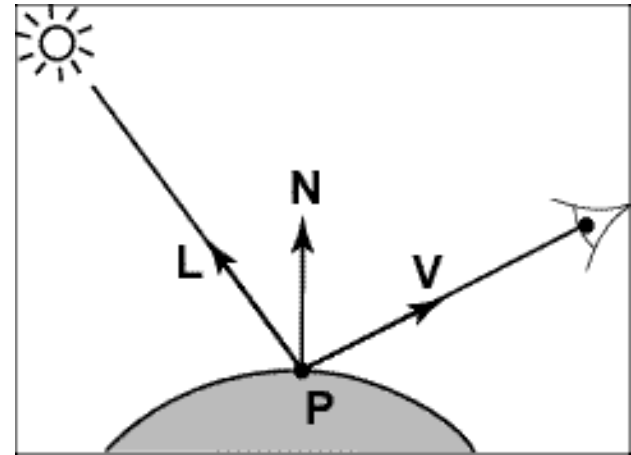
# Light sources

- 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:

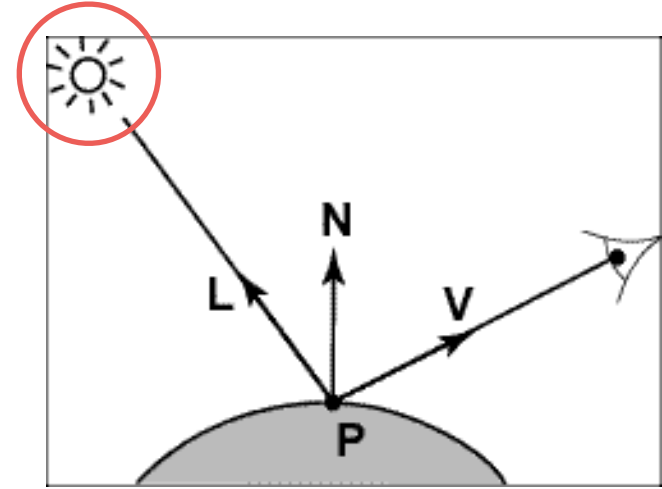
- How light interacts with the scene
- How a pixel value is related to light energy in the world



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

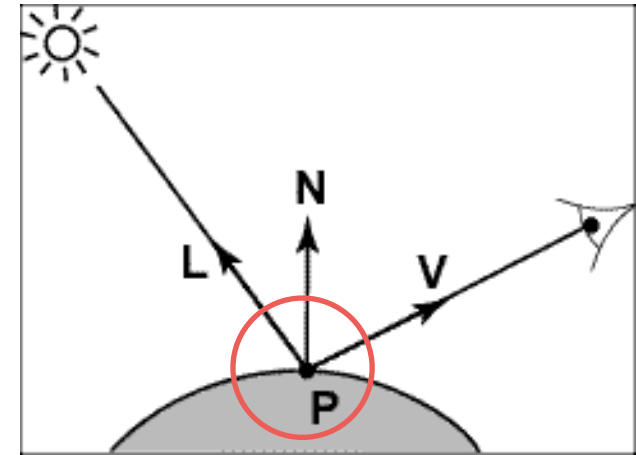
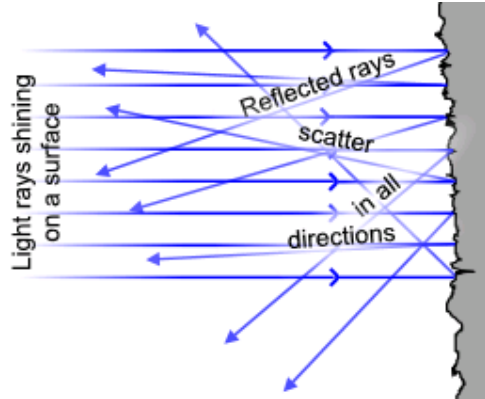
# Directional Lighting

