Physical Nature of Light and Color

Image Processing

About me

ITMO

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- More than 20 years of IT research and development
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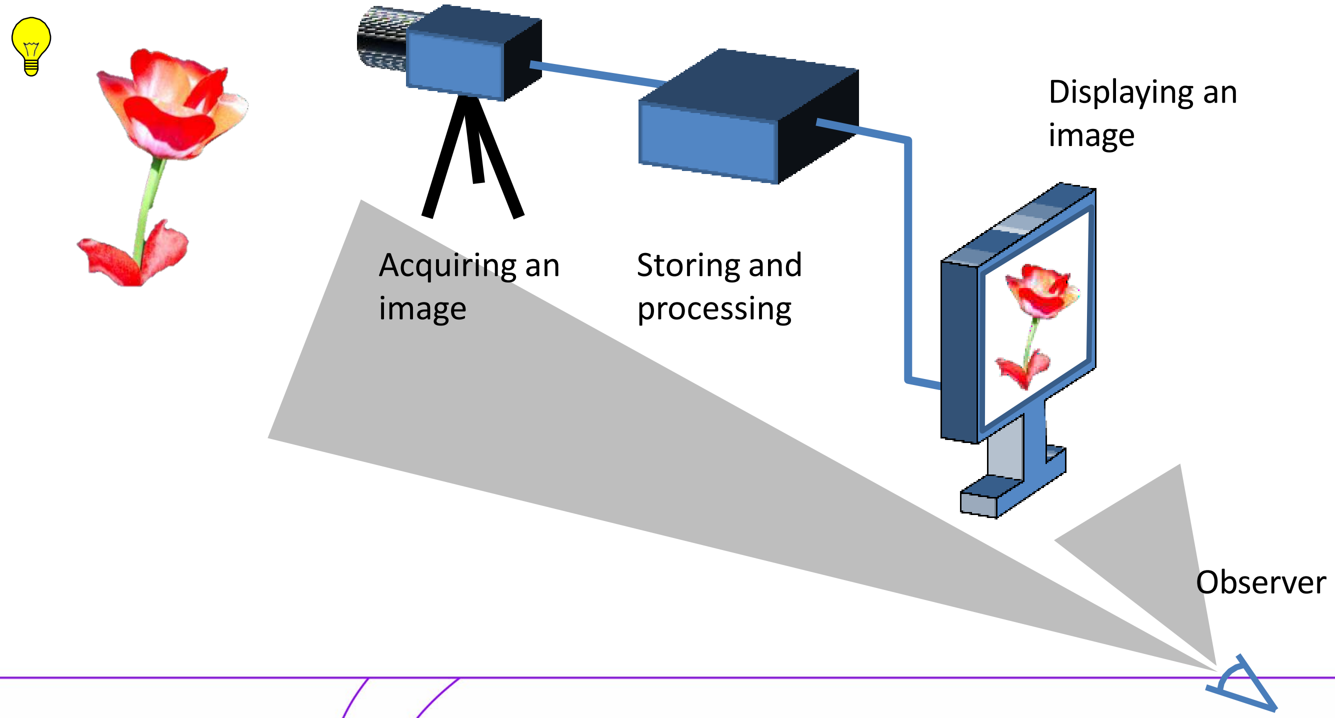
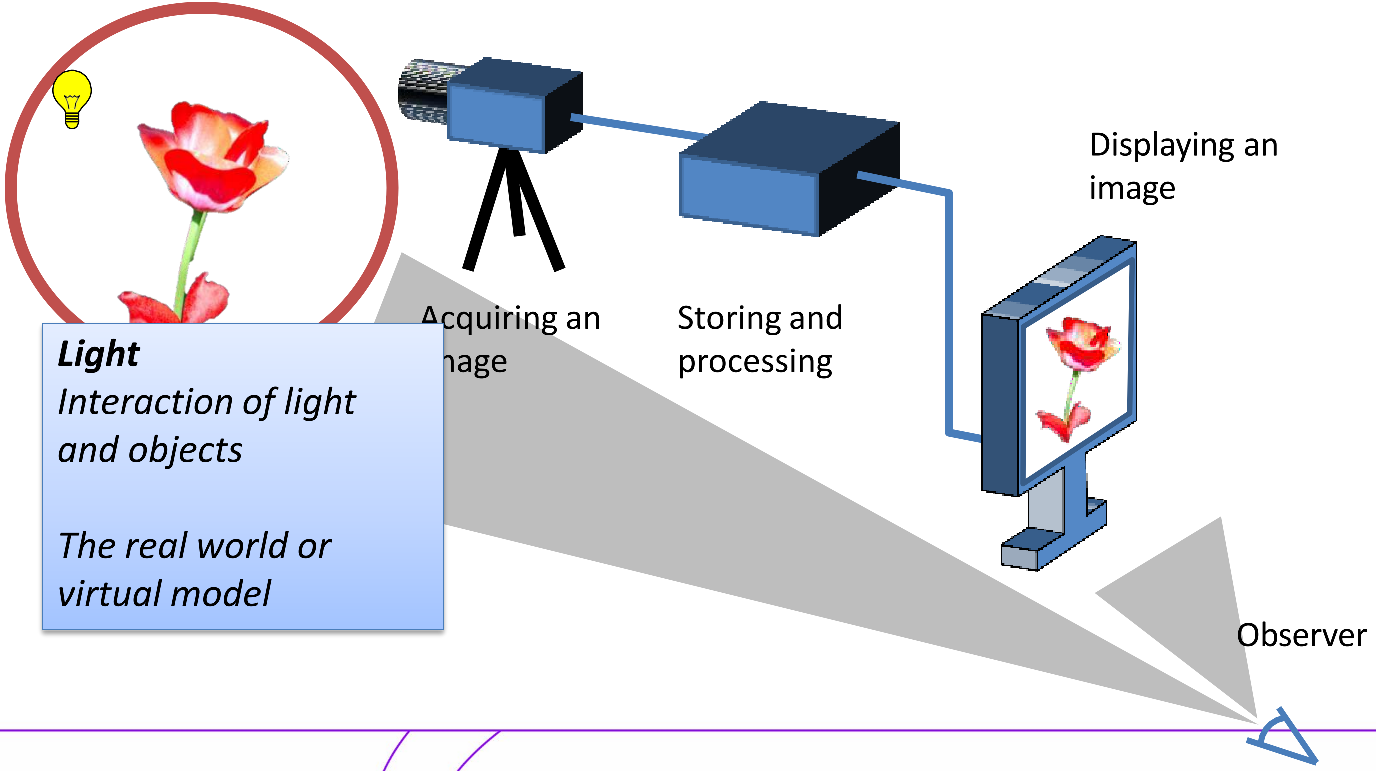
Outline

- Light and wave nature of light
- Radiometry: basic terms
- Photometry: basic terms

