HDR Imaging Introduction

dr. Francesco Banterle

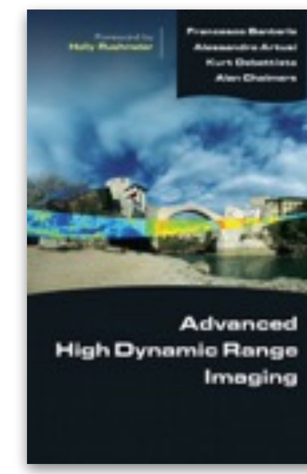
francesco.banterle@isti.cnr.it

Who I am

2004 | 2007 | 2007 | 2009 | 2010

Reference material

- “High Dynamic Range Imaging”, Reinhard et al. 2010, Morgan Kaufmann
- “Advanced High Dynamic Range Imaging”, Banterle et al. 2011, CRC press
- “High Dynamic Range Imaging”, Mantiuk et al. 2015, Wiley (free):
    - http://pages.bangor.ac.uk/~eesa0c/pdfs/mantiuk15hdri.pdf
- “Inverse Tone Mapping” (Chapter 1 and 2) Banterle 2009 (free):
    - http://wrap.warwick.ac.uk/55447/



Exam

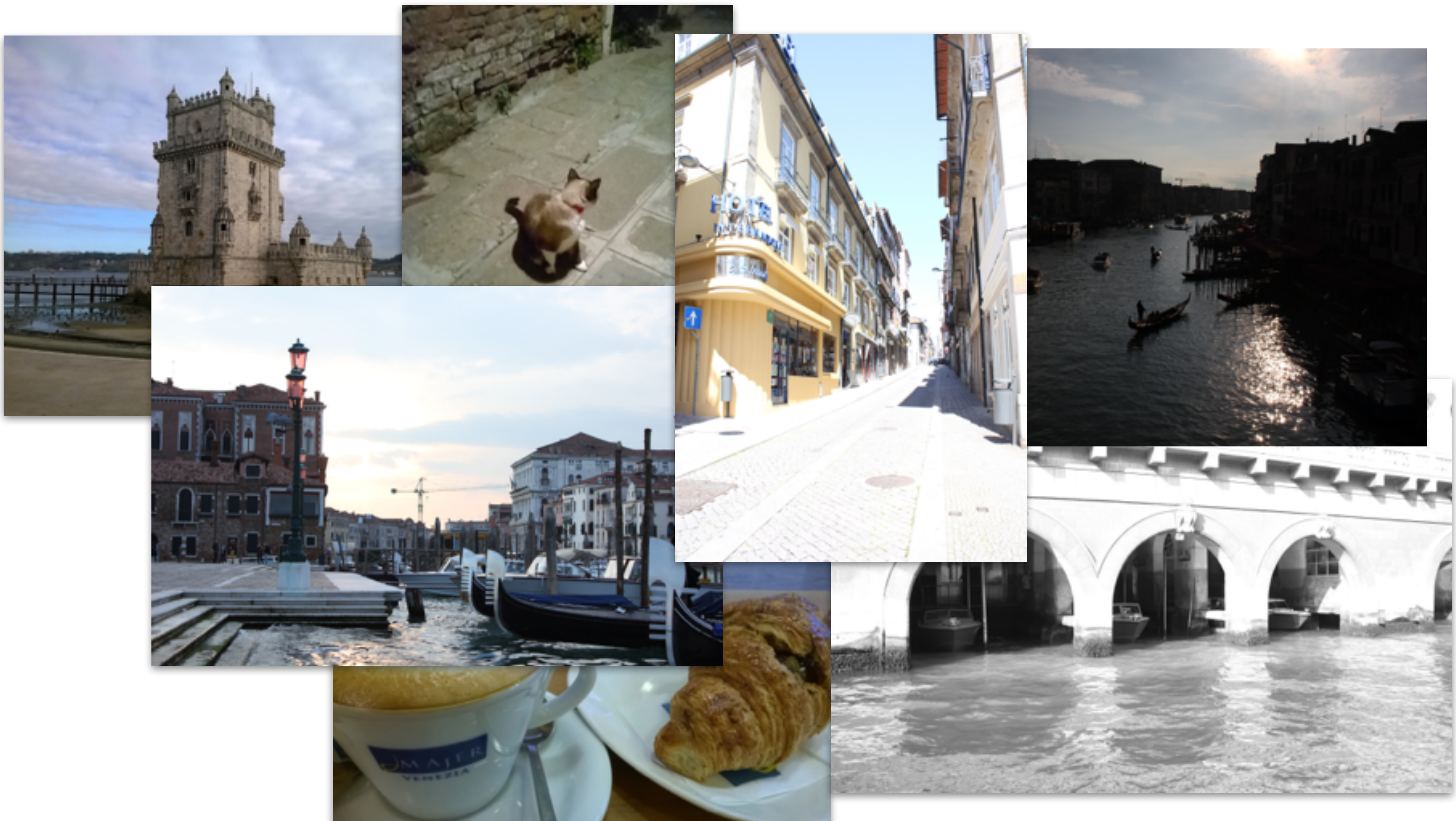
- Writing an essay on a topic from a few papers
- Programming project:
  - MATLAB extending HDR Toolbox + report
  - C++ extending Piccante + report

and now we start…

Photography

- There are imaging sensors everywhere:
  - Mobile phones
  - Point-and-shoot
  - DSLR
  - Drones

Photography



Photography

facebook

Pinterest

Instagram

flickr

The New York Times

BBC NEWS

NATIONAL GEOGRAPHIC

Photography

- I bought a reflex, nice, am I a photographer?

MISSING

Henri Cartier-Bresson

MISSING

Rome

Photography

- I bought a reflex, nice, am I a photographer?
    - I have some doubts…

Photography

- I bought a reflex, nice, am I a photographer?
  - I have some doubts…

Photography

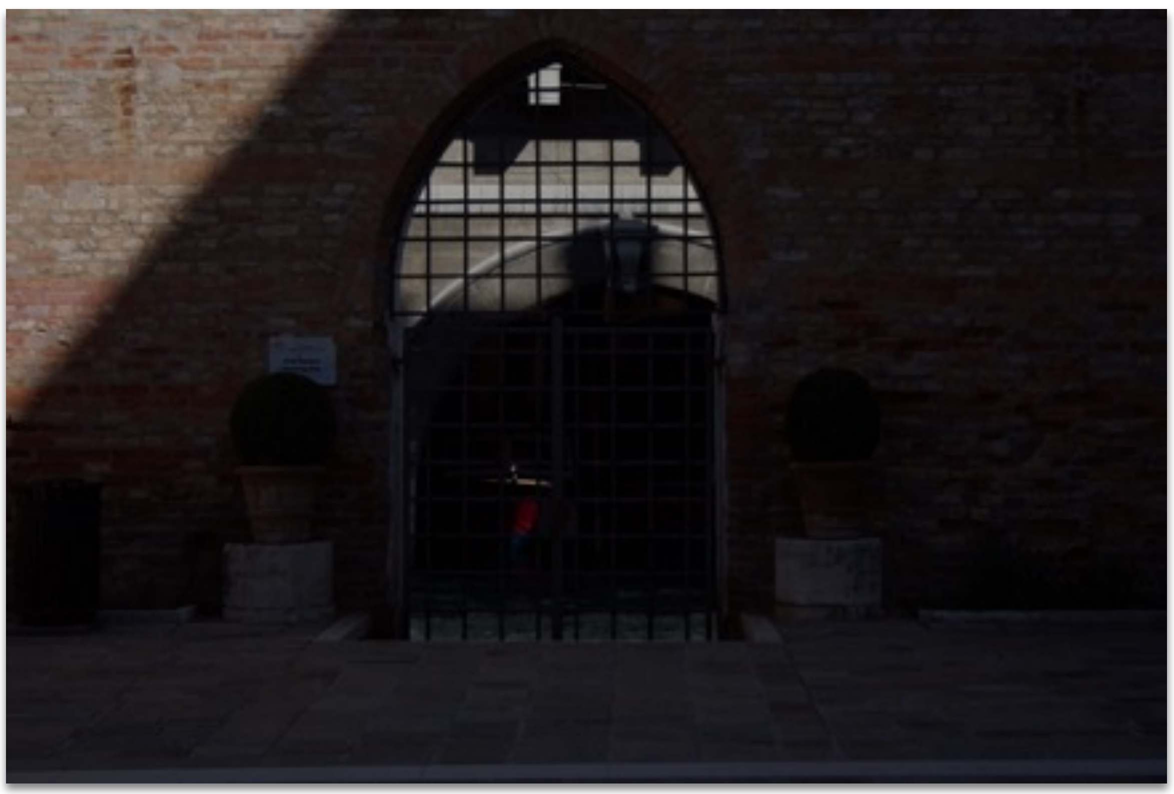
- How do I become a photographer?
  - Knowledge of the scene structure/geometry
  - Knowledge of my gear
  - Knowledge of light
  - It takes ages….

Photography

- How do I become a photographer?
  - Knowledge of the scene structure/geometry
  - Knowledge of my gear
  - Knowledge of light
  - It takes ages….