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





# Lambertian Reflectance

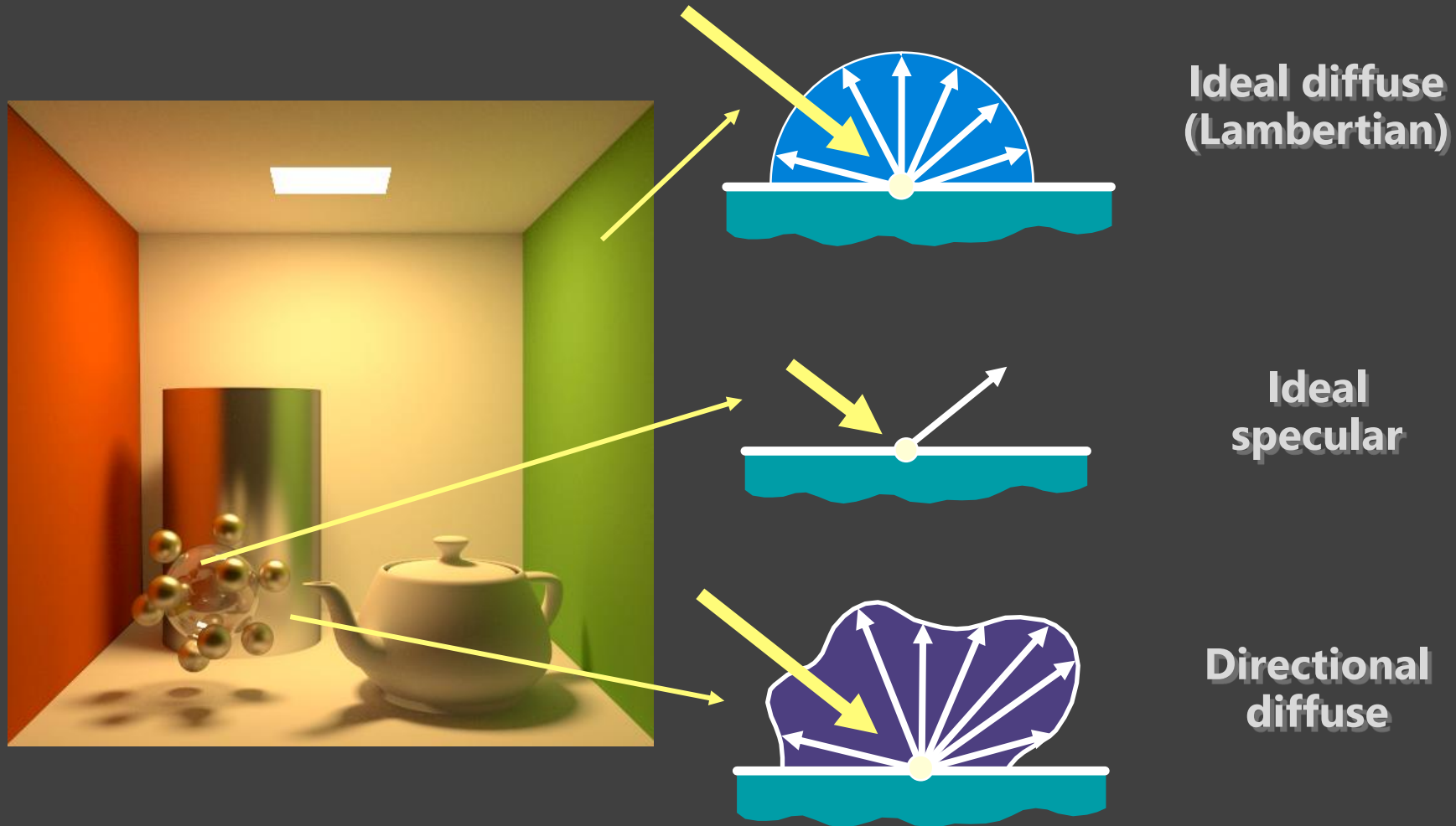


$$I = N \cdot L$$

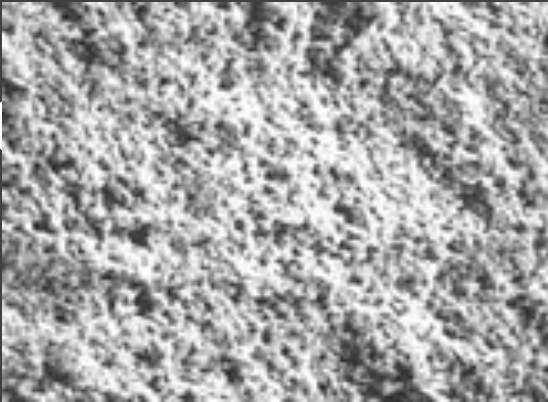
Image intensity  $\equiv$  Surface normal  $\cdot$  Light direction

