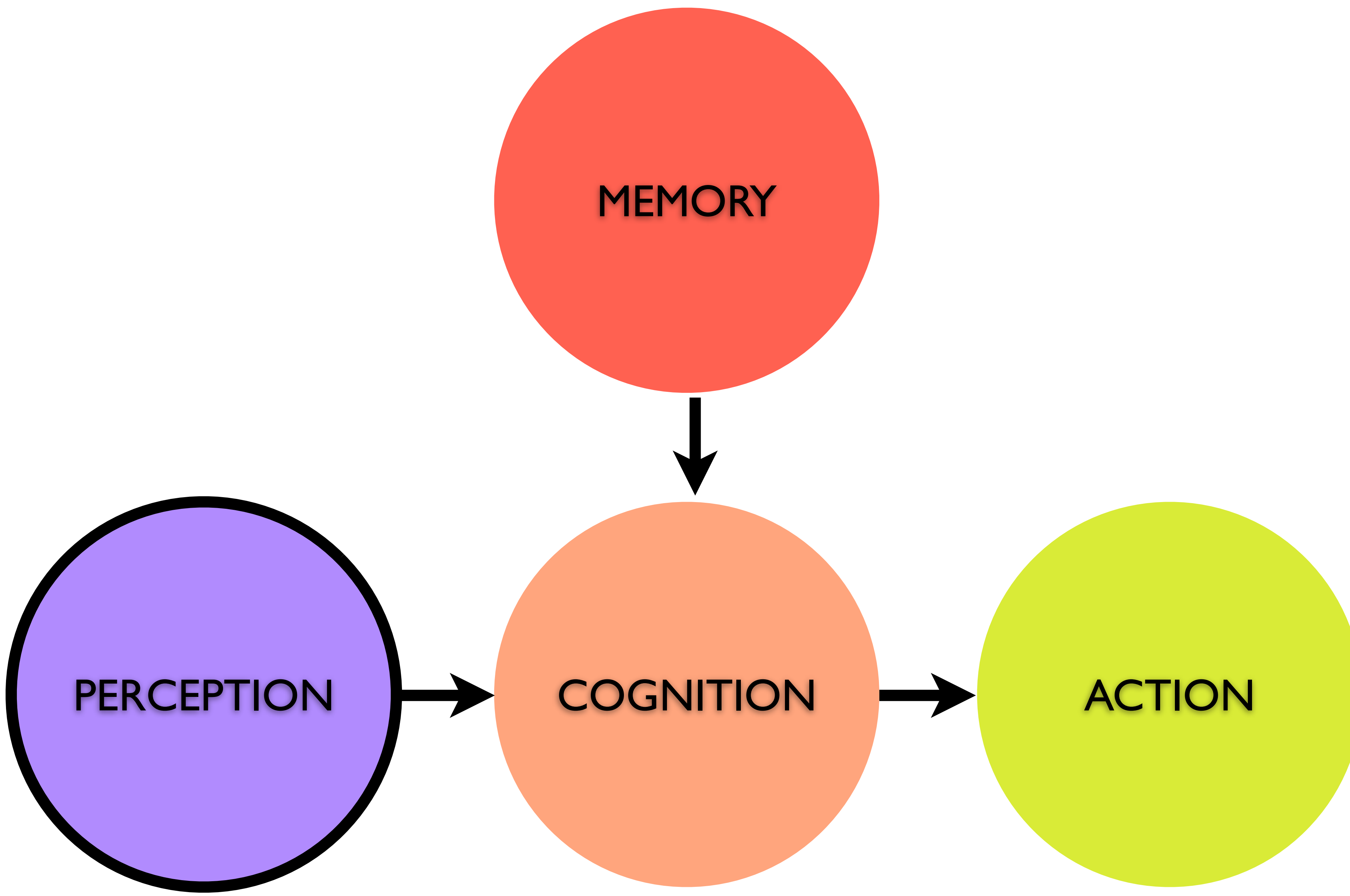
15-381 ARTIFICIAL INTELLIGENCE

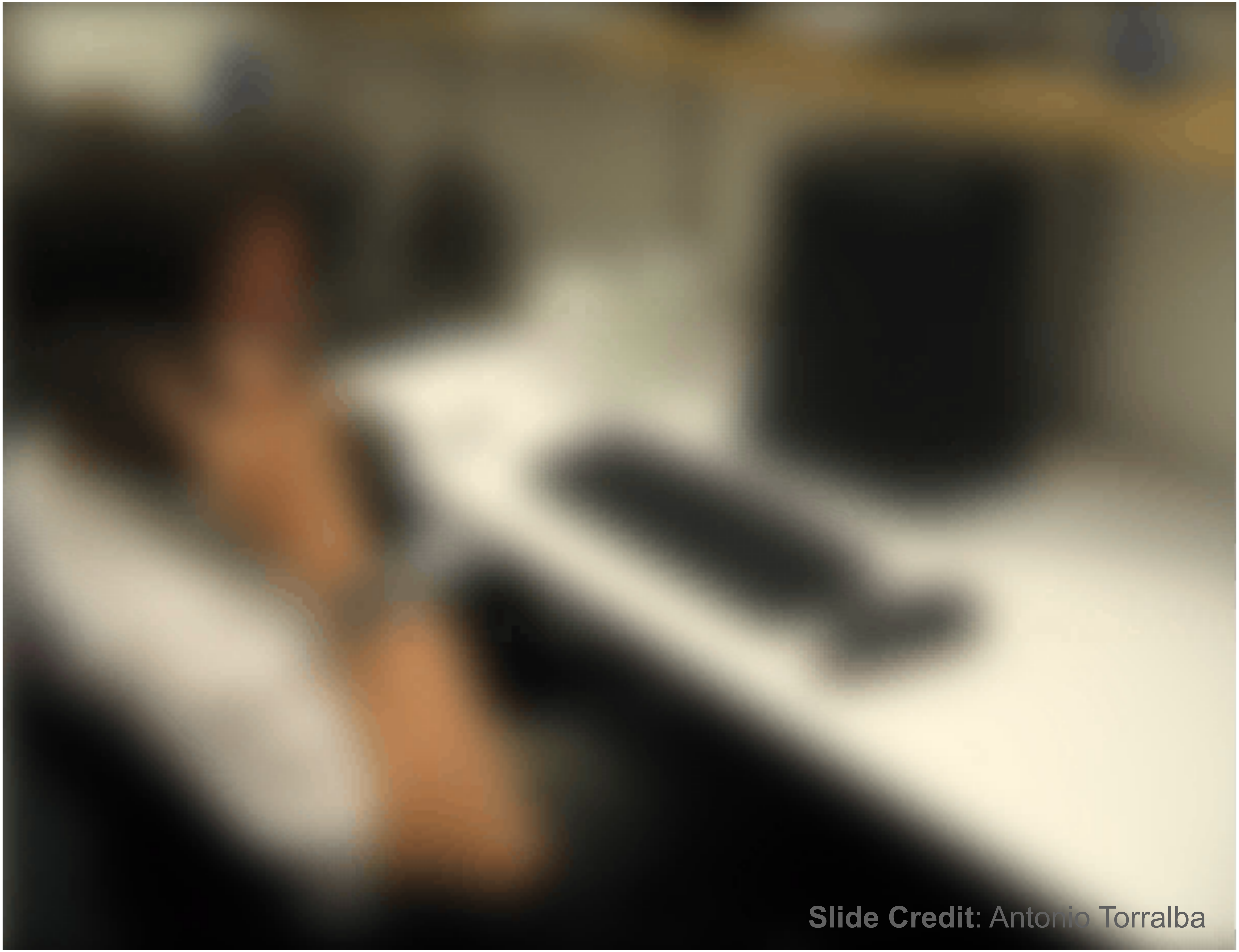
LECTURE 13: PERCEPTION: IMAGE FORMATION

FALL 2010

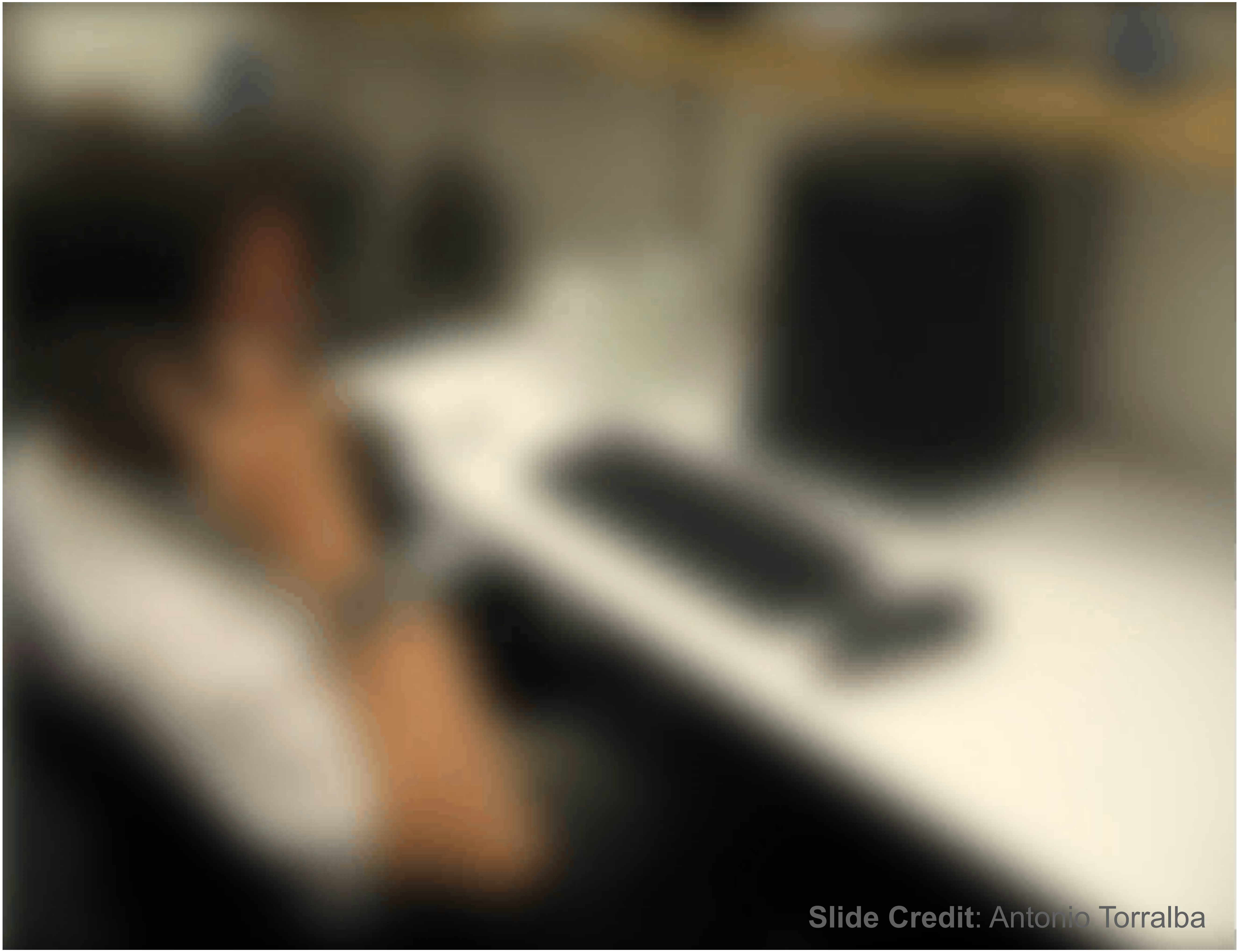


Wednesday, October 13, 2010

decision vs prediction


Slide Credit: Antonio Torralba

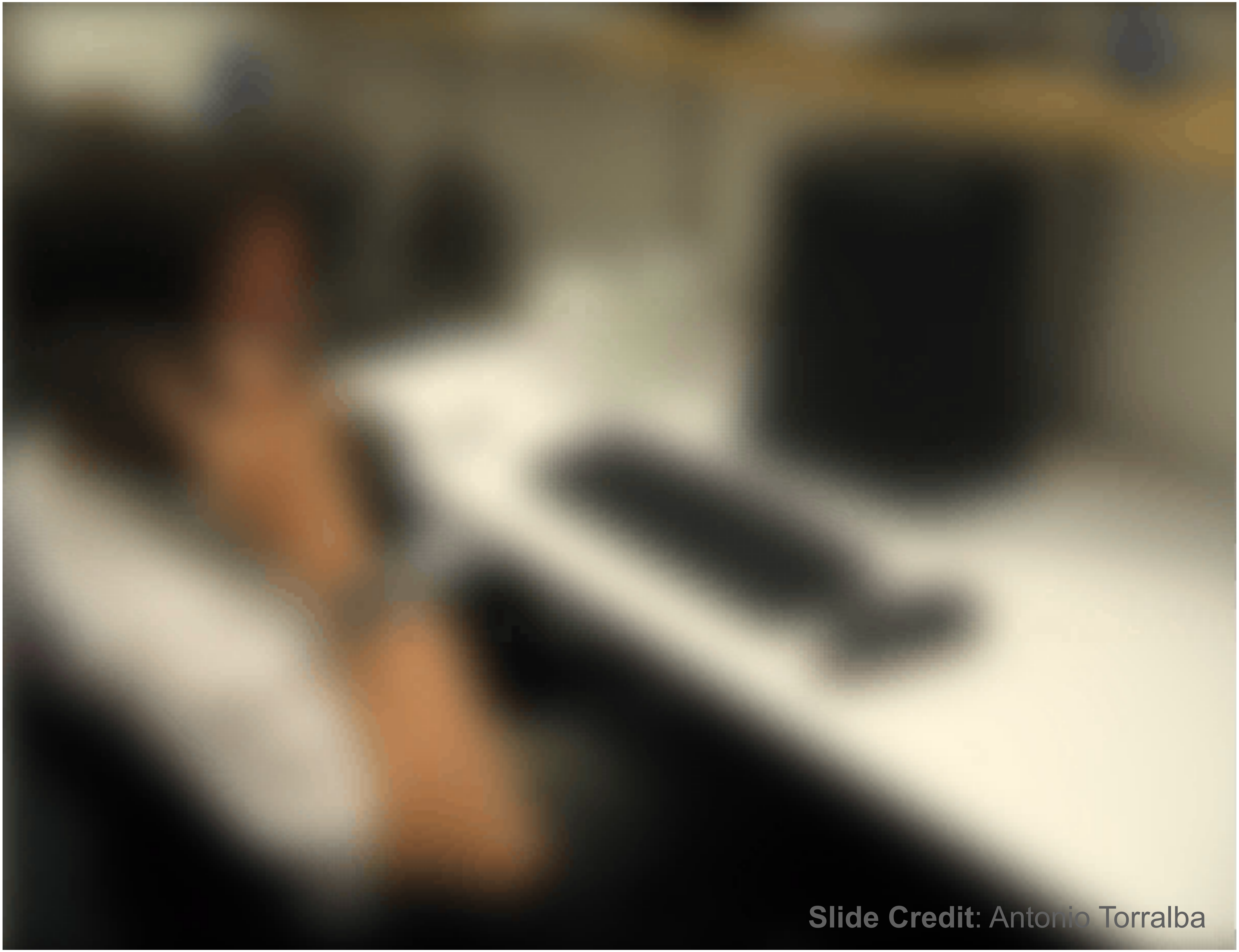
What did you see?


Slide Credit: Antonio Torralba


Slide Credit: Antonio Torralba

"THE EYE SEES ONLY WHAT THE MIND IS PREPARED TO COMPREHEND."

--- Henri Bergson, 1927


Slide Credit: Antonio Torralba

WHY IS SCENE UNDERSTANDING FROM IMAGES HARD?