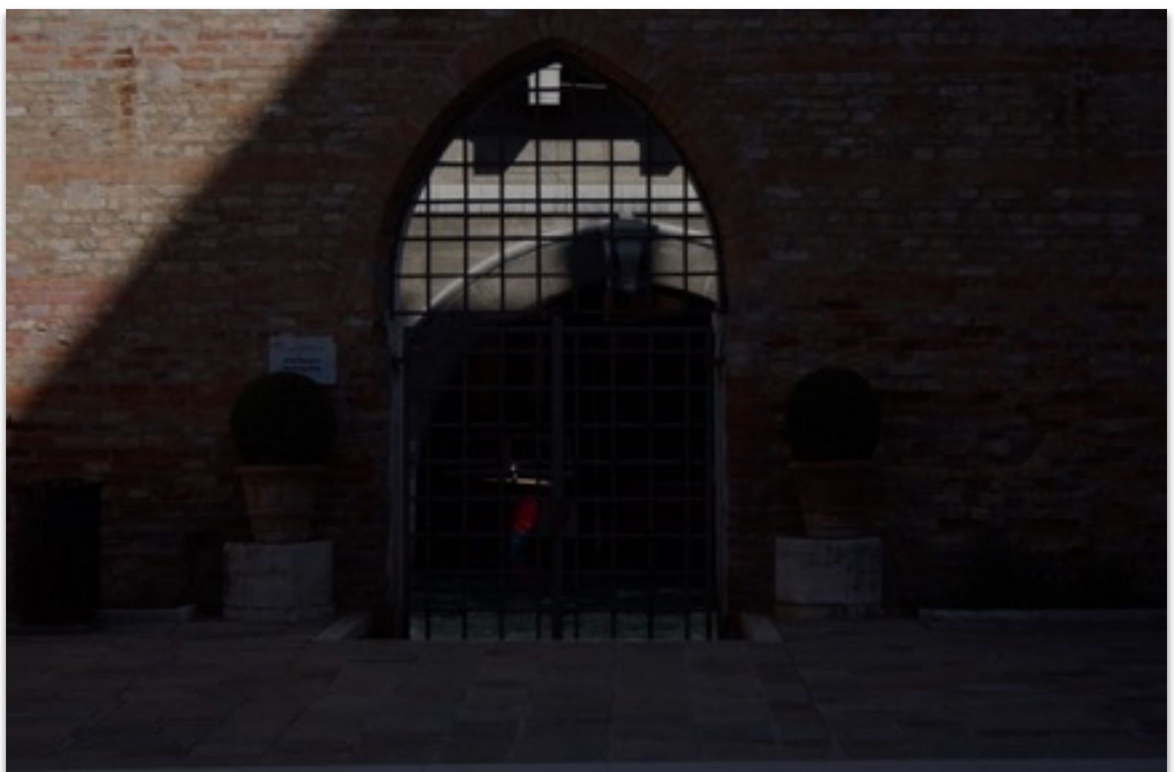
Exposure time

Exposure time



under-exposed

Exposure time



under-exposed

over-exposed

Exposure time

Ca’ Foscari, Venezia

All exposures

MISSING

Gustave Le Gray

MISSING

Bring upon the water

The Film

MISSING

32 more intensities
levels of paper

The Film

MISSING

Ansel Adams

MISSING

The Tetons and the Snake River

Digital Photography

Lies of Digital Photography

- Manufacturer racing on reaching more pixel rather than “better pixel”
- 8-bit for each color channel:
  - red, green, and blue
  - Total 24-bit —> 16M colors
- Are 16M colors a lot?
  - Not really, we are missing a key point: intensities!

Lies of Digital Photography

- A digital camera can capture only 8-bit; more or less 256:1
    - Three more intensities than paper
- The human visual system (HVS) can:
    - perceive 10,000:1 at the same time
    - perceive 1,000,000:1 in total with adaptation

High Dynamic Range Imaging

- To extend the range (high) that can be captured in a scene of current digital cameras
- To match what can the HVS can perceive and beyond:
  - Picard and Mann 1995
  - Debevec and Malik 1997

High Dynamic Range Imaging

- How?
  - As Le Gray achieved it:
    - more photographs of the same scene
    - combine these photographs in a single one

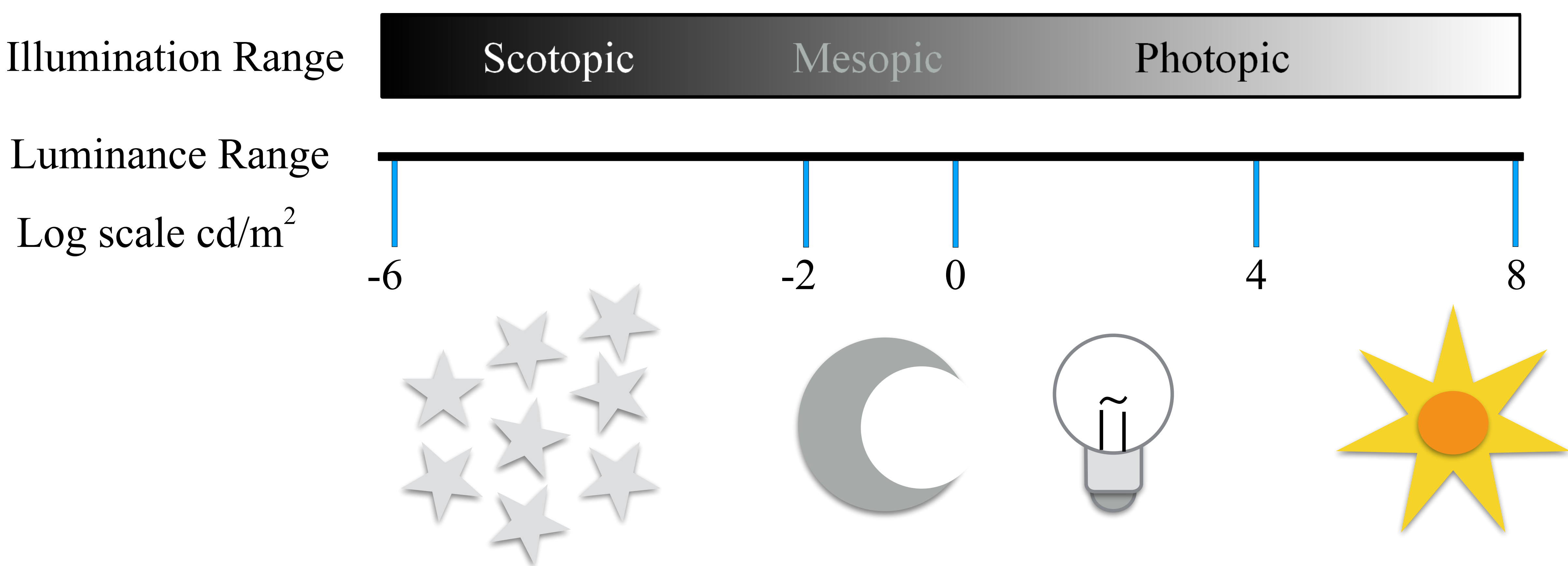
High Dynamic Range Imaging

High Dynamic Range Imaging

High Dynamic Range Imaging

High Dynamic Range Imaging

What can we see?



High Dynamic Range Imaging

- HDR technology allows to
    - capture all intensities in a real-world scene
    - compress them in an efficient way
    - manipulate them
    - visualize them on different displaying technologies

HDR Imaging: what do we need to know?

- We need to know:
  - what we are measuring
  - what color spaces are
  - how a display works
  - how a camera roughly works

a now, something completely different…

A bit of Radiometry

- Radiometry is the science of "measuring light"
- Light is radiant energy (Q):
  - measured in Joules (J)
- The flow of radiant energy, Radiant Power (P):
  - measured in Watt (W = J/s)

Irradiance

- Power incident upon unit area dA:

Definition	**Unit**
$E = \frac{dP}{dA}$	$\mathrm{W/m^2}$

Irradiance

- Power incident upon unit area dA:

Definition	**Unit**
$E = \frac{dP}{dA}$	$\mathrm{W/m^2}$

Irradiance

- Power incident upon unit area dA:

Definition	**Unit**
$E = \frac{dP}{dA}$	$\mathrm{W/m^2}$

Radiance

- Power incident on a unit surface area dA from a unit set of directions dω

Definition	**Unit**
$L = \dfrac{d^2 P}{dA \cos\theta d\omega}$	$\mathrm{W/m^2/sr}$

Radiance

- Power incident on a unit surface area dA from a unit set of directions dω

Definition	**Unit**
$L = \dfrac{d^2 P}{dA \cos\theta d\omega}$	$\mathrm{W/m^2/sr}$

Radiance

- Power incident on a unit surface area dA from a unit set of directions dω

Definition **Unit**

$$L = \frac{d^2 P}{dA \cos\theta d\omega} \qquad \mathrm{W/m^2/sr}$$

Radiance

- Power incident on a unit surface area dA from a unit set of directions dω

Definition	**Unit**
$L = \frac{d^2 P}{dA \cos\theta d\omega}$	$\mathrm{W/m^2/sr}$