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

# Materials - Three Forms



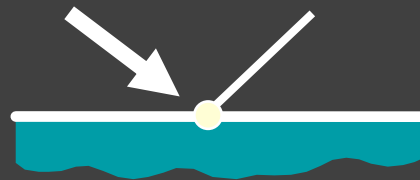
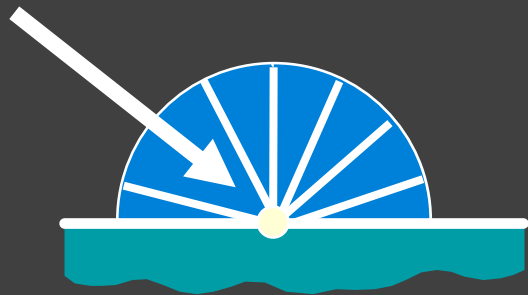
# Reflection



Ideal diffuse  
(Lambertian)

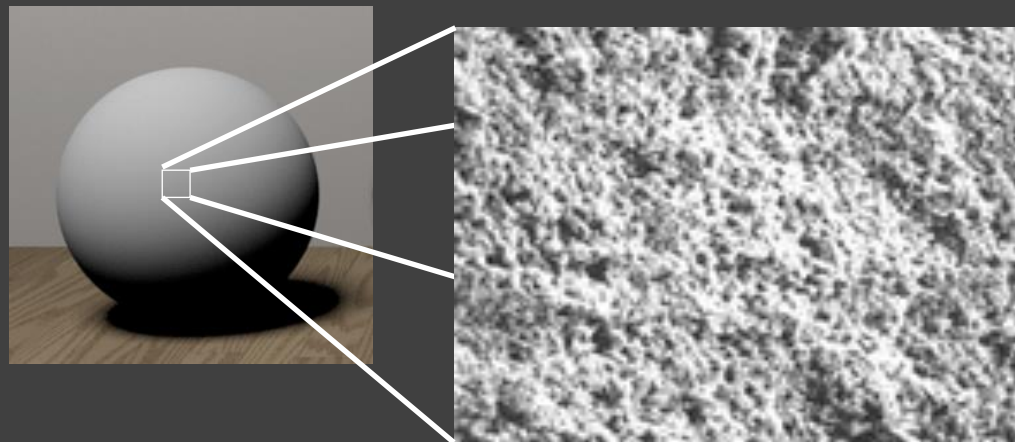
Ideal  
specular

Directional  
diffuse

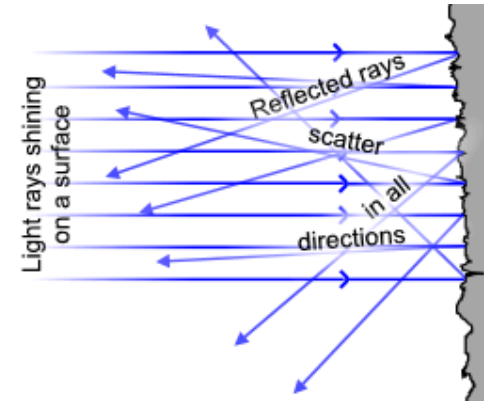
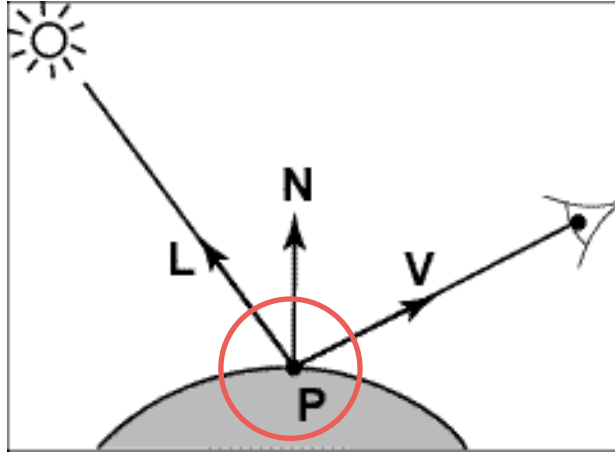