VIEW

ILLUMINATION

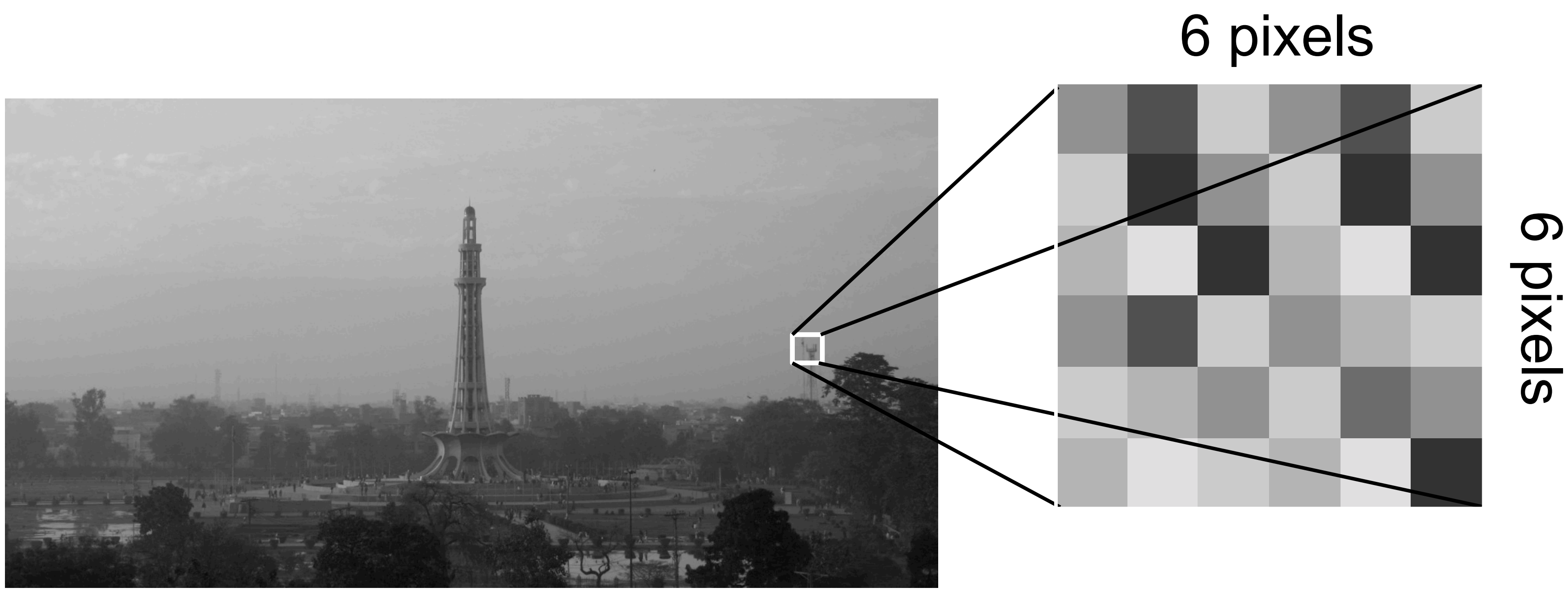
Credit: Shimon Ullman

INTRA-CLASS VARIATION

CREDIT: FEI-FEI, FERGUS & TORRALBA

ARTICULATION

THE SET OF ALL IMAGES



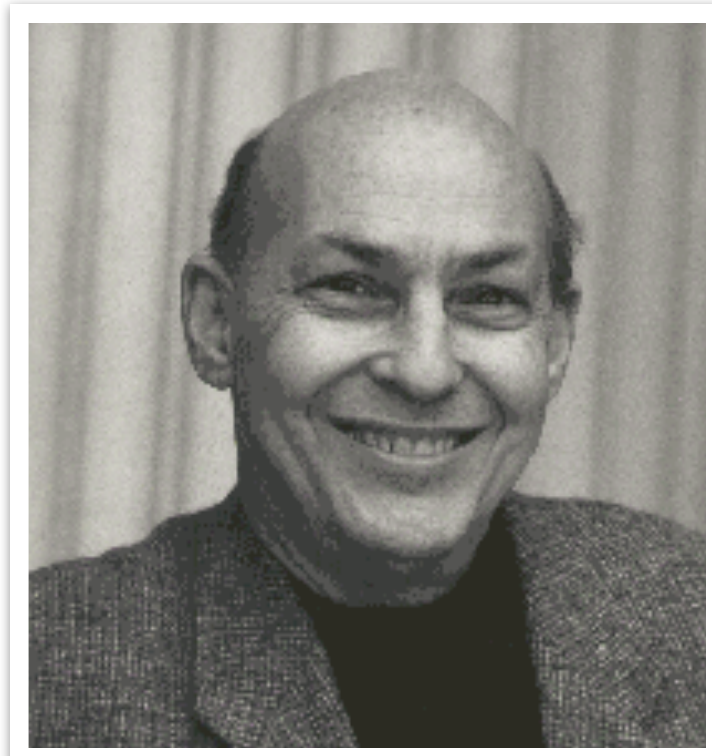
181	223	53	170	210	52
55	242	177	66	246	185
75	29	239	78	22	233
183	219	44	76	66	43
58	79	90	48	191	177
73	38	70	82	24	234

Size of the Set of all possible 9x9 patches ⟶ $255^{9 \times 9} = 8.51 \times 10^{194}$

$$\frac{640 \times 480}{9 \times 9} \times \underset{\text{fps}}{30} \times \underset{\text{secs}}{60} \times \underset{\text{mins}}{60} \times \underset{\text{hrs}}{24} \times \underset{\text{days}}{365} \times \underset{\text{people}}{6{,}000{,}000{,}000} \times \underset{\text{years}}{200{,}000} = 4.31 \times 10^{27}$$

Credit: "KANADE'S THEOREM"

1950s



"The best way to learn about a difficult problem
is to give it to an intrepid undergraduate

WHERE DOES A PIXEL COME FROM?

2048 x 3072 x 3

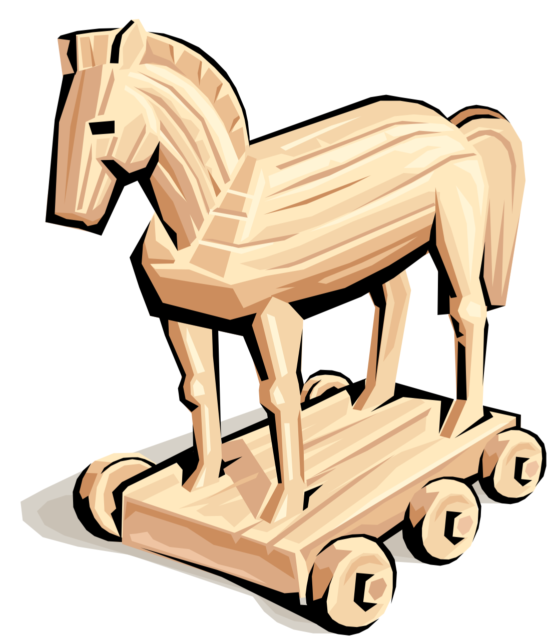
$$\begin{bmatrix} \text{red} \\ \text{green} \\ \text{blue} \\ x \\ y \end{bmatrix} = \begin{bmatrix} 178 \\ 172 \\ 158 \\ 545 \\ 1540 \end{bmatrix}$$

radiometry — this lecture

geometry (x, y) — next lecture

INTROMISSIVE THEORY OF VISION

- Greeks understood geometry but not radiometry
  - Euclid's Optica, 300 BC
  - Ptolemy's Almagest, 147 AD
- "Light" travels in straight lines
  - But which way?



EXTROMISSIVE THEORY OF VISION

- Abu Ali Ibn al-Haytham, 1039 AD
  - *Kitaab al-Manazir* (Perspectiva)
- Direction of light by argument
  - "…when the eye looks into exceedingly bright lights, it suffers greatly because of them."
  - How could a ray from the eyes reach the distant stars the moment we open our eyes?
- (One of the) Earliest construction of Camera Obscura
  - Al-Bait al-Muthlim (The Dark Chamber)
  - Observed that the aperture size is related to sharpness

PINHOLE CAMERA

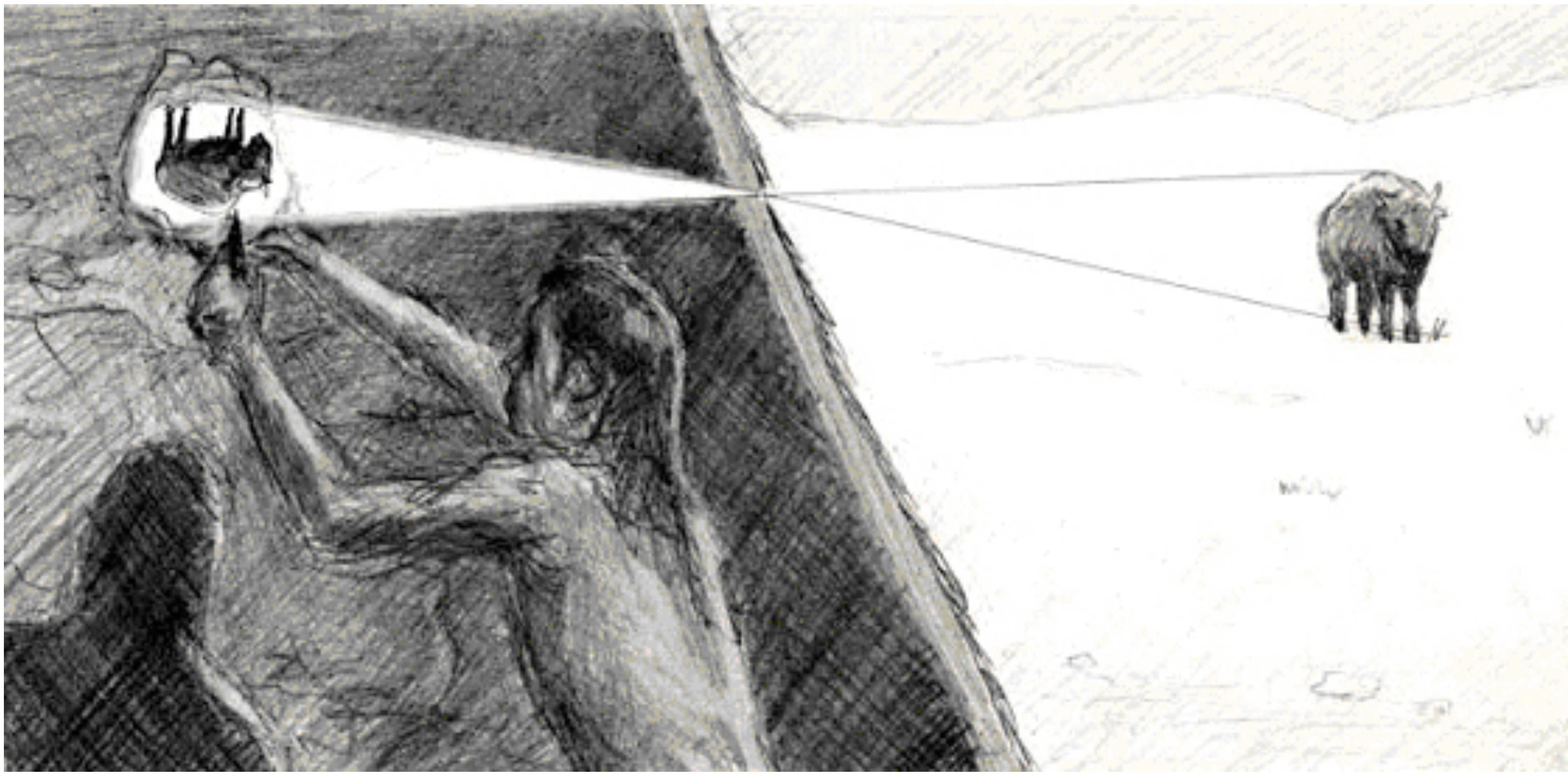


Image Source: Le Ministère de la Culture et de la Communication - The Cave Of Lascaux

PINHOLE CAMERA

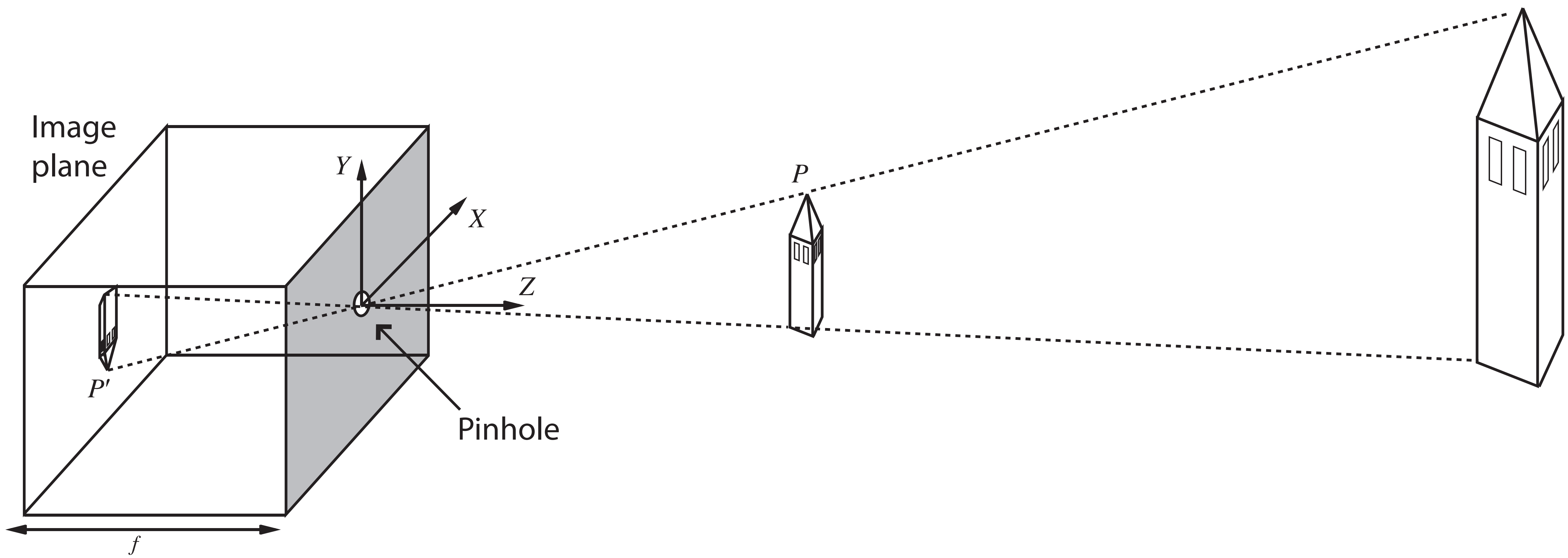


IMAGE FORMATION

- RADIOMETRY
- OPTICS
- GEOMETRY

RADIOMETRY

LIGHT TRANSPORT

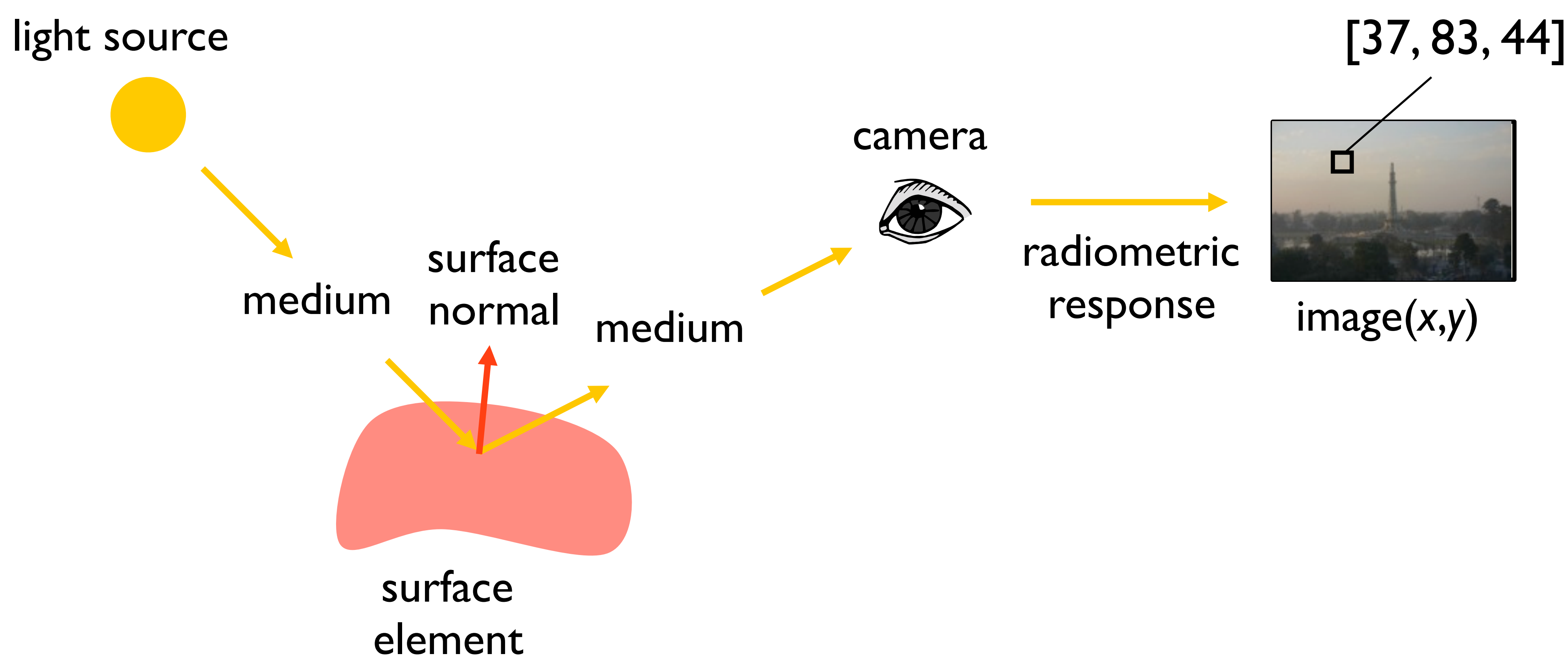
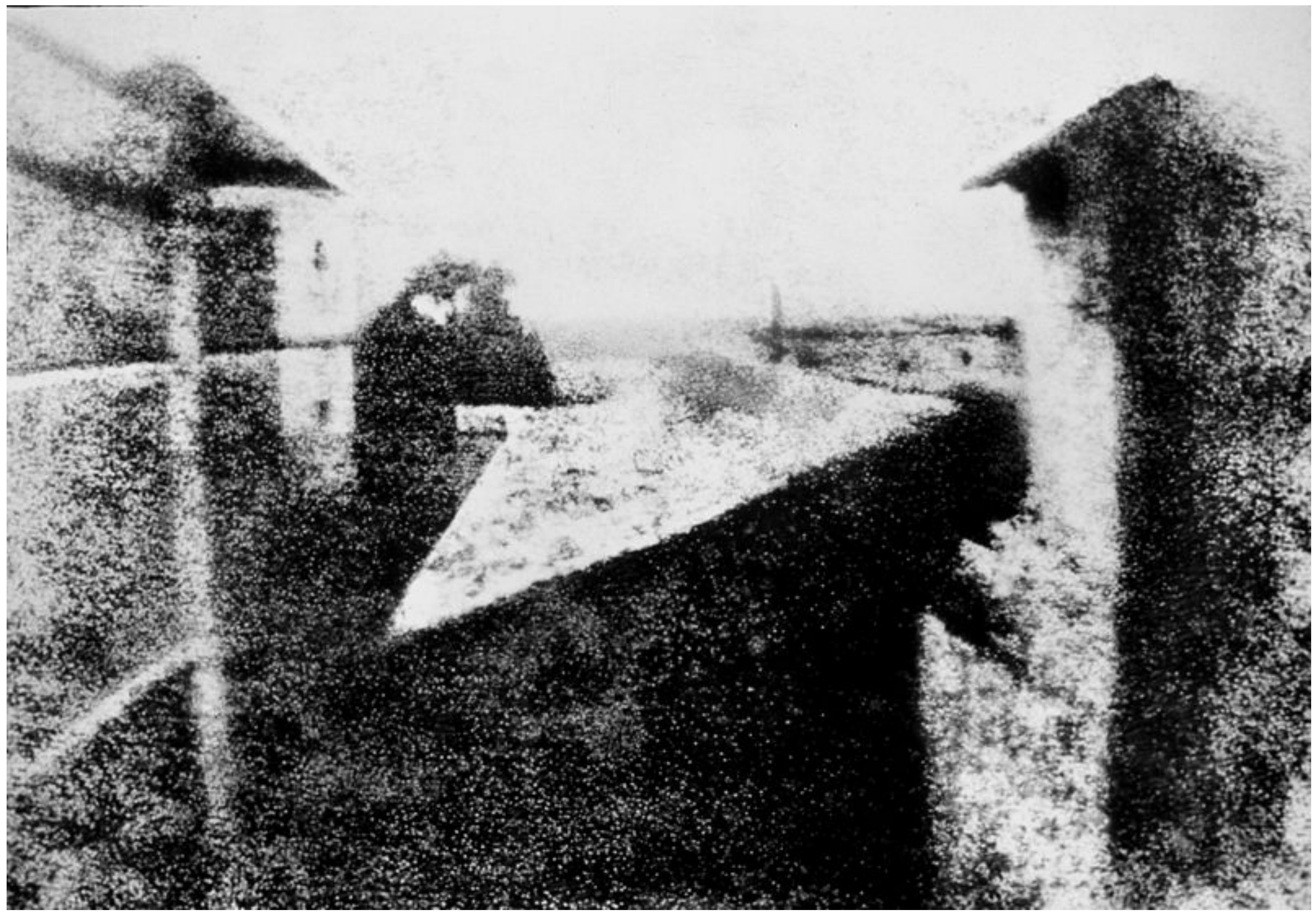


