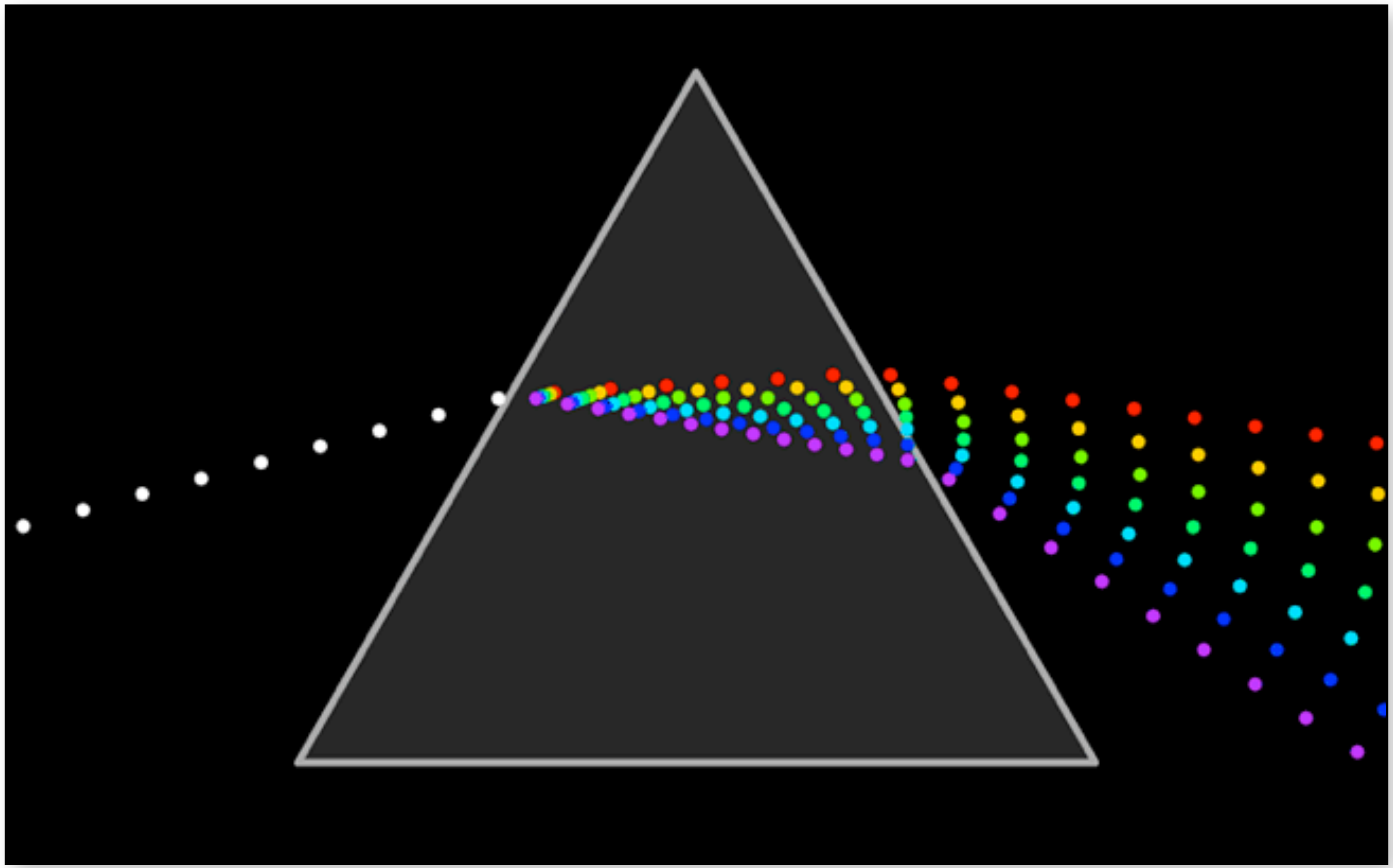
Rendering Algorithms

Light



Prof. Wojciech Jarosz

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(with slide improvements from Jan Novák)

Dartmouth

Basic Ray Tracing Pipeline

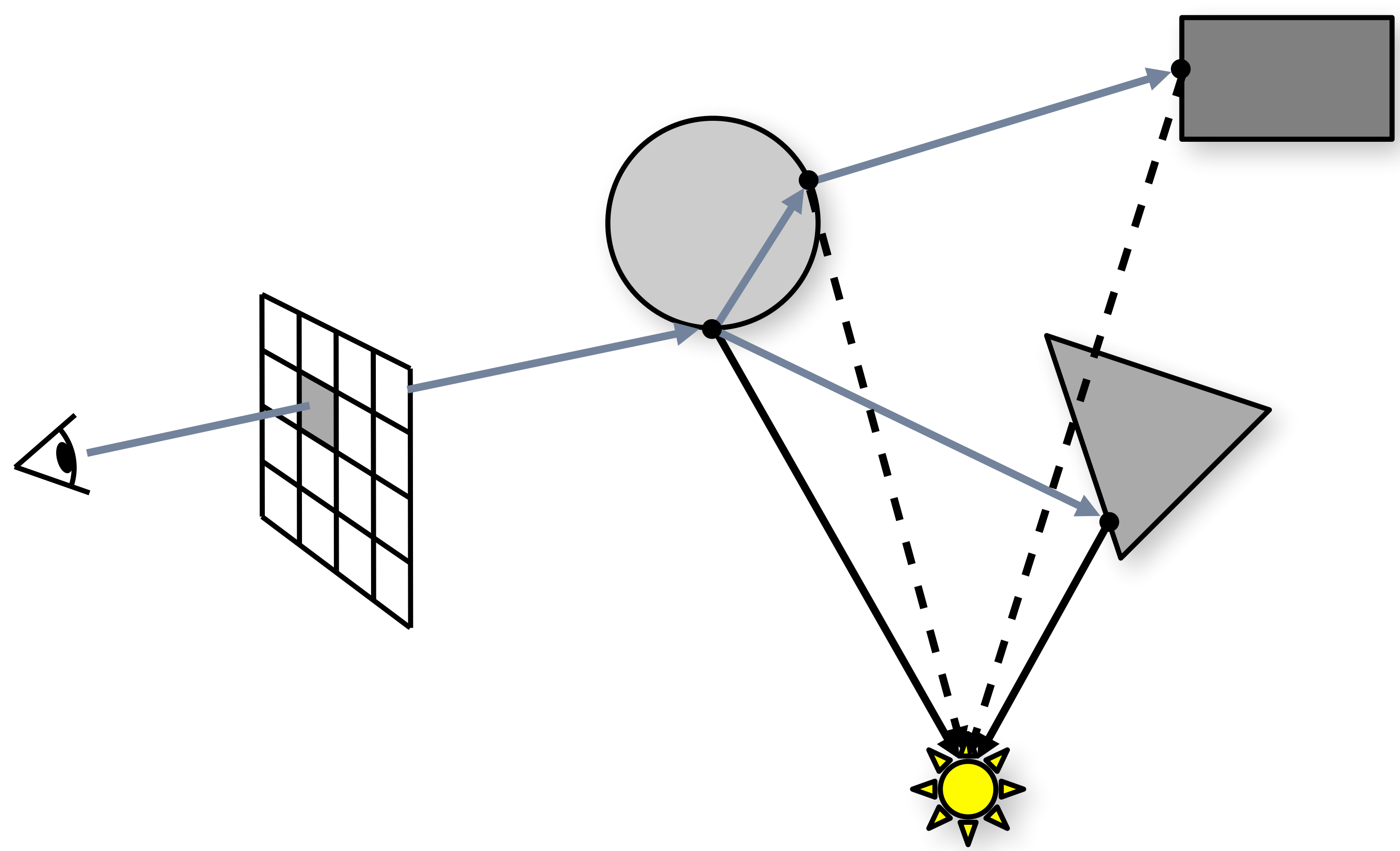
Ray Generation

↓

Intersection

↓

Shading



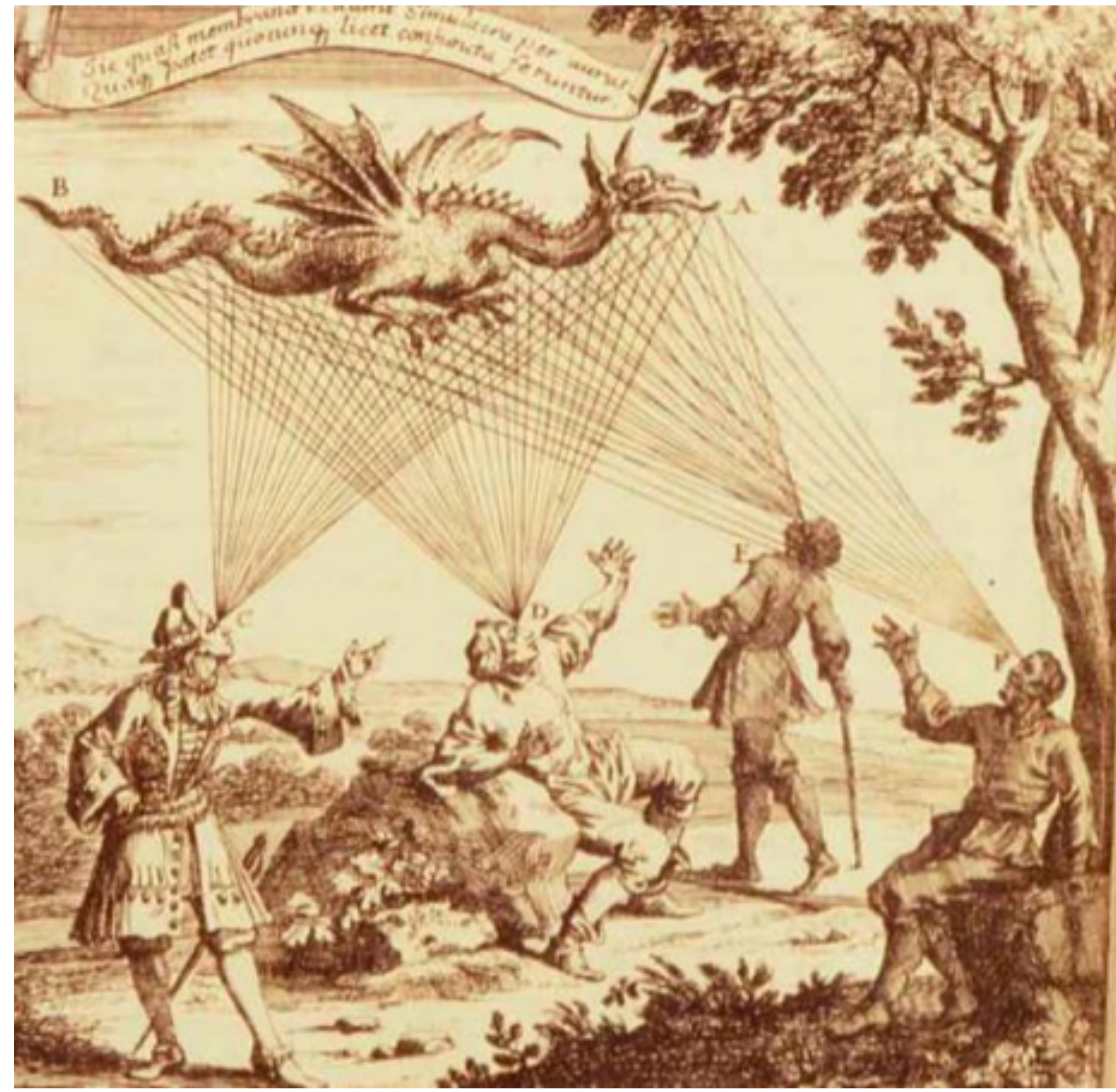
Today's Menu

- Light Theories - historical introduction
- What is light, how is it created?
- How do we quantify light?