# Ideal Diffuse Reflection

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



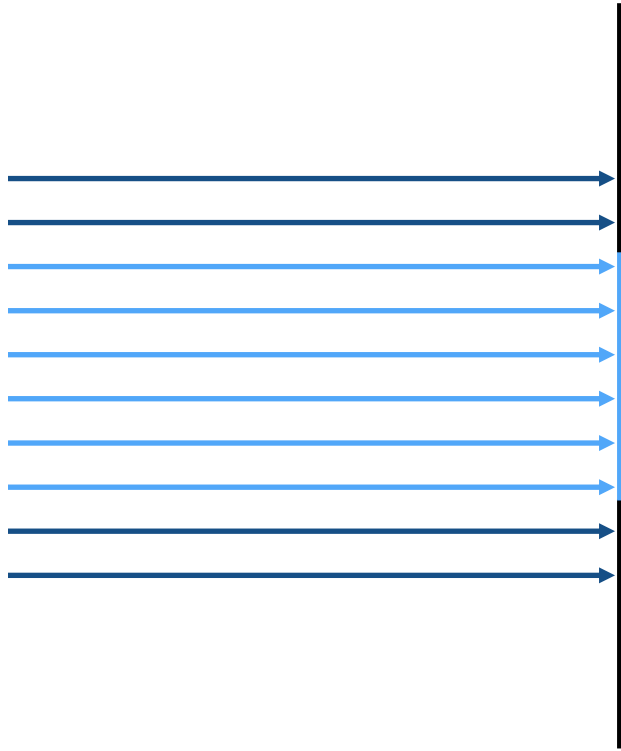
# Lambertian Reflectance



1. Reflected energy is proportional to cosine of angle between L and N (**incoming**)
2. Measured intensity is viewpoint-independent (**outgoing**)