Light and color in a graphical system



Light and color in a graphical system

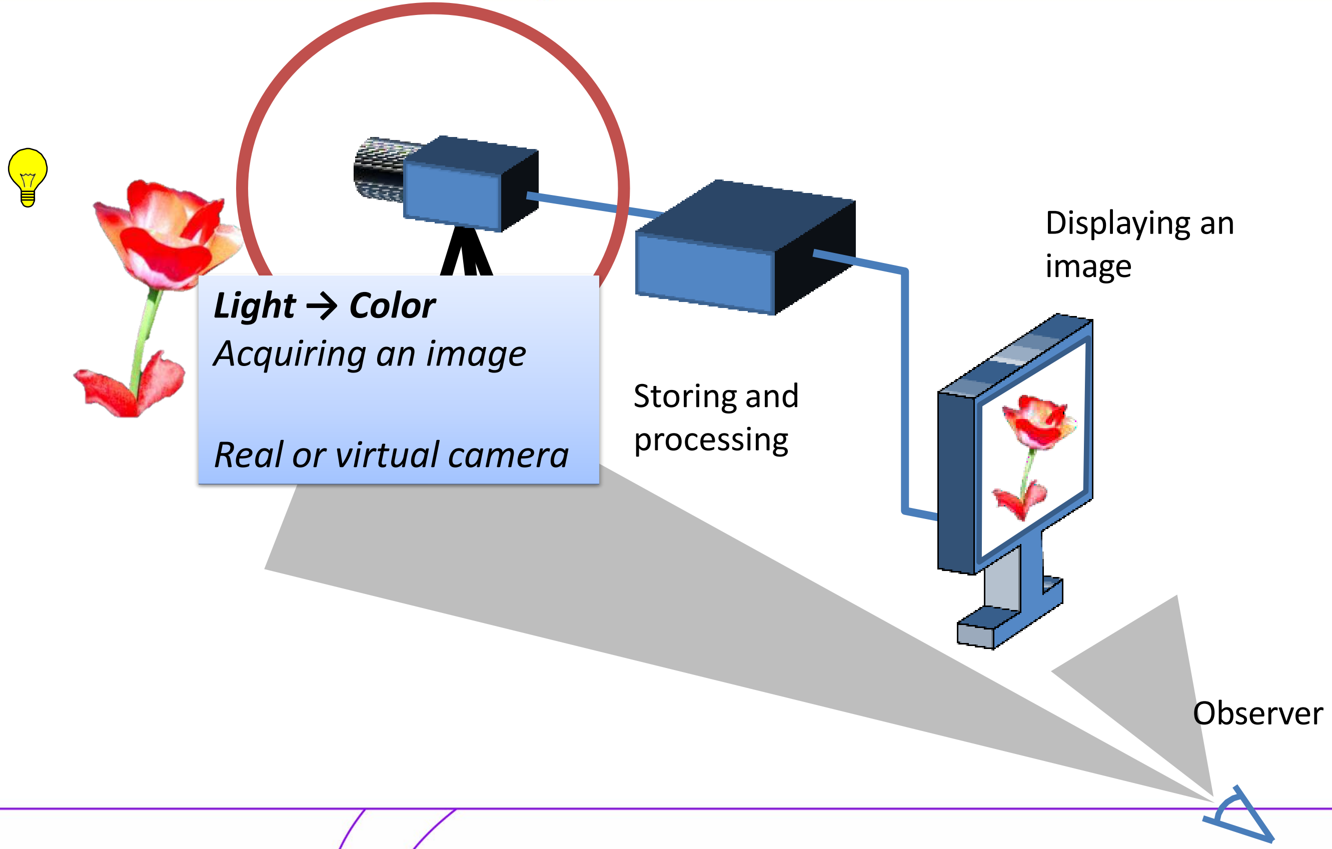


Light

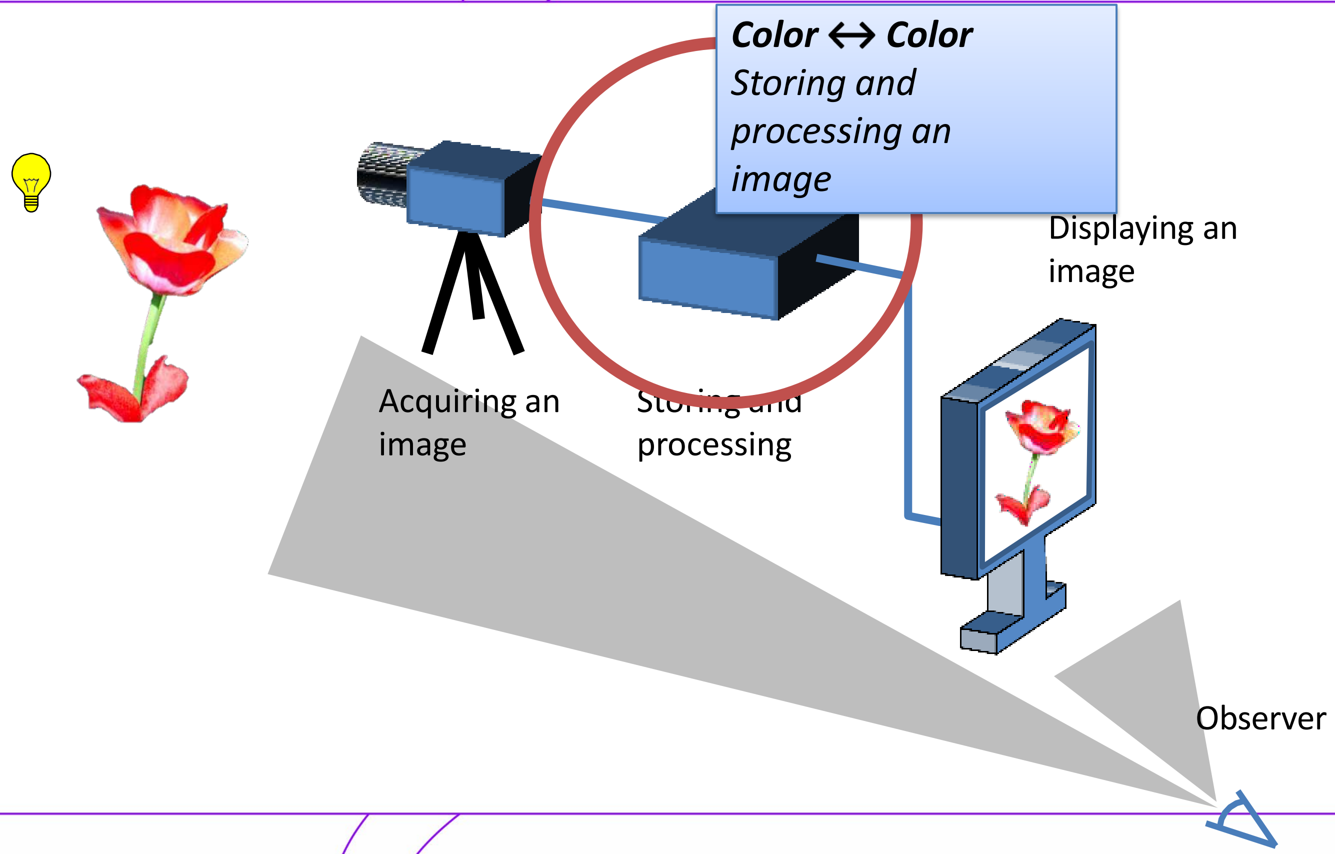
Interaction of light and objects

The real world or virtual model