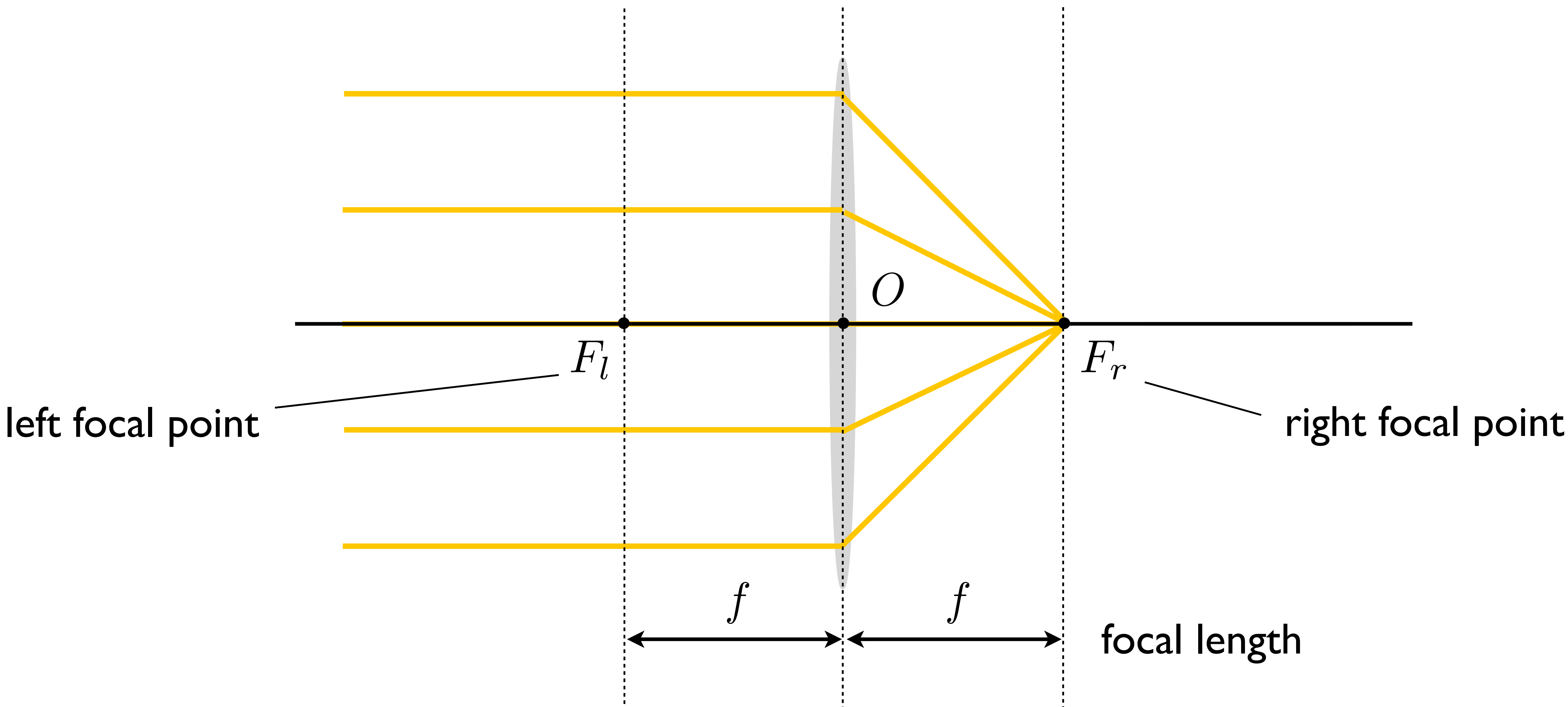
IMAGE FORMATION



NIEPCE, 1826

OPTICS

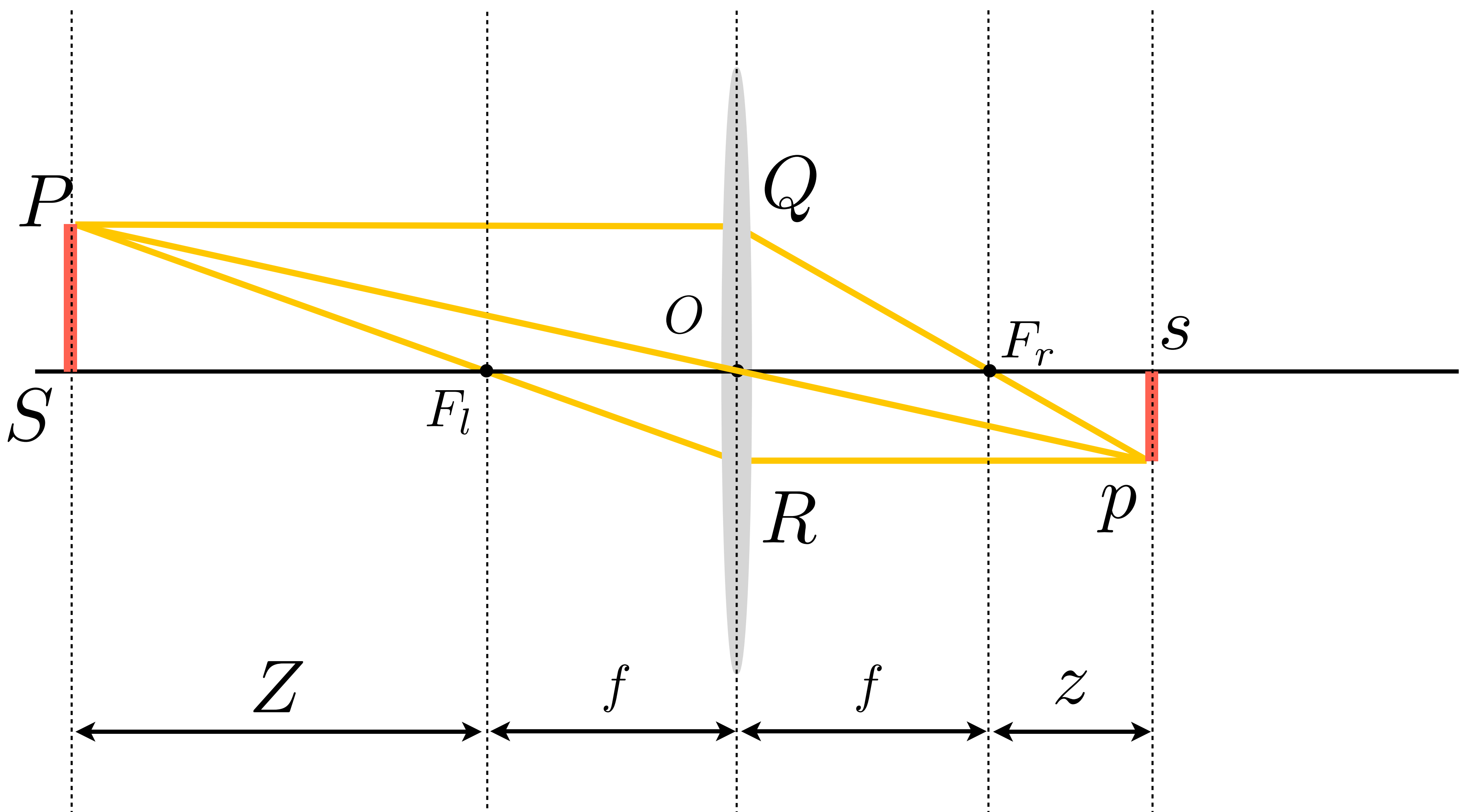
THIN LENSES



1. ANY RAY ENTERING THE LENS PARALLEL TO THE AXIS ON ONE SIDE GOES THROUGH THE FOCUS ON THE OTHER SIDE
2. ANY RAY ENTERING THE LENS FROM THE FOCUS ON ONE SIDE EMERGES PARALLEL TO THE AXIS ON THE OTHER SIDE

OPTICS

THIN LENSES



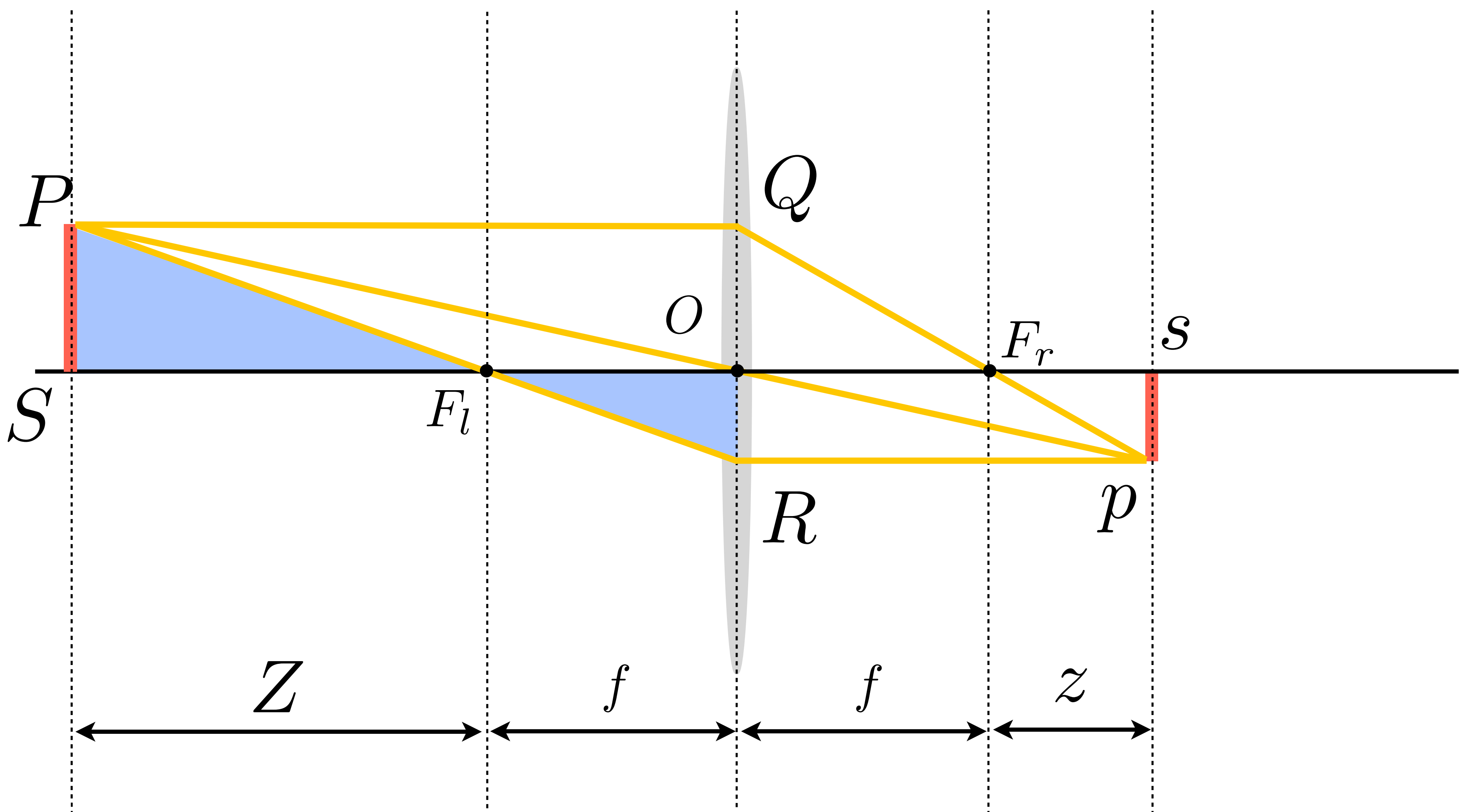
1. ANY RAY ENTERING THE LENS PARALLEL TO THE AXIS ON ONE SIDE GOES THROUGH THE FOCUS ON THE OTHER SIDE

2. ANY RAY ENTERING THE LENS FROM THE FOCUS ON ONE SIDE EMERGES PARALLEL TO THE AXIS ON THE OTHER SIDE

HOW ARE Z AND z RELATED TO *f*?