Radiant Exitance

- Power emitted emitted per unit area

Definition	**Unit**
$M = \frac{dP}{dA}$	$\mathrm{W/m^2}$

Radiant Exitance

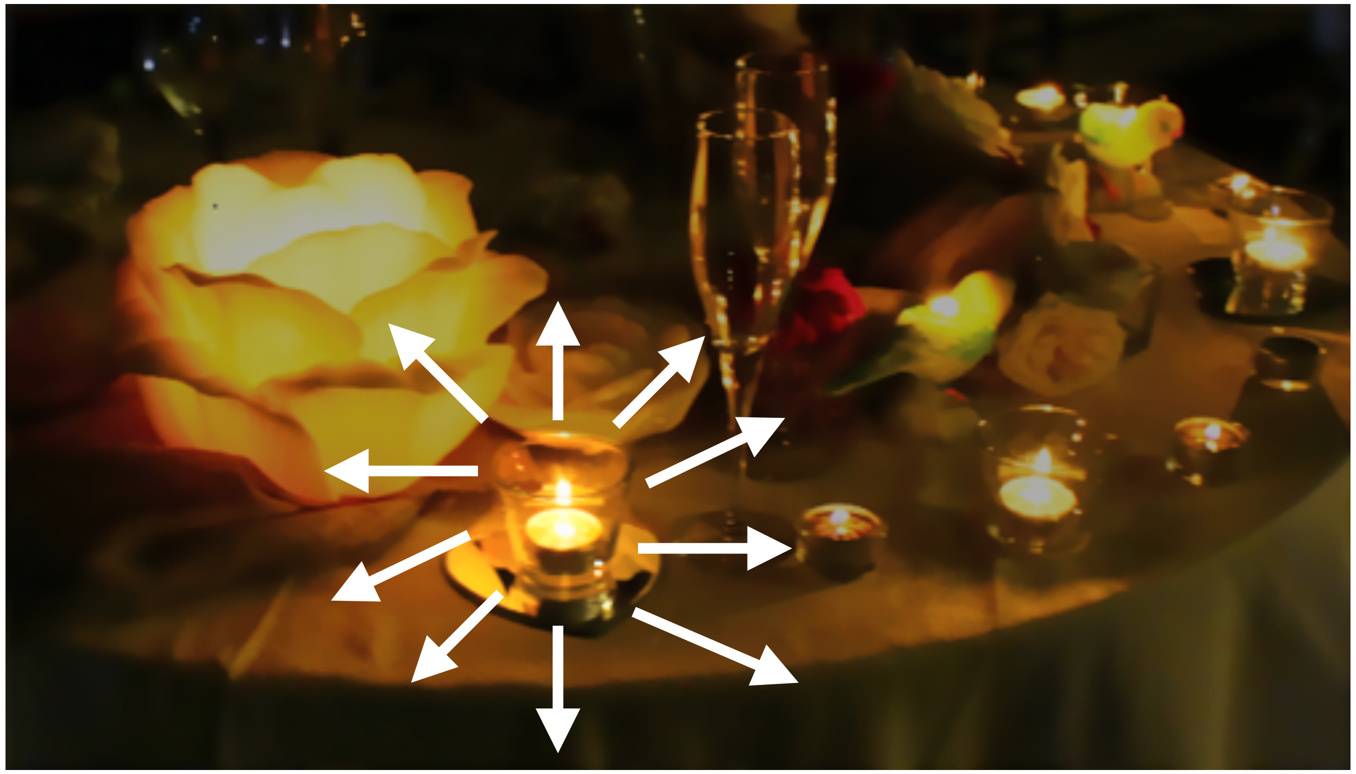
- Power emitted emitted per unit area

Definition	**Unit**
$M = \dfrac{dP}{dA}$	$\mathrm{W/m^2}$

Radiant Exitance

- Power emitted emitted per unit area

Definition	**Unit**
$M = \frac{dP}{dA}$	$\mathrm{W/m^2}$



Radiant Intensity

- Power per solid angle dω

Definition	**Unit**
$I = \frac{dP}{d\omega}$	$\mathrm{W/sr}$

Radiant Intensity

- Power per solid angle dω

Definition	Unit
$I = \frac{dP}{d\omega}$	$\mathrm{W/sr}$

Radiant Intensity

- Power per solid angle dω

Definition	Unit
$I = \frac{dP}{d\omega}$	$\mathrm{W/sr}$

Radiant Intensity

- Power per solid angle dω

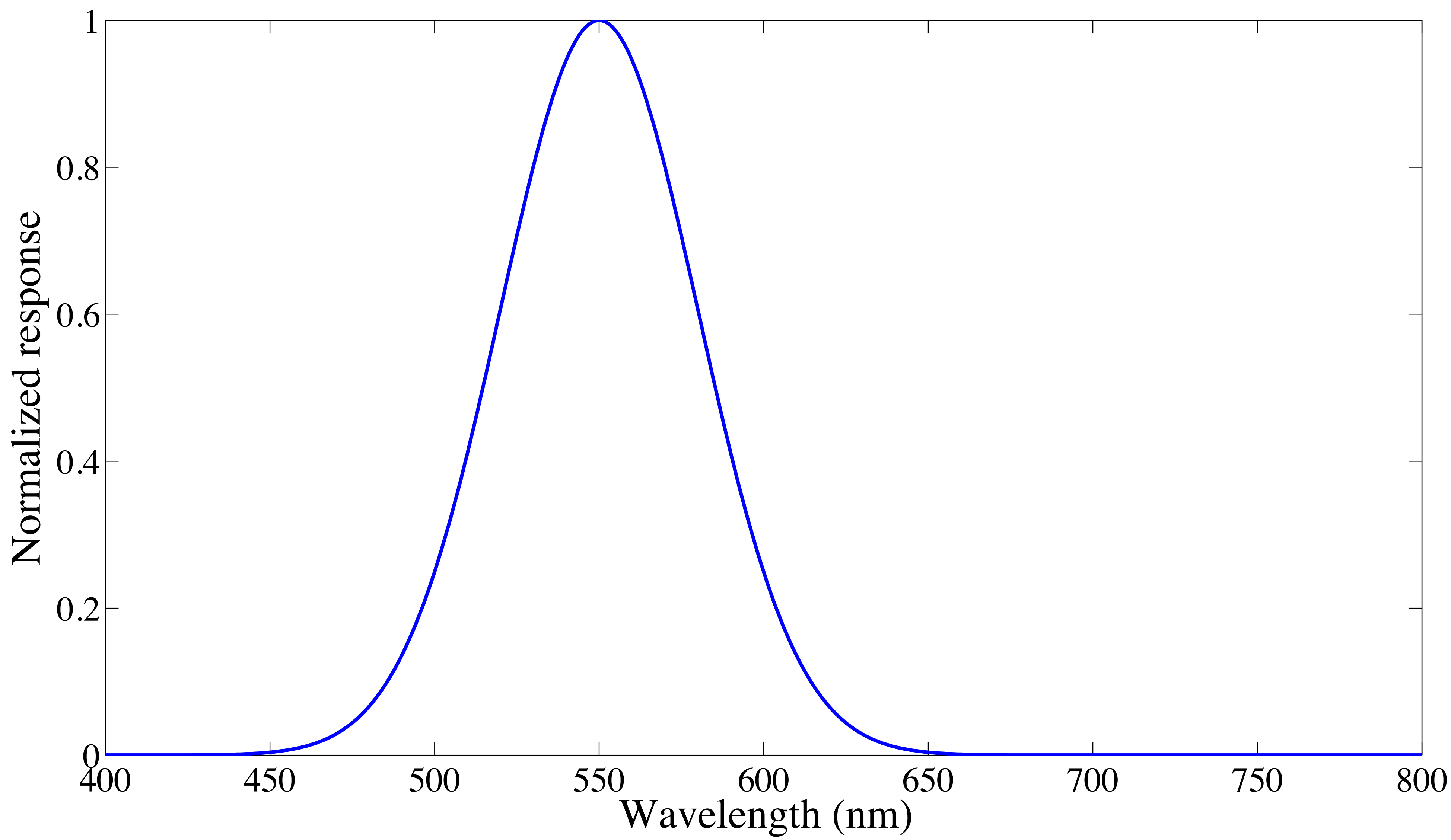
Definition	**Unit**
$I = \frac{dP}{d\omega}$	$\mathrm{W/sr}$

A bit of Photometry

- It is basically Radiometry taking into account the human eye response at different wavelength
- V(λ) is the spectral sensitivity curve proposed by the Commission Internationale de l'Eclairage (CIE)
- Basically, each quantity is weighted V(λ):

$$L_v = \int_{380}^{830} L_e(\lambda) V(\lambda) d\lambda$$

Photometry



CIE standard observer photopic luminous efficiency curve

A bit of Photometry

- All previous radiometry terms have photometry counterparts:
  - Radiant Power —> Luminous Power (P_v) [lm] (lumen)
  - Radiant Energy —> Luminous Energy (Q_v) [lm s]
  - Radiant Exitance —> Radiant Exitance (M_v) [lm/m2]
  - Irradiance —> Illuminance (E_v) [lm/m2]
  - Radiant Intensity —> Luminous Intensity (I_v) [lm/sr] = cd (candela)
  - Radiance —> Luminance (L_v) [cd/m2] = Nit

Notes on measurements

- Linear: 10^6 cd/m^2
- Order of magnitude (log10): 6
- f-stop (log2): 19.93 stops

A bit of Photometry: Contrast

- Give a rough idea of relative luminance in the scene
  - useful
- Formally, a relationship between the darkest and brightest value in the scene. Different contrasts:
  - Weber: $$C_{\mathrm{W}} = \frac{L_{\max} - L_{\min}}{L_{\min}}$$
  - Michelson $$C_{\mathrm{M}} = \frac{L_{\max} - L_{\min}}{L_{\max} + L_{\min}}$$
  - Ratio: $$C_{\mathrm{R}} = \frac{L_{\max}}{L_{\min}}$$