Light and color in a graphical system



Light and color in a graphical system



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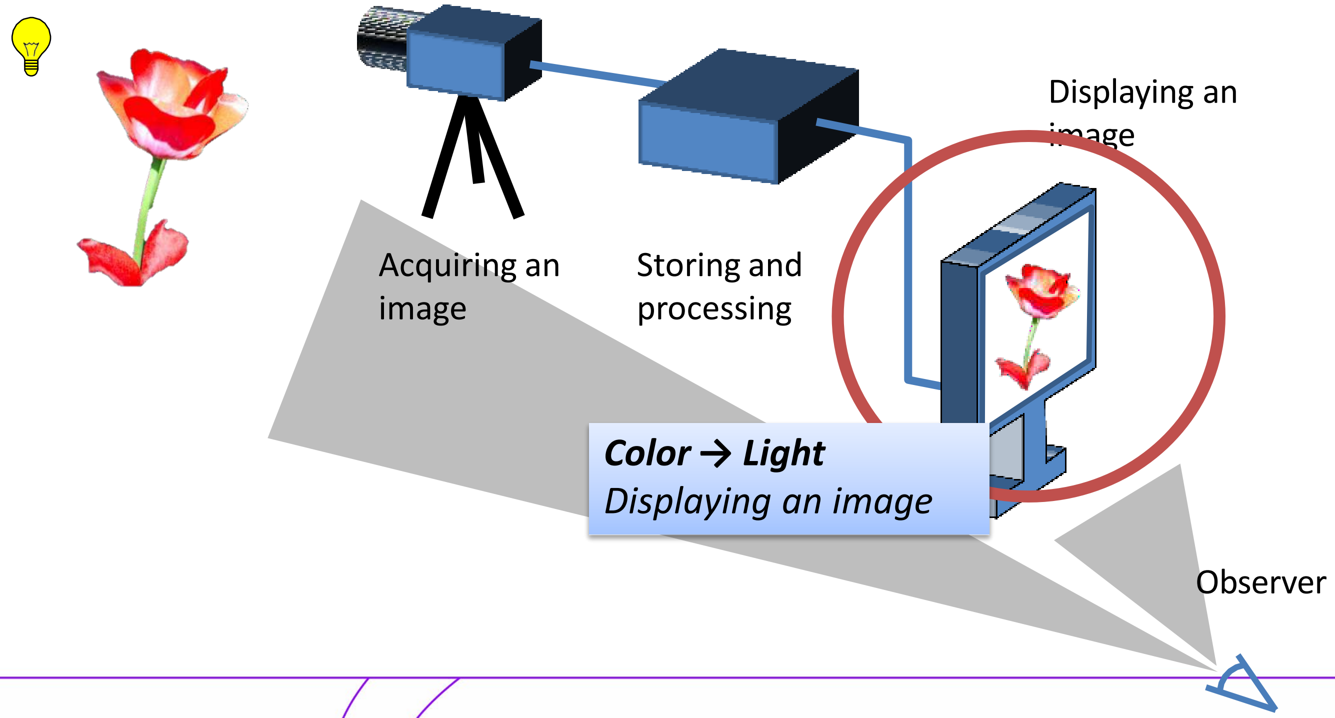
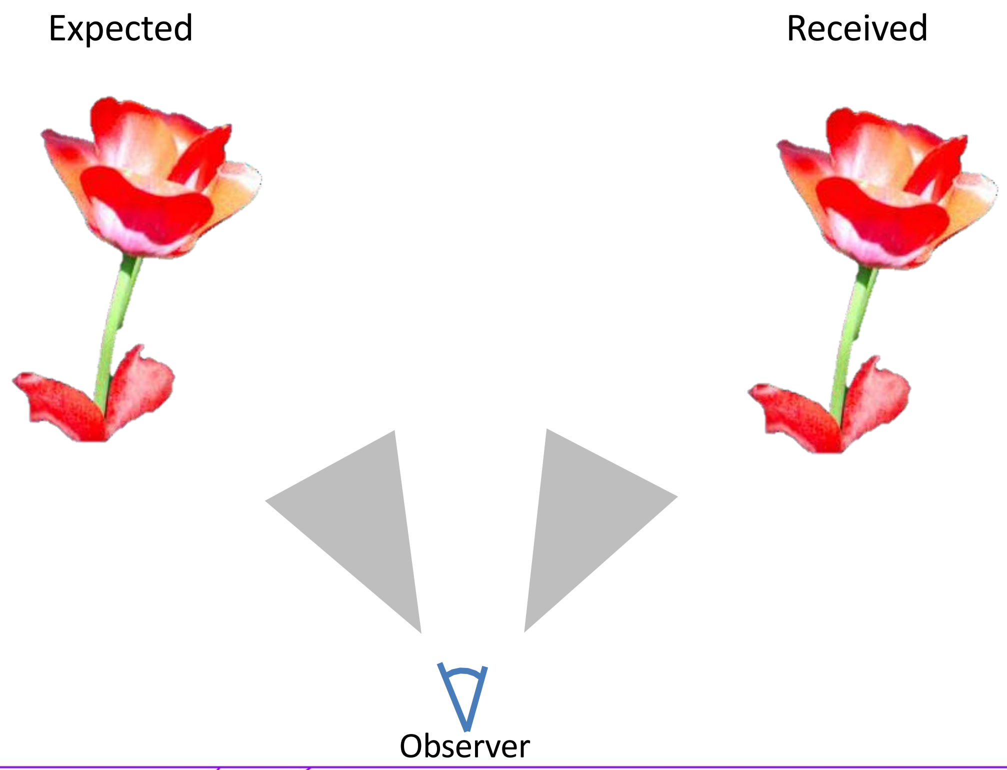
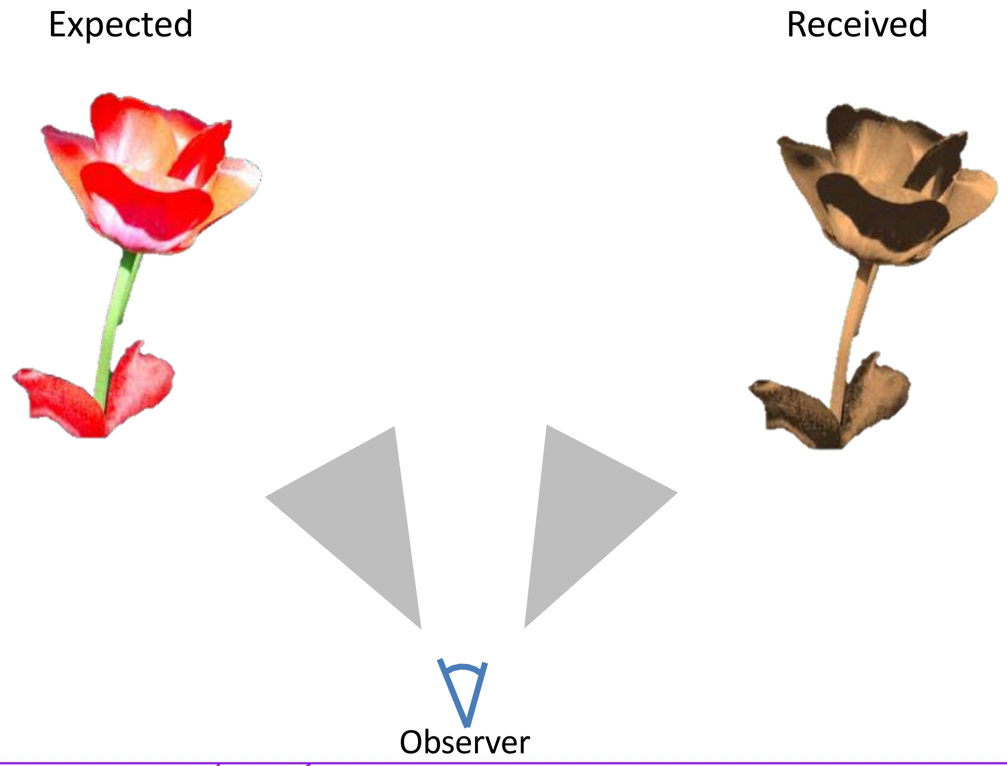