OPTICS

SIMILAR TRIANGLES

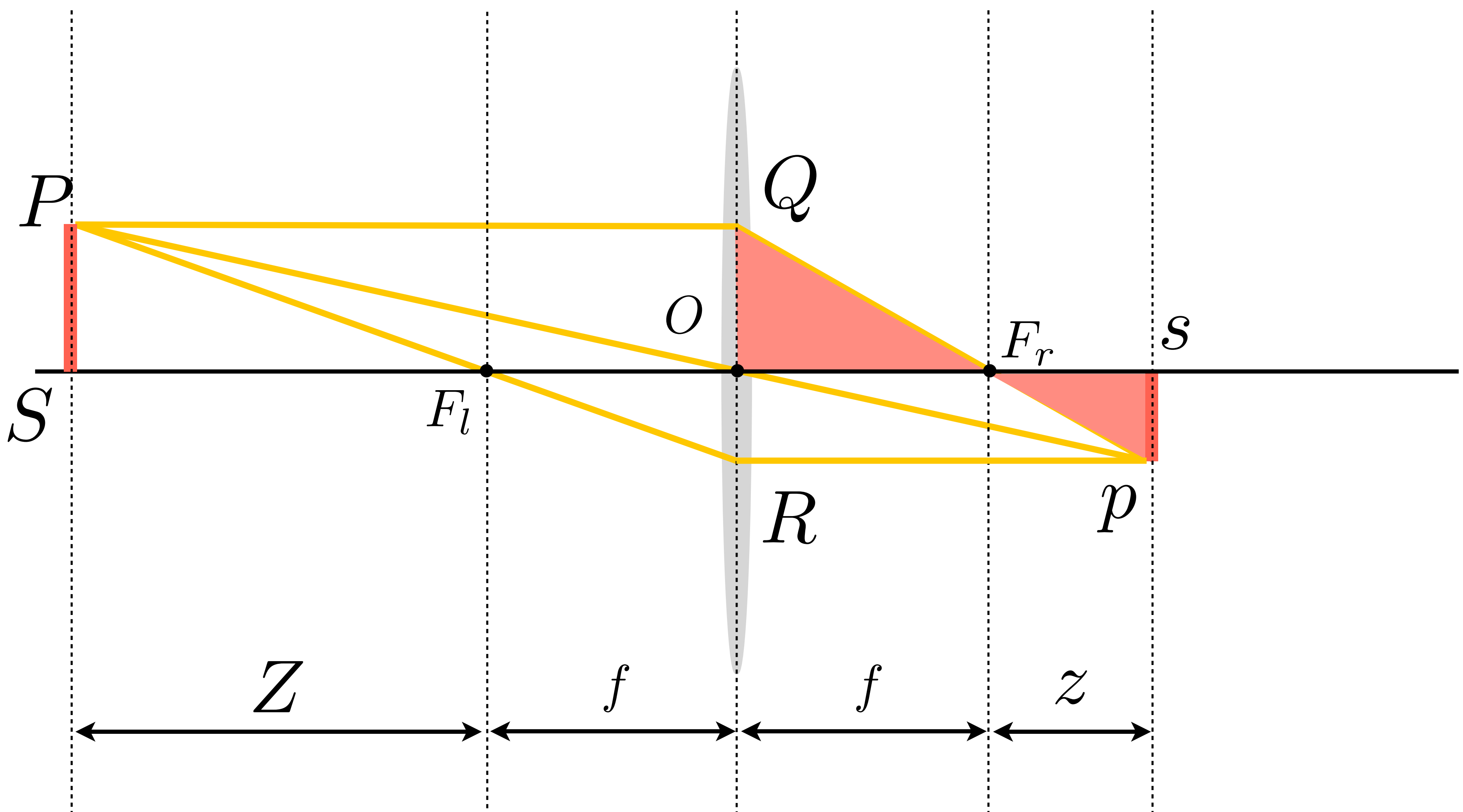


$$\frac{|PS|}{|OR|} = \frac{|SF_l|}{|F_lO|}$$

$$\frac{|PS|}{|sp|} = \frac{Z}{f}$$

OPTICS

SIMILAR TRIANGLES



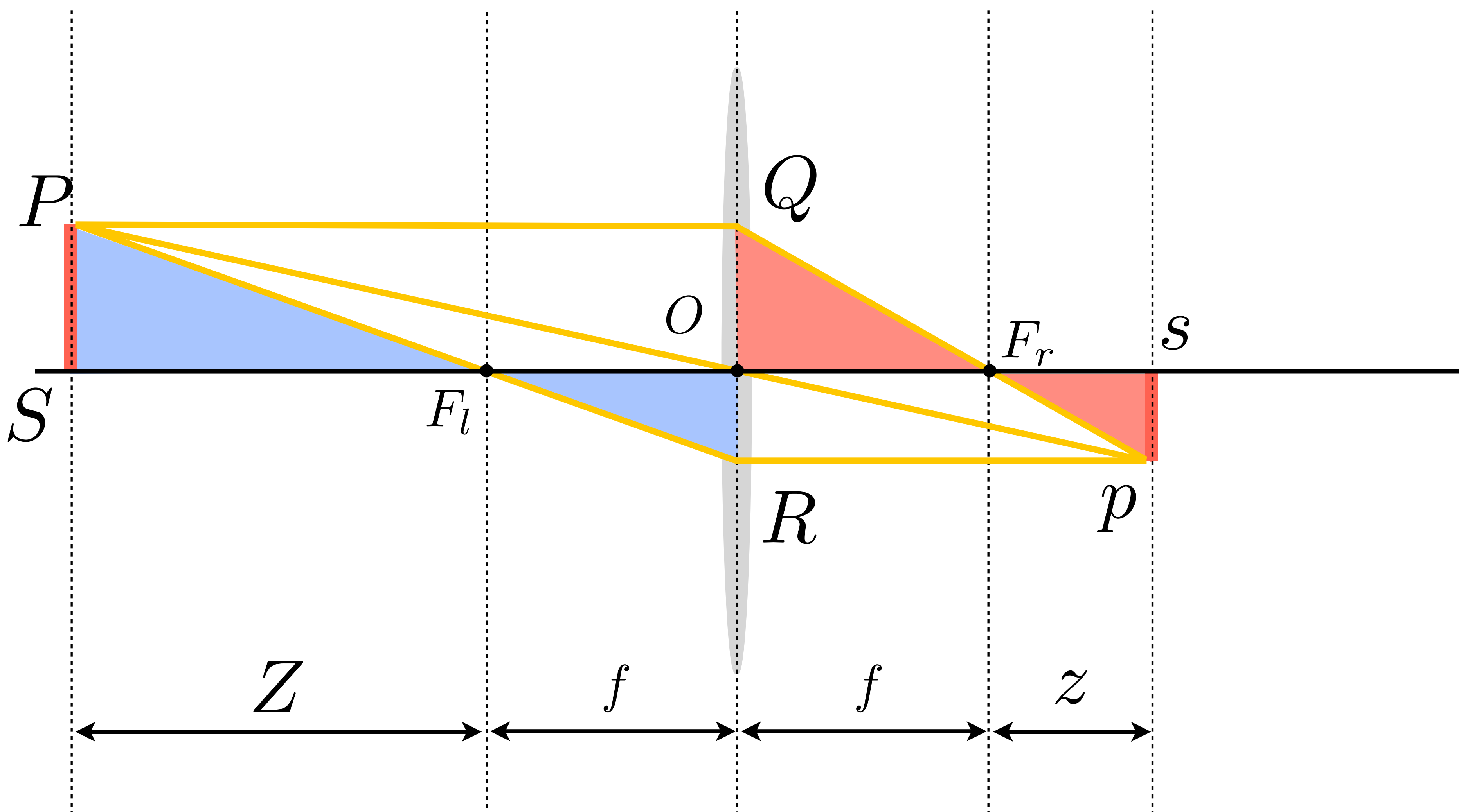
$$\frac{|QO|}{|sp|} = \frac{|F_rO|}{|sF_r|}$$

$$\frac{|PS|}{|sp|} = \frac{Z}{f}$$

$$\frac{|PS|}{|sp|} = \frac{f}{z}$$

OPTICS

RELATING Z AND z

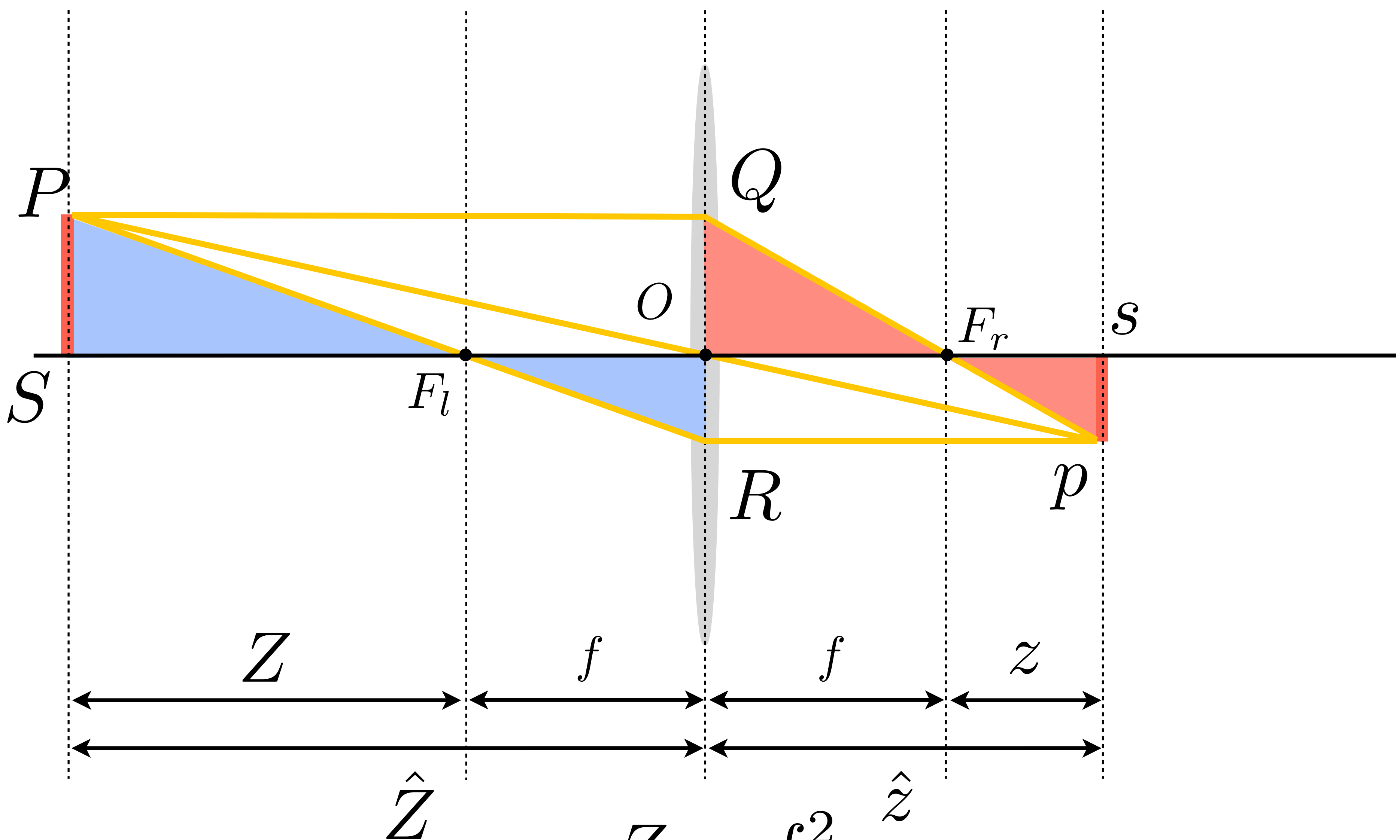


$$\frac{|PS|}{|sp|} = \frac{Z}{f} \qquad \frac{|PS|}{|sp|} = \frac{f}{z}$$

$$zZ = f^2$$

OPTICS

FUNDAMENTAL EQUATION OF THIN LENSES

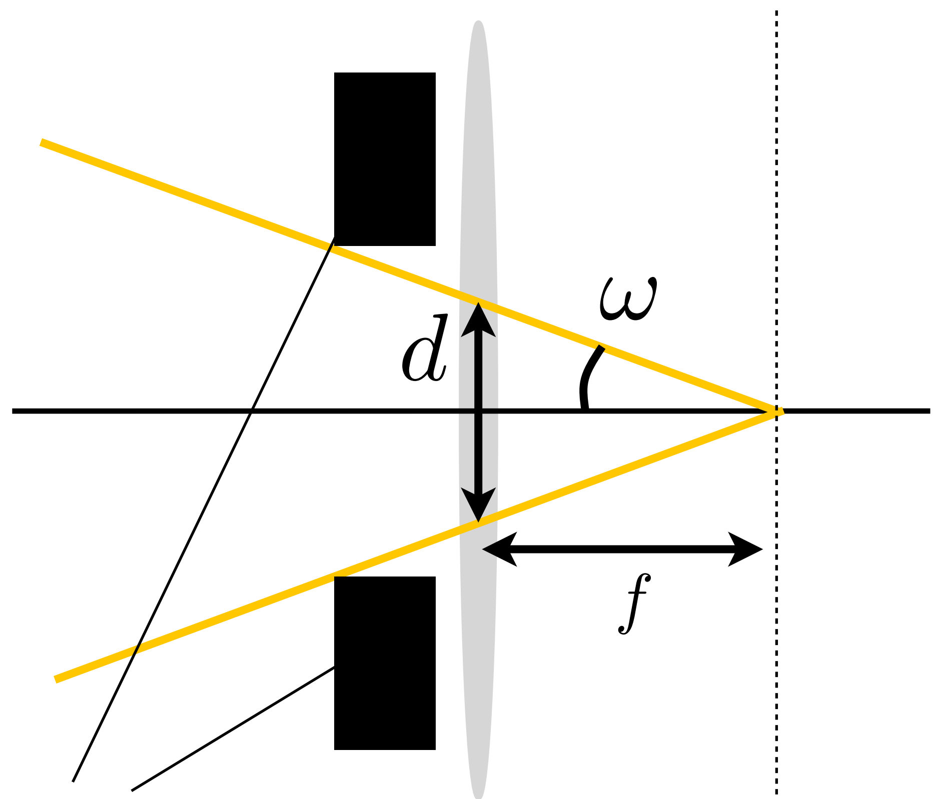


$$zZ = f^2$$

$$\frac{1}{\hat{Z}} + \frac{1}{\hat{z}} = \frac{1}{f}$$

Discovered by Edmund Halley in 1693 (of Halley's comet fame).

FIELD OF VIEW



aperture

$$tan(\omega) = \frac{d}{2f}$$

effective diameter

field of view

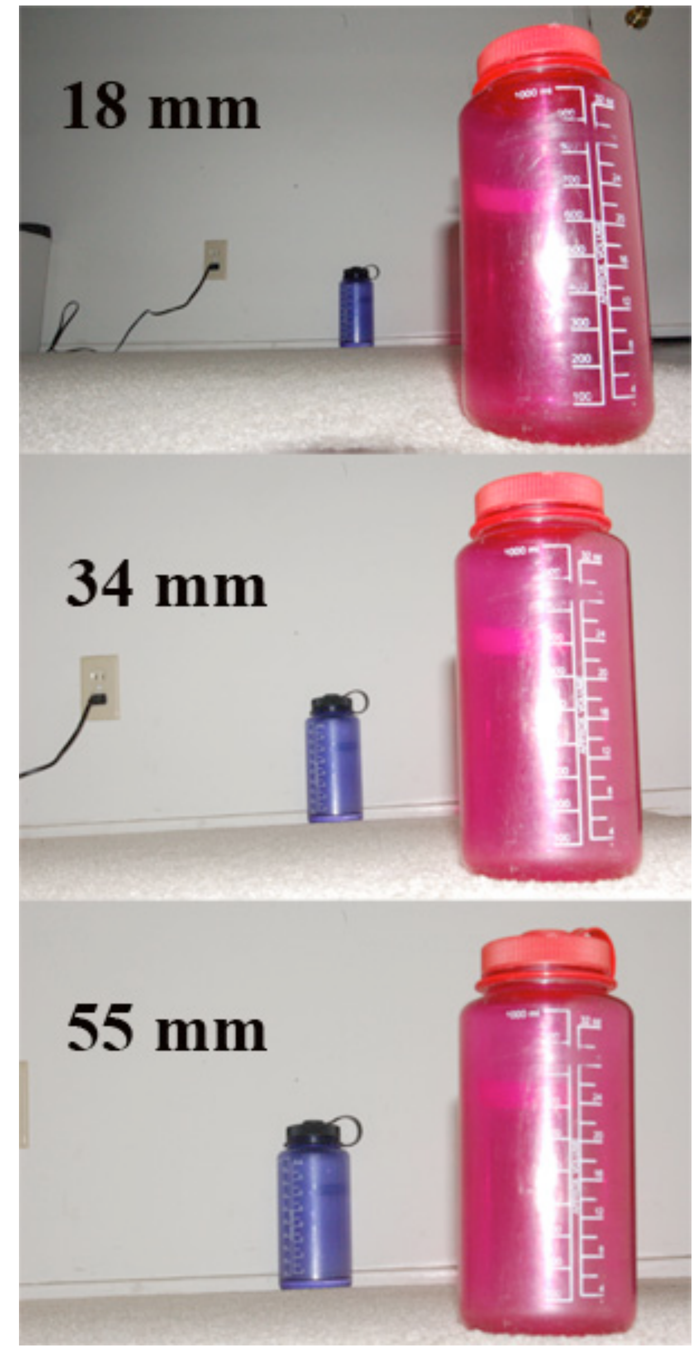
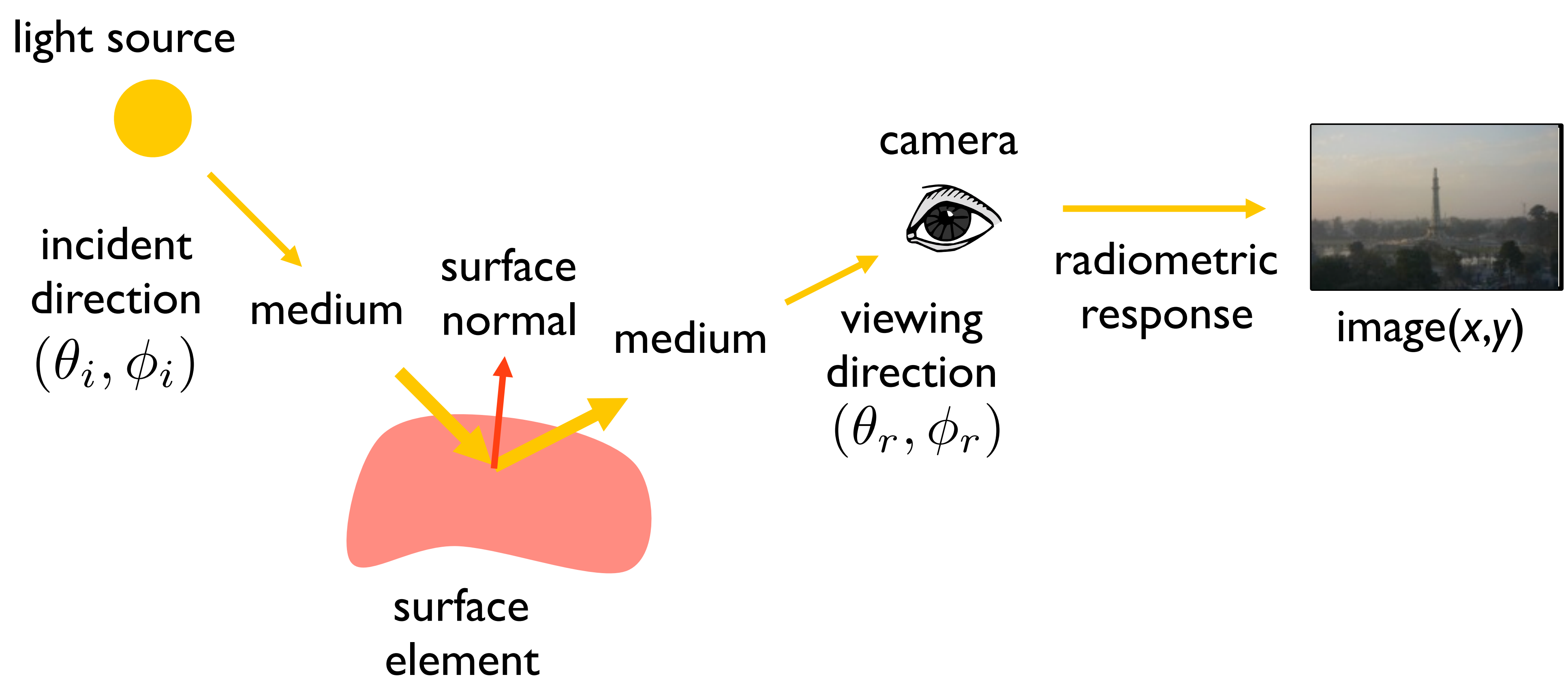


Image source: Wikipedia

Effective diameter is usually much smaller than the physical diameter because of the aperture.