Light Theories

Divine Fire (350 BC)

Plato Aristotle



Reflection of Light (300 BC)

Empodocles

Euclid

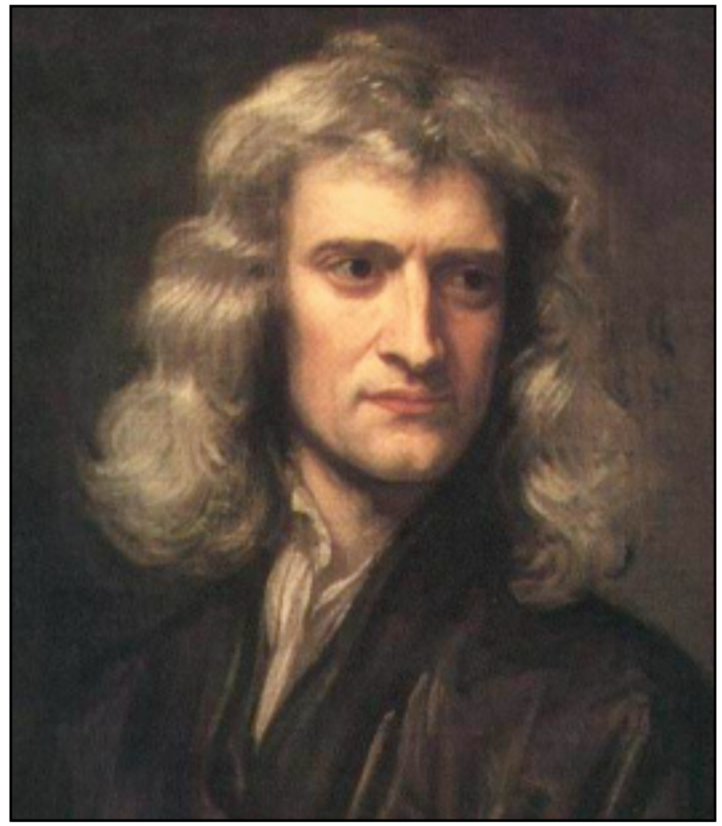
Refraction of Light (1621, 1657)

Snell

Fermat

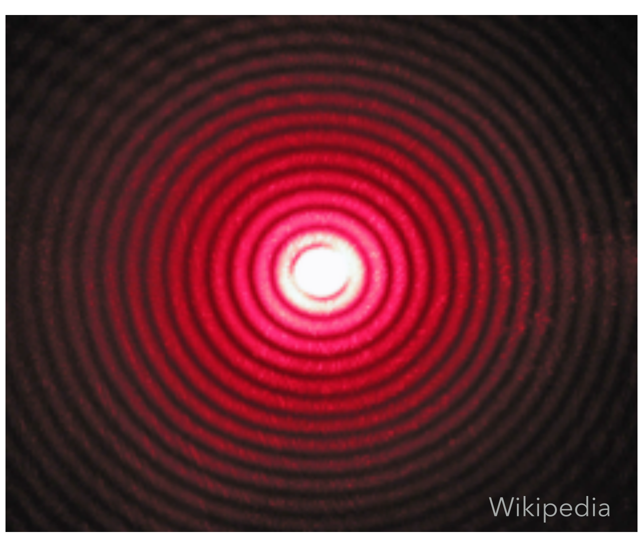
Bending, Dispersion, Polarization

Grimaldi



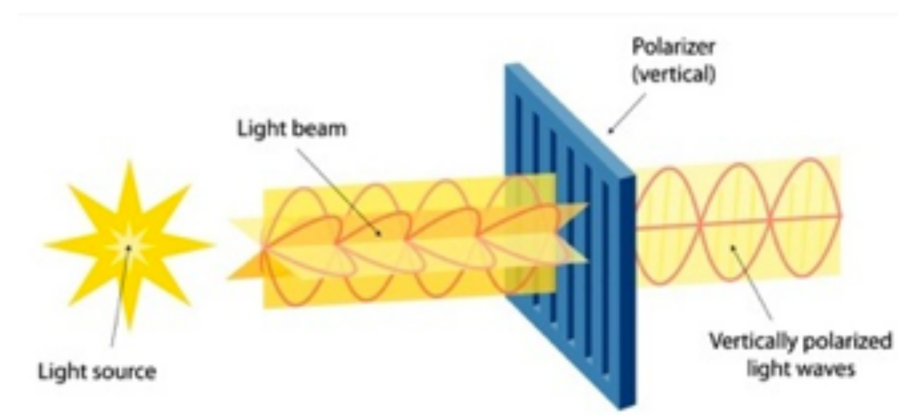
Newton

Huygens



Wikipedia

Adam Hart-Davis



www.physics.louisville.edu

Race for a Comprehensive Theory

Huygens

Wave Theory

- first enunciated by Aristotle
- space filled with elastic aether
- every wave point acts as a source of a new wave
- explains diffraction, interference, polarization

Newton

Corpuscular Theory

- first enunciated by Democritus
- everything (including light) consists of particles
- predicted faster speeds in optically thicker media
- explains photoelectric effect

Light Emission

Light Emission

- Incandescence
  - Blackbody radiation
- Luminescence
  - Atomic emission
  - Molecular emission
  - Stimulated emission
  - Florescence / Phosphorescence
  - Chemiluminescence / Bioluminescence

Incandescence

- Visible light produced from heat

A Blackbody

- A hypothetic body that completely absorbs all wavelengths of thermal radiation incident on it. Such bodies do not reflect light, and therefore appear **black** if their temperatures are low enough so as not to be self-luminous.
- Thermal equilibrium requires all blackbodies heated to a given temperature to emit thermal radiation with the same spectrum.

source: wolfram.com

Blackbody Emission

- Thermal vibrations cause atoms & molecules to emit photons across a continuous spectrum
- In a perfect blackbody, the color spectrum of the emission is defined purely by the temperature of the material
- The spectrum is given by Planck's law

Planck's Law

- Planck's Law:

$$L_\lambda(T) = \frac{2hc^2}{\lambda^5 \left(e^{\frac{hc}{\lambda k_B T}} - 1 \right)}$$

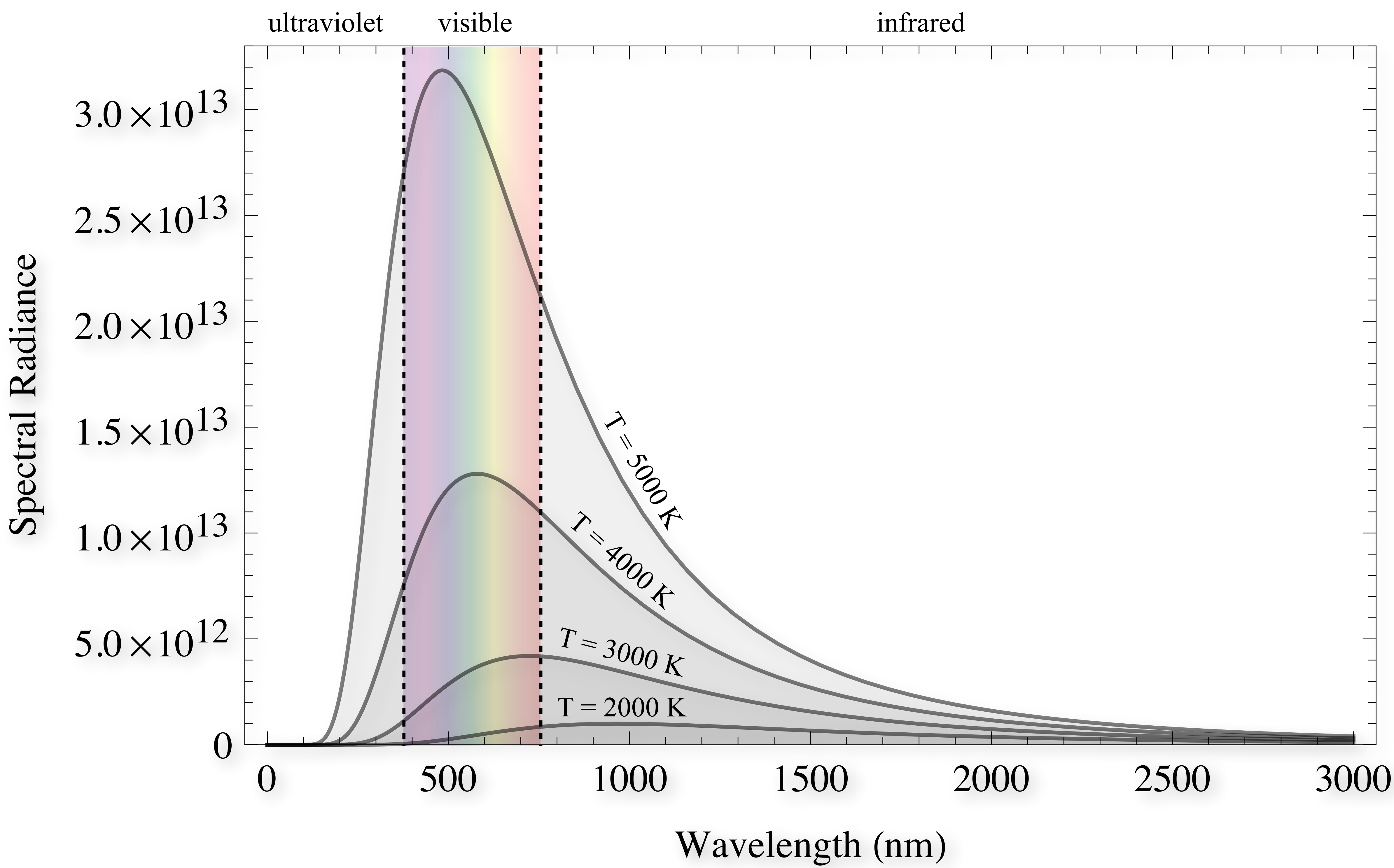
where:

$$c \approx 2.998 \times 10^9 \text{ m} \cdot \text{s}^{-1} \qquad \text{(speed of light in vacuum)}$$

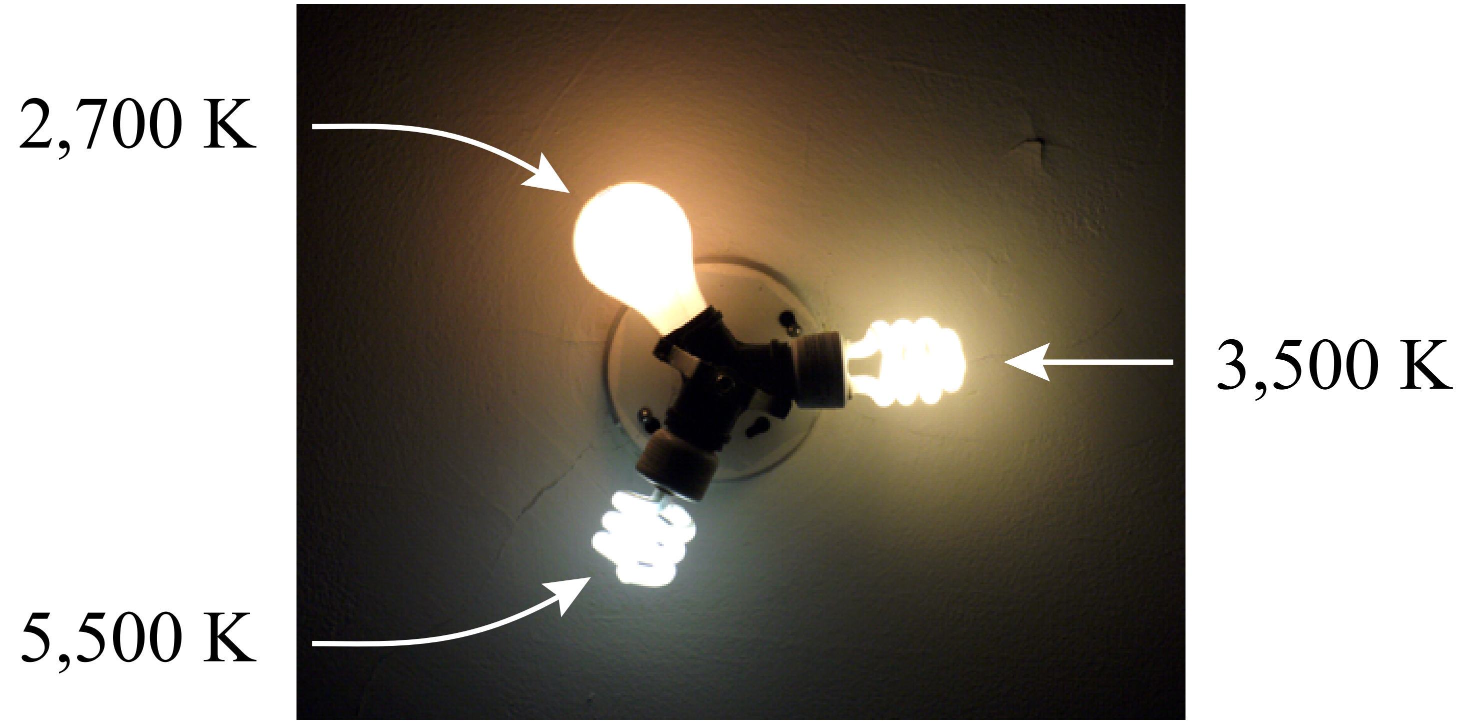
$$h \approx 6.626 \times 10^{-34} \text{ J} \cdot \text{s} \qquad \text{(Planck's constant)}$$