A bit of Photometry: Statistics

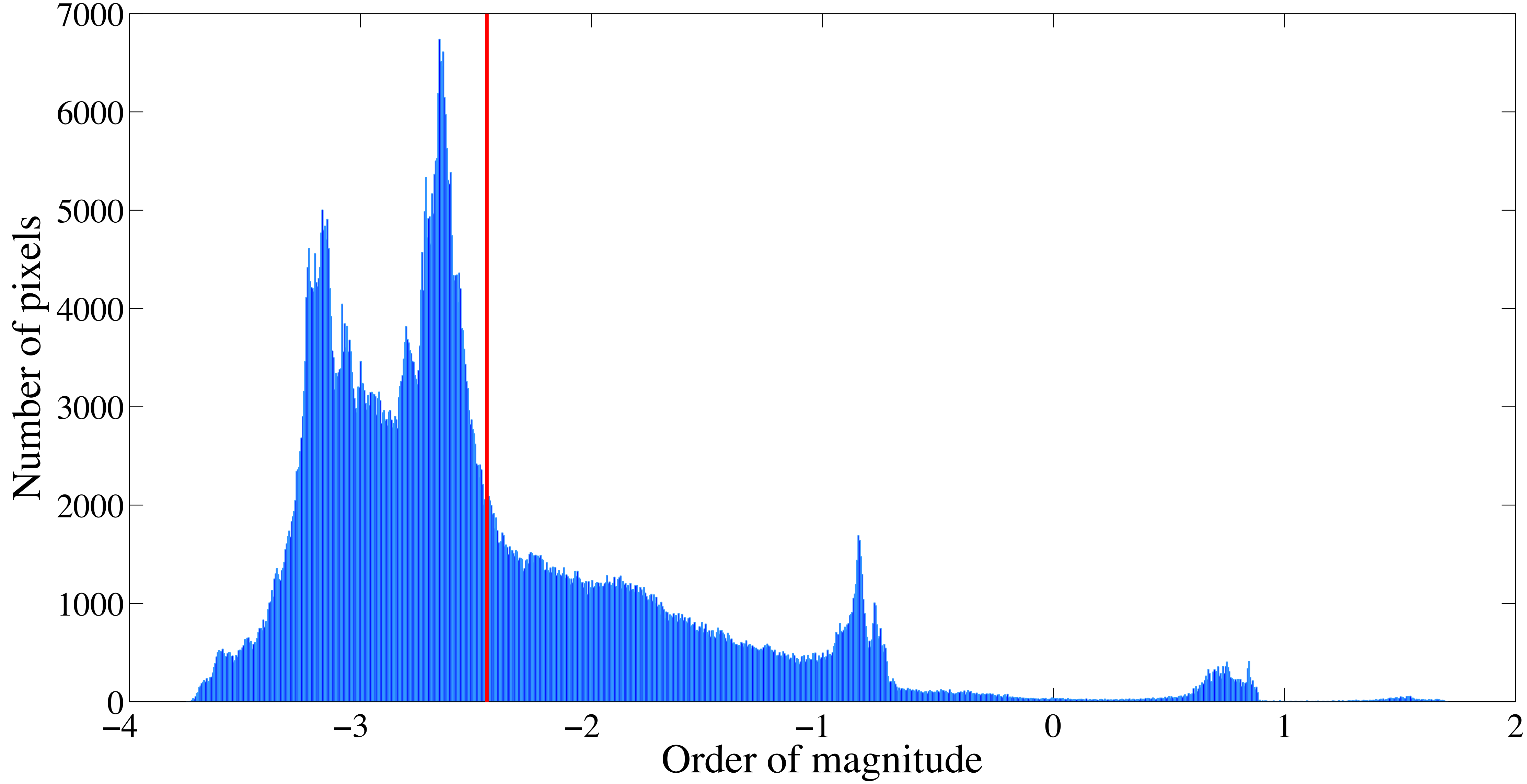
- Another important statistics is geometric mean, especially in the case of HDR imaging:

$$L_{\mathrm{H}} = \prod_{i=1}^{N} \big(L(\mathbf{x}_i) + \epsilon\big)^{\frac{1}{N}} =$$

$$= \exp\left(\frac{1}{N}\sum_{i=1}^{N} \log\big(L(\mathbf{x}_i) + \epsilon\big)\right) \qquad \epsilon > 0$$

$$L_{\mathrm{avg}} = \frac{1}{N}\sum_{i=1}^{N} L(\mathbf{x}_i)$$

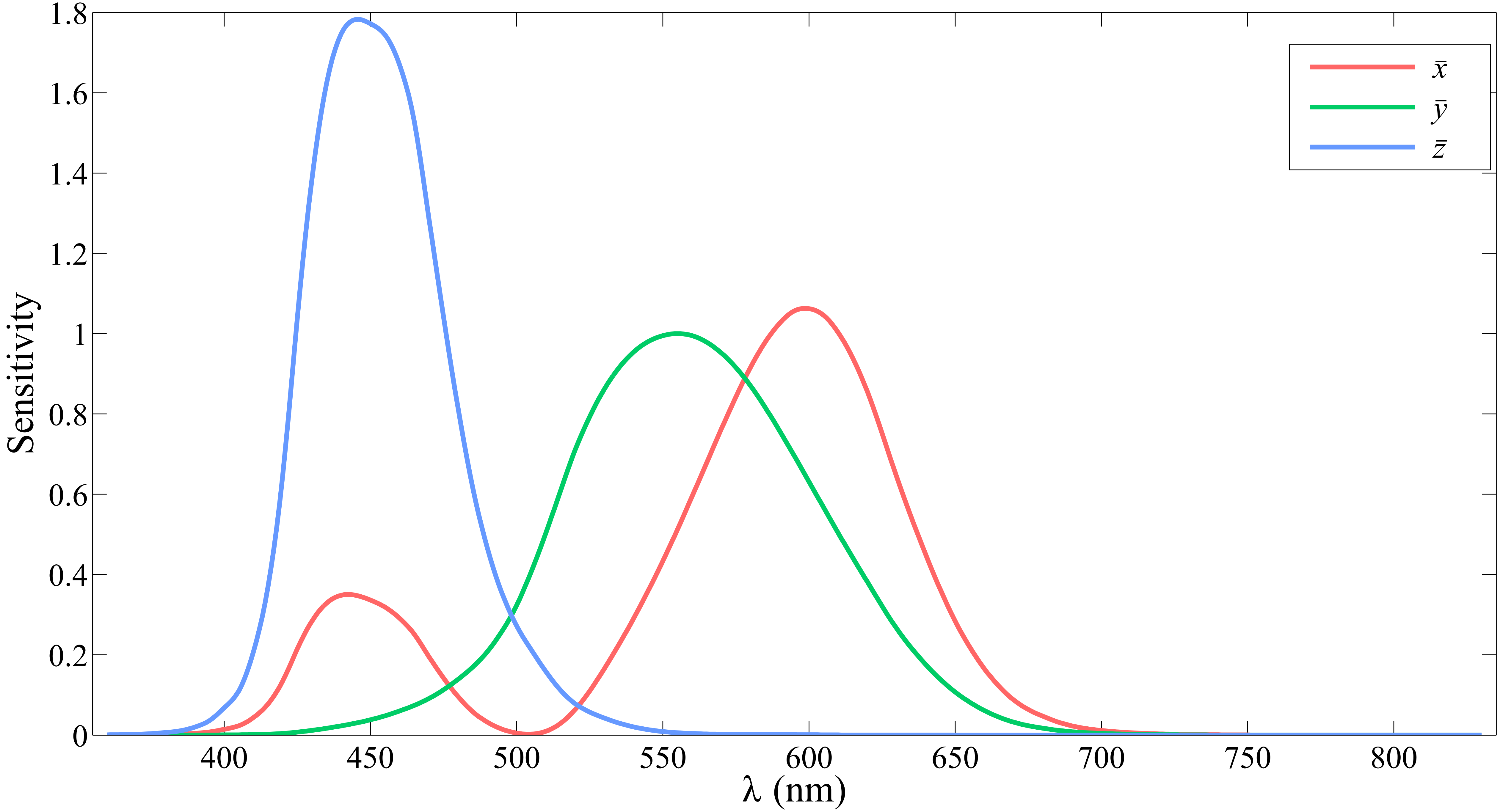
A bit of Photometry: Statistics



A bit of Colorimetry

- “Assigning numbers to physically defined stimuli”
- Milestone in colorimetry:
  - most of perceived colors can be matched by adding light from three suitable “**pure stimuli**” or “**primary stimuli**”
  - For each spectral target, the intensity of the primaries can be adjusted to create a match