SURFACE IRRADIANCE TO SURFACE RADIANCE



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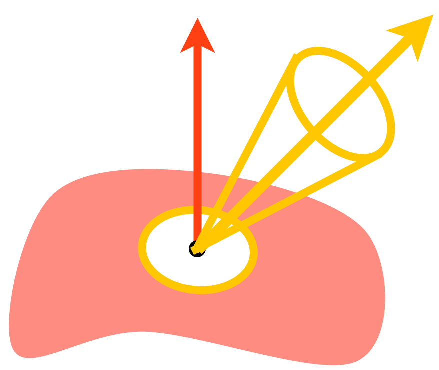
Assume perfect medium, i.e., no attenuation of light

RADIANCE AND IRRADIANCE

Amount of light **emitted** from a surface in a particular direction

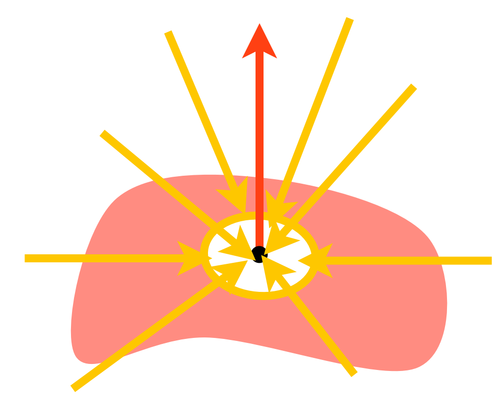
Power traveling at some point in a specified direction, per unit area perpendicular to the direction of travel, per unit solid angle:



RADIANCE

How much light is **arriving** at a particular location?

Total power arriving at a surface point computer by adding irradiance over all incoming directions

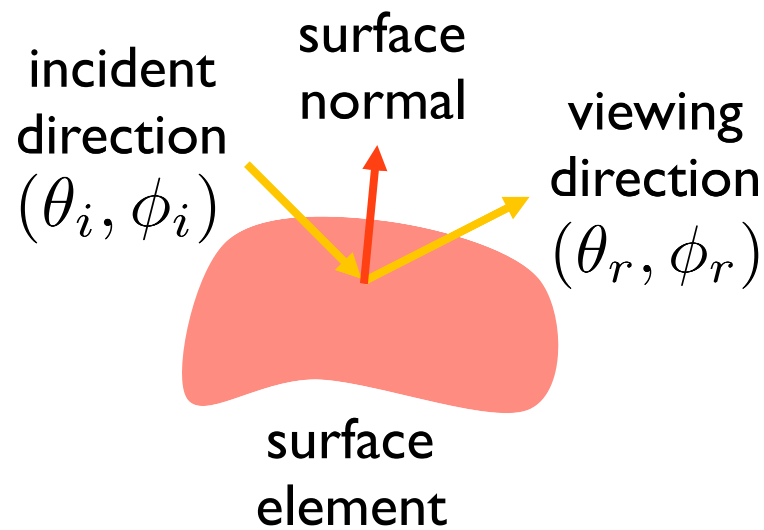


IRRADIANCE

Assume perfect medium, i.e., no attenuation of light

BRDF

BI-DIRECTIONAL REFLECTANCE DISTRIBUTION FUNCTION



$E_{\text{surface}}(\theta_i, \phi_i)$: Irradiance at surface in direction (θ_i, ϕ_i)

$L_{\text{surface}}(\theta_r, \phi_r)$: Radiance of surface in direction (θ_r, ϕ_r)

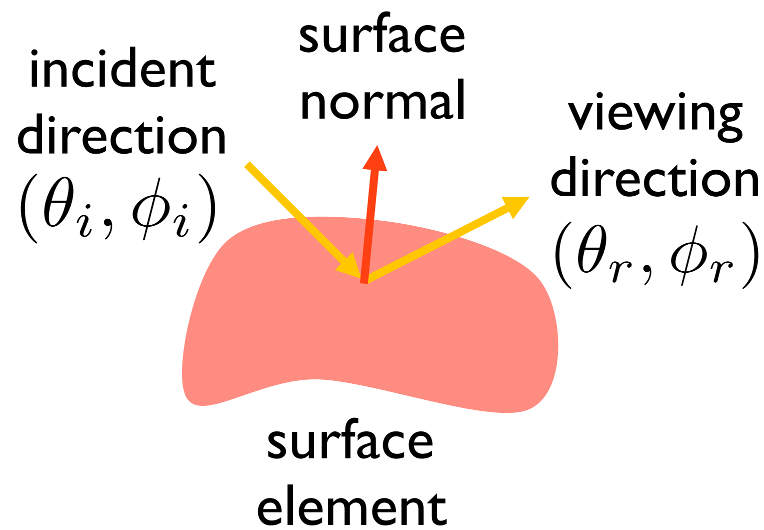
$$L_{\text{surface}}(\theta_r, \phi_r) = f(\theta_i, \phi_i; \theta_r, \phi_r) E_{\text{surface}}(\theta_i, \phi_i)$$

BRDF

$$f(\theta_i, \phi_i; \theta_r, \phi_r) = \frac{L_{\text{surface}}(\theta_r, \phi_r)}{E_{\text{surface}}(\theta_i, \phi_i)}$$

BASED ON SLIDE BY SRINIVASA NARASIMHAN

BRDF: IMPORTANT PROPERTIES

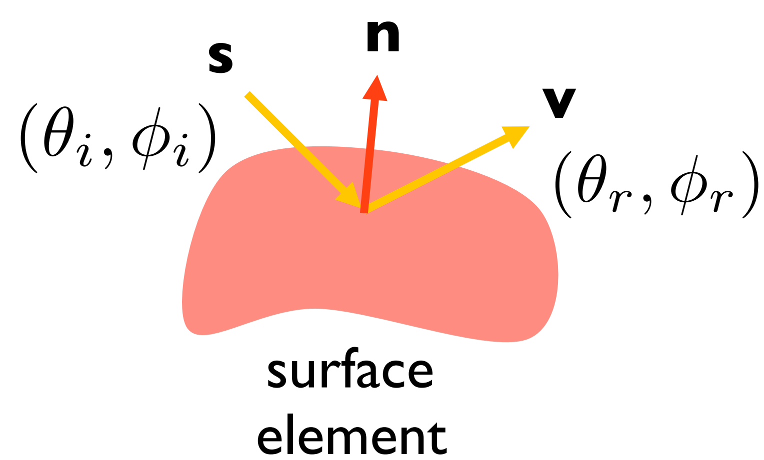


- ROTATIONAL SYMMETRY
  - BRDF DOES NOT CHANGE WHEN SURFACE IS ROTATED ABOUT NORMAL
  - BRDF IS A FUNCTION OF THREE VARIABLES: $f(\theta_i, \theta_r, \phi_i - \phi_r)$
- HELMHOLTZ RECIPROCITY
  - BRDF DOES NOT CHANGE WHEN INCIDENT AND VIEWING DIRECTIONS ARE SWAPPED

$$f(\theta_i, \phi_i; \theta_r, \phi_r) = f(\theta_r, \phi_r; \theta_i, \phi_i)$$

BASED ON SLIDE BY SRINIVASA NARASIMHAN

BRDF: LAMBERTIAN REFLECTANCE



- SURFACE APPEARS EQUALLY BRIGHT FROM ALL DIRECTIONS
  - LAMBERTIAN BRDF IS CONSTANT (W.R.T VIEW): $f(\theta_i, \phi_i; \theta_r, \phi_r) = \rho$
  - SURFACE RADIANCE:

$$\underbrace{L}_{\text{RADIANCE}} = \underbrace{\rho}_{\text{ALBEDO (BRDF)}} \underbrace{\overbrace{I}^{\text{LIGHT INTENSITY}} \mathbf{n} \cdot \mathbf{s}}_{\text{IRRADIANCE}}$$

BASED ON SLIDE BY SRINIVASA NARASIMHAN

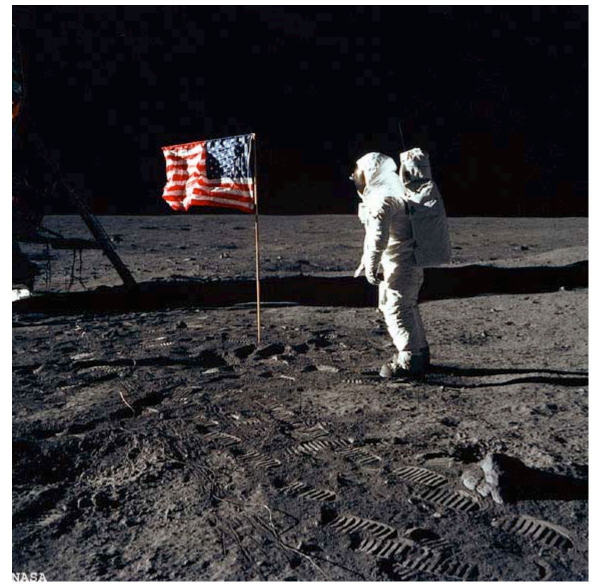
Lambert's Law

IS THIS SURFACE LAMBERTIAN?

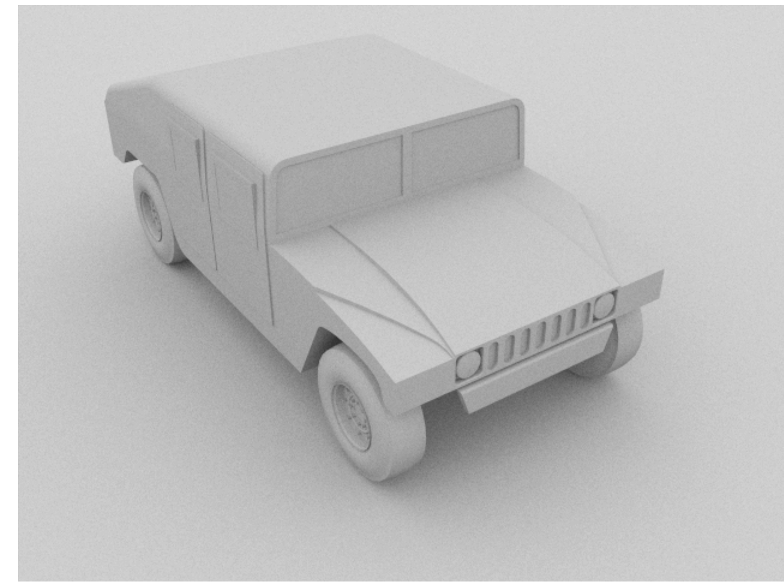
Nearly.

EXAMPLES OF LAMBERTIAN SURFACES

SAND



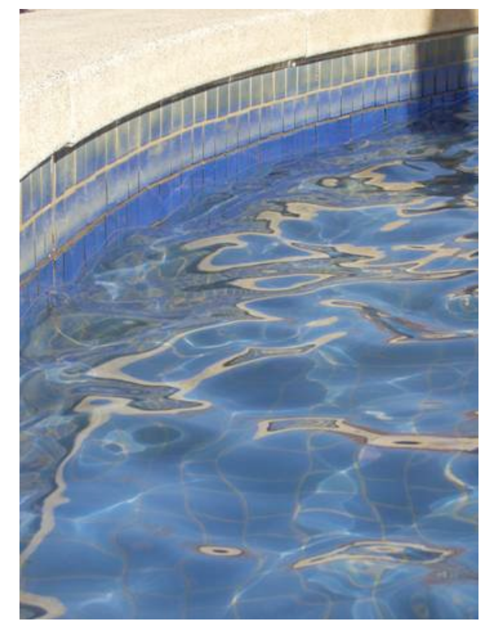
PLANETARY SURFACE



CG RENDERING

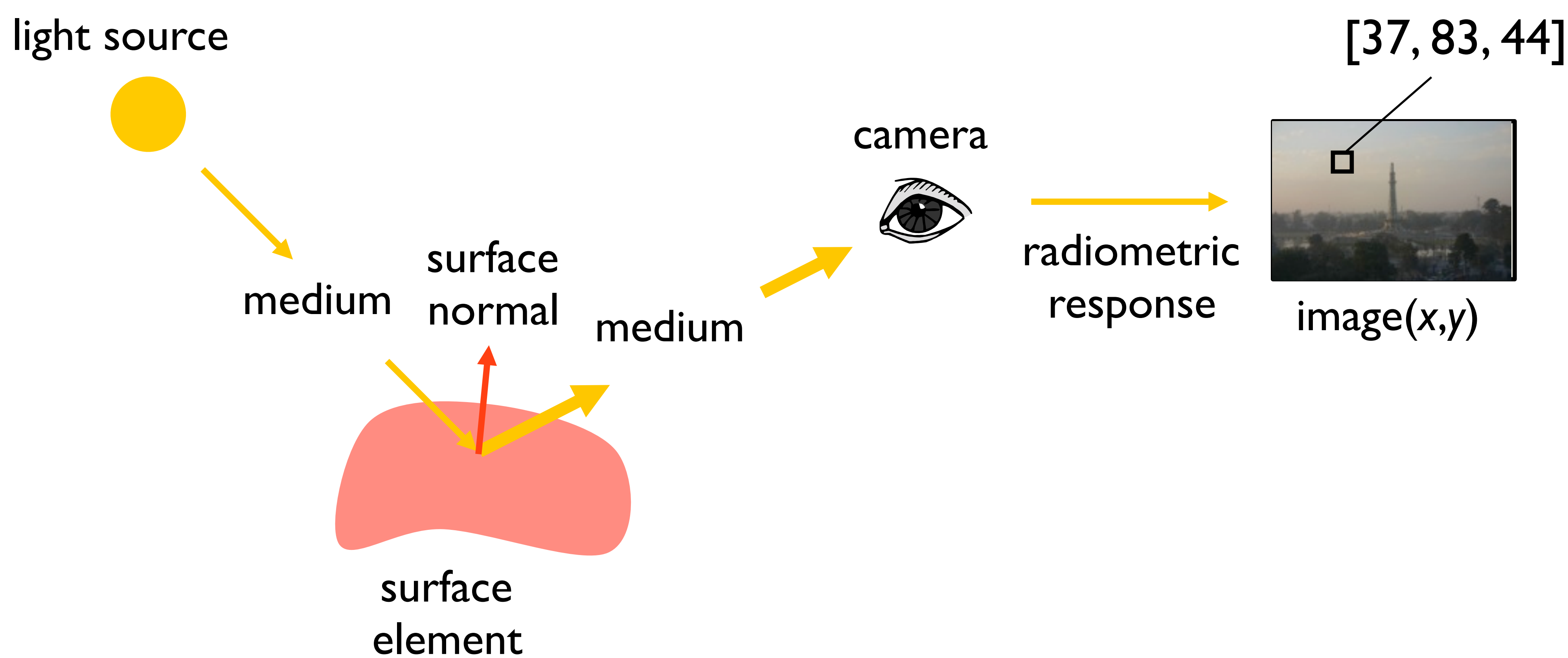
CLAY

EXAMPLES OF NON-LAMBERTIAN SURFACES?



Shiny, specular, fluorescent, interreflective, refractive, transparent...

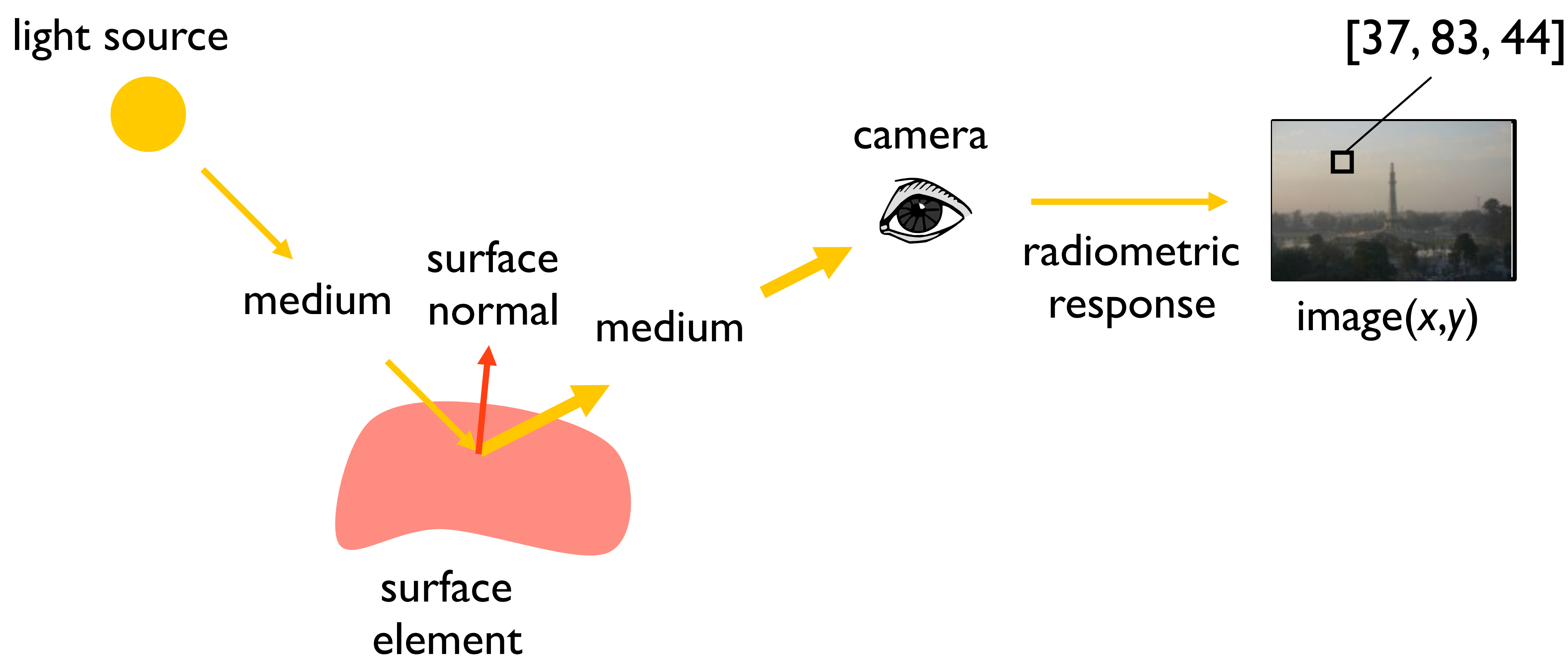
SURFACE RADIANCE TO IMAGE IRRADIANCE



Medium assumed to be perfect again.