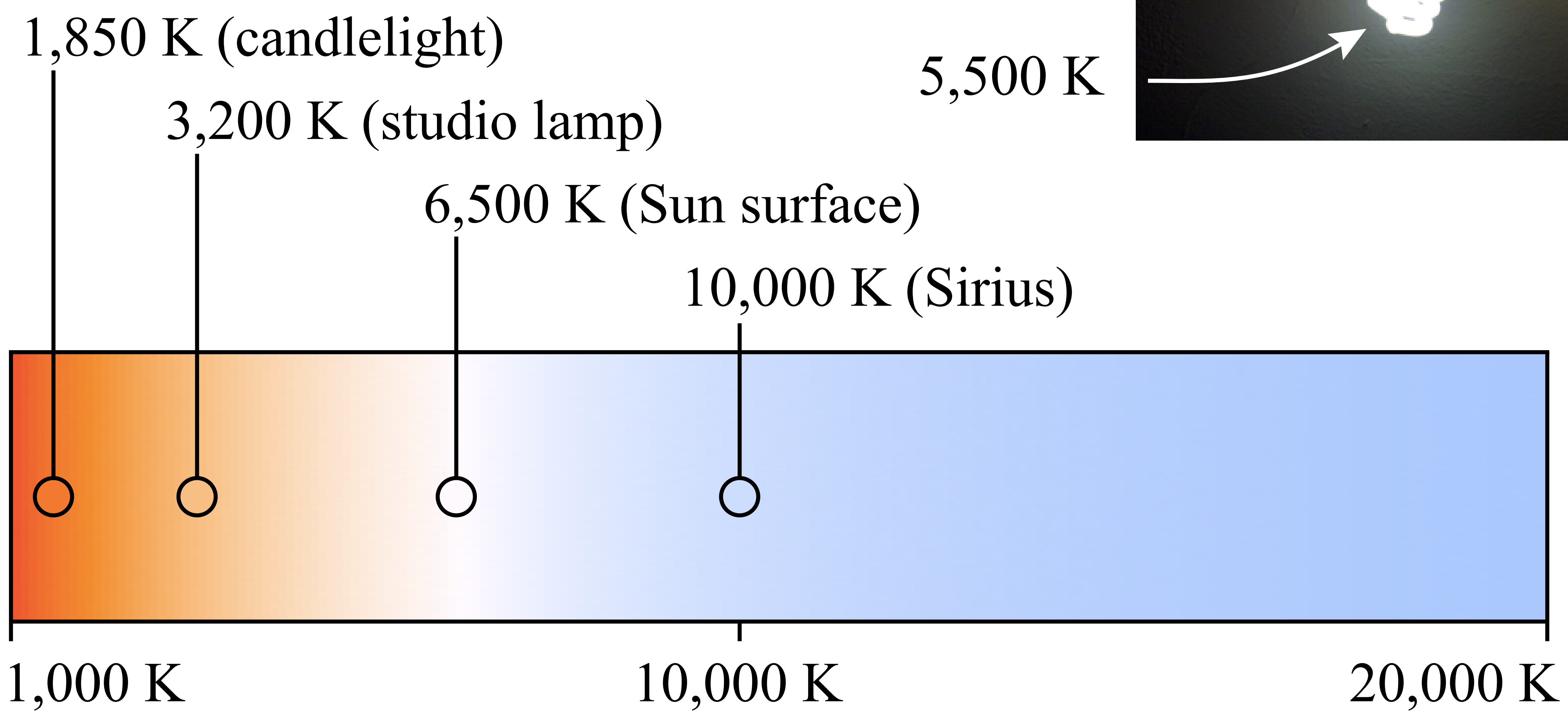
$$k_B \approx 1.381 \times 10^{-23} \text{ J} \cdot \text{K}^{-1} \qquad \text{(Boltzmann constant)}$$

Blackbody Spectrum



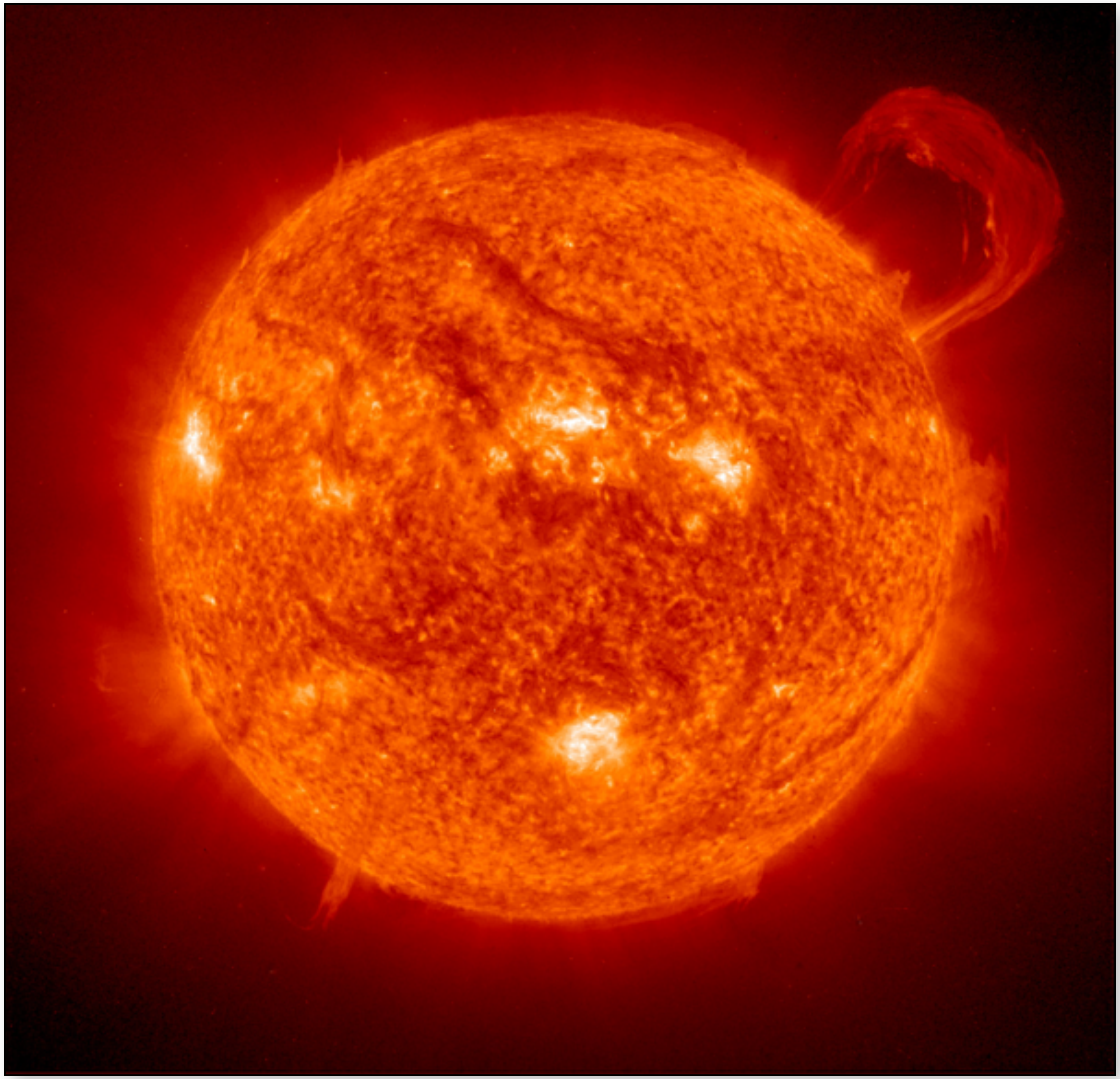
Blackbody Examples





Blackbody Examples

Blackbody Examples

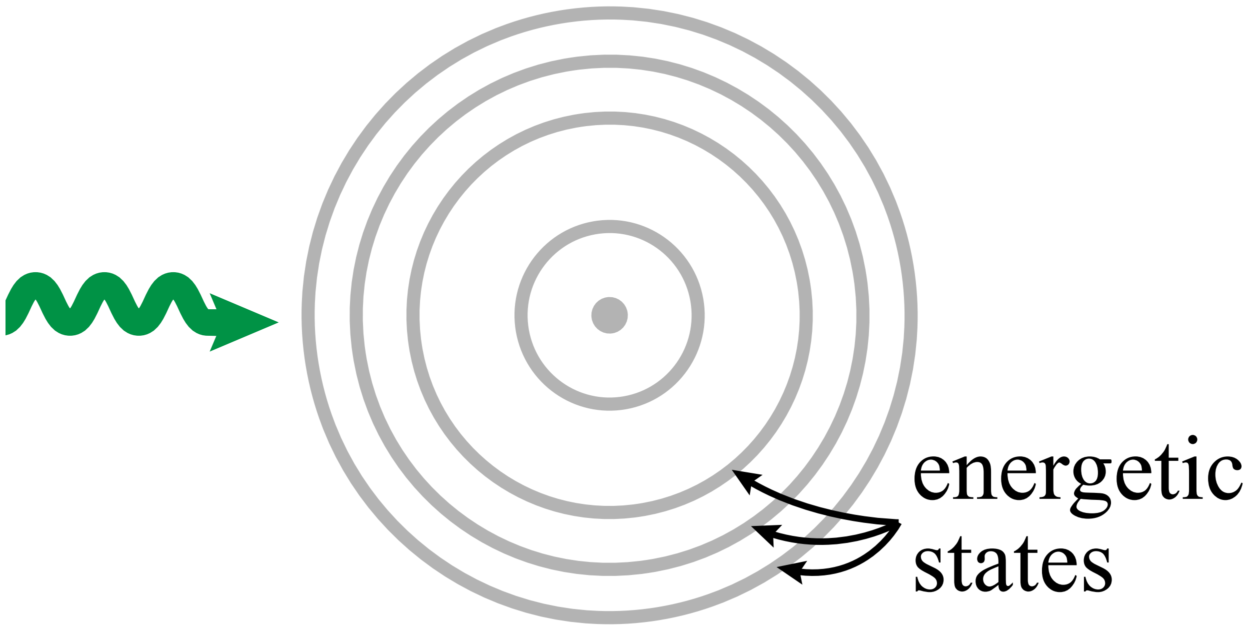


Blackbody Examples

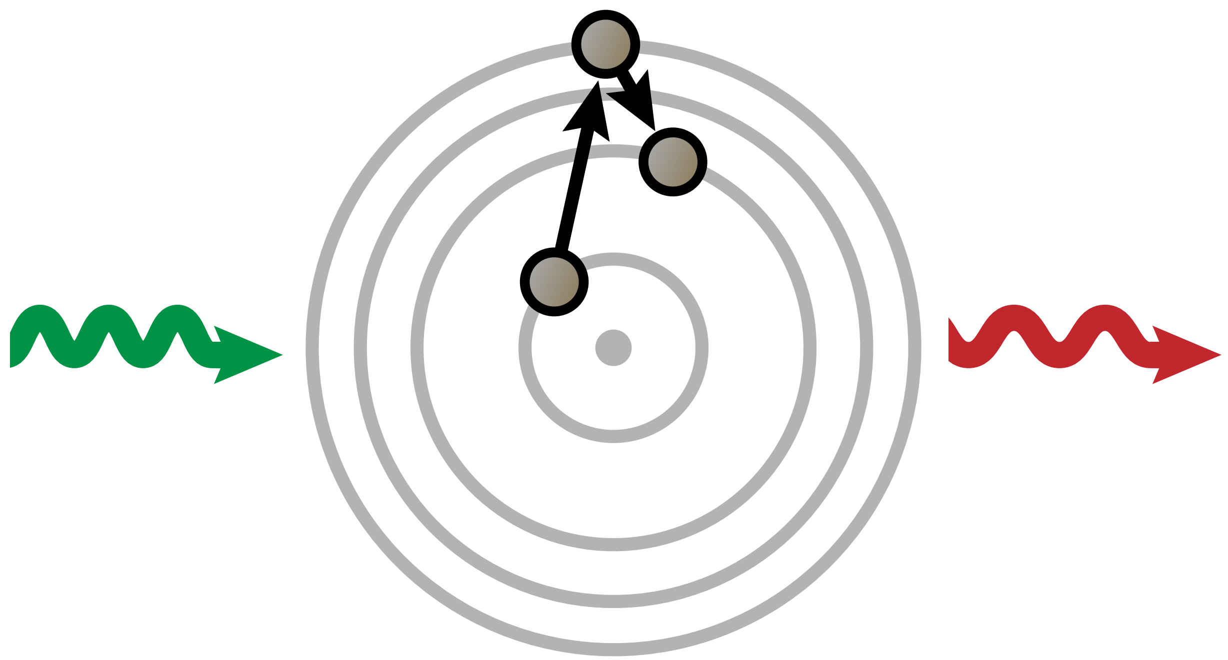
Luminescence

- Emission of light by a substance not resulting from heat
- Can be caused by chemical reactions, electrical energy, subatomic motions, or stress on a crystal.