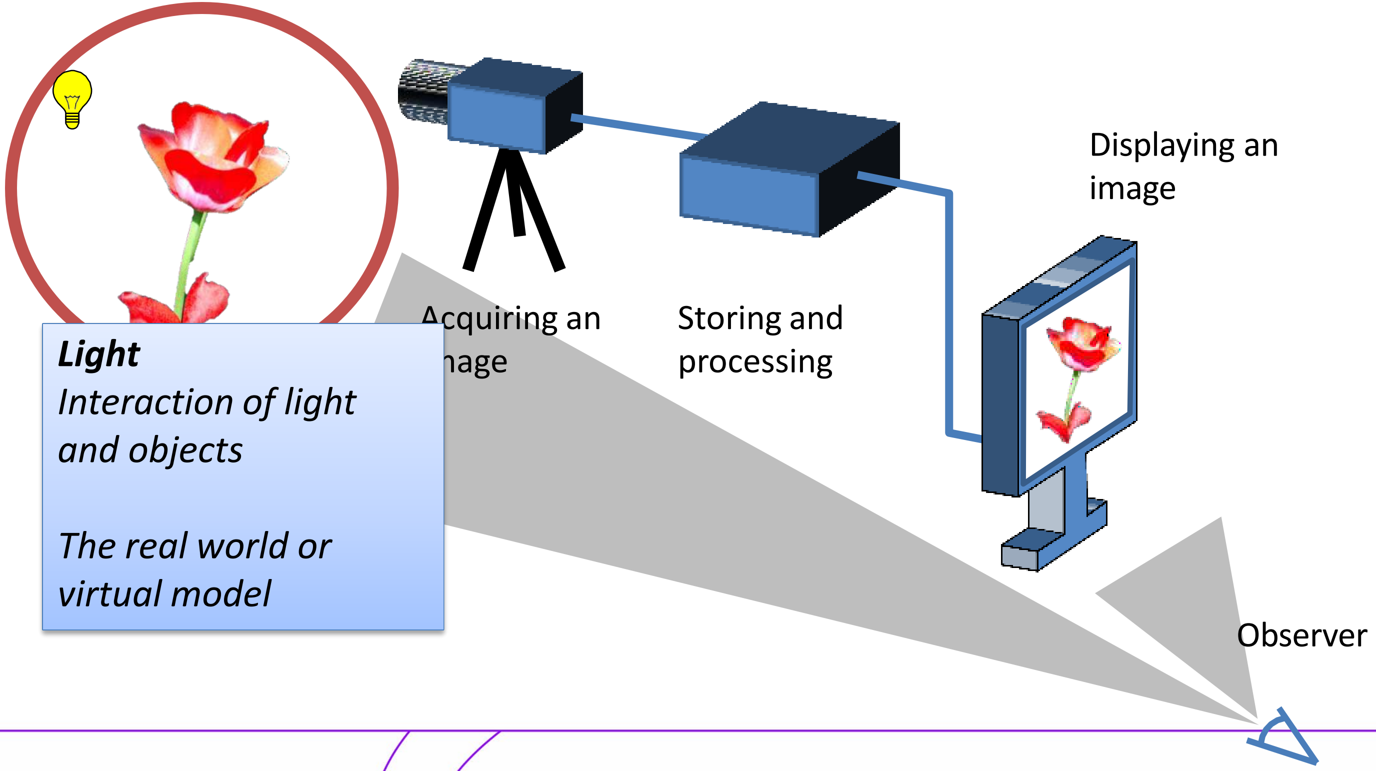
The «good» system



The «bad» system



Light and color in a graphical system



Light: dual nature

Electromagnetic wave

– wave optics

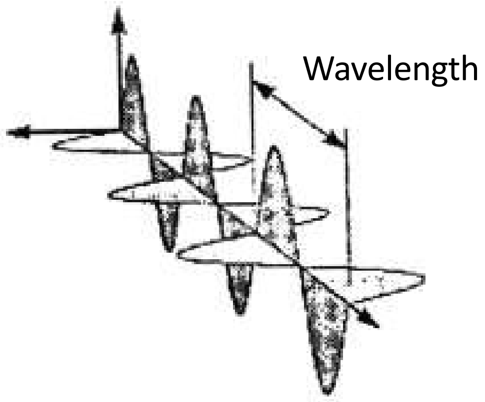
Stream of particles

– geometrical optics

The reasons for duality are explained in quantum optics

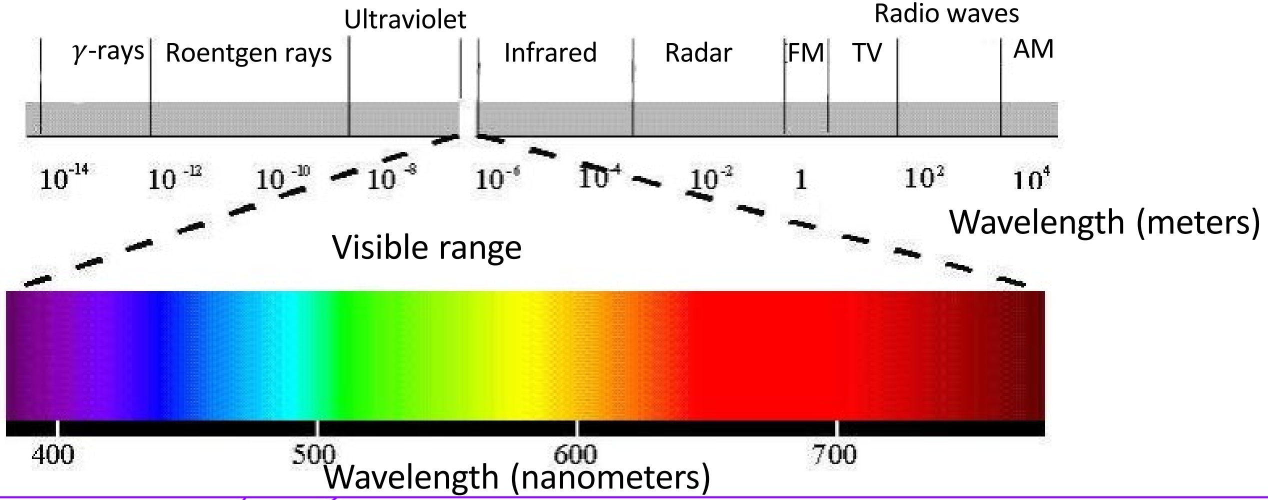
Light: electromagnetic waves or particles

- Dual nature of light
  - Electromagnetic waves
  - Stream of particles
- Light wave parameters: amplitude, wavelength, polarization
  - Amplitude ~ energy
  - Measured in Watts
    (Watt = Joule/Second)
- Is emitted by discrete quanta called photons



Visible wavelengths range ~400-700nm

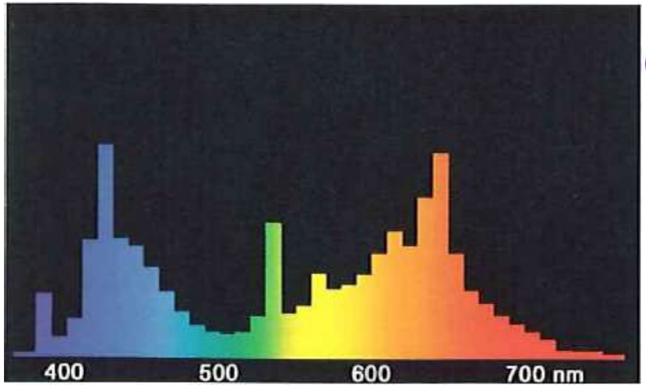
- Visible light is in range of 400-700 nanometers
  - 380-470 nm violet and blue color
  - 500-560 nm green color
  - 590-760 nm red color
- In smaller intervals of this range the color of radiation corresponds to different color shades

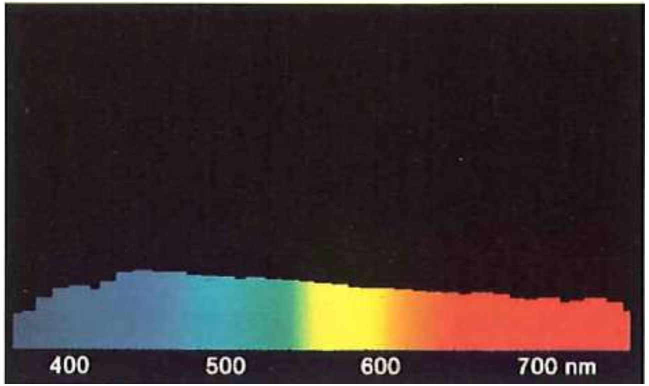


Light is a flow of waves

Light: flow of waves with different wavelengths, different amplitudes and different polarizations

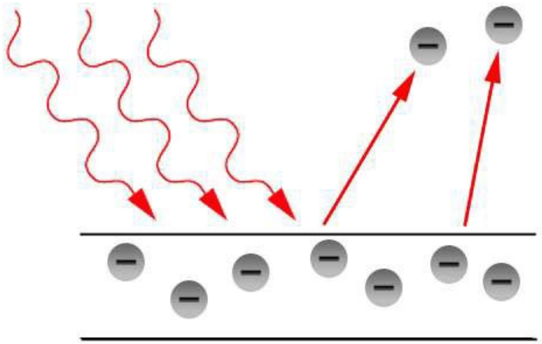
- Can be considered as the sum of monochromatic emissions