SURFACE RADIANCE TO IMAGE IRRADIANCE

PINHOLE CASE



$$E_{\text{image}}(p) = L_{\text{surface}}(P) \cdot \text{constant}$$

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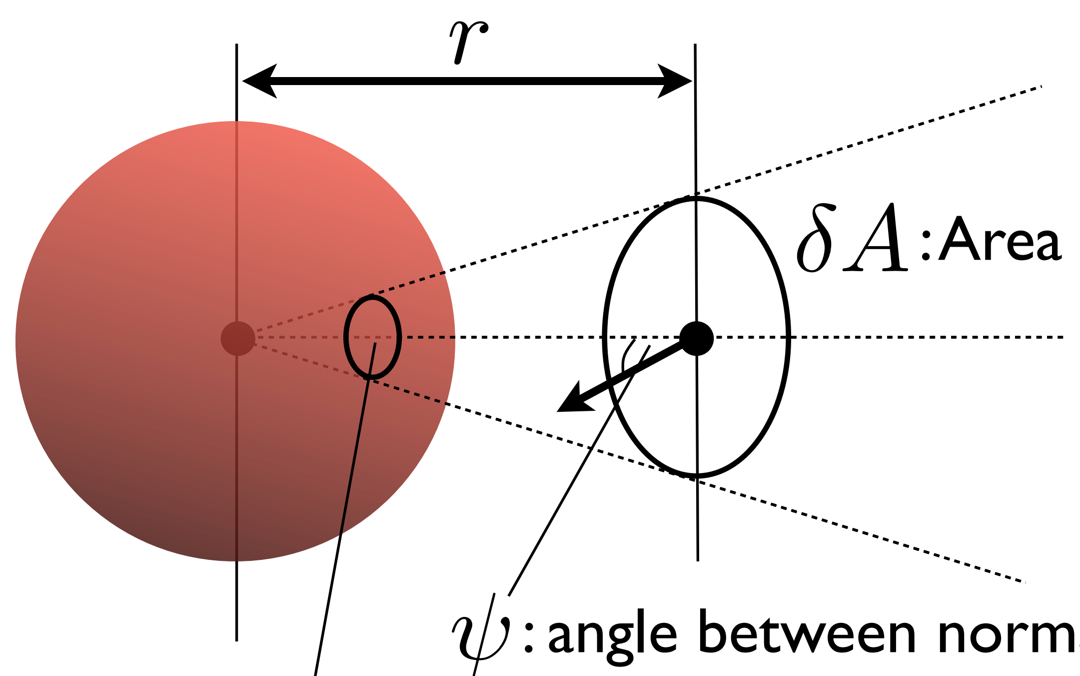
Image Radiance = Surface Reflectance x constant

SOLID ANGLE

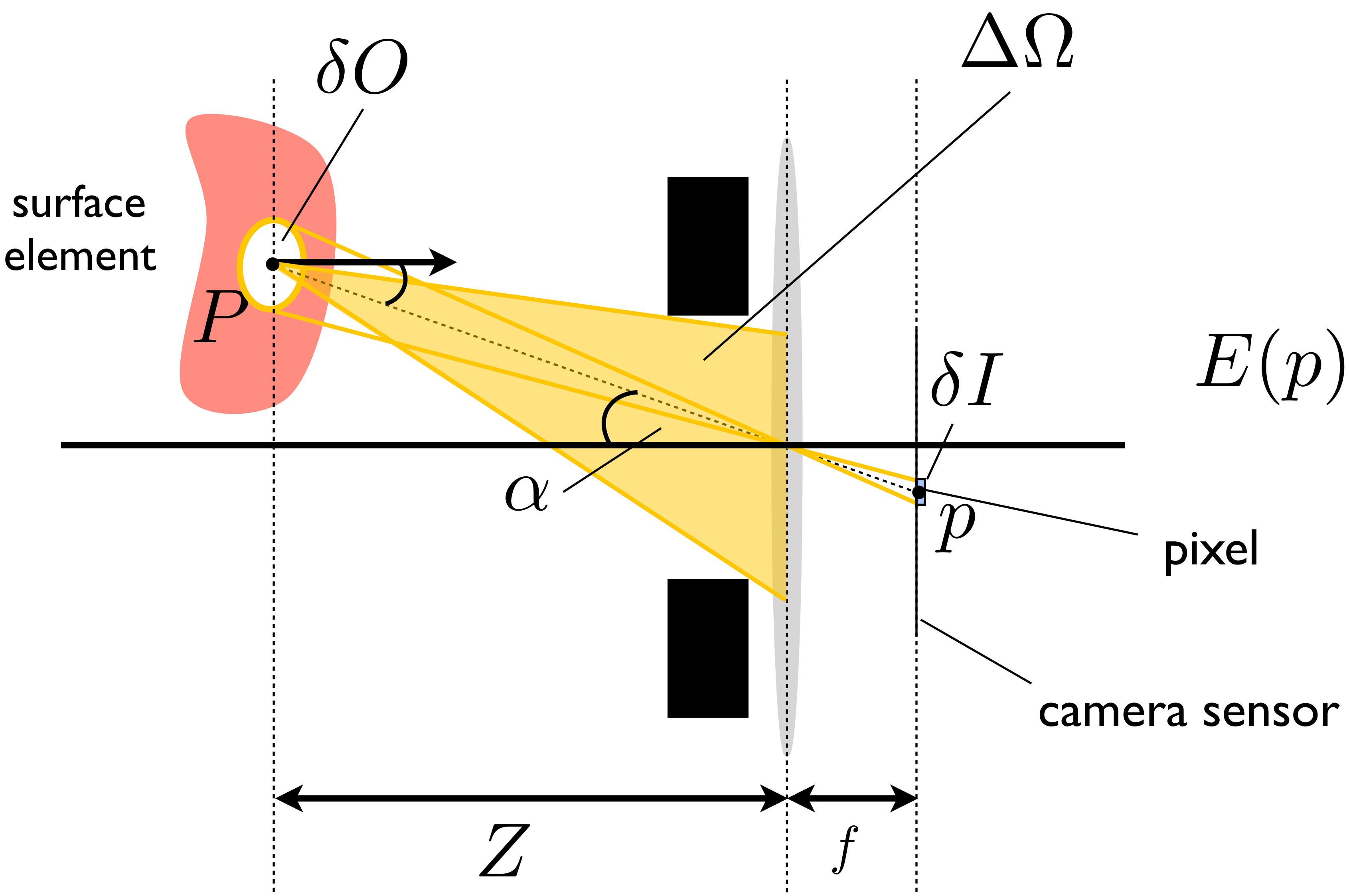


solid angle

$$\delta\omega = \frac{\delta A \cos(\psi)}{r^2}$$

Solid angle!

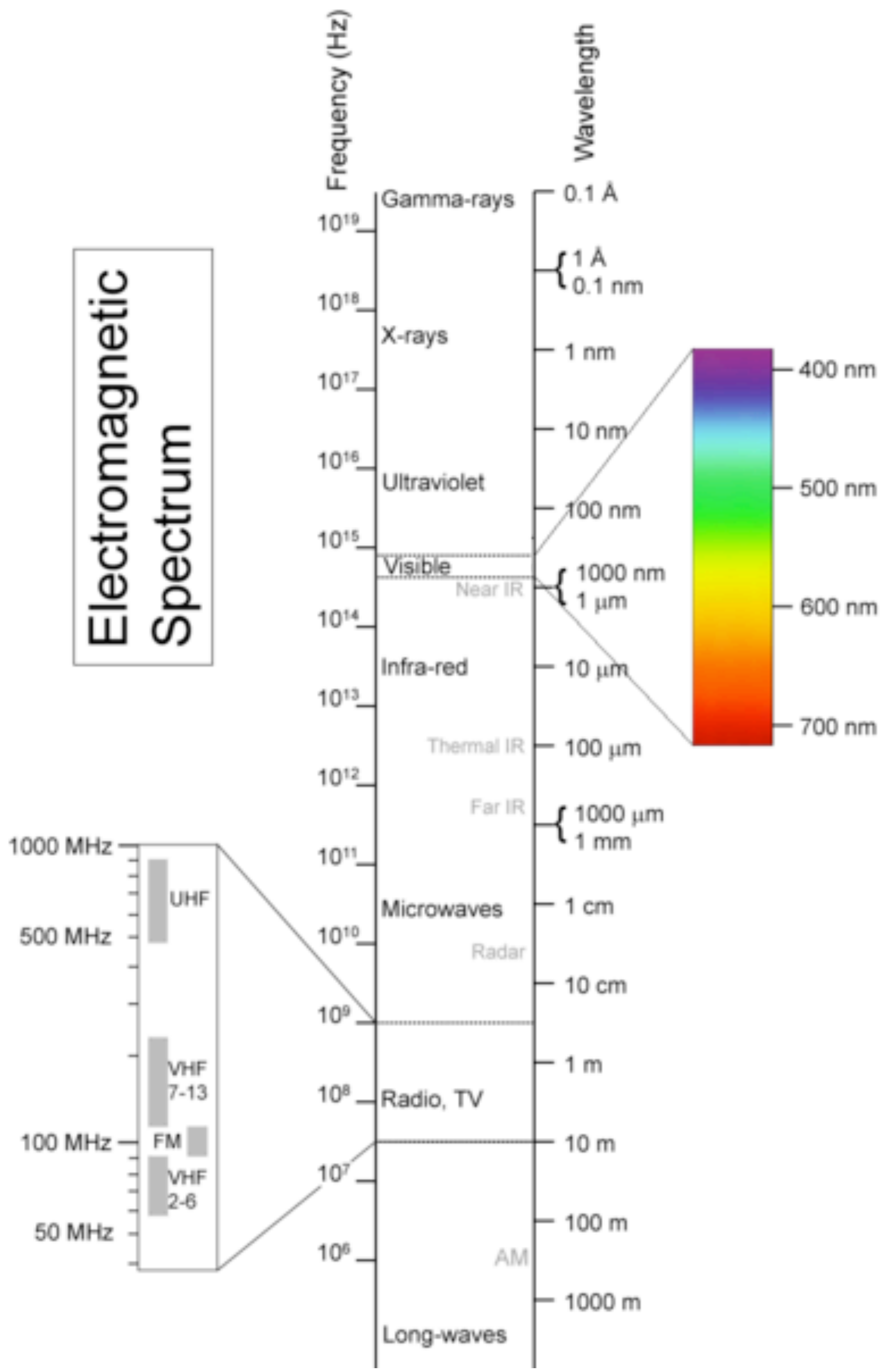
SURFACE RADIANCE TO IMAGE IRRADIANCE



$$E(p) = L(P)\frac{\pi}{4}\frac{d^2}{f^2}\cos^4(\alpha)$$

Solid angle!