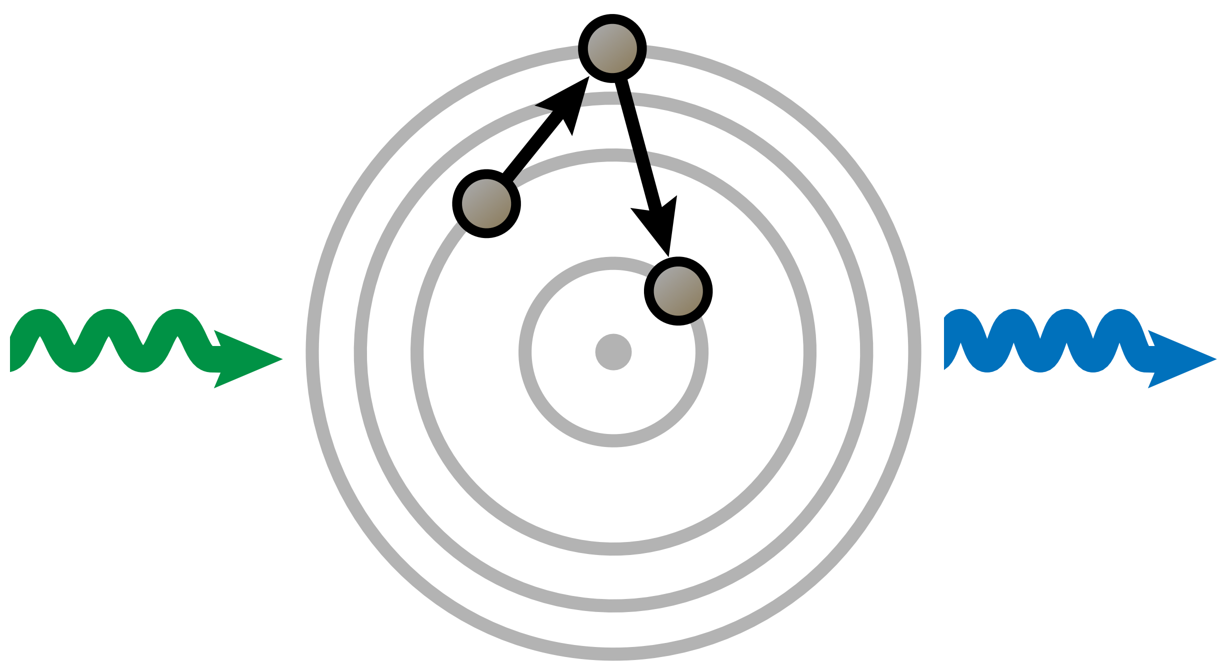
Atomic Emission



Atomic Emission

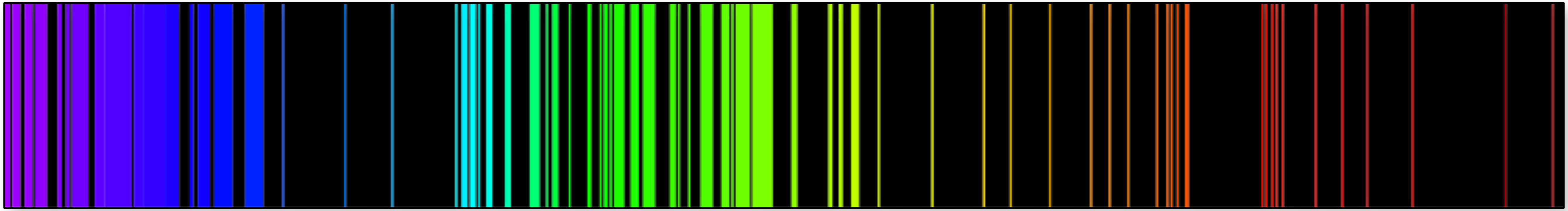


Atomic Emission



Atomic Emission

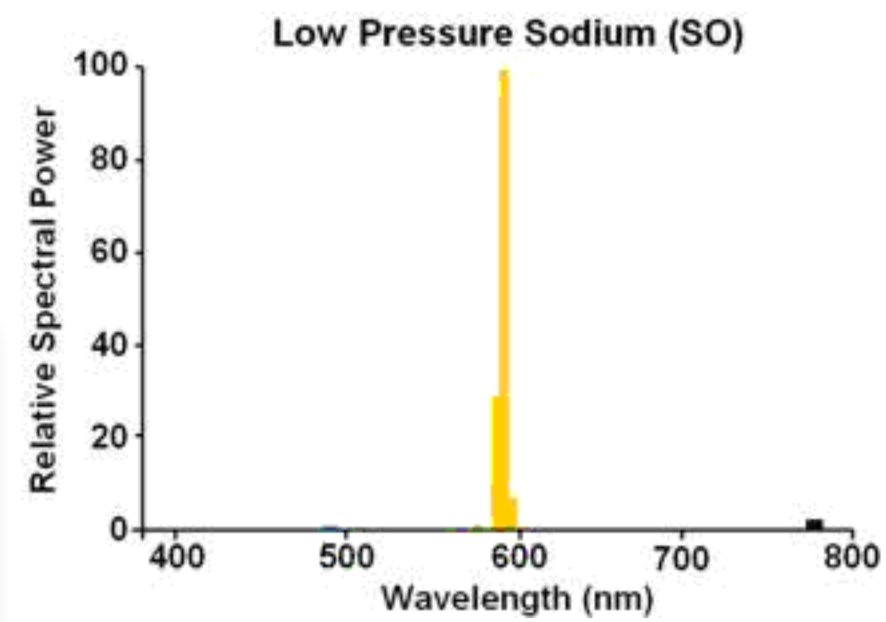
Emission spectrum of Hydrogen



Emission spectrum of Iron

Sodium Vapor Lights

Light emitted at 589nm and 589.6nm



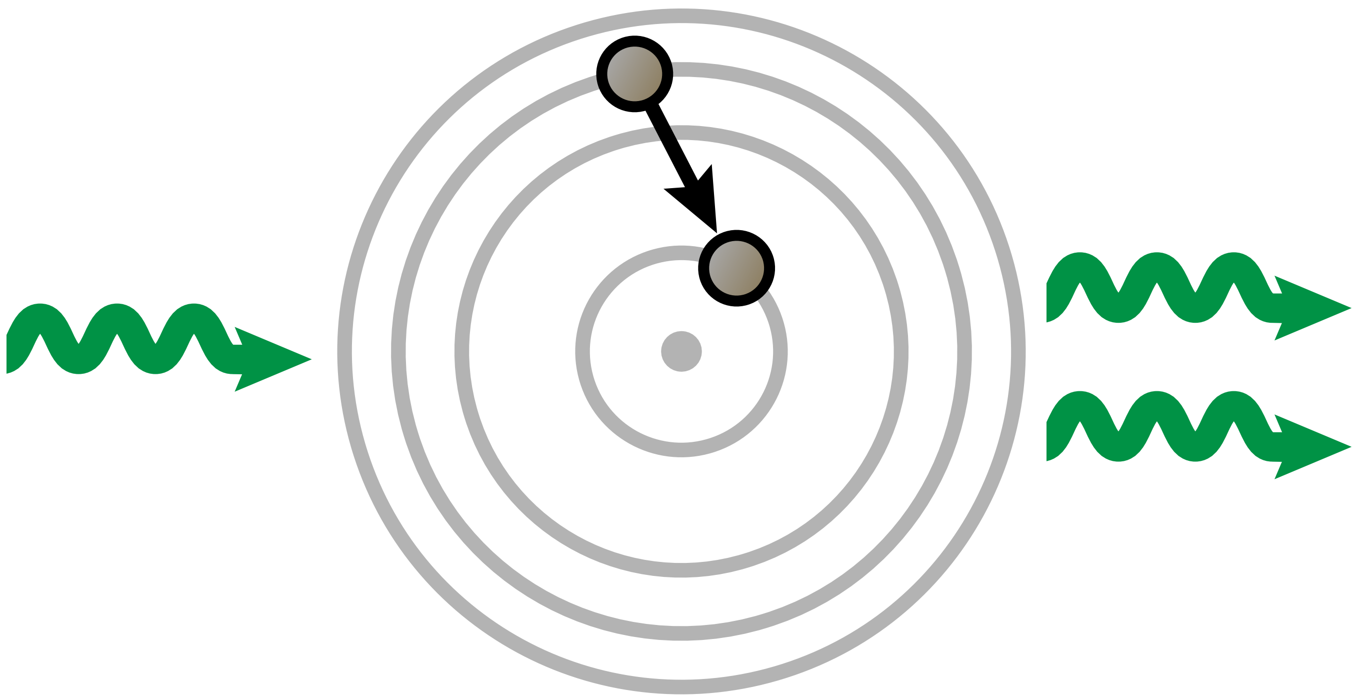
Molecular Emission

- Similar to atomic emission, but due to internal vibrational degrees of freedom, the orbital energy levels are not as precise
- With molecular emission photons are emitted in narrow bands rather than at precise frequencies
- Examples
  - Aurora borealis (excited N_2, N_2 ions, and O)
  - Blue of a candle flame (mainly C_2 and CH_x)

Aurora Borealis

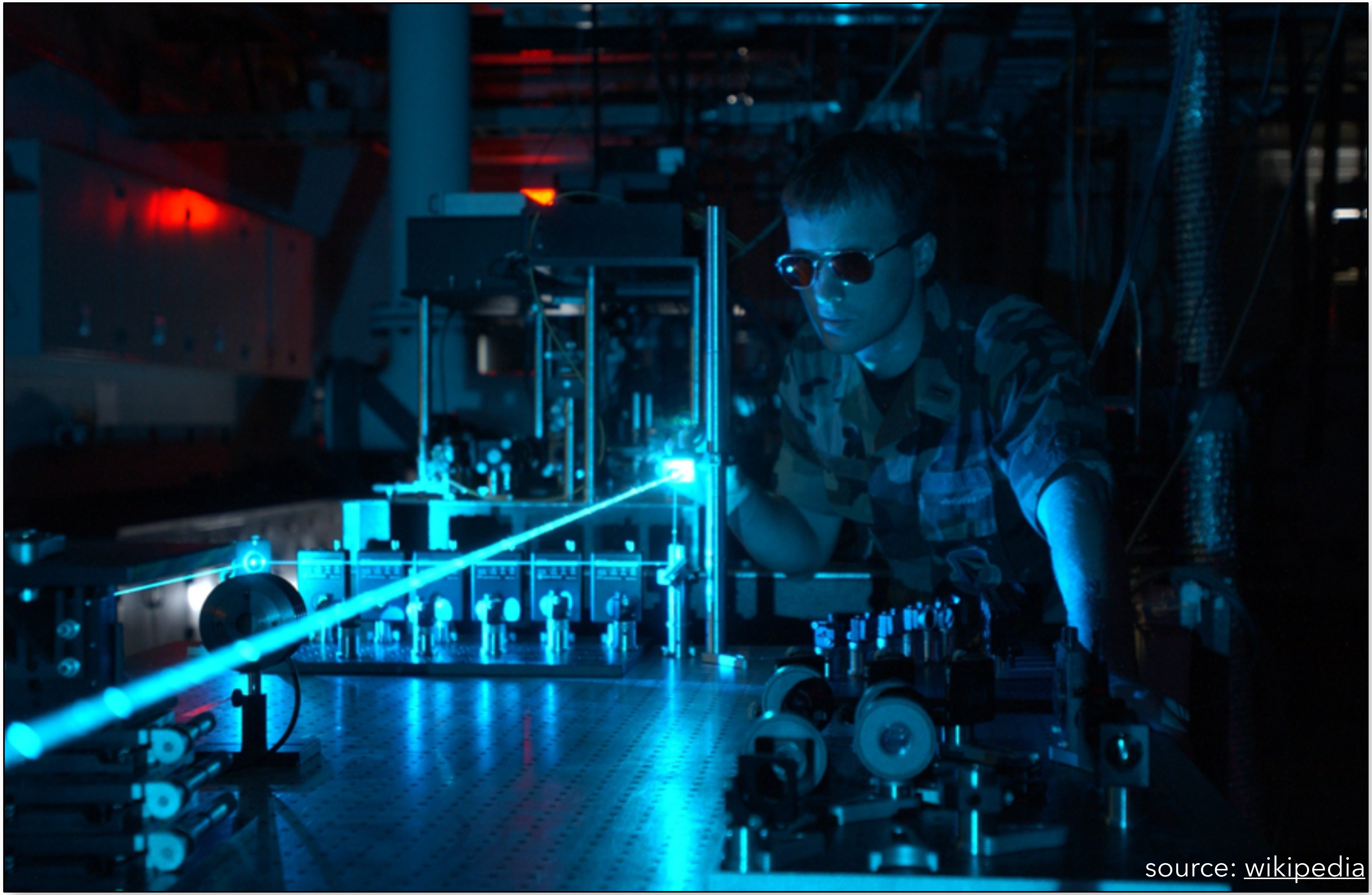
Aurora Borealis

Stimulated Emission

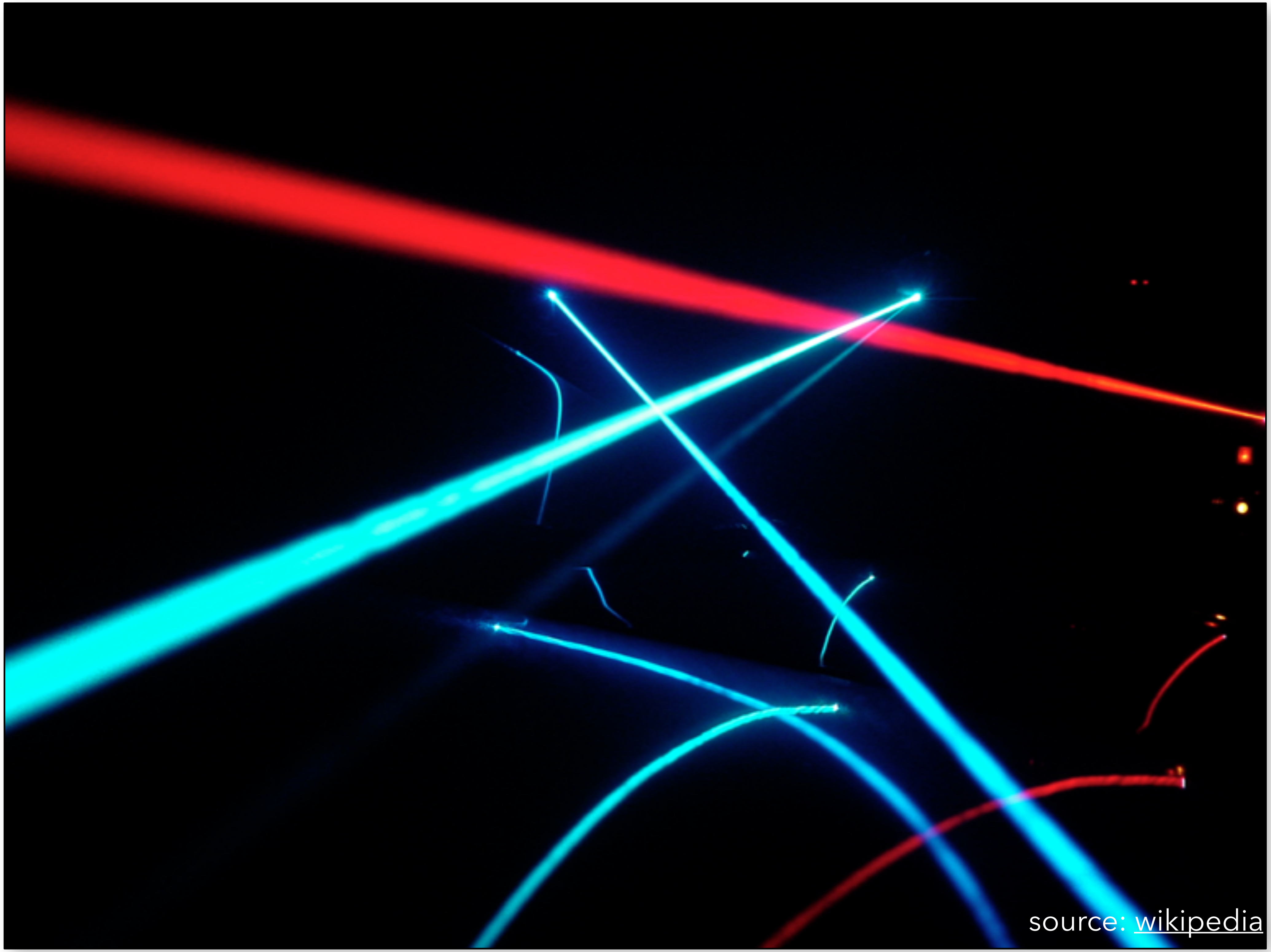


- Example
  - LASER: **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation