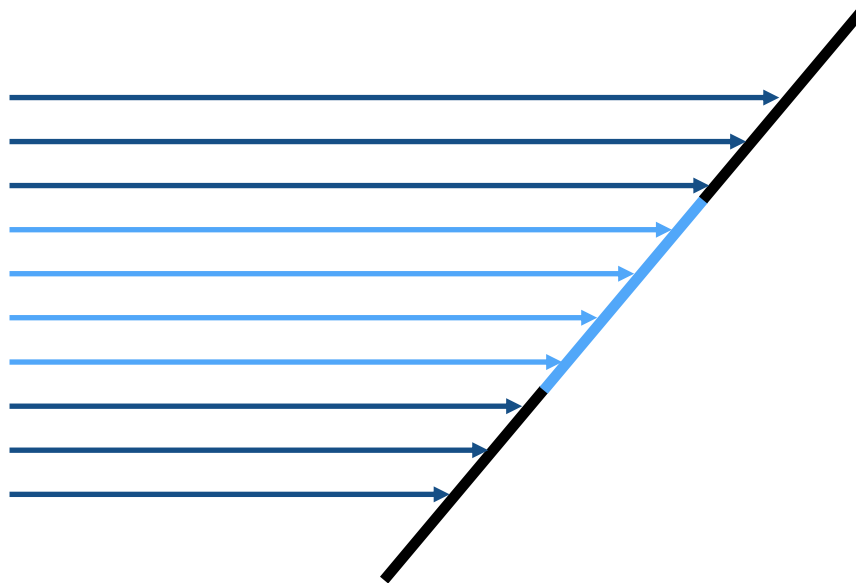
# Lambertian Reflectance: Incoming

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



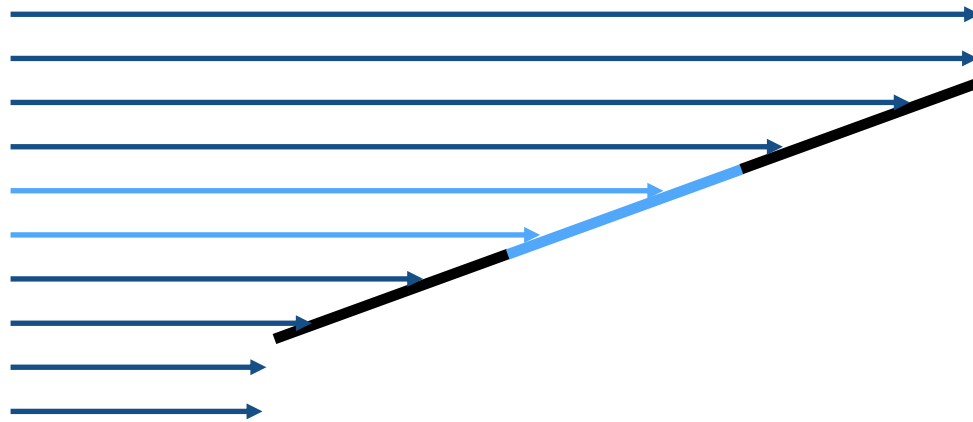
# Lambertian Reflectance: Incoming

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# Lambertian Reflectance: Incoming

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

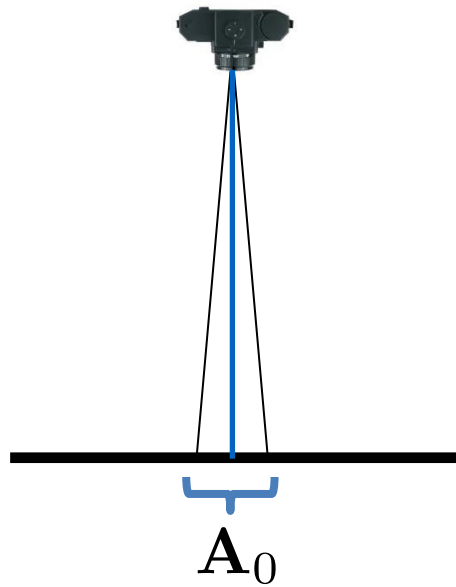


Light hitting surface is proportional to the **cosine**



# Lambertian Surfaces: Appearance vs Reflected Photons

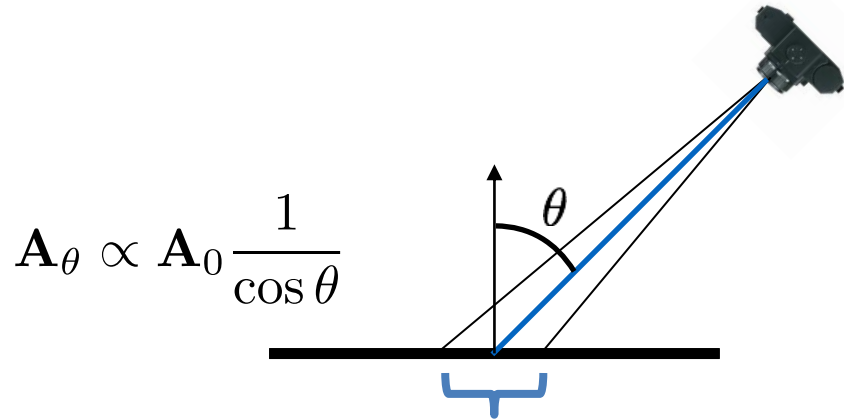
- Appearance is the same from every angle
- Radiant Intensity? (how many photons reflected per angle)



$$Pixel = \mathbf{B}_0 \mathbf{A}_0 = \mathbf{B}_\theta \mathbf{A}_\theta$$

# Lambertian Surfaces: Appearance vs Reflected Photons

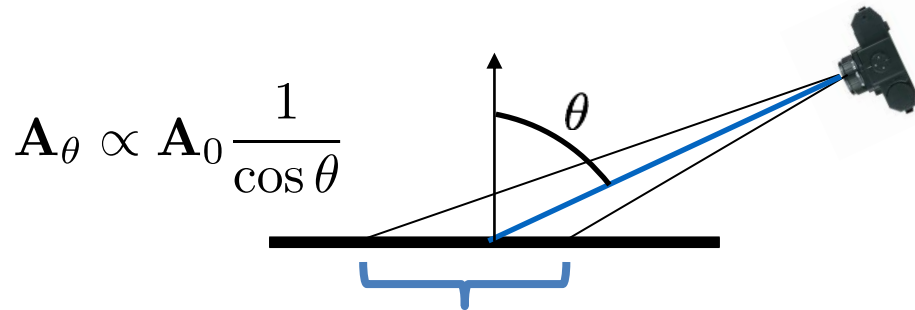
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# Lambertian Surfaces: Appearance vs Reflected Photons