CIE XYZ: matching functions



CIE XYZ

- The linear combination of the three spectral functions can produce a spectral signal which may visually match to a linear combination of the primaries:

$$I(\lambda) = \overline{x}(\lambda)X + \overline{y}(\lambda)Y + \overline{z}(\lambda)Z$$

$$X = \int_{380}^{830} I(\lambda)\overline{x}(\lambda)d\lambda$$

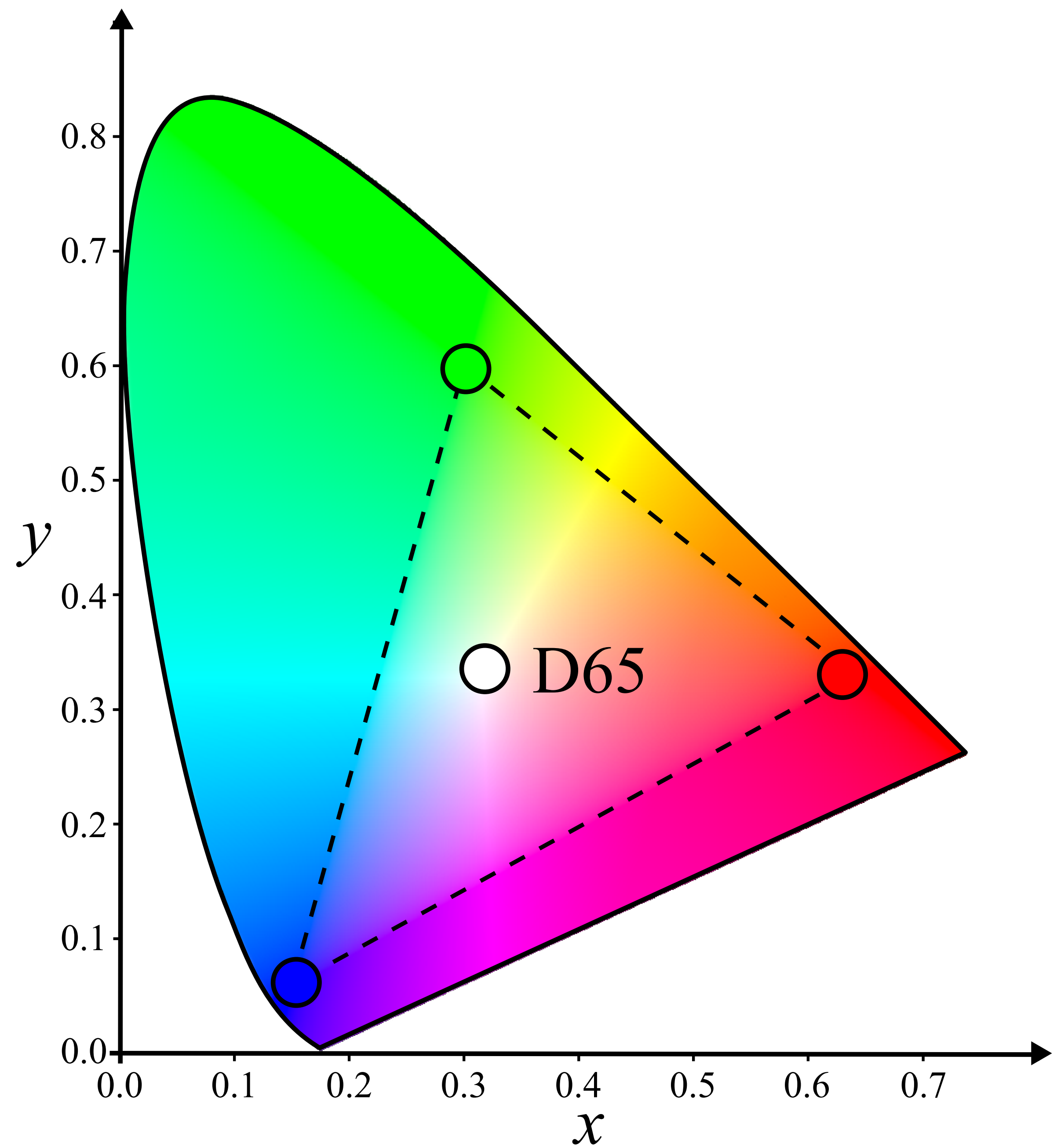
$$Y = \int_{380}^{830} I(\lambda)\overline{y}(\lambda)d\lambda$$

$$Z = \int_{380}^{830} I(\lambda)\overline{z}(\lambda)d\lambda$$

CIE XYZ: Chromaticities

$$x = \frac{X}{X+Y+Z}$$

$$y = \frac{Y}{X+Y+Z}$$



Color Spaces

- Two messages:
    - Mathematical equations creating a relationship between a color triplet and a CIE XYZ color triplet
    - Defining a color gamut; i.e. what colors can be represented (a volume in the color space)

RGB Color Space

- Defining a color as a triplet of specific (device dependent) red, green, and blue primaries with a given white point (wp)
- For example, the ITU-R BT.709 has:

$$
\begin{aligned}
R_{x,y} &= (0.64, 0.33) \\
G_{x,y} &= (0.3, 0.6) \\
B_{x,y} &= (0.15, 0.06) \\
WP_{x,y} &= (0.3127, 0.329)
\end{aligned}
$$

- which leads to:

$$
\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.412 & 0.358 & 0.181 \\ 0.213 & 0.715 & 0.072 \\ 0.019 & 0.119 & 0.950 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}
$$

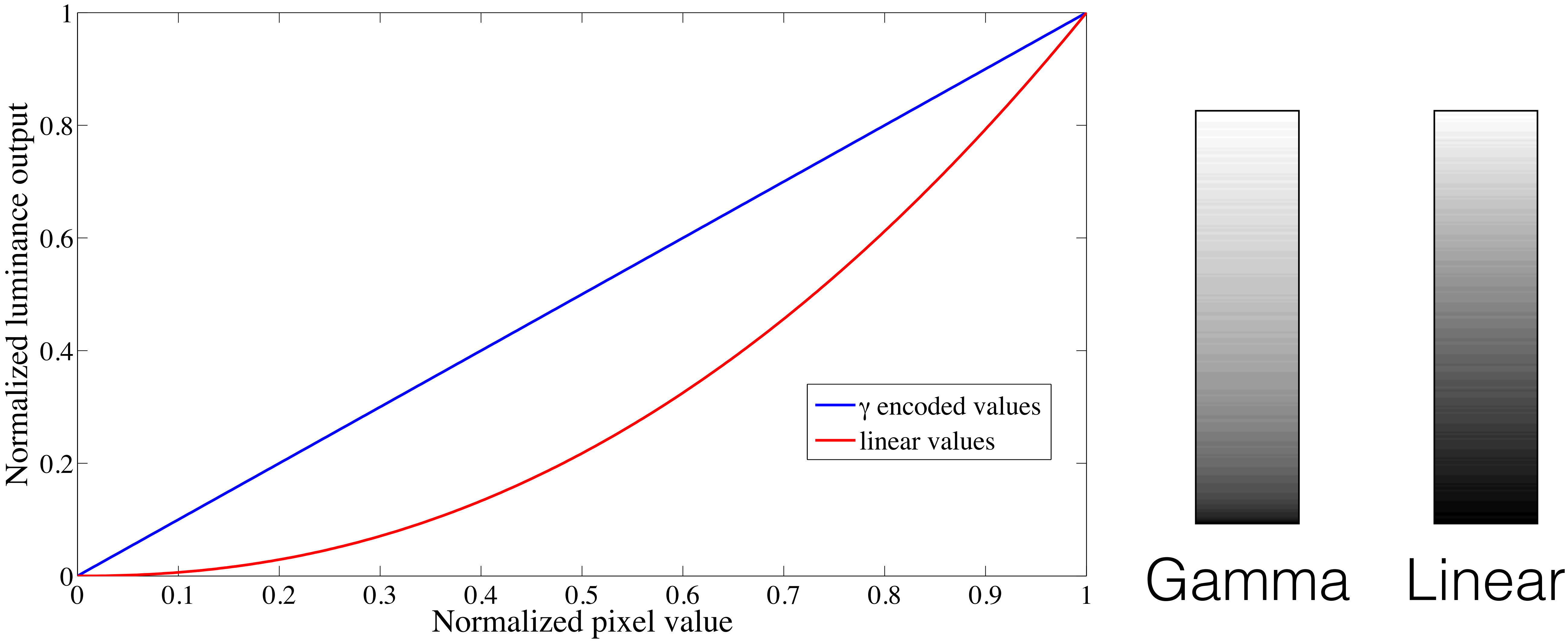
sRGB Color Space

- LCD and CRT monitors can not display linear signal; i.e. the relationship, f, between output intensity and input voltage is not linear

- f is typically modeled as a gamma function

$$L_v = kV^\gamma$$

sRGB Color Space: visualization on CRT/LCD monitors



sRGB Color Space

- A standard RGB color space for monitors
- Primaries and white point from ITU-R BT.709
- Taking into account non-linearity of displays:

$$C_{\mathrm{sRGB}} = \begin{cases} 12.92 C_{\mathrm{linear}} & \text{if } C_{\mathrm{linear}} \leq 0.0031308 \\ (1+0.055) C_{\mathrm{linear}}^{\frac{1}{2.4}} - 0.055 & \text{otherwise} \end{cases}$$

and now….
inside a camera…

Inside the Camera

- Main properties of a camera when taking a shot:
  - Focal Length
  - Aperture
  - Shutter speed
  - ISO

Inside the Camera: Focal Length

- Focal length is the distance (typically mm) over which initially collimated rays are brought in focus