Lasers



Lasers



Fluorescence

- Fluorescence occurs when light striking a surface is *briefly* (10^{-8} s) absorbed and then re-emitted at a lower frequency
- Examples
  - Fluorescent lights
  - Blacklight

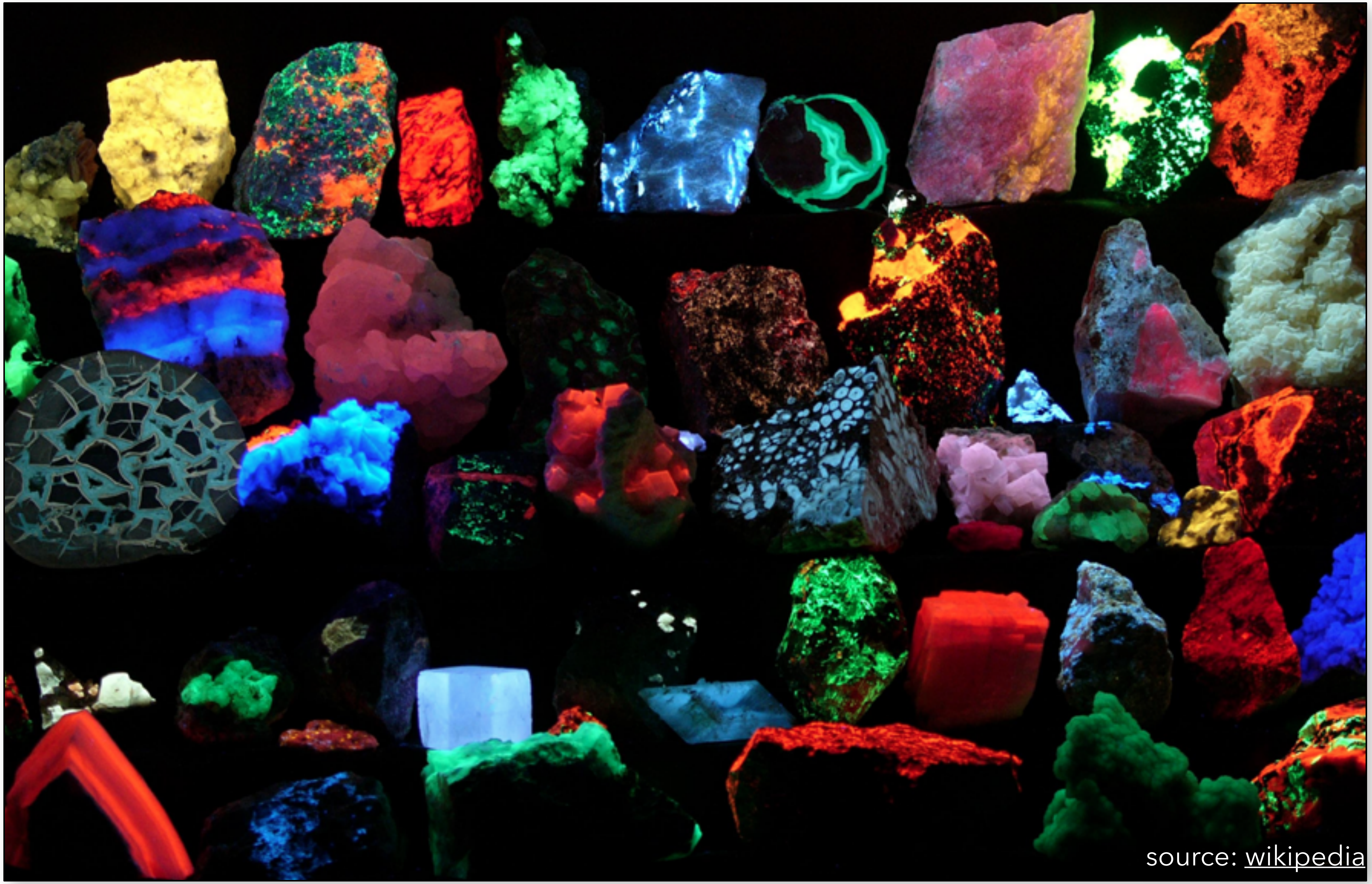
Fluorescent Lamps

- A fluorescent lamp is a type of lamp that uses electricity to excite mercury vapor in argon or neon gas, resulting in a plasma that produces short-wave ultraviolet light (254nm). This light then causes a phosphor to fluoresce, producing visible light.

Blacklights

- Blacklights are a subset of fluorescent lamps that are used to provide near ultraviolet light (at about 360 nm wavelength). They are built in the same fashion as conventional fluorescent lamps but the glass tube is coated with a phosphor that converts the short-wave UV within the tube to long-wave UV rather than to visible light.

Fluorescent Minerals under Blacklight

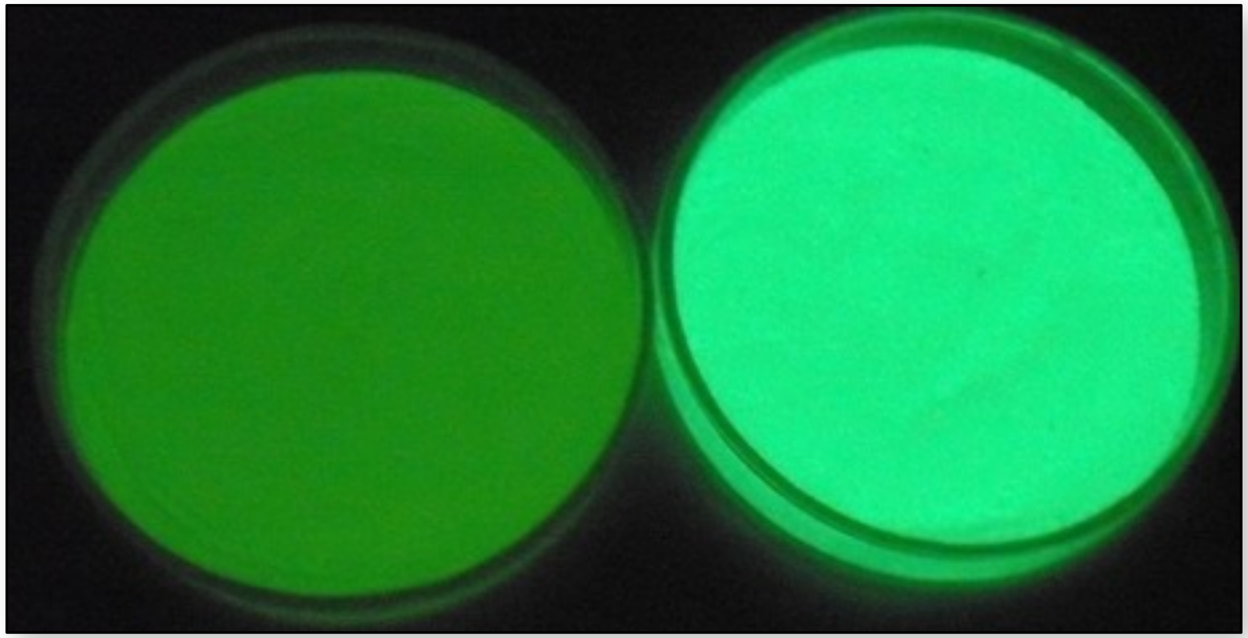


Phosphorescence

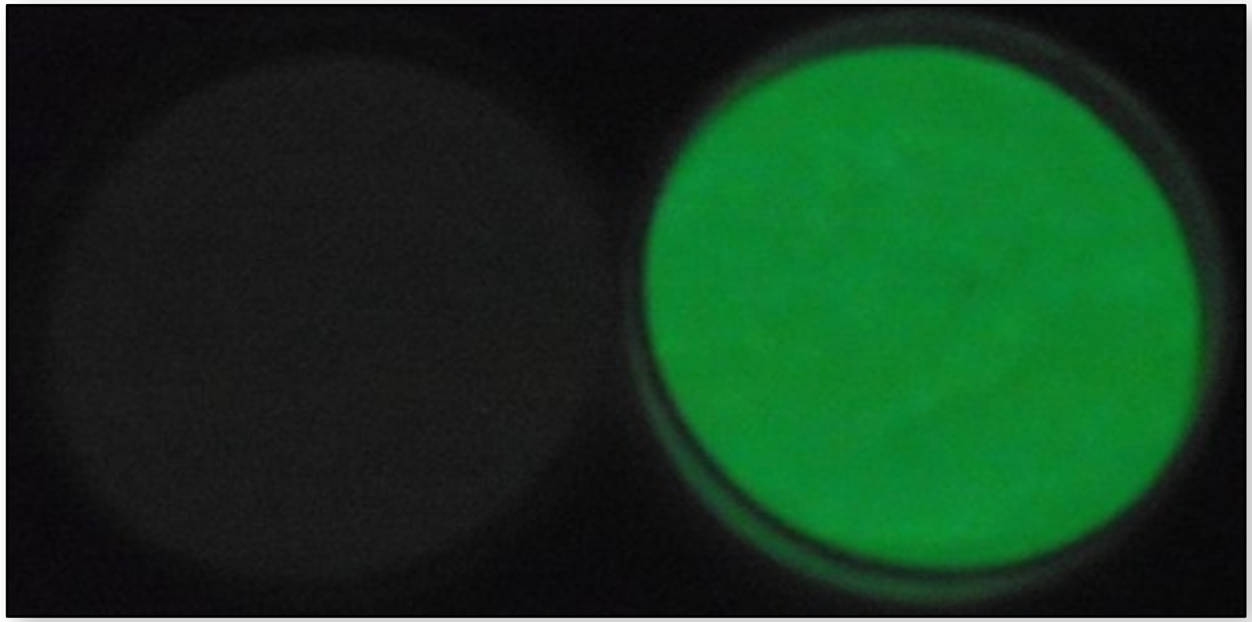
- Phosphorescence is essentially the same as fluorescence except there may be a longer delay between absorption and emission. This causes an exponential decay in emission after the source is removed. The remission is dependent on the temperature.
- Examples
  - TV (CRT) phosphors
  - Glow-in-the-dark paint