Photoelectric effect

- Emission of electrons by an incident light
  - Albert Einstein's photoelectric effect experiment, 1905
  - A beam of light could eject electrons from metal
  - Light consists of photons with energy that depends on the frequency
  - If the frequency is over a certain limit, then it would have sufficient energy to eject an electron from metal
- Is one of the foundations of the photon theory (particle theory)

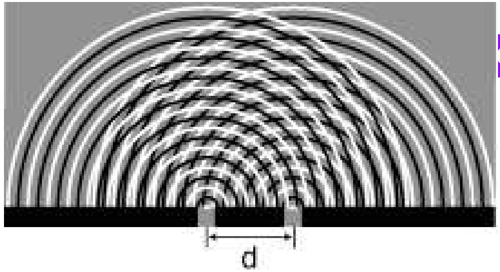


Geometrical optics

- The Fermat's principle
- The law of rectilinear light propagation
- The law of independent light ray propagation
- The law of light reflection
- The law of light refraction (Snell’s law)
- The law of light ray reversibility

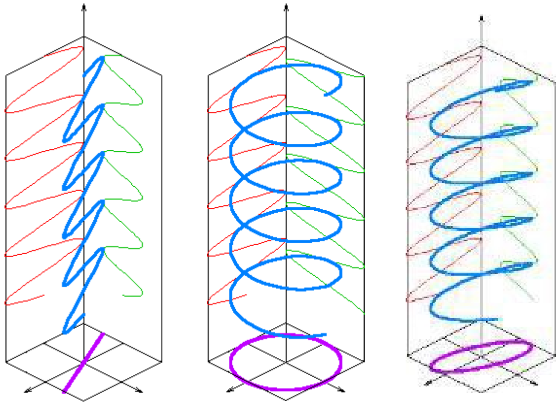
Wave nature of light: diffraction and interference

- The phenomenon of transformation of a wave propagating in space
  - Thomas Young experiments, 1901
  - If the light consisted of the small particles, the alternating light and dark bands would not have occurred
- Occurs at comparable wavelengths and sizes of medium inhomogeneity
- When the size of inhomogeneities is 3-4 orders of magnitude greater than the wavelength, diffraction can be neglected



Wave nature of light: polarization

- Light wave is a transverse wave



Polarization: example

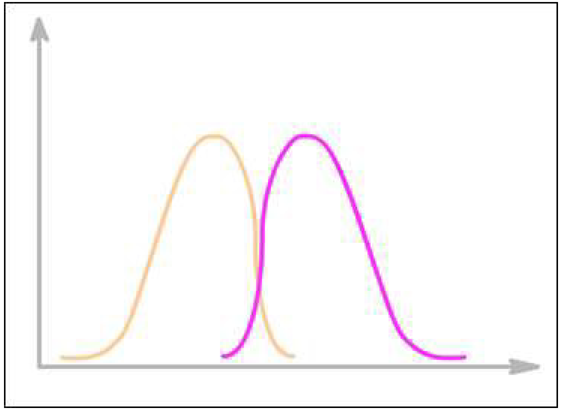
https://commons.wikimedia.org/wiki/File:CircularPolarizer.jpg

Fluorescence, phosphorescence

Non-thermal self luminescence of a substance.

Photoluminescence – self glow caused by an incident light (visible and UV)

- absorbs shorter wave and emits a longer one
- fluorescence (only when exposed to light)
- phosphorescence



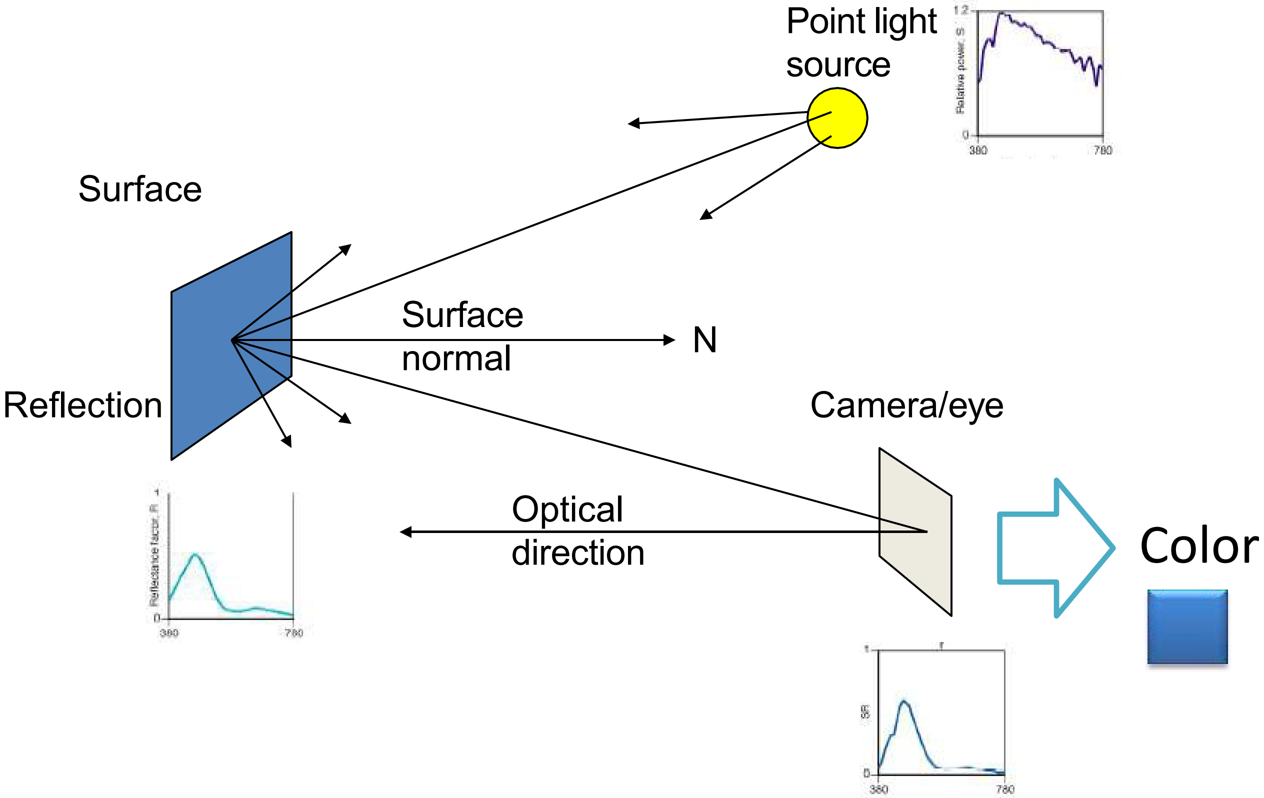
https://en.wikipedia.org/wiki/Image:Tonic_water_uv.jpg