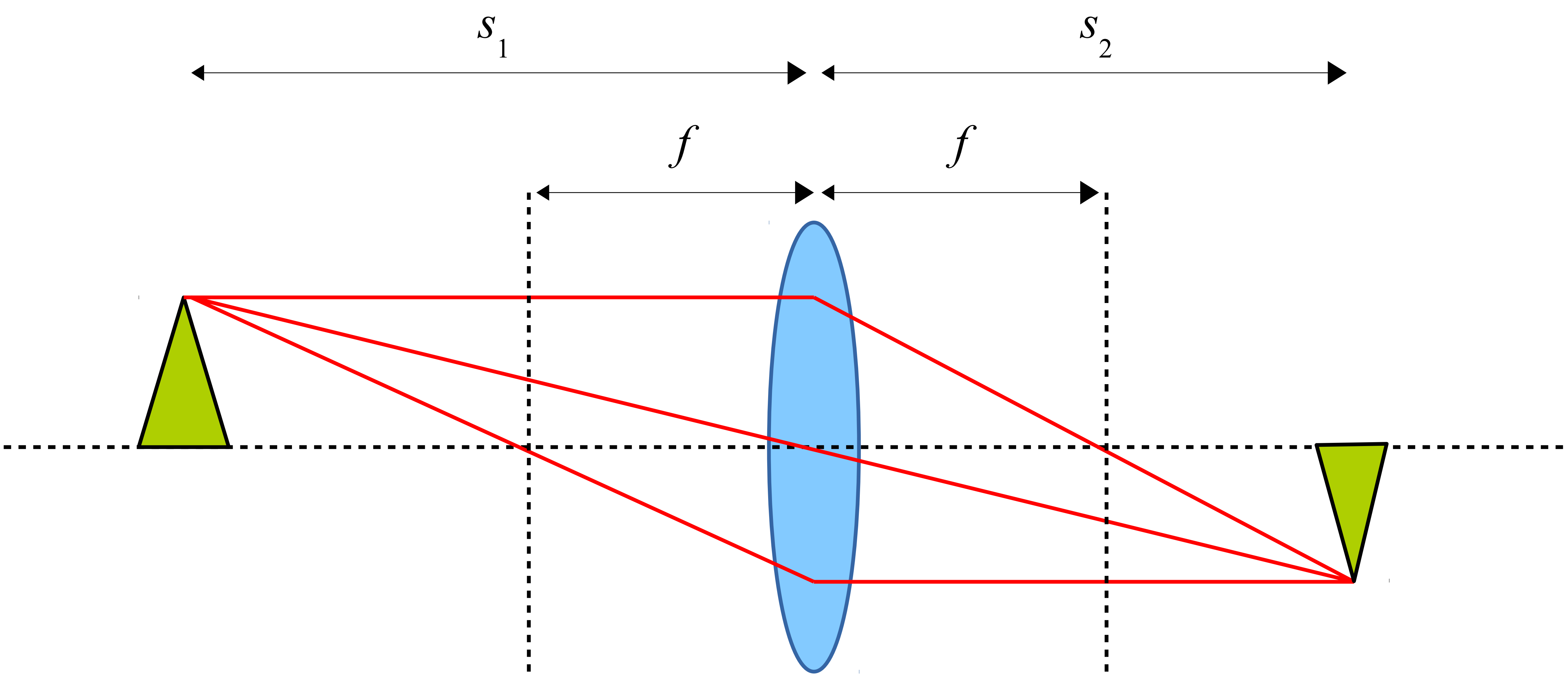
- It is an important feature of an optical system, e.g. camera's lens

- Field of view (FOV) and Focal Length have the following relationship:

$$\mathrm{FOV} = \arctan\left(\frac{x}{2f}\right)$$

- where x is the diagonal in mm of the sensor/film

Inside the Camera: Focal Length



$$\frac{1}{S_1} + \frac{1}{S_2} = \frac{1}{f}$$

Inside the Camera: Focal Length

18mm

35mm

55mm

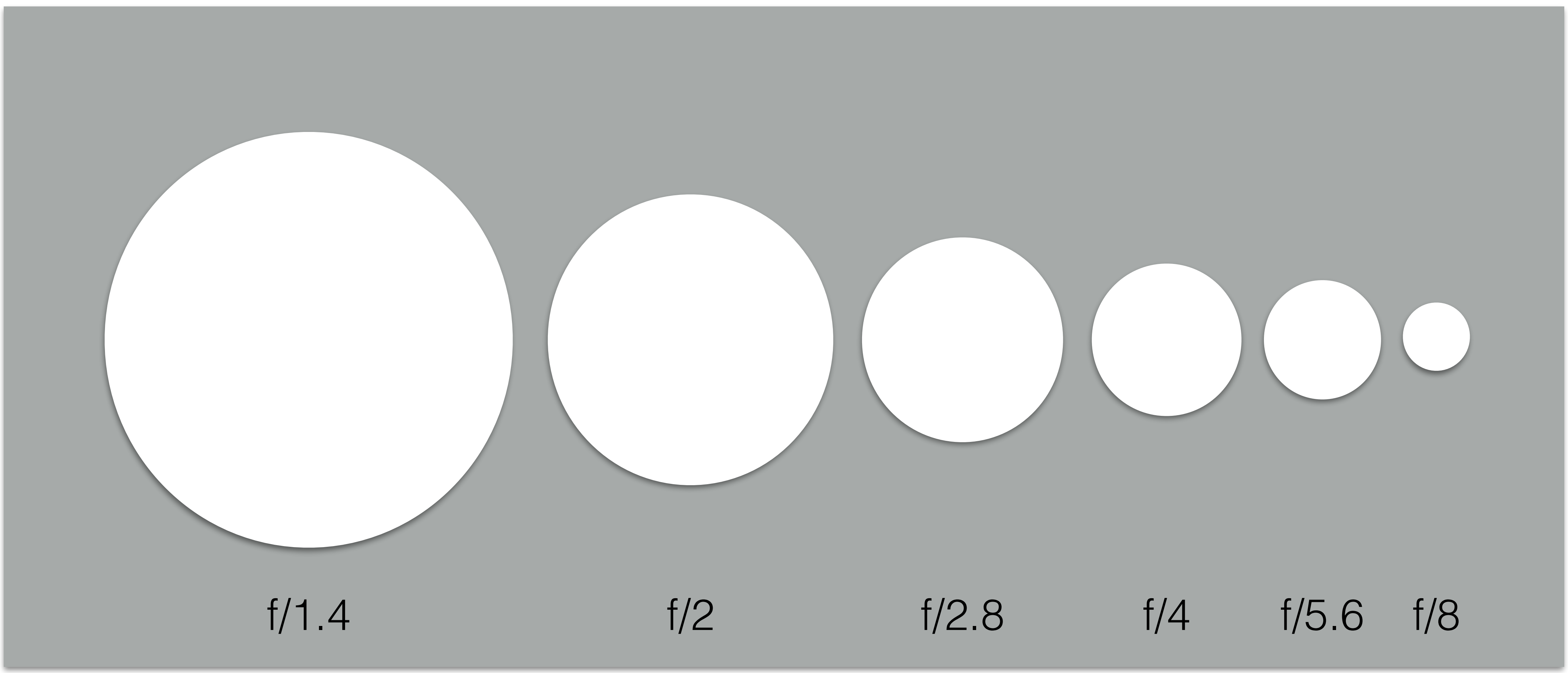
Inside the Camera: Aperture

- f-number N:

$$N = \frac{f}{d}$$

- f is the focal length
- d is the diameter of the entrance pupil

Inside the Camera: Aperture

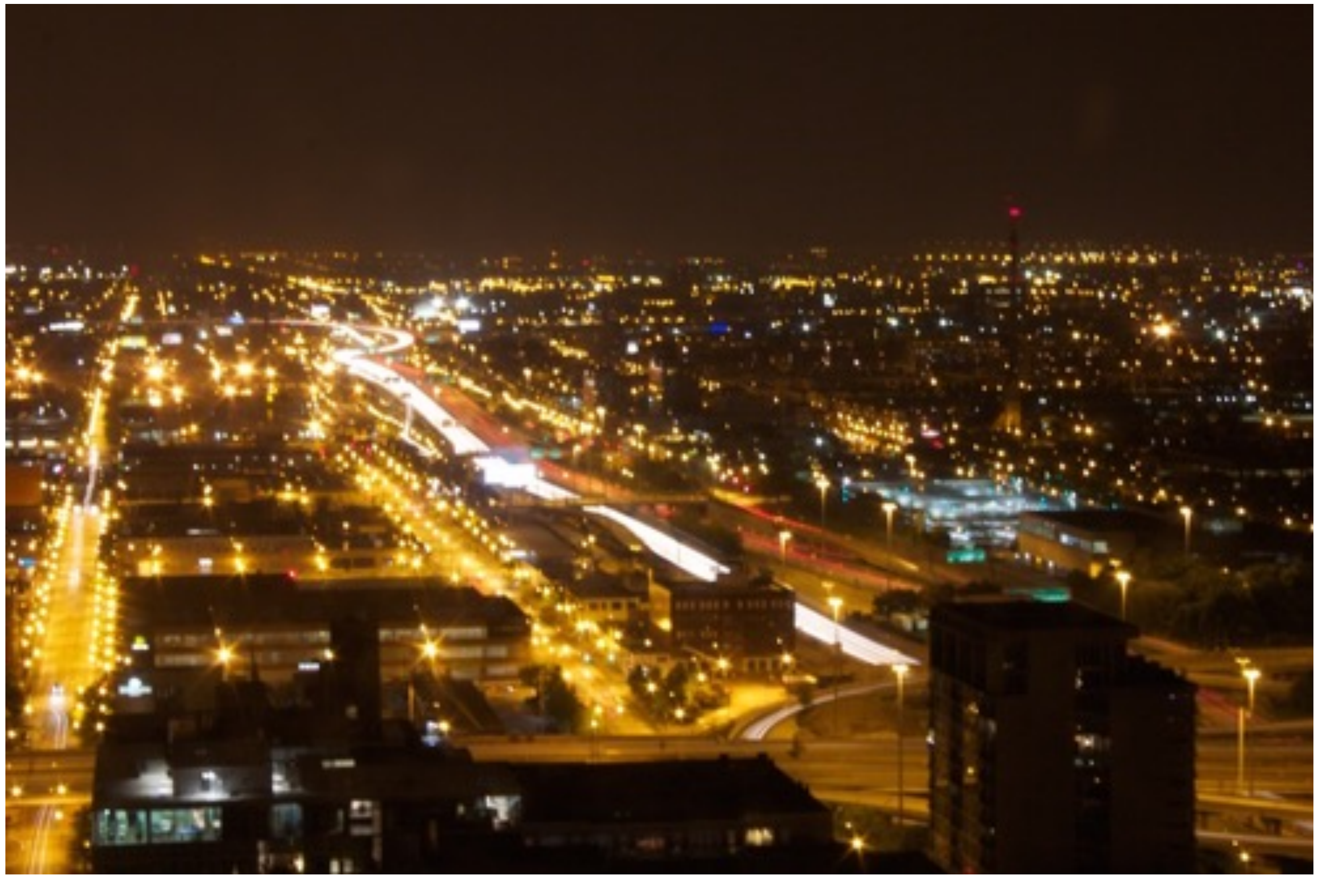


Inside the Camera: Aperture

Inside the Camera: Aperture

Inside the Camera: Shutter speed

- Shutter speed or exposure time: length of time a camera's shutter is open; proportional to the amount of light that enters