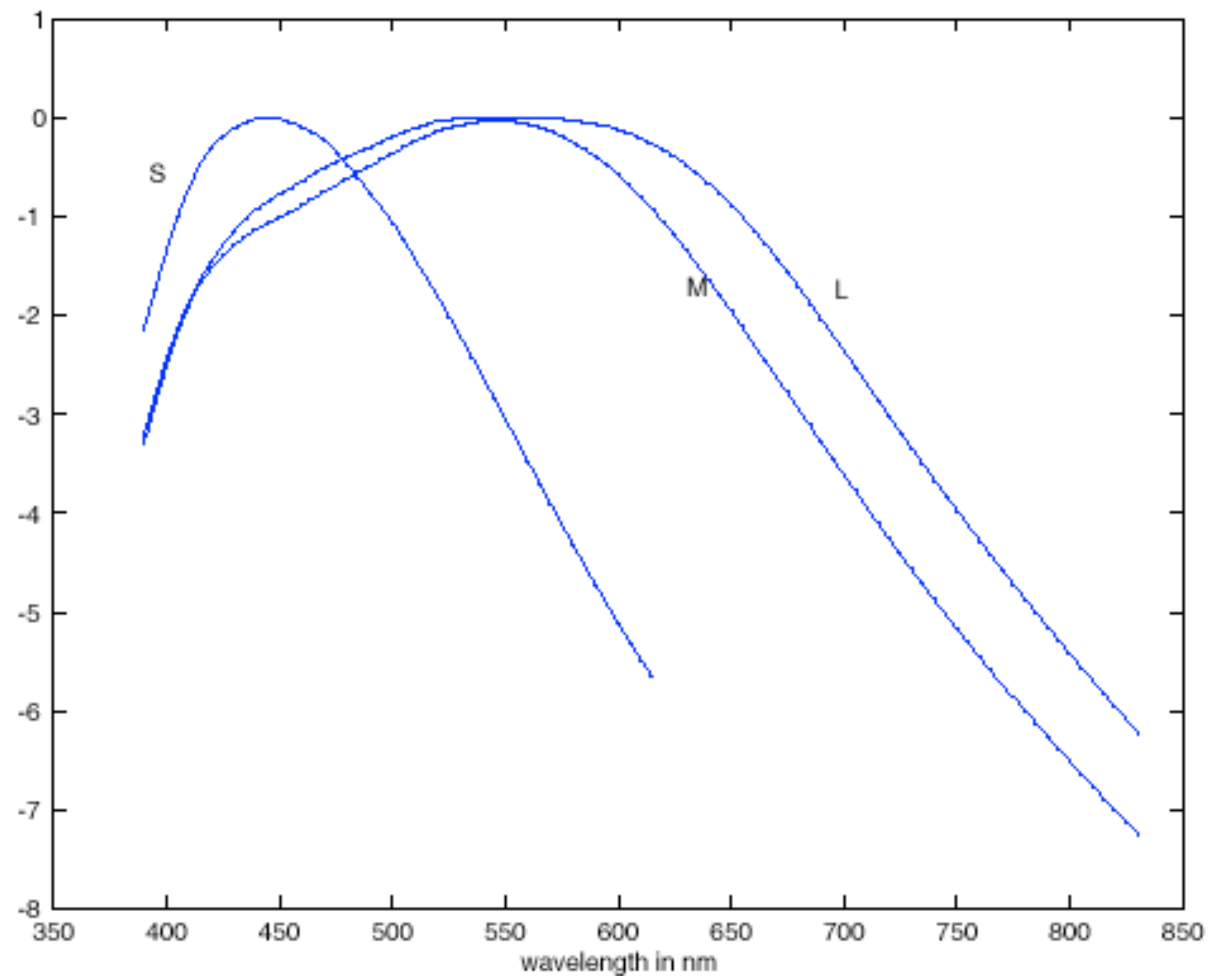
COLOR IMAGING



- DIFFERENT FREQUENCIES CORRESPOND TO DIFFERENT COLORS
- SUN EMITS MOST ENERGY IN THE VISIBLE SPECTRUM

COLOR IMAGING

RECEPTOR SENSITIVITY



$$p_k = \int \sigma_k(\lambda) E_{\mathrm{image}}(\lambda) d\lambda$$

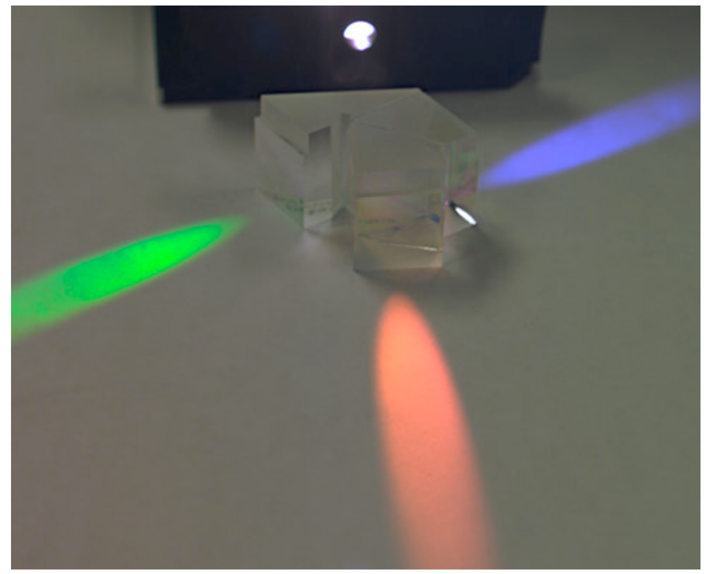
brightness

sensitivity

image irradiance

COLOR IMAGING

CHARGE COUPLED DEVICES

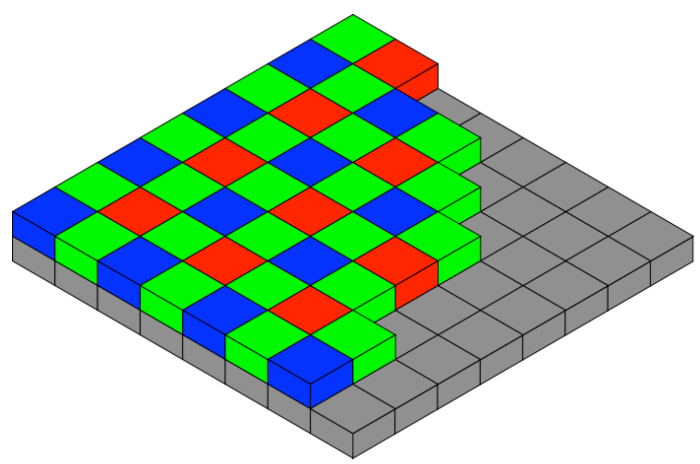


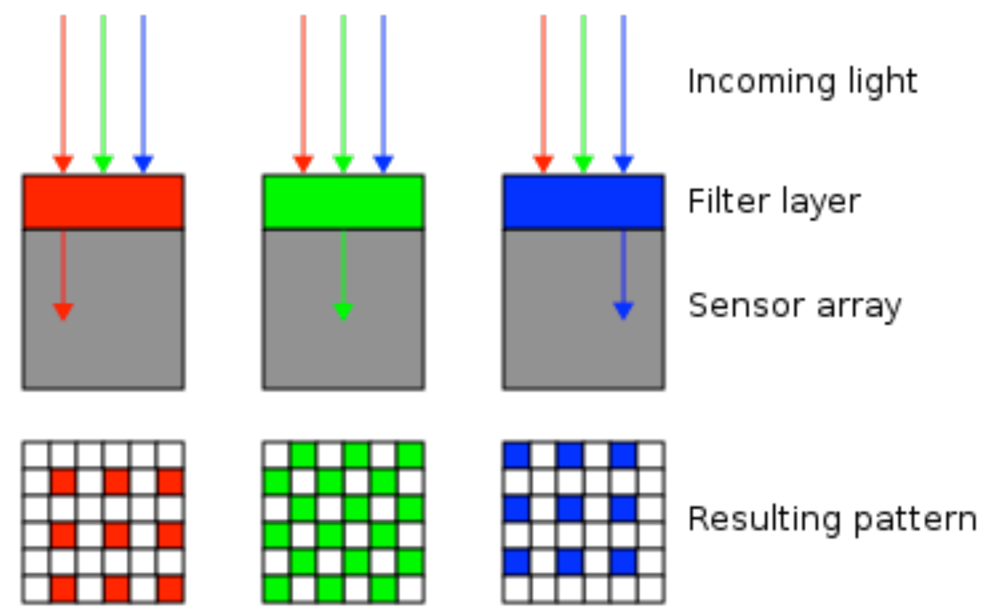
- CCD: IMAGE IRRADIANCE TO INTENSITY
- THREE CCD
  - CORRESPONDING TO RED, GREEN, BLUE FREQUENCIES
- TRICHORIC PRISM ASSEMBLY

CCD: Charge-coupled device
CMOS: Complementary metal-oxide-semiconductor

COLOR IMAGING

CHARGE COUPLED DEVICES





- ONE CCD
  - BAYER FILTER
  - DEMOSAICING

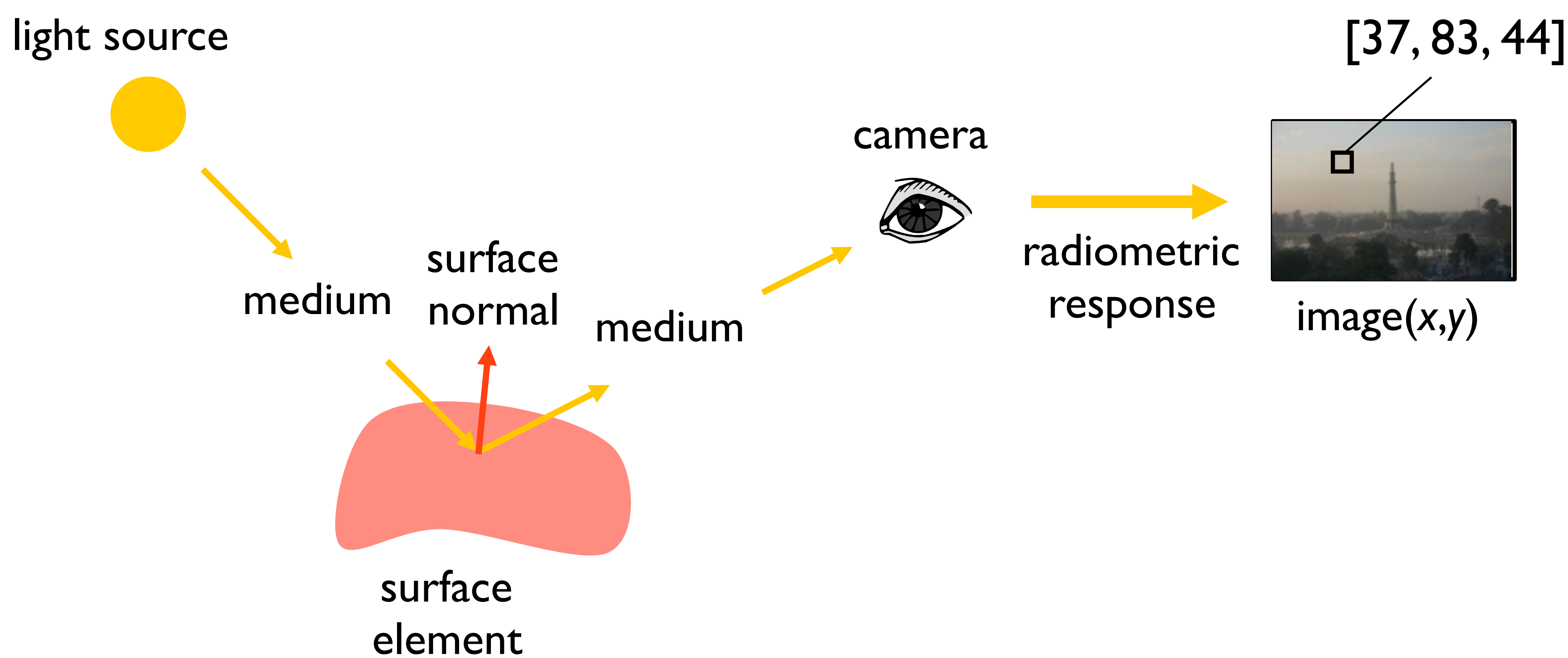
IMAGE SOURCE: WIKIPEDIA

CCD: Charge-coupled device
CMOS: Complementary metal-oxide-semiconductor

SERGEI MIKHAILOVICH PROKUDIN-GORSKII

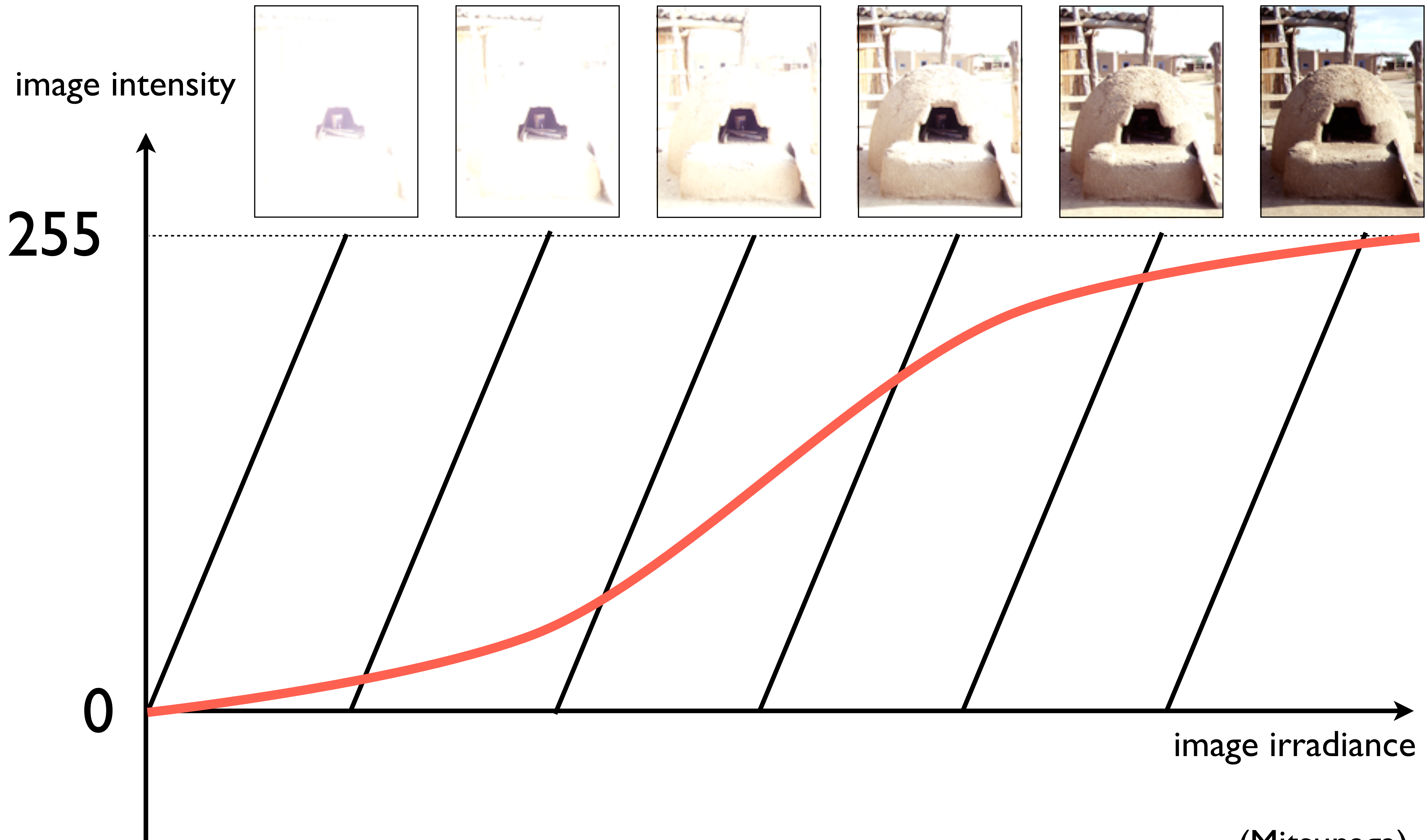
(1911)

SURFACE RADIANCE TO IMAGE IRRADIANCE

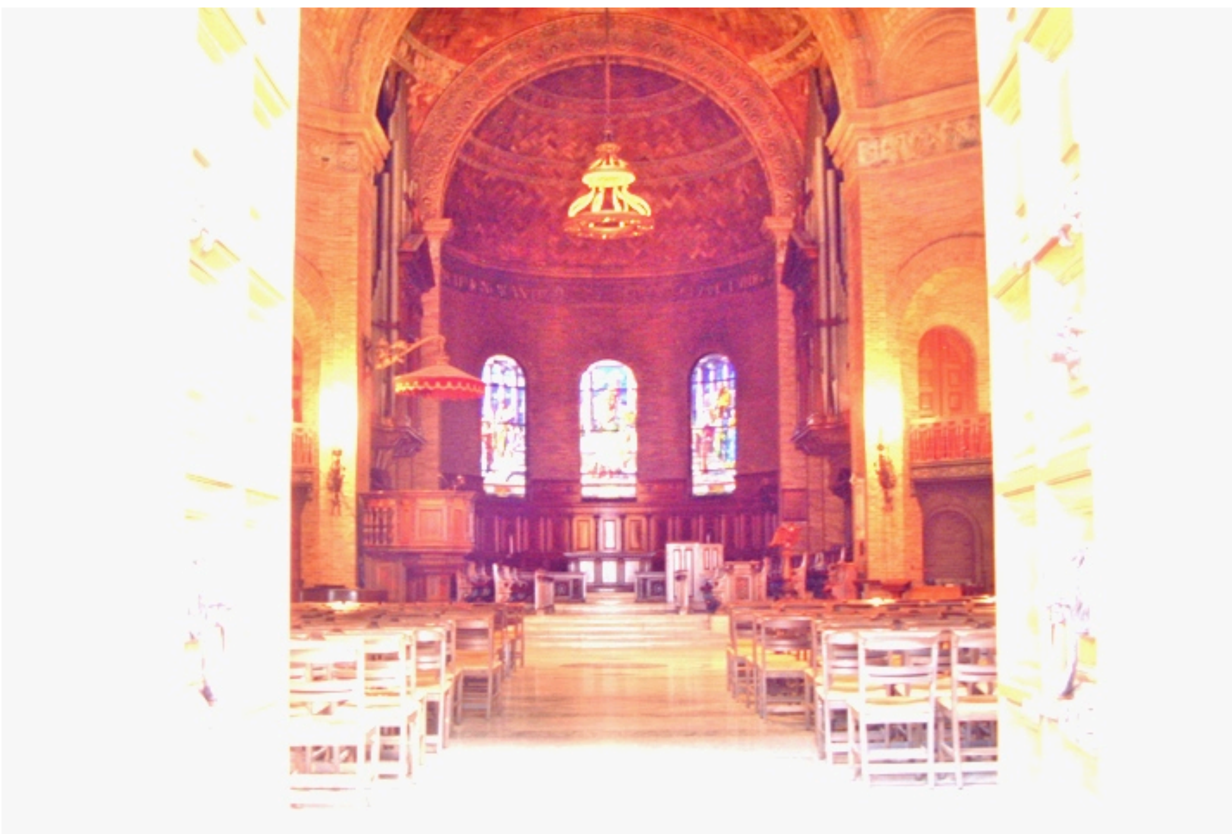
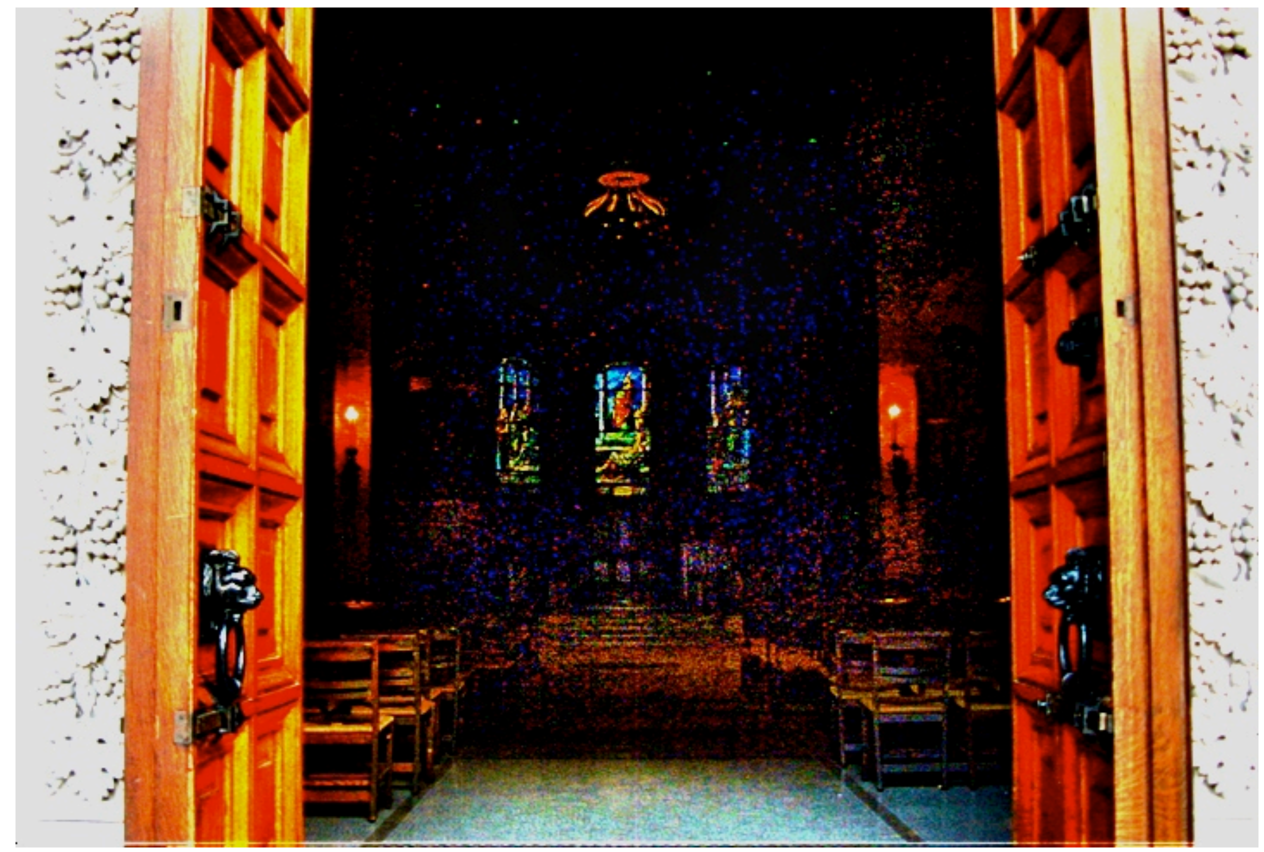


CAMERA RESPONSE

IMAGE IRRADIANCE TO INTENSITY



(Mitsunaga)