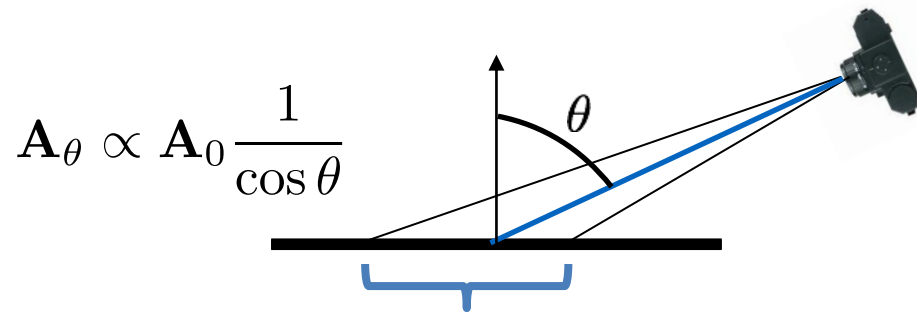
- Appearance is the same from every angle
- Radiant Intensity? (how many photons reflected per angle)



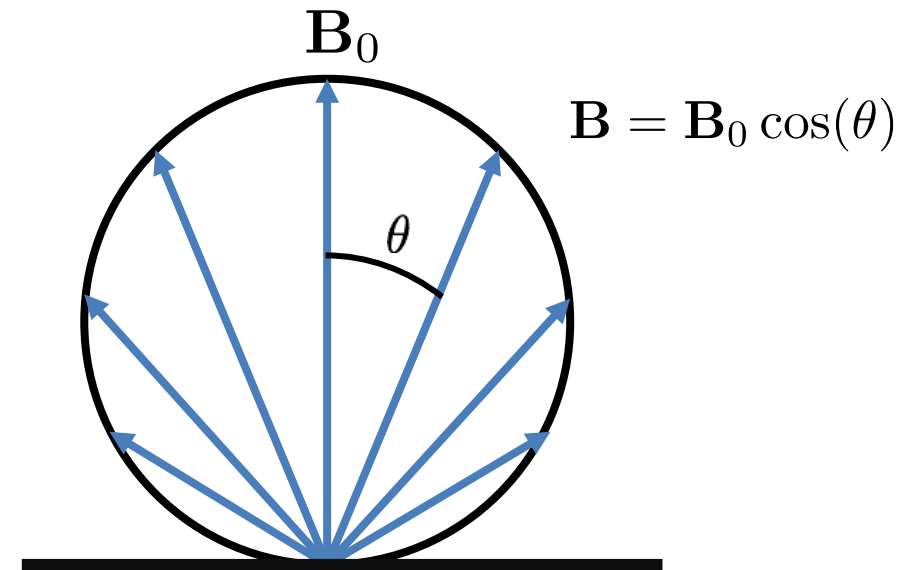
$$Pixel = \mathbf{B}_0 A_0 = \mathbf{B}_{\theta} A_{\theta}$$

# Lambertian Surfaces: Appearance vs Reflected Photons

- Appearance is the same from every angle
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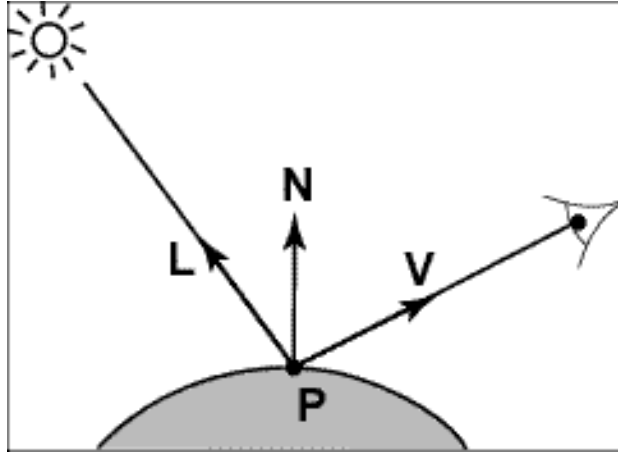
$$Pixel = \mathbf{B}_0 \mathbf{A}_0 = \mathbf{B}_{\theta} \mathbf{A}_{\theta}$$