Inside the Camera: ISO

- ISO or film speed is a measure of the sensitivity of a sensor or a film to light. It can be measured in many scales, a typical scale is ASA firstly proposed by Kodak for film:
  - Asa is arithmetic: 200 ASA is twice 100 ASA
- Lower ISO values:
  - less noise
  - requiring more light
- Higher ISO values:
  - more noise
  - requiring less light

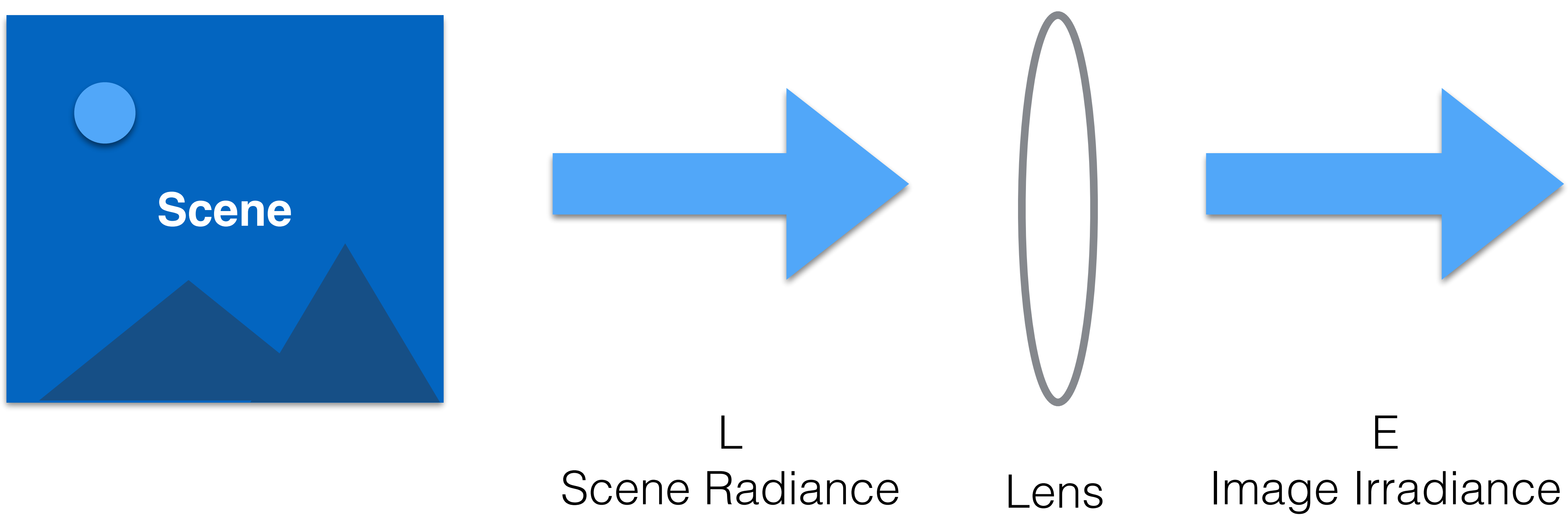
Inside the Camera: ISO

Inside the Camera: ISO

Inside the Camera: ISO

Inside the Camera: E and L

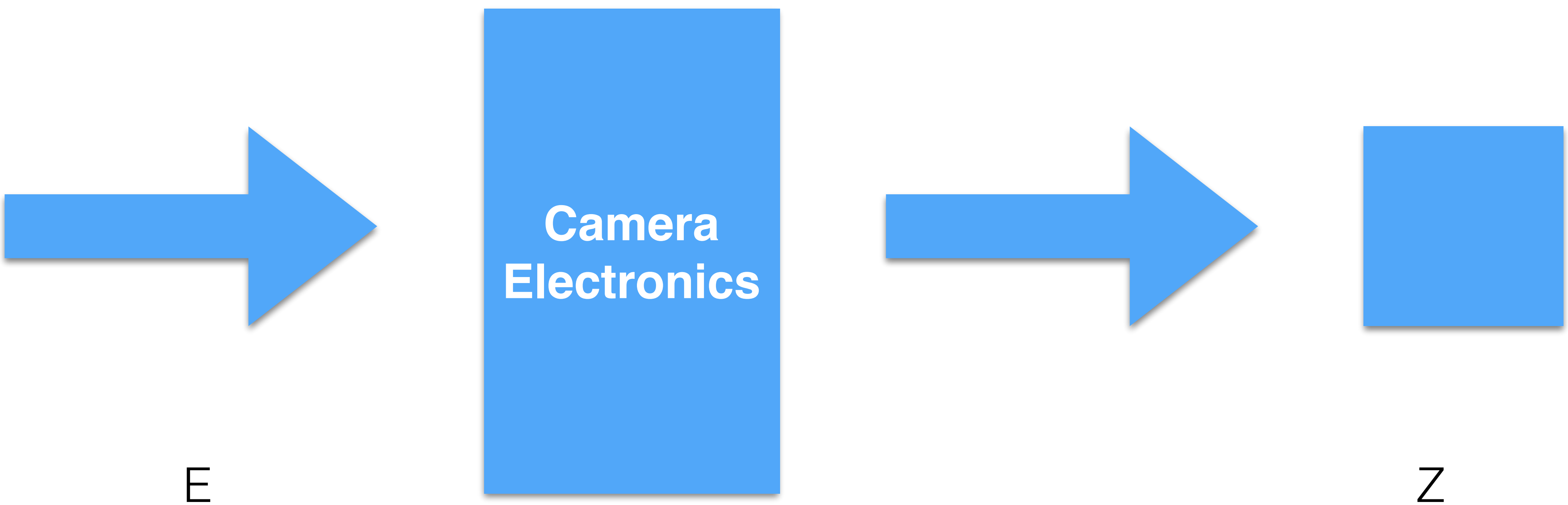
Before light hits the image plane



Linear Mapping
between L and E

Inside the Camera: E and L

After light hits the image plane

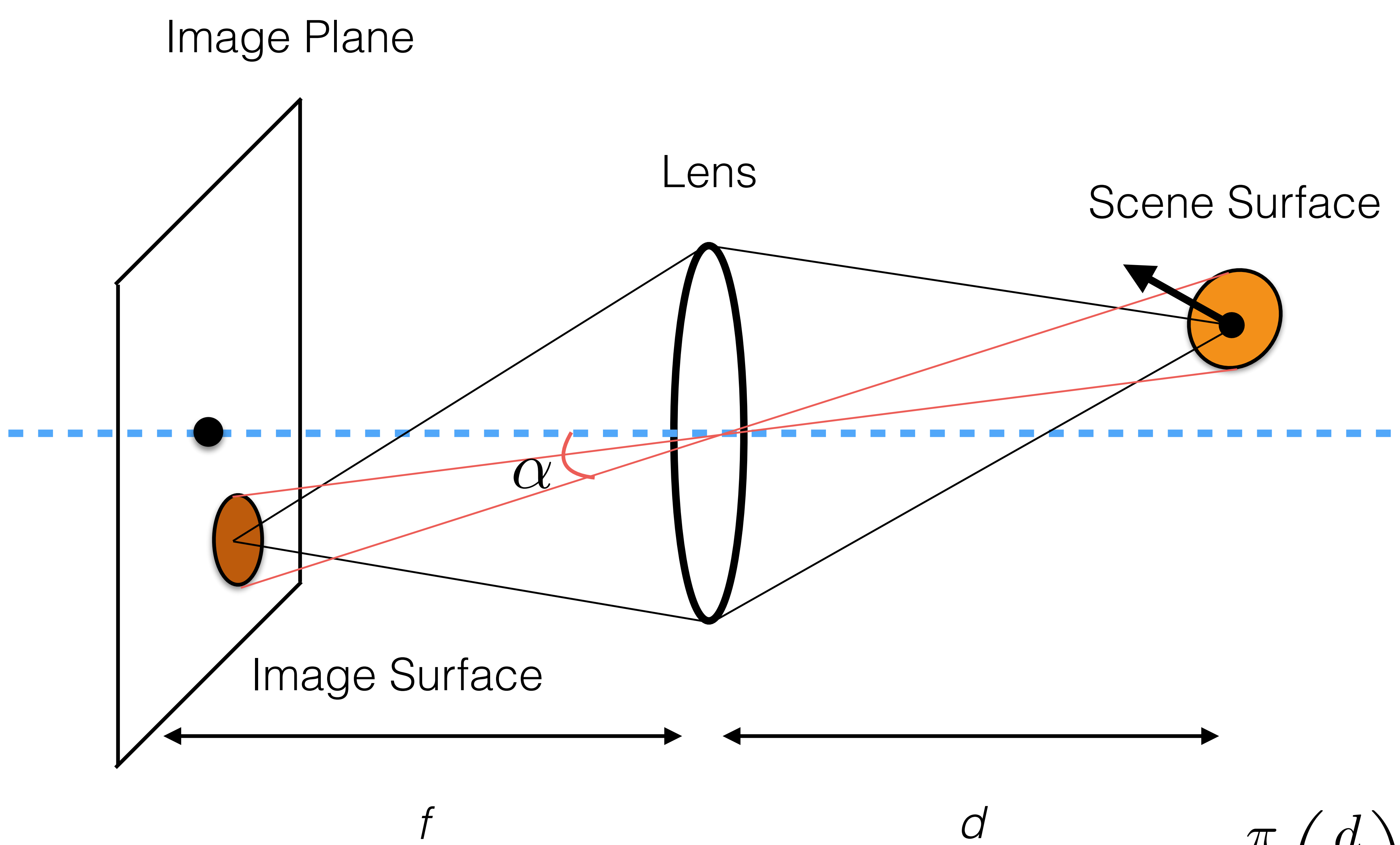


E
Image Irradiance

Z
Pixel value in [0,255]

between E and Z
Non linear mapping!

Inside the: Camera: E and L



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

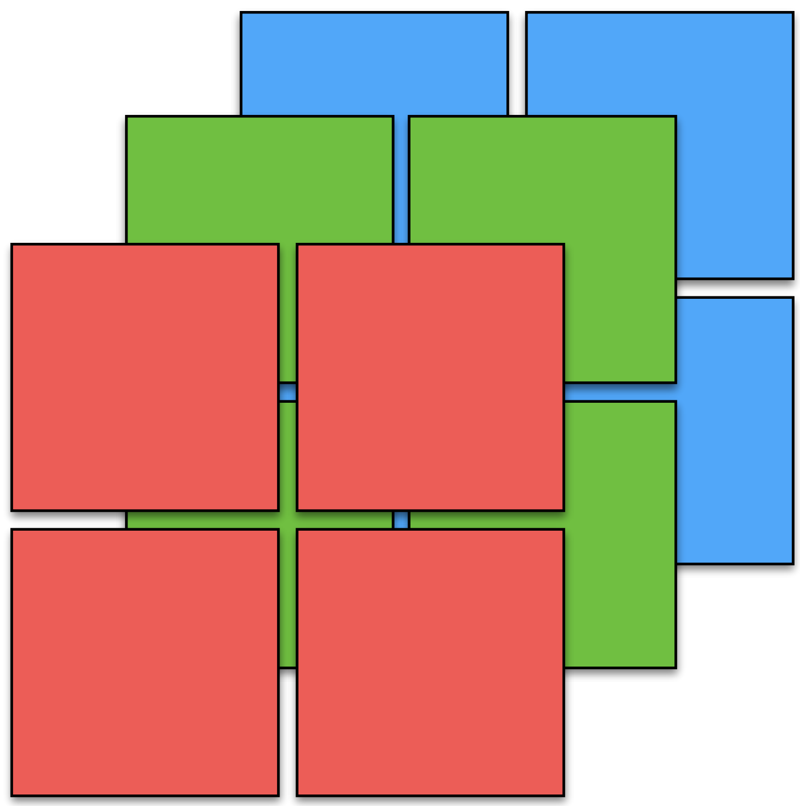