Phosphorescent Pigments

After 1 minute



ZnS vs. aluminate



After 4 minute

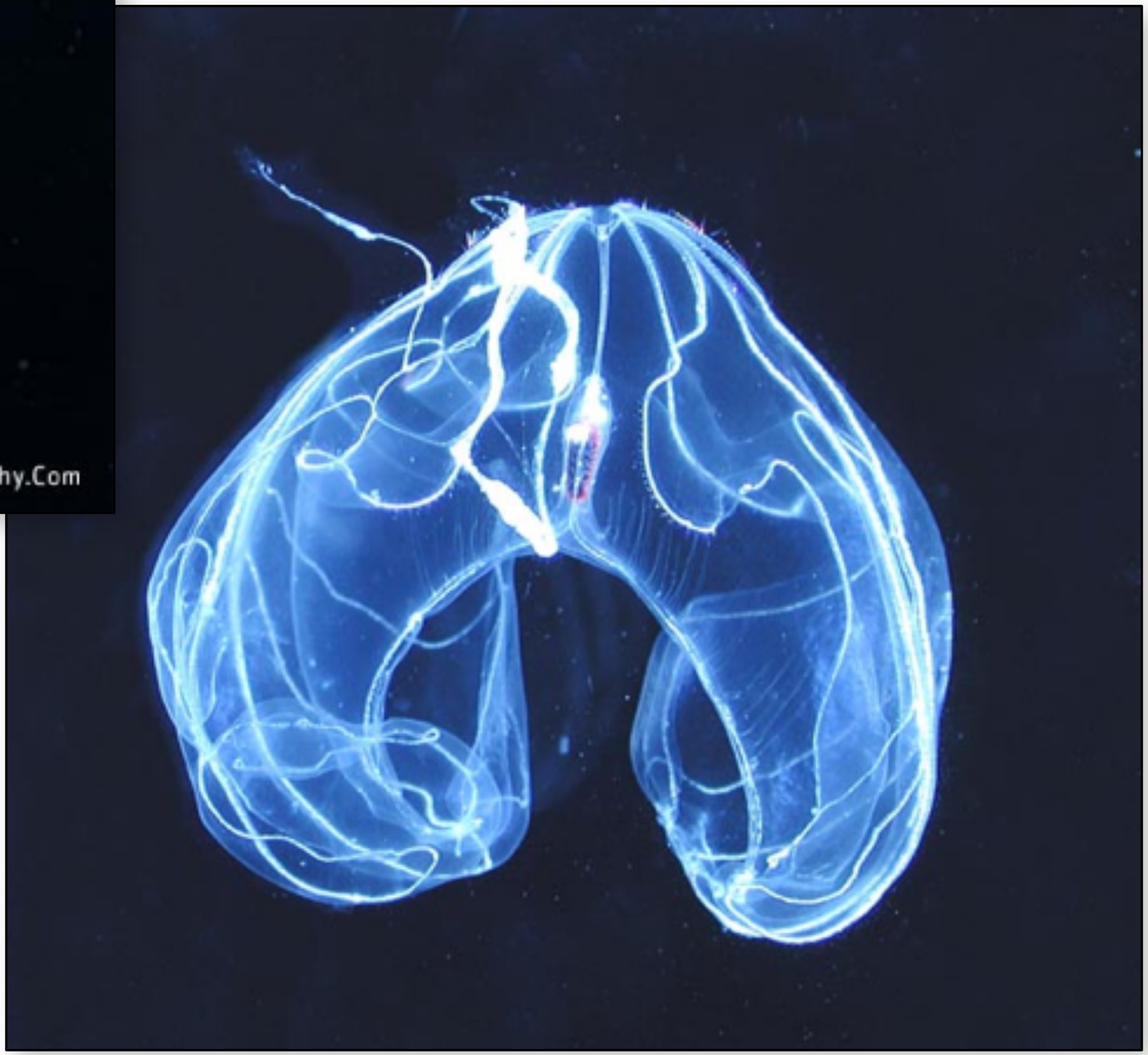
Phosphorescent Mushrooms

Chemiluminescence & Bioluminescence

- Chemiluminescence is emission of light as the result of a chemical reaction
- Bioluminescence is chemiluminescence which originates inside an organism.

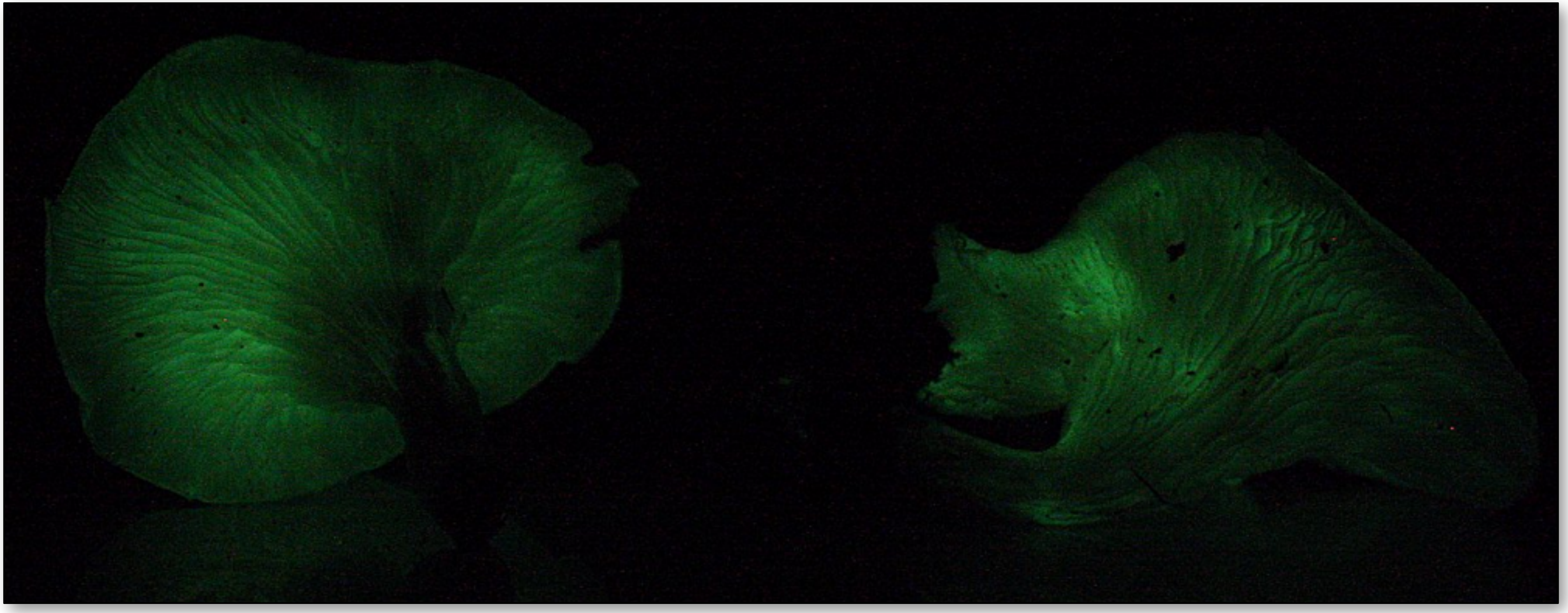
Bioluminescence

Bioluminescence



Bioluminescence

Bioluminescence



Bioluminescent Fungus

Panellus stipticus

What is this?

Noctilucales - “Sea Sparkle”

Light Emission Recap

- Incandescence
  - Blackbody radiation
- Luminescence
  - Atomic emission
  - Molecular emission
  - Stimulated emission
  - Florescence / Phosphorescence
  - Chemiluminescence / Bioluminescence

Quantifying Light

Radiometry

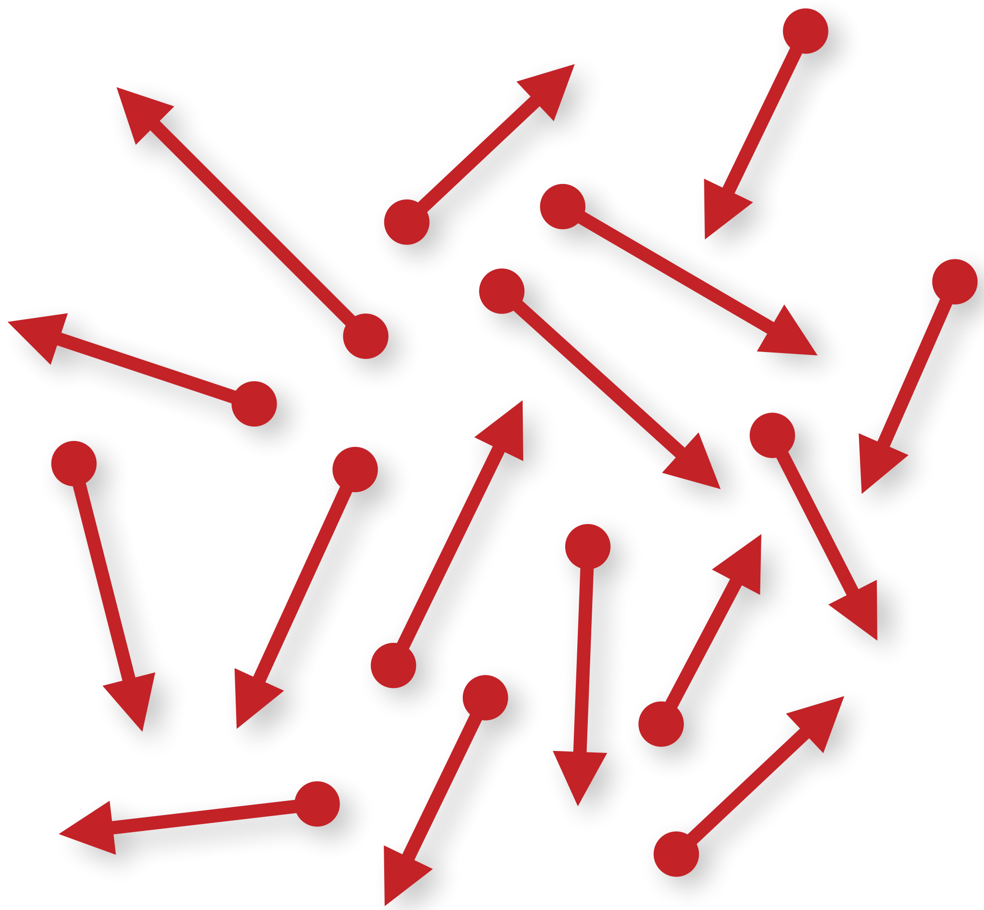
- *Radiometry* studies the measurement of electromagnetic radiation, including visible light.
- *Visible Light* is any radiation that is capable of directly causing visual sensation.
  [International Lighting Vocabulary [CIE 1987]]

Radiometry

- Assume light consists of photons with:
  - $\mathbf{x}$: Position
  - $\vec{\omega}$: Direction of travel
  - λ: Wavelength
- Each photon has an energy of: $\dfrac{h\,c}{\lambda}$
  - $h \approx 6.63 \cdot 10^{-34}\ \mathrm{m}^2 \cdot \mathrm{kg/s}$: Planck's constant
  - $c = 299,792,458\ \mathrm{m/s}$: speed of light in vacuum
  - Unit of energy, Joule: $[\mathrm{J} = \mathrm{kg} \cdot \mathrm{m}^2/\mathrm{s}^2]$

Radiometry

- How do we measure the energy flow?



- Measuring energy means "counting photons"

Radiometry

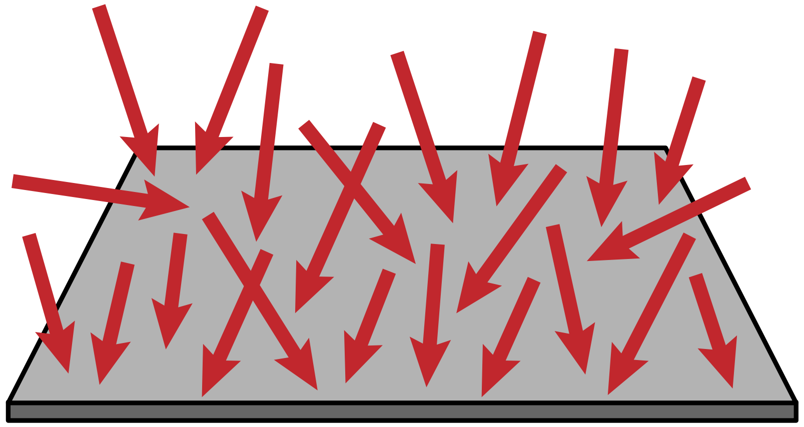
- Basic quantities (depend on wavelength)
  - flux Φ
  - irradiance E
  - radiosity B
  - intensity I
  - radiance L

will be the most important quantity for us

Flux (Radiant Flux, Power)

- total amount of radiant energy passing through surface or space *per unit time*

$$\Phi(A) \qquad \left[\frac{J}{s} = W\right]$$

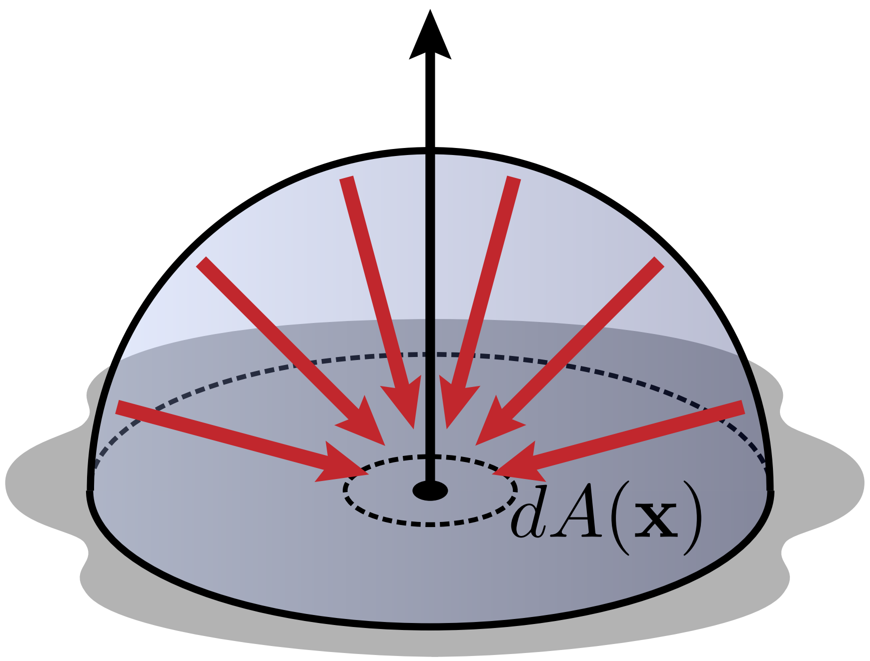


- examples:
  - number of photons hitting a wall per second
  - number of photons leaving a lightbulb per second