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

$$Pixel = \mathbf{B}_0 \mathbf{A}_0 \frac{\cos \theta}{\cos \theta}$$

# Image Formation Model: Final



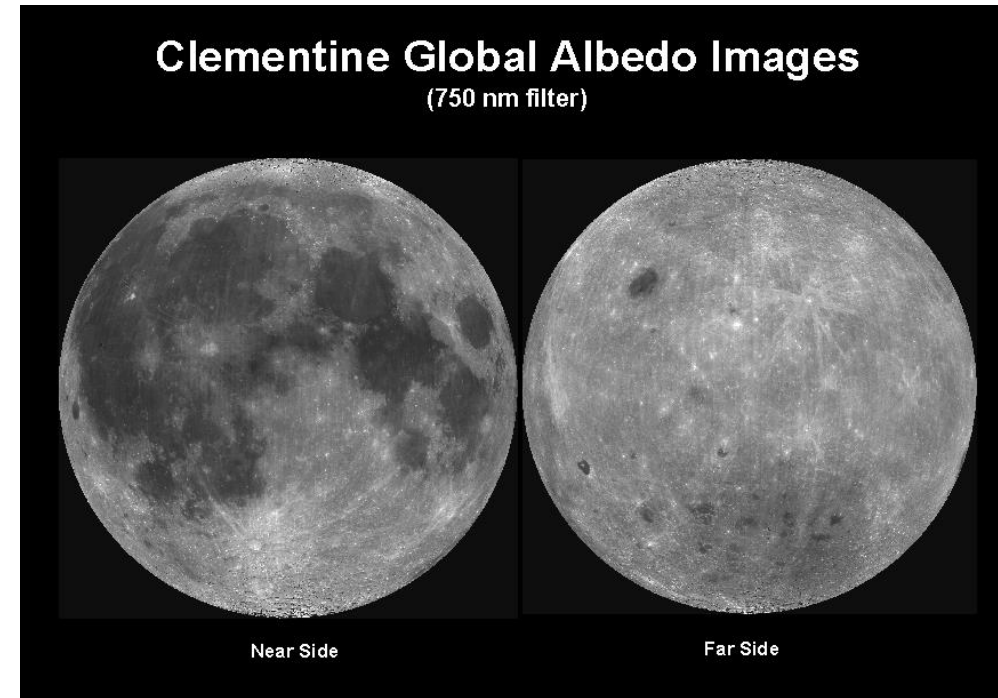
$$I = k_d \mathbf{N} \cdot \mathbf{L}$$

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

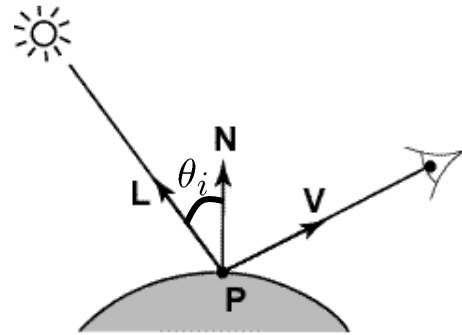
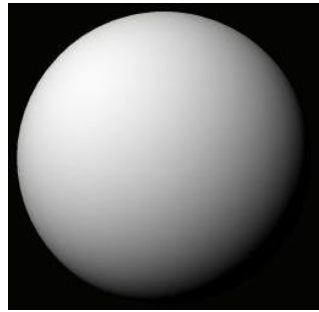
Surface	Typical albedo
Fresh asphalt	0.04 <sup>[4]</sup>
Open ocean	0.06 <sup>[5]</sup>
Worn asphalt	0.12 <sup>[4]</sup>
Conifer forest (Summer)	0.08, <sup>[6]</sup> 0.09 to 0.15 <sup>[7]</sup>
Deciduous trees	0.15 to 0.18 <sup>[7]</sup>
Bare soil	0.17 <sup>[8]</sup>
Green grass	0.25 <sup>[8]</sup>
Desert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



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?**