Inside the Camera: E and L

- A small note:
  - Modern camera lenses already take $E = L\frac{\pi}{4}\left(\frac{d}{f}\right)^2 \cos^4 \alpha$ into account
  - Therefore, this value can be assumed to be mostly constant, especially for f/8 or smaller apertures

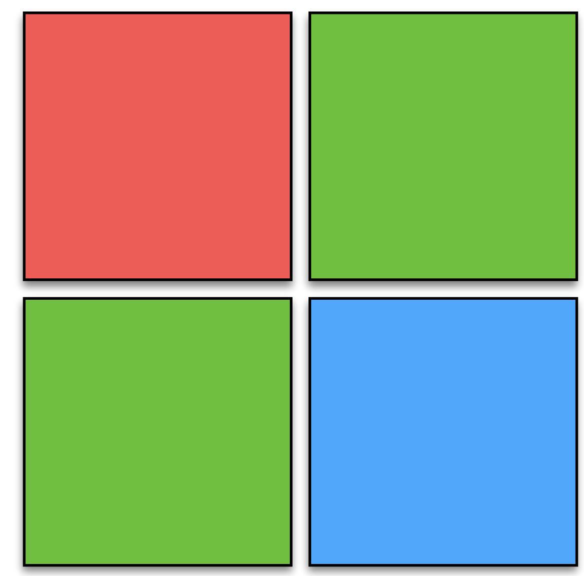
Inside the Camera: Bayer Filter

- Only in rare cases, cameras have a sensor for each color channel; red, green, and blue.
  - Why? It is very expensive!
- Common solution; the bayer pattern:
  - each color is capture with a mask which varies spatially

Inside the Camera: Bayer Filter



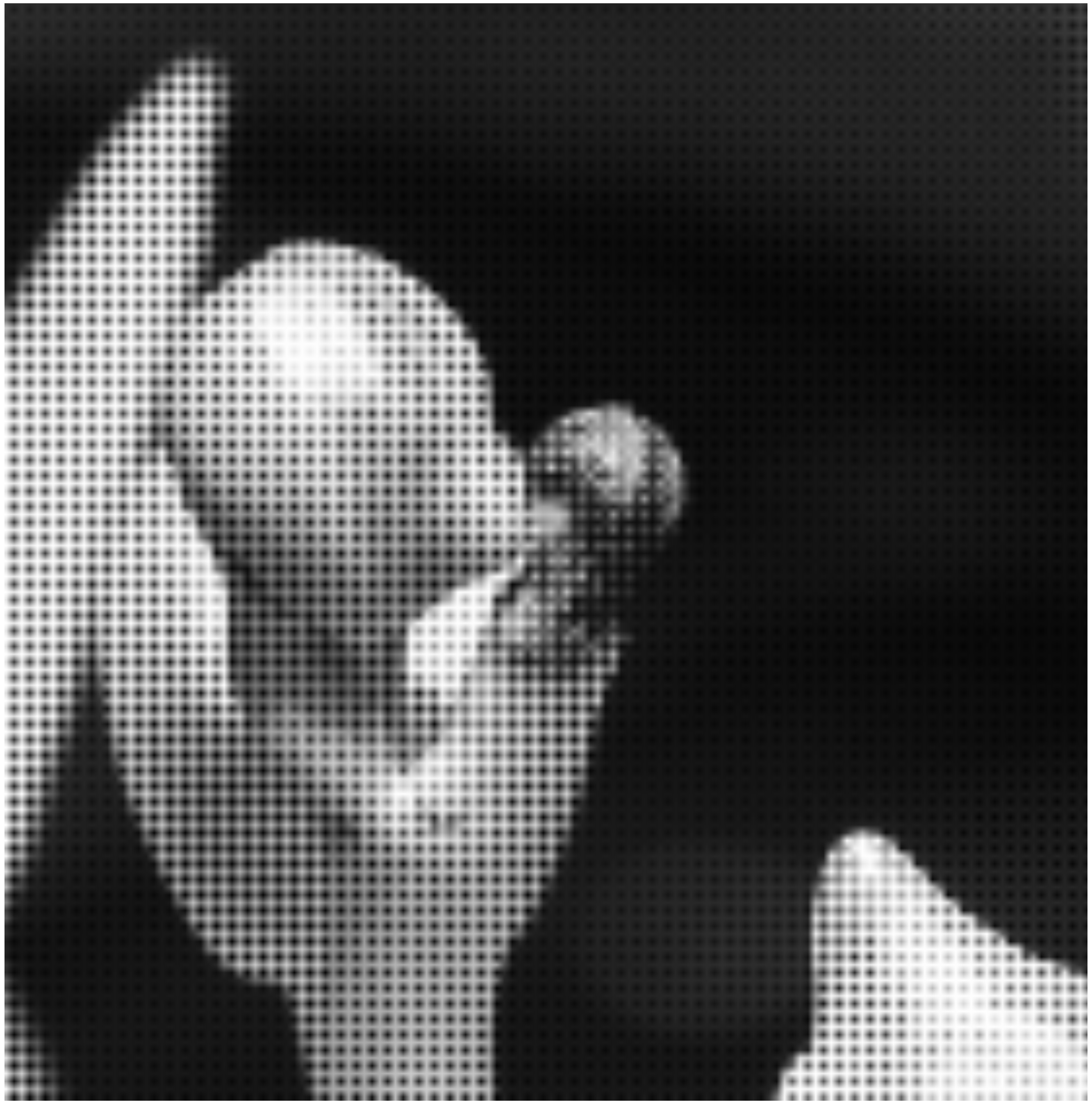
three sensor solution



Bayer sensor solution

Inside the Camera: Bayer Filter

Inside the Camera: Bayer Filter



Inside the Camera: Bayer Filter

Image with Bayer Filter

Reconstructed Image

Inside the Camera: Bayer Filter

Image with Bayer Filter

Reconstructed Image

questions?