Irradiance

- *area density* of flux
- flux per unit area **arriving** at a surface

$$E(\mathbf{x}) = \frac{d\Phi(A)}{dA(\mathbf{x})} \left[\frac{W}{m^2}\right]$$

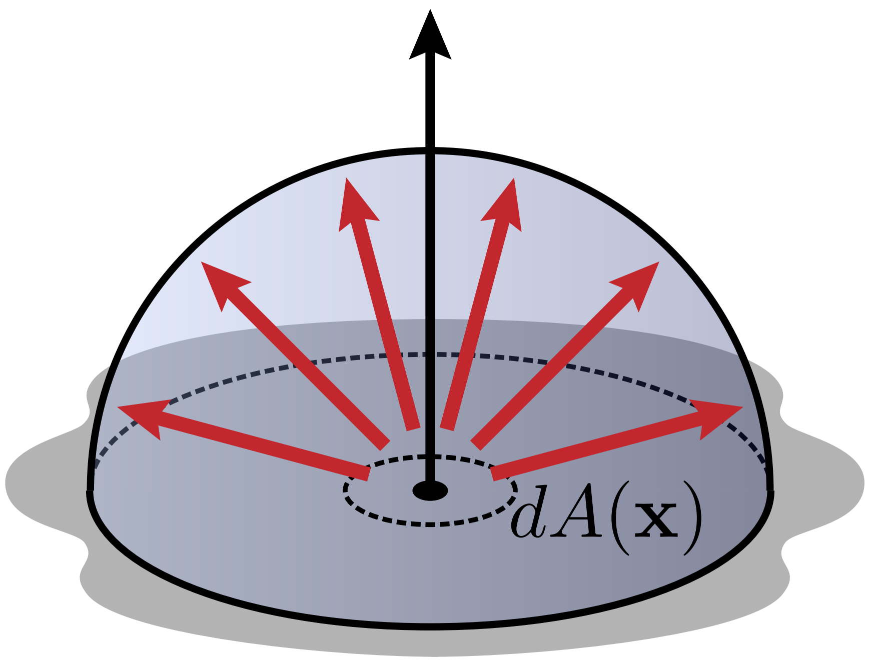


- example:
  - number of photons **hitting** a small patch of a wall per second, *divided* by size of patch

Radiosity (Radiant Exitance)

- *area density* of flux
- flux per unit area **leaving** a surface

$$B(\mathbf{x}) = \frac{d\Phi(A)}{dA(\mathbf{x})} \left[\frac{W}{m^2}\right]$$

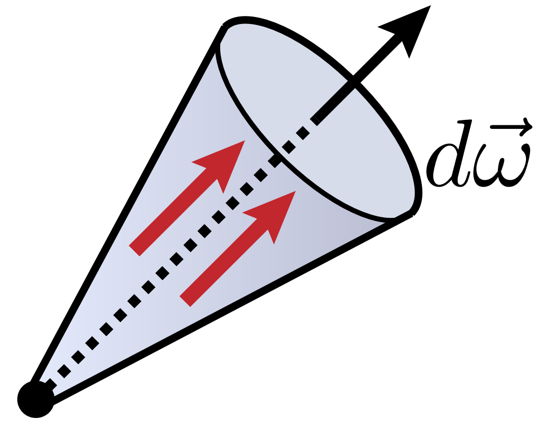


- example:
  - number of photons **reflecting off** a small patch of a wall per second, *divided* by size of patch

Radiant Intensity

- *directional density* of flux
- power (flux) per solid angle

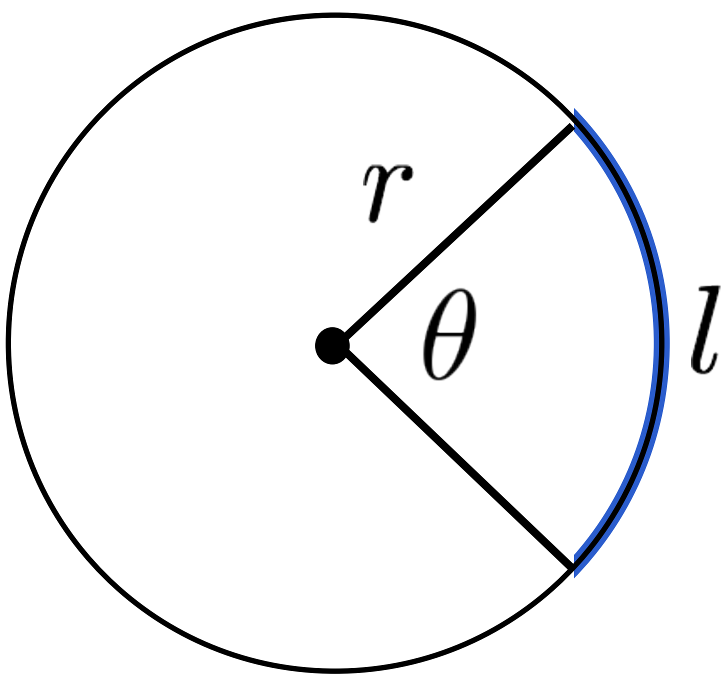
$$I(\vec{\omega}) = \frac{d\Phi}{d\vec{\omega}} \qquad \left[\frac{W}{sr}\right]$$



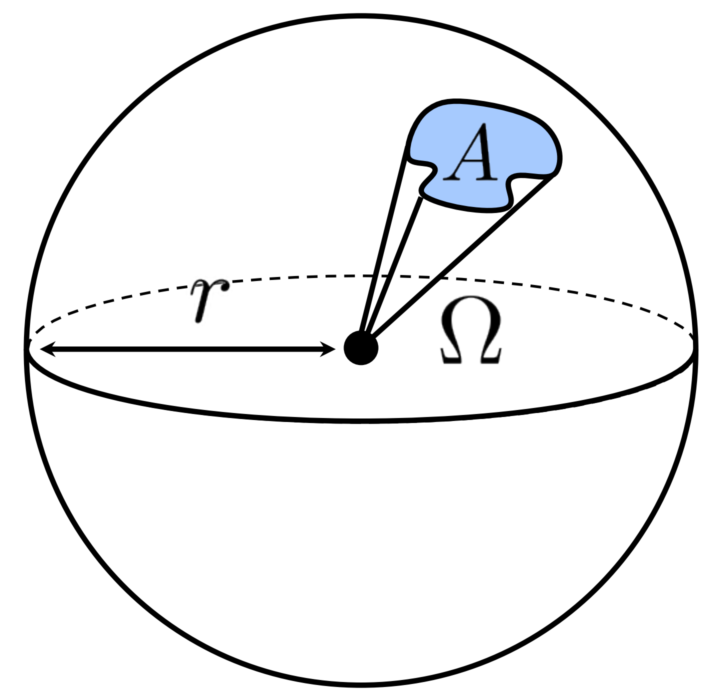
Solid Angle

- Angle
  - circle: 2π radians

- Solid angle
  - sphere: 4π steradians



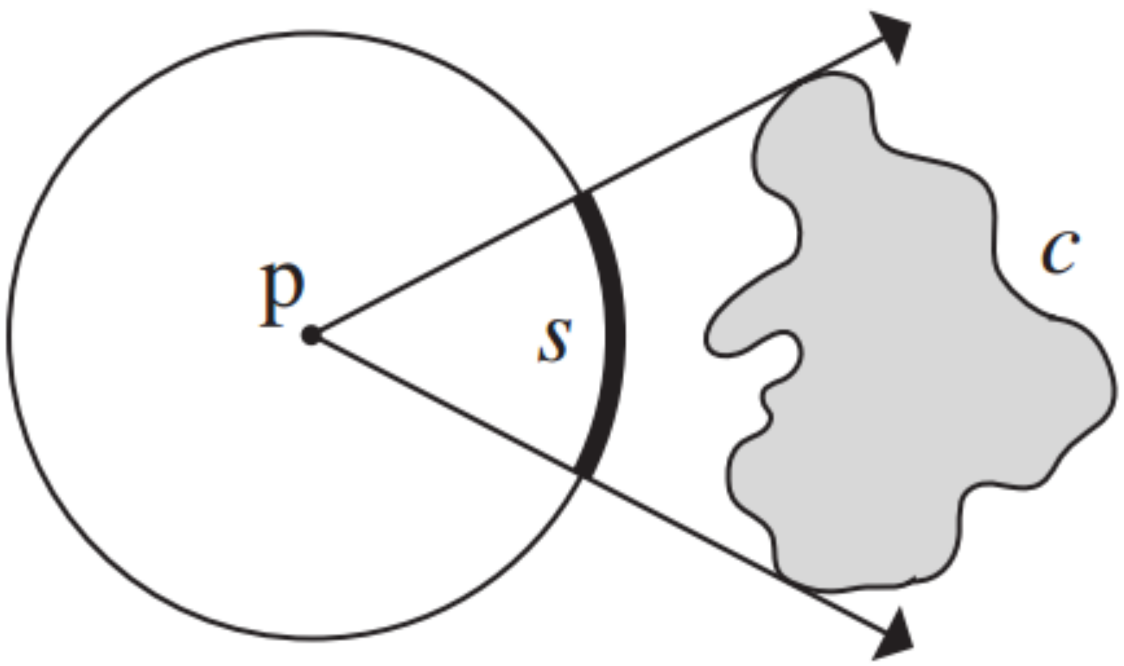
$$\theta = \frac{l}{r}$$

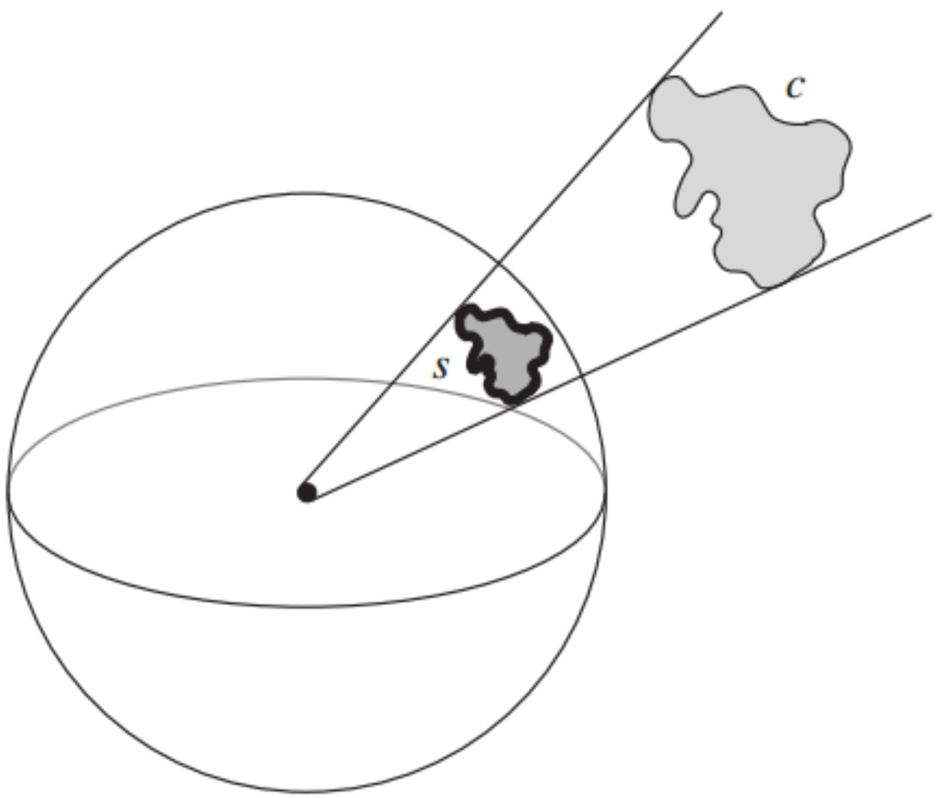


$$\Omega = \frac{A}{r^2}$$

Subtended (Solid) Angle

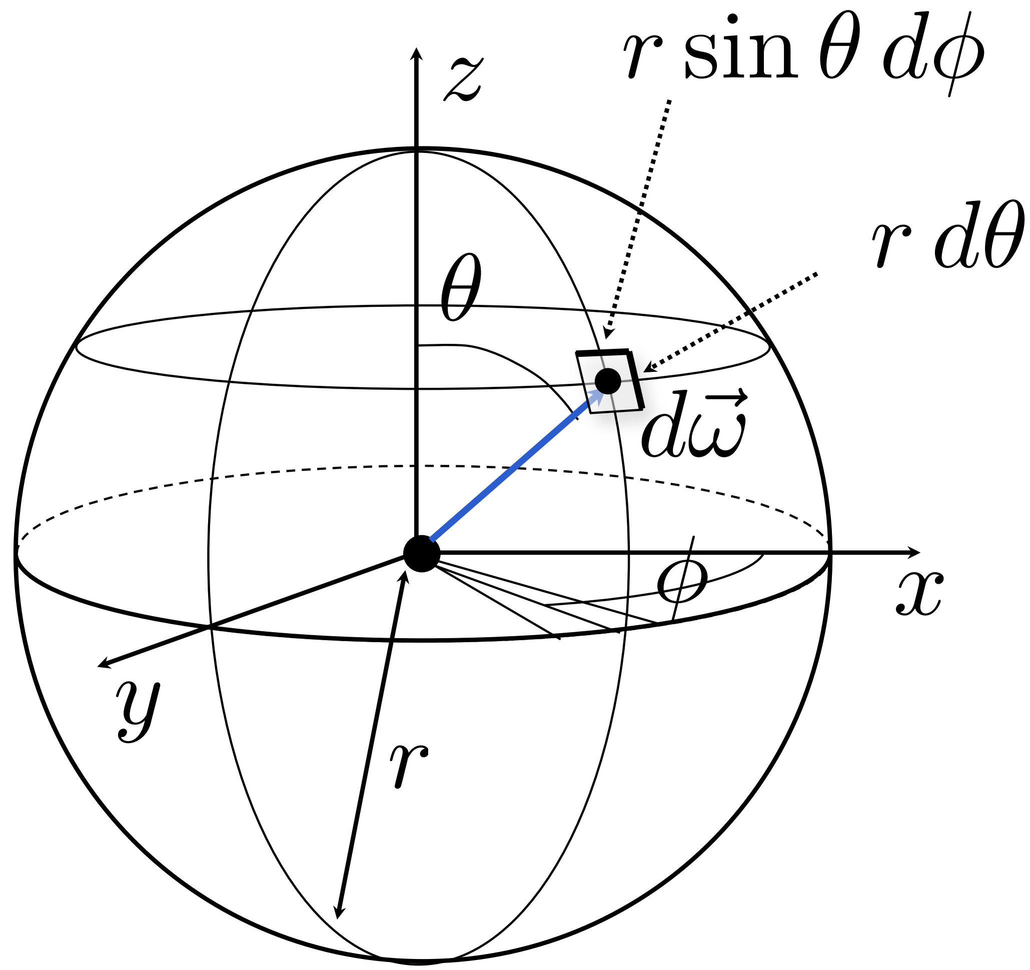
- Length/area of object's projection onto a unit circle/sphere