Radiometry

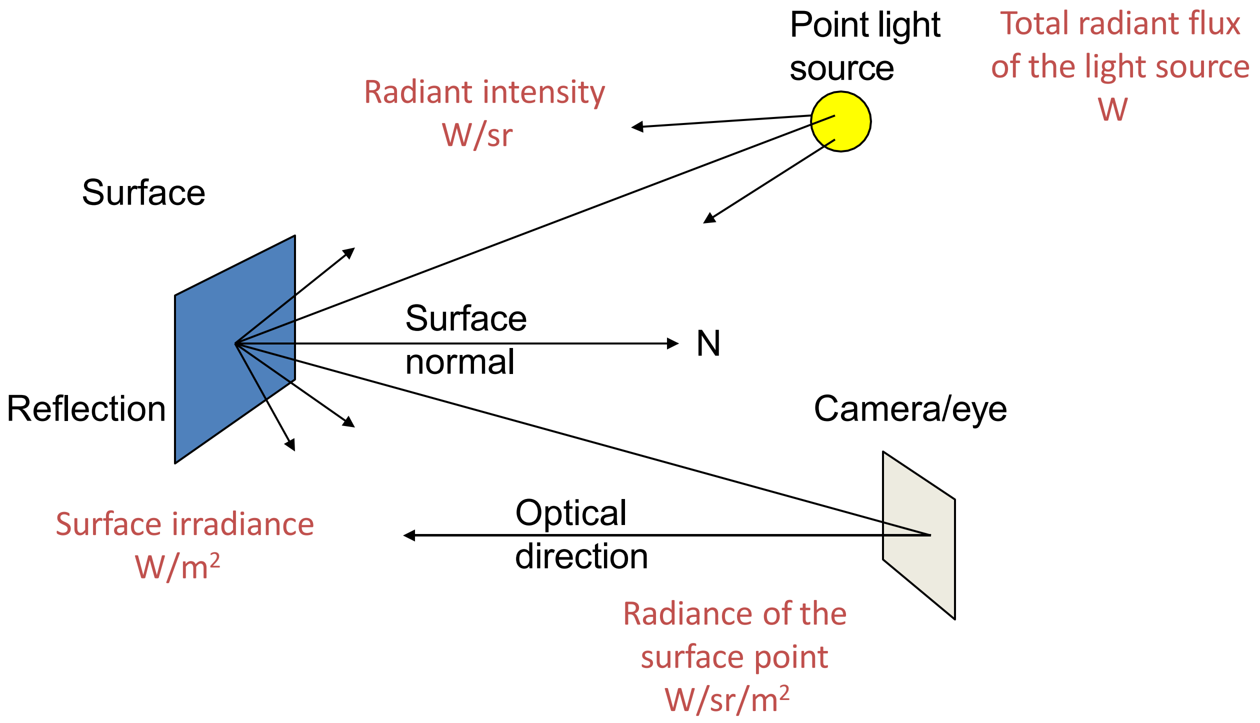
- Radiometry is the science of measuring electromagnetic radiation
  - Including visible light

- Radiometry does not consider the peculiarities of human perception
- Based on radiation as a flow of particles (geometric optics)
- However, it is possible to take some elements of wave optics into account

Light propagation



Radiometric units



Radiometry: base assumptions

- **Linearity**

  The total effect of two input signals is always equal to the sum of the effects of each signal separately
- **Conservation of energy**

  After transformation, an energy cannot produce more energy than it was initially
- **No polarization**

  The only property of light is its wavelength distribution (frequency distribution)
- **No fluorescence and phosphorescence**

  The behavior of light at one wavelength (frequency) is independent of the behavior at another
- **Stationary process**

  The distribution of light energy is independent of time

Radiometry: limitations

Impossible to measure some physical effects :

- Diffraction
- Interference
- Polarization
- Fluorescence
- Phosphorescence

(However, the last three can be accounted)

Radiant energy

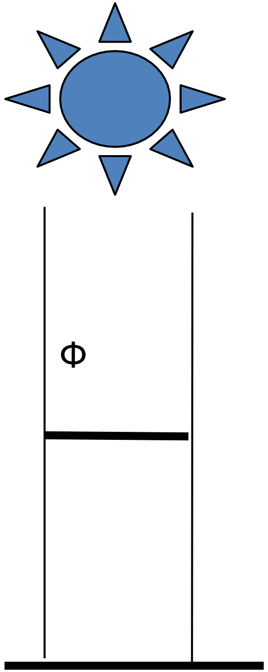
Notation: **Q**

Units: **J** (Joule)

- Not too handy as have to account the whole energy emitted by body (e.g., when being heated)
- Have to describe the properties of the energy flow:
  - Velocity
  - Direction
  - Density
  - etc.

Radiant flux

Flux is the energy emitted per unit of time for a given surface



- Notation: **Φ**
- $\Phi = dQ / dt$
- Units: **W**
  (Watt = Joule/Second)
- Stationary process

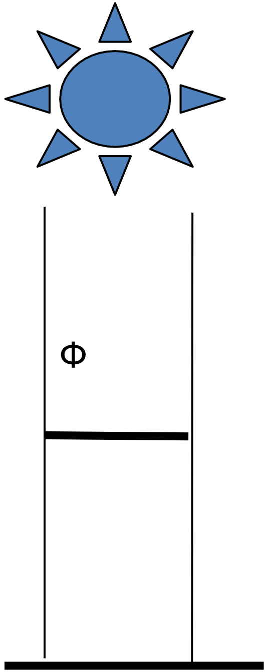
Radiant flux: measuring

- Place the light source

- Measure the change in the temperature of the plate at a given time interval

$$Q = cm\Delta T$$
$$\Phi = Q/\Delta t$$

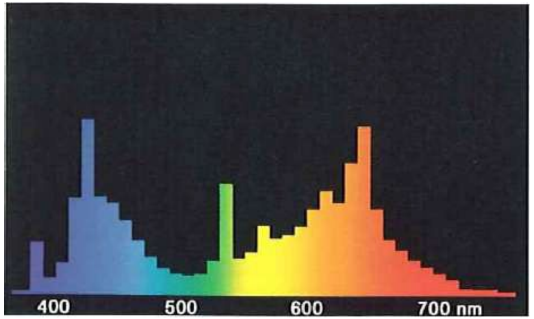
c - specific heat capacity

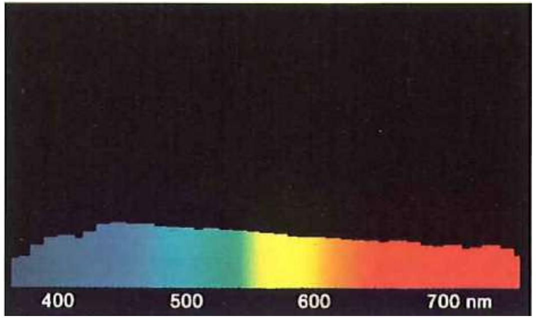


Radiant flux spectral density

- Φ defines the total characteristic over all wavelengths
- Φ_λ defined the radiant flux at a given wavelength

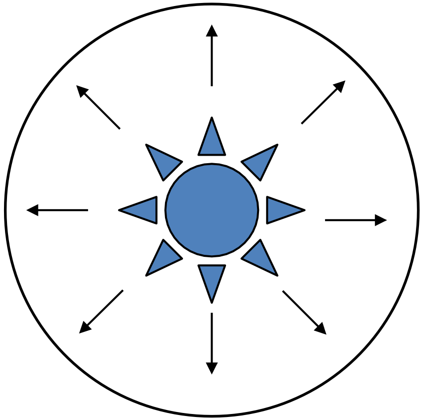
$$\Phi = \int \Phi_\lambda \, \mathbf{d}\lambda$$





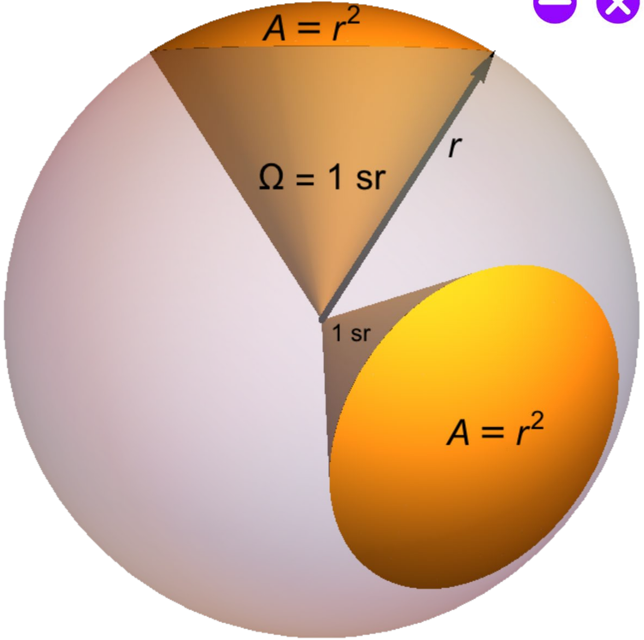
Total radiant flux

- It is often necessary to measure the total radiant flux of a light source
- The entire amount of energy emitted by the body over a period of time (exposure)
- Characterizes the light source, cannot be enlarged, only concentrated
- More detailed values are needed
  - Distribution by direction
  - Distribution by area