RADIOMETRIC RESPONSE

IMAGE IRRADIANCE TO INTENSITY

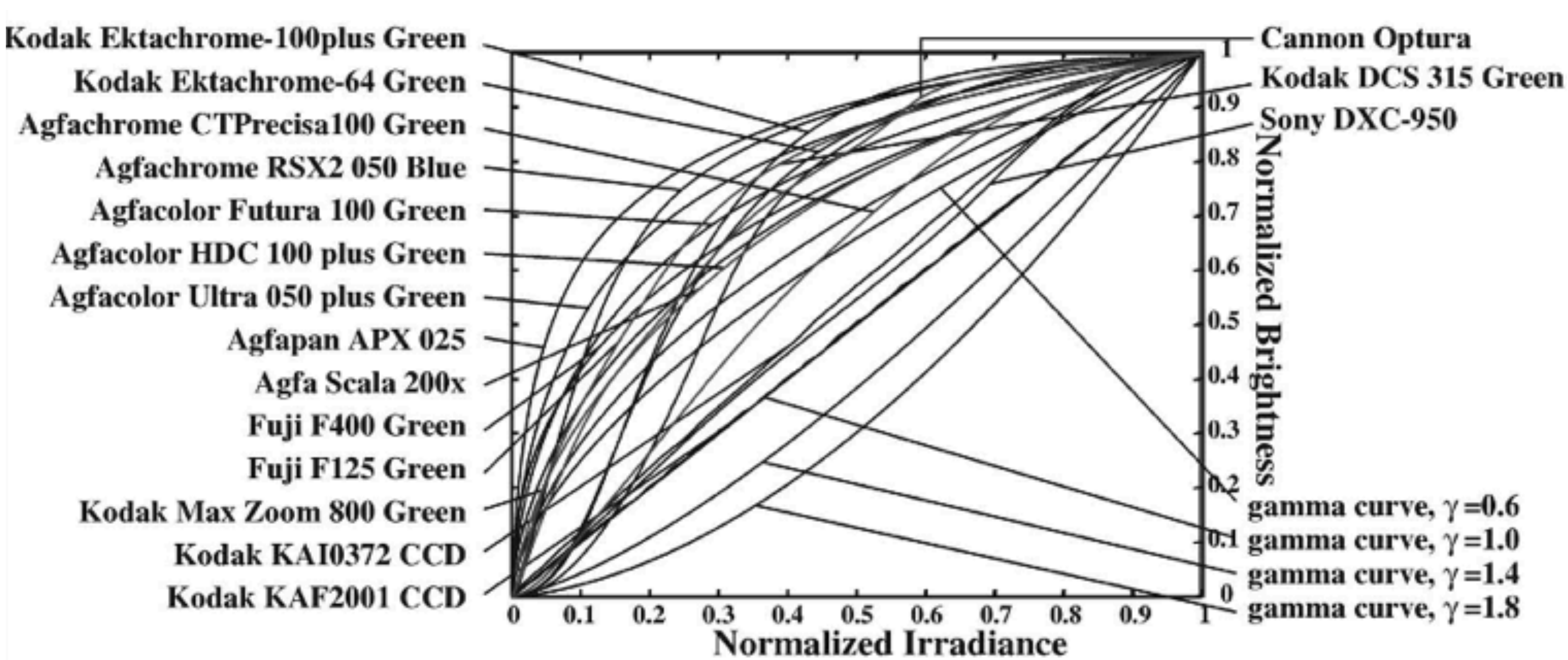


Image source: Grossberg and Nayar, Modeling the Space of Camera Response Functions, TPAMI, 2004

DYNAMIC RANGE

- OFFICE INTERIOR
- INDIRECT LIGHT FROM WINDOW
- 1/60TH SEC SHUTTER
- F/5.6 APERTURE

Based on slides by Paul Debevec

DYNAMIC RANGE

- OUTSIDE IN THE SHADE
- 1/1000TH SEC SHUTTER
- F/5.6 APERTURE
- 16 TIMES AS MUCH LIGHT AS INSIDE

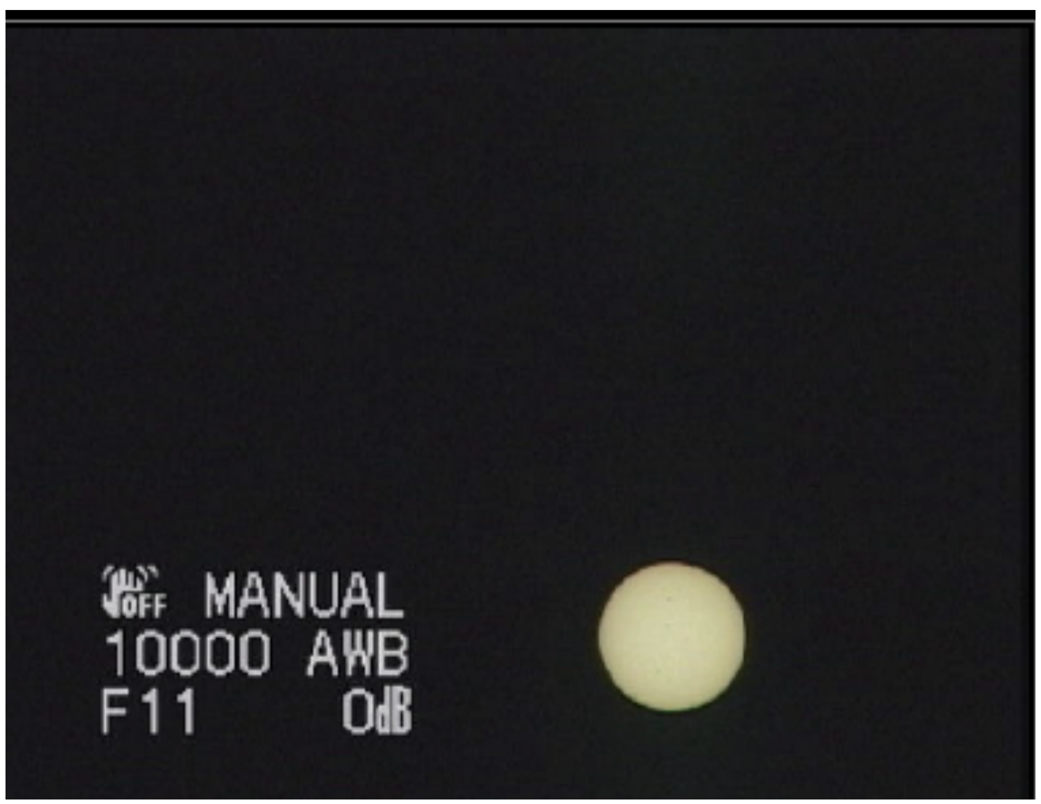
Based on slides by Paul Debevec

DYNAMIC RANGE

- OUTSIDE IN THE SUN
- 1/1000TH SEC SHUTTER
- F/11 APERTURE
- 64 TIMES AS MUCH LIGHT AS INSIDE

Based on slides by Paul Debevec

DYNAMIC RANGE



- STRAIGHT **AT** THE SUN
- 1/10,000TH SEC SHUTTER
- F/11 APERTURE
- 5,000,000 TIMES AS MUCH LIGHT AS INSIDE

Based on slides by Paul Debevec

DYNAMIC RANGE

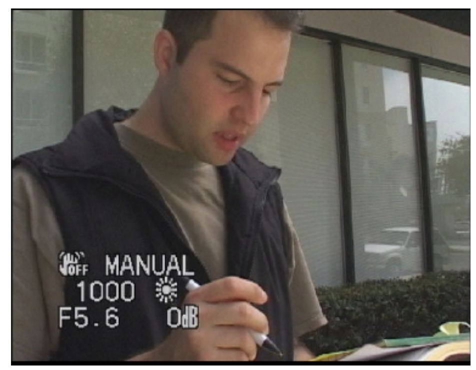
- VERY DIM ROOM
- 1/4TH SEC SHUTTER
- F/1.6 APERTURE
- 1/1500TH THE LIGHT AS INSIDE

Based on slides by Paul Debevec

HIGH DYNAMIC RANGE

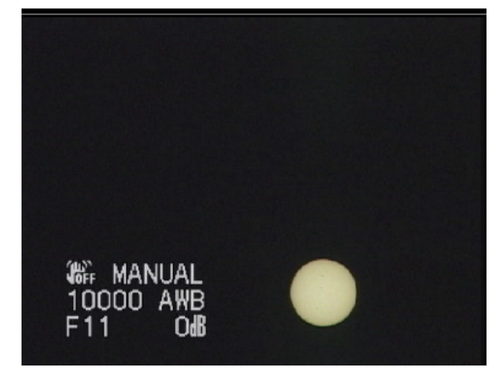
1

1500



25,000

400,000

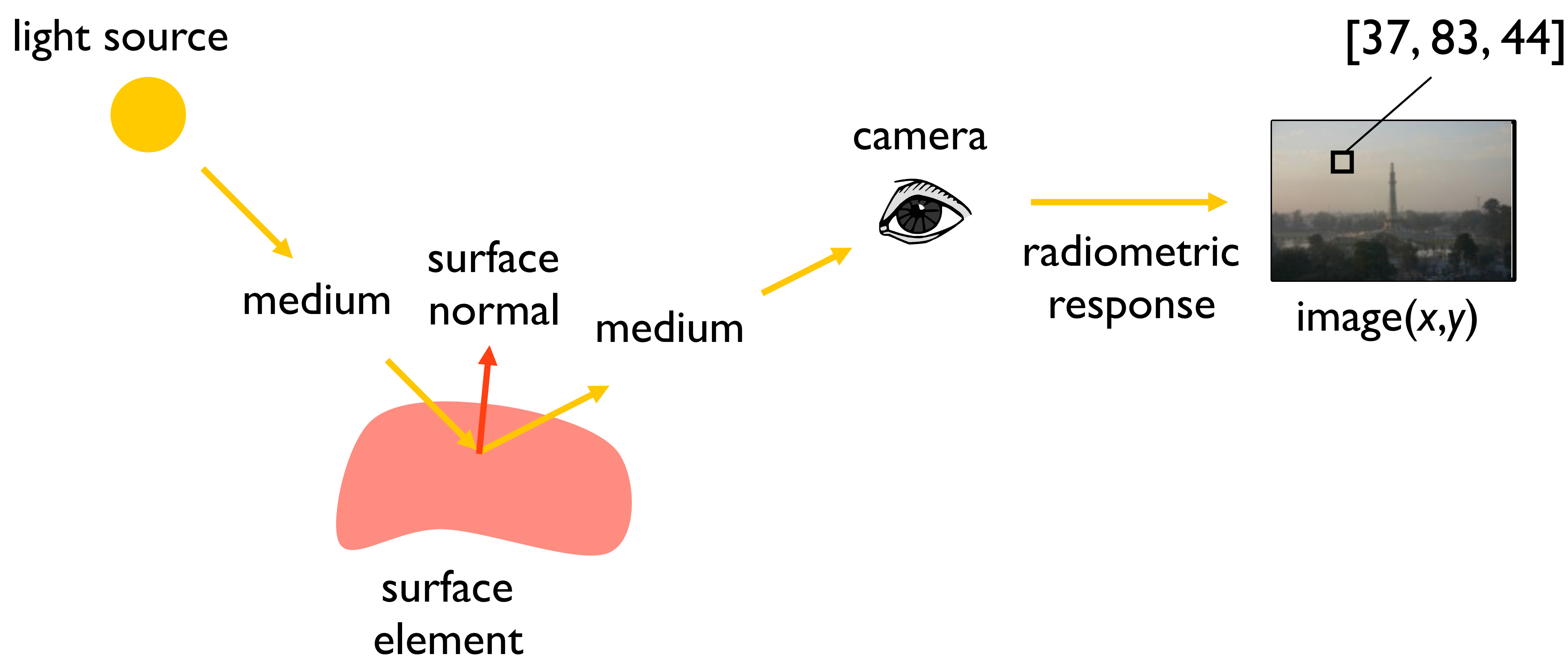


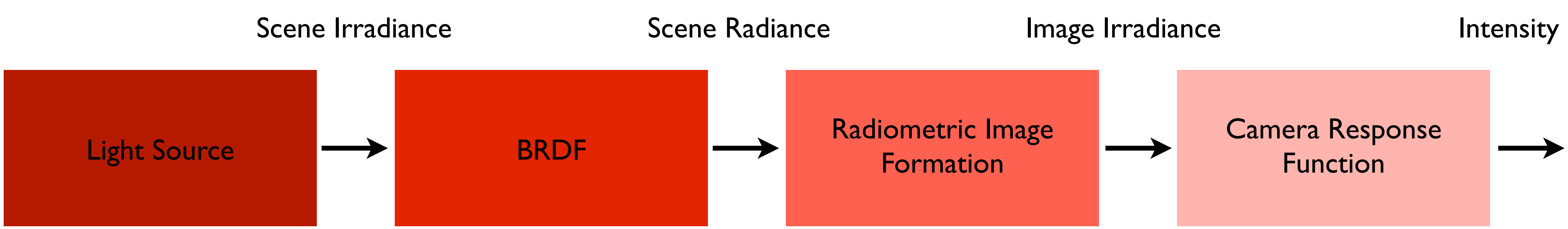
2,000,000,000

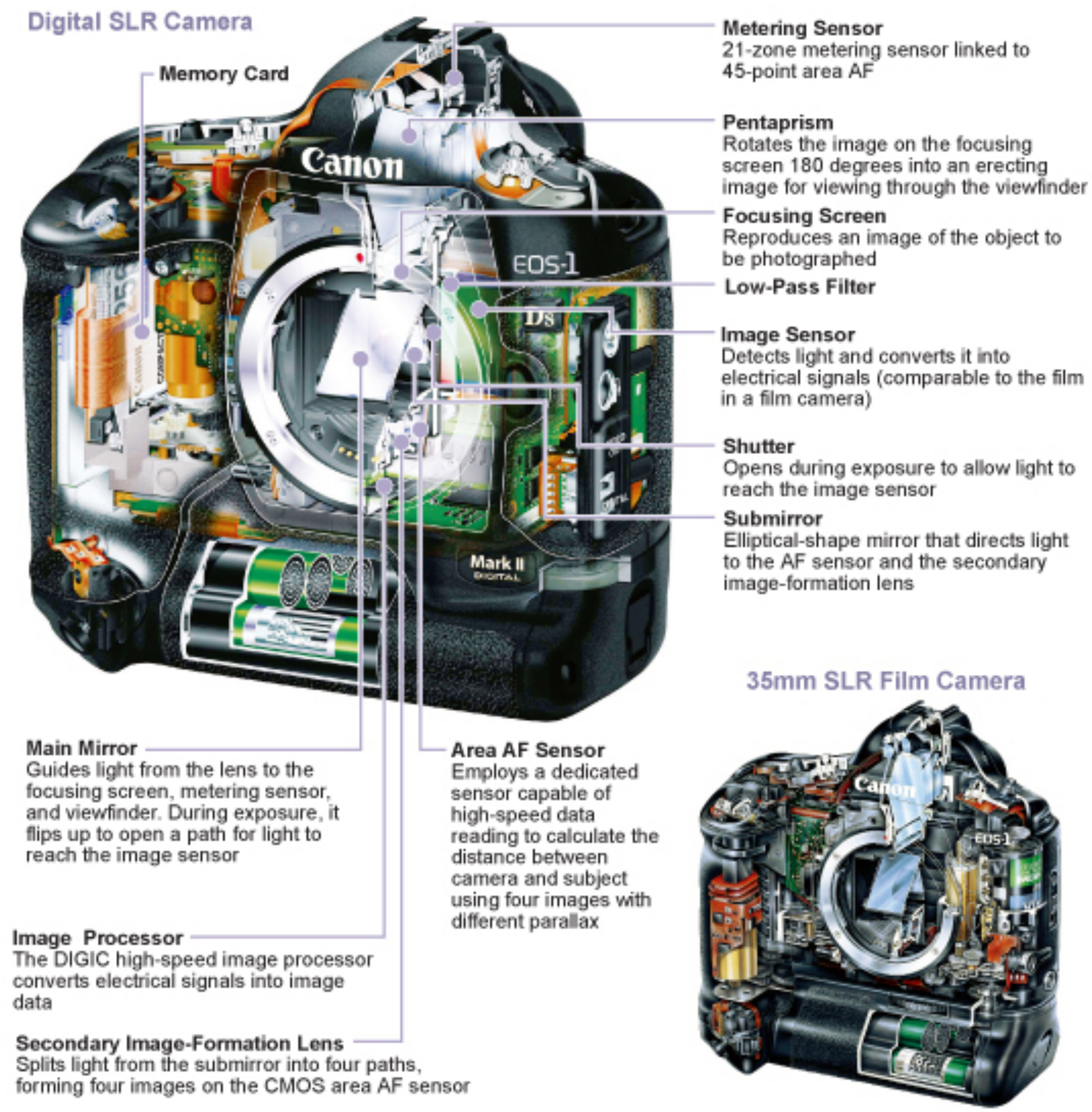
Based on slides by Paul Debevec

RADIOMETRY

LIGHT TRANSPORT






Digital SLR Camera
Memory Card
Metering Sensor
21-zone metering sensor linked to 45-point area AF
Pentaprism
Rotates the image on the focusing screen 180 degrees into an erecting image for viewing through the viewfinder
Focusing Screen
Reproduces an image of the object to be photographed
Low-Pass Filter
Image Sensor
Detects light and converts it into electrical signals (comparable to the film in a film camera)
Shutter
Opens during exposure to allow light to reach the image sensor
Submirror
Elliptical-shape mirror that directs light to the AF sensor and the secondary image-formation lens
Main Mirror
Guides light from the lens to the focusing screen, metering sensor, and viewfinder. During exposure, it flips up to open a path for light to reach the image sensor
Area AF Sensor
Employs a dedicated sensor capable of high-speed data reading to calculate the distance between camera and subject using four images with different parallax
Image Processor
The DIGIC high-speed image processor converts electrical signals into image data
Secondary Image-Formation Lens
Splits light from the submirror into four paths, forming four images on the CMOS area AF sensor
35mm SLR Film Camera

Canon.com

NEXT LECTURE

GEOMETRY