Differential Solid Angle

- Differential area on the unit sphere around direction $\vec{\omega}$



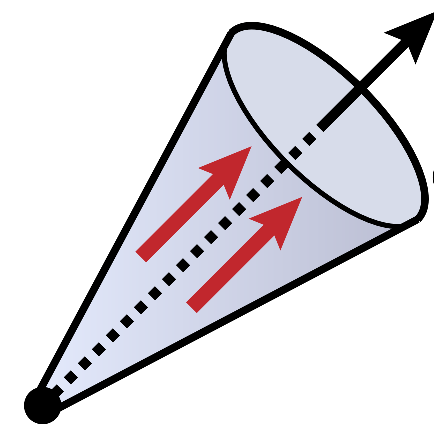
$$dA = (r d\theta)(r \sin\theta d\phi)$$

$$d\vec{\omega} = \frac{dA}{r^2} = \sin\theta d\theta d\phi$$

$$\Omega = \int_{S^2} d\vec{\omega} = \int_0^{2\pi}\int_0^{\pi} \sin\theta d\theta d\phi = 4\pi$$

Radiant Intensity

- *directional density* of flux
- power (flux) per solid angle



$$I(\vec{\omega}) = \frac{d\Phi}{d\vec{\omega}} \qquad \left[\frac{W}{sr}\right]$$

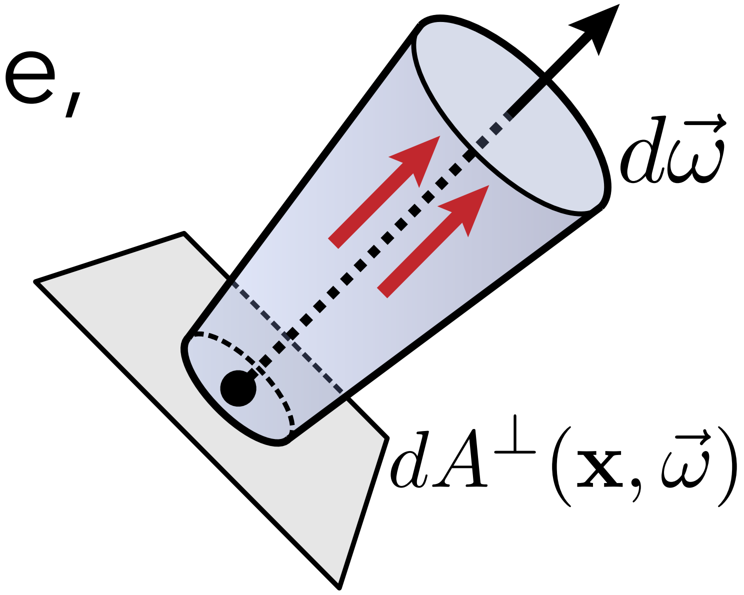
$$\Phi = \int_{S^2} I(\vec{\omega})\, d\vec{\omega}$$

$$\Phi = 4\pi I$$ (for an isotropic point source)

- example:
  - power per unit solid angle emanating from a point source

Radiance

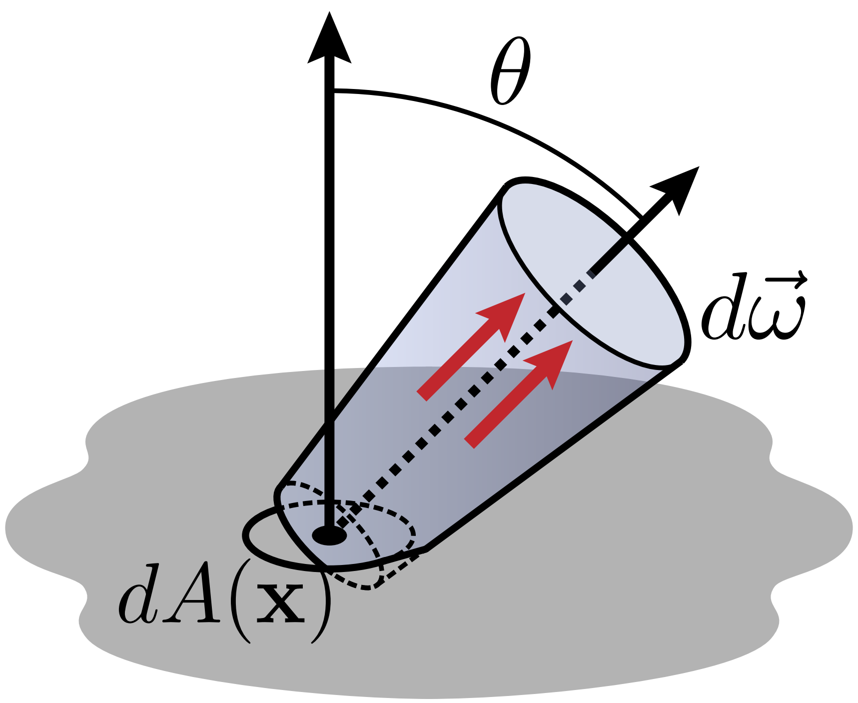
- intensity per perpendicular unit area
- flux density per unit solid angle, per perpendicular unit area



$$L(\mathbf{x},\vec{\omega}) = \frac{dI(\vec{\omega})}{dA^{\perp}(\mathbf{x},\vec{\omega})} \qquad \left[\frac{W}{m^2 sr}\right]$$

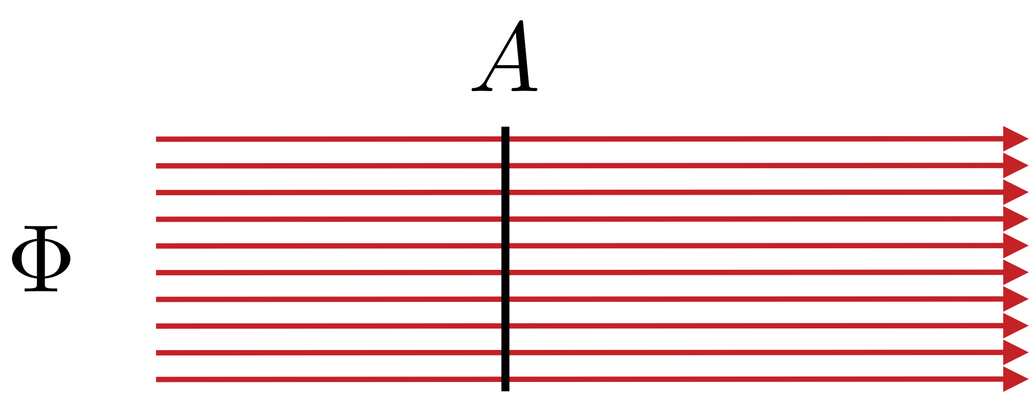
$$= \frac{d^2\Phi(A)}{d\vec{\omega}\,dA^{\perp}(\mathbf{x},\vec{\omega})}$$

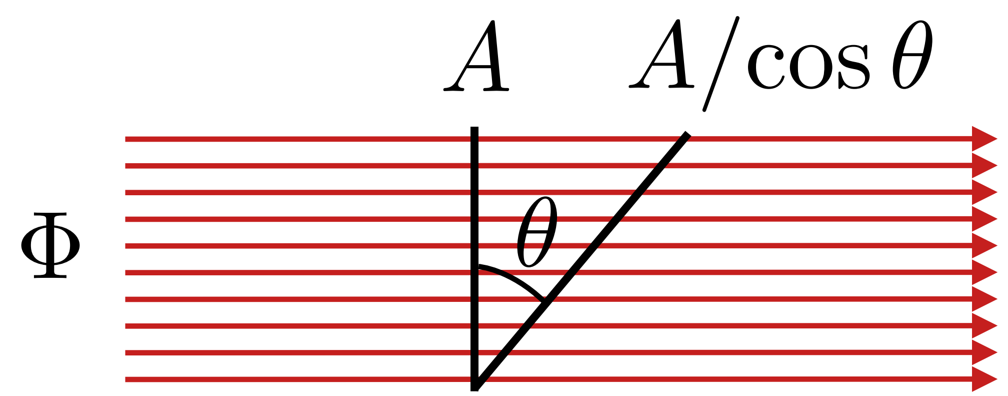
$$= \frac{d^2\Phi(A)}{d\vec{\omega}\,dA(\mathbf{x})\cos\theta}$$



Radiance

- Lambert's Cosine Law



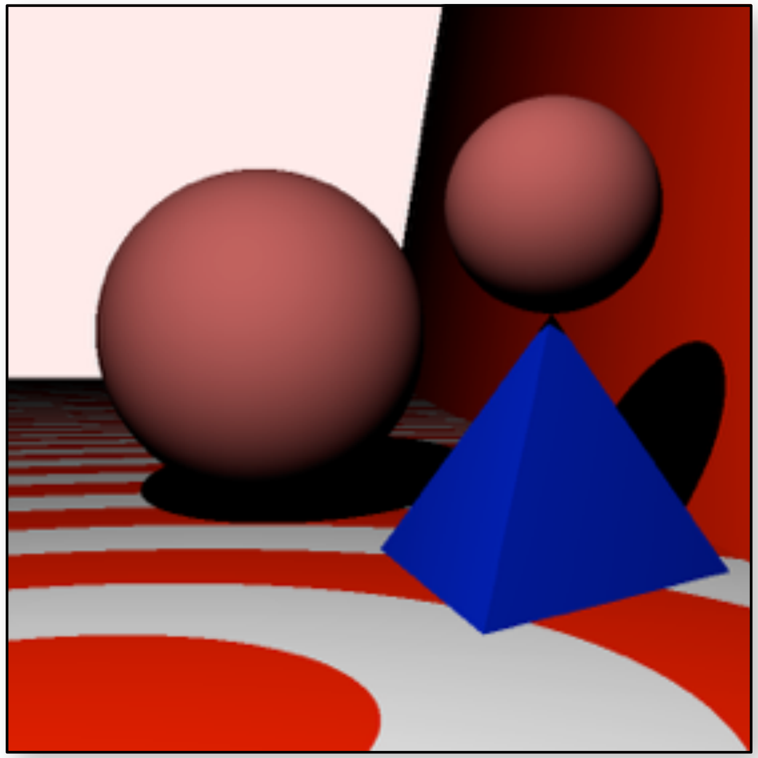


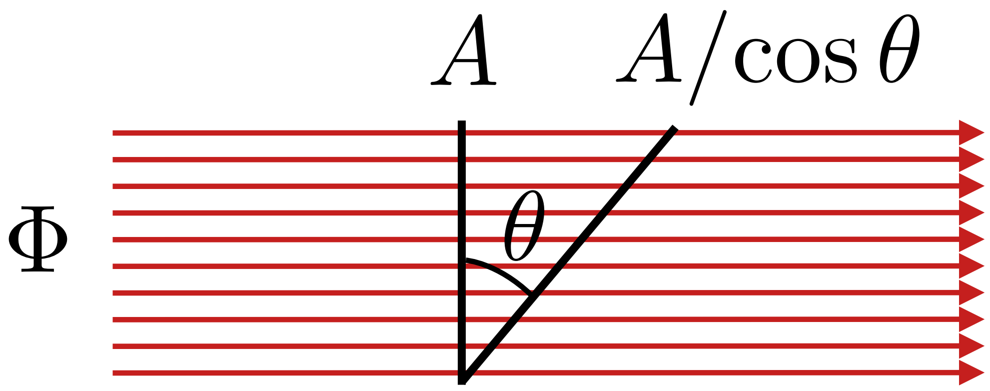
$$E = \frac{\Phi}{A}$$

$$E = \frac{\Phi}{A/\cos\theta} = \frac{\Phi}{A}\cos\theta$$

Radiance

- Lambert's Cosine Law