Solid angle

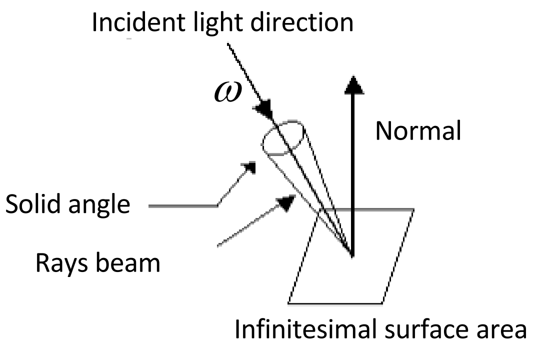
- The part of the space
  - Is the union of all rays emanating from a given point
  - And intersecting some surface
- Equal to the area of a segment of a unit sphere corresponding to the projection of the surface onto this sphere
- The whole sphere's solid angle is 4π
- For a sphere of radius R and projection area S, the solid angle is equal to S/R^2
- Units: *steradian (sr)*



https://commons.wikimedia.org/wiki/File:Solid_Angle,_1_Steradian.svg

Radiant intensity

- The density of the light radiant flux passing through the solid angle
- Notation: **I**
- Units: **W/sr**



$$I = \frac{d\Phi}{d\omega}$$

Connection between total radiant flux and radiant intensity

$$\Phi = \int \boldsymbol{I}\,\mathbf{d}\,\omega = \boldsymbol{I}\int \mathbf{d}\,\omega = \mathbf{4}\pi \boldsymbol{I}$$

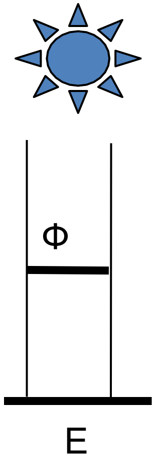
Irradiance and radiocity

- Units are needed to describe the radiant flux incident on the surface or emitted from the surface
- The density of the light radiant flux passing through a given area
- Since we don't know the direction of the light propagation, two symmetrical terms are used
  - irradiance for incident light
  - radiant exitance (radiocity) for emitted light

Irradiance

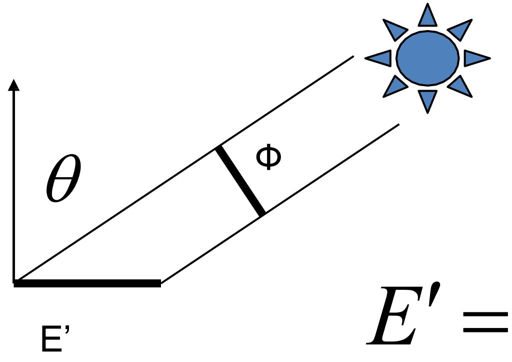
- Notation: **E**
- Units: **W/m²**
  (Watts per square meter)

$$E = \frac{d\Phi}{dS}$$

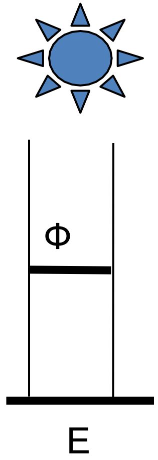


Irradiance and ”cosines law”

- In many lighting models, *cosines* is used as a multiplier
- True for parallel beams

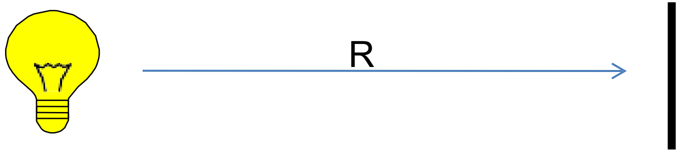


$$E' = E\cos\theta$$



Irradiance and radiance intensity: the inverse square law

Let a plane with an area A be illuminated by a point light source at a distance R

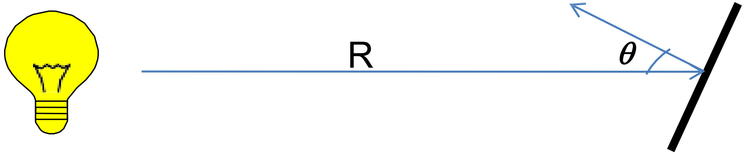


$$E = \frac{d\Phi}{dA} = \frac{I\,d\omega}{dA} = \frac{I\,dA}{R^2\,dA} = \frac{I}{R^2}$$

$$d\omega = \frac{dA}{R^2}$$

The inverse square law and "cosines" law

- Let a plane with an area A be illuminated by a point light source at a distance R
- At an angle θ *(theta)*



$$E = \frac{\mathrm{d}\Phi}{\mathrm{d}A} = \frac{I\,\mathrm{d}\omega}{\mathrm{d}A} = \frac{I\,\mathrm{d}A\cos\theta}{R^2\,\mathrm{d}A} = \frac{I\cos\theta}{R^2}$$

$$\mathrm{d}\omega = \frac{\mathrm{d}A\cos\theta}{R^2}$$

Radiant exitance

- Notation: **M**
- Units: **W/m²**
  (Watts per square meter)

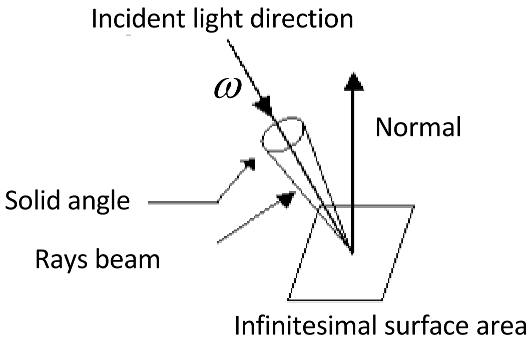
- Also called **radiosity**

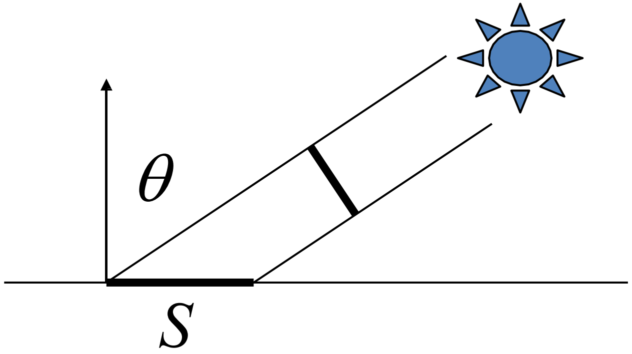
$$M = \frac{d\Phi}{dS}$$

Radiance

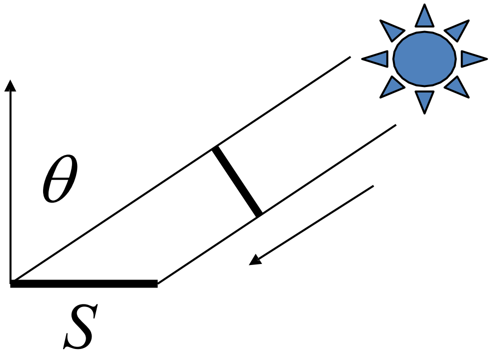
- The most important unit
- Arbitrary light source
- The density of the radiant flux incident at the unit area site, passing through a unit solid angle
- Notation: **L**
- Units: **W / (sr * m²)** (Watts per steradian per square meter)

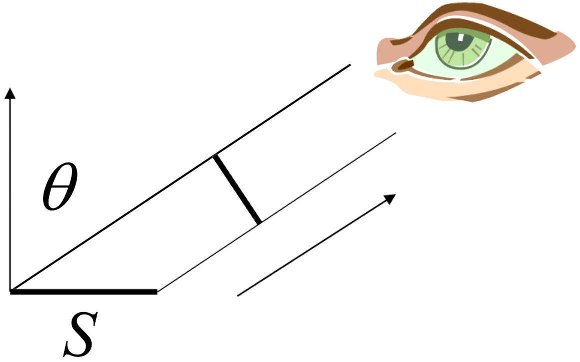
$$L = \frac{d^2\Phi}{d\omega dS \cos\theta}$$





Incident and emitted radiance





Connection between radiometric units

Radiance

Radiant intensity

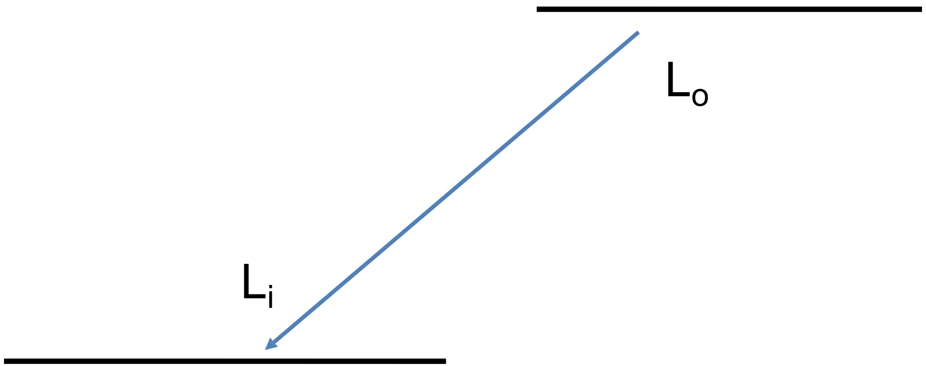
Irradiance

Radiosity

$$L = \frac{dI}{dS\cos\theta} = \frac{dE}{d\omega\cos\theta} = \frac{dM}{d\omega\cos\theta}$$

Radiance properties

- Losslessly transmitted in a vacuum



- The photo camera stores the radiance values
- The human eye reacts on radiance (brightness)

Lambertian light source

- Lambertian light source have constant radiance
  L = const
- So, it looks the same from all directions

- Properties:
  - $I = I_0 \cdot \cos(\Theta)$
  - $M = \pi \cdot L$
  - A luminous flat disk is indistinguishable from a hemisphere
    - Sun is a Lambertian light source

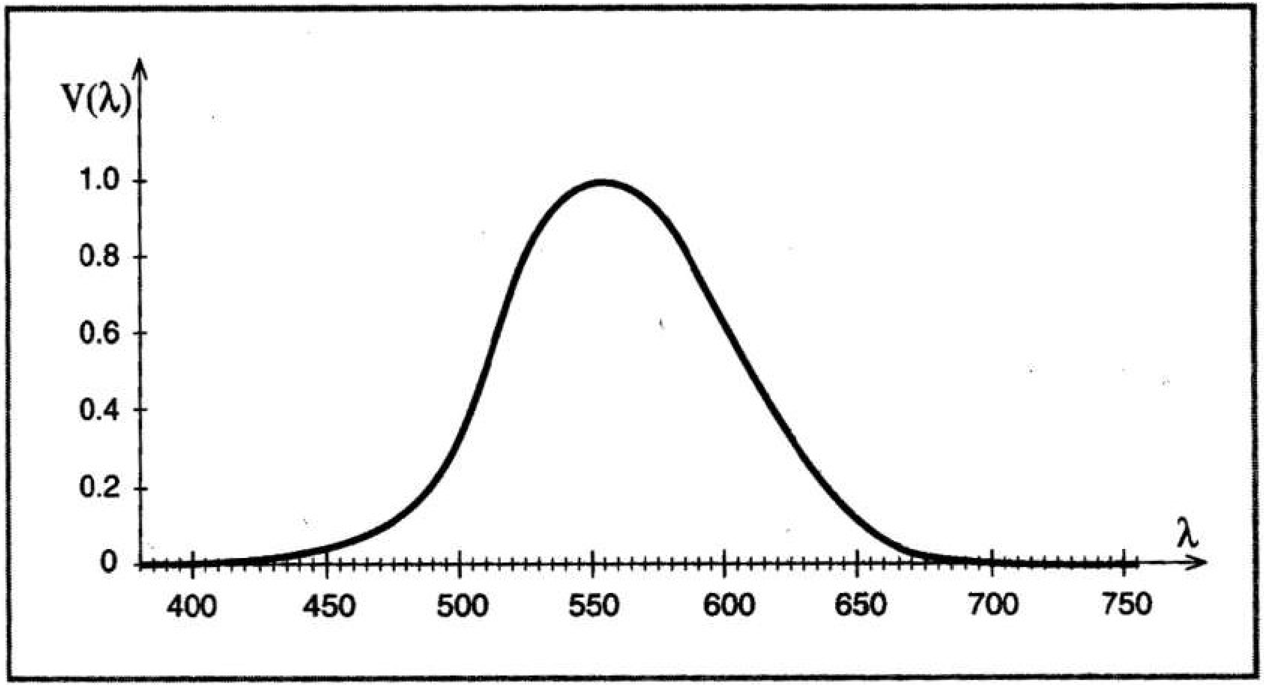
Sample radiometric values

Name	Value
The total radiant flux of gas-filled tungsten incandescent lamp	82 W
The radiant flux of a typical helium-neon laser of medium power at 632.8nm	5 mW
The radiant flux of typical 40W daylight lamp	23.2 W
The beyond atmospheric irradiance at a mean earth orbit	1267 W/m^2
The direct irradiance of the Earth, clear sky, winter, South-East of the US, midday	852 W/m^2
The hemispherical irradiance of the Earth, clear sky, winter, South-East of the US, midday	686 W/m^2
The radiance at the Sun surface	2.3e7 $W/m^2/sr$
The visible radiance of the Sun from the Earth	1.4e7 $W/m^2/sr$

Photometry

- Photometry can be considered of as a subset of radiometry in which all radiometric units have been modified to account for the sensitivity of the human eye

Spectral luminous efficiency function V(λ)



Conversion between radiometric and photometric units

$$Q_v = 683 \int_{380}^{780} Q_\lambda V(\lambda)\,\mathrm{d}\lambda$$

Q_v – one of units Φ, I, E, M, L

Luminous flux

- Luminous flux – lm (*lumen*)
  - Radiant flux (W, Watt) assessed by human eye visual perception
  - Radiant flux weighted by the spectral luminous efficiency function

Luminous intensity

- Luminous intensity - cd (*candela*, lm/sr)
  - Historically, It was measured with an "etalon candle"

- If light source luminous intensity is equal to 1 cd in all directions, then the total luminous flux is equal to 4π lm

- The coefficient 683 that we met before comes exactly from the definition of the candela, so that 1 candela is approximately equal to the luminous intensity of a candle

Illuminance

- Illuminance – lx (*lux*, lm/m^2)
  – Irradiance - W/m^2

Luminance

- Luminance – nit ($cd/m^2/sr$)
  - Radiance - $W/m^2/sr$

Radiometric and photometric units

Radiometric units	Units	Photometric units	Units
Radiant flux	W	Luminous flux	**lm (lumen)**
Radiance intencity	W/sr	Luminous intensity	**cd (candela)** = lm/sr
Irradiance, radiocity	W/m^2	Illuminance, luminocity	**lx (lux)** = lm/m^2
Radiance	$W/m^2/sr$	Luminance	**nit** = $cd/m^2/sr$

Additional reading

- DeCusatis, C., "Handbook of Applied Photometry."
  AIP Press (1997)
- McCluney, W. R., “Introduction to Radiometry and Photometry”,
  Artech House (1994)

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FOR YOUR TIME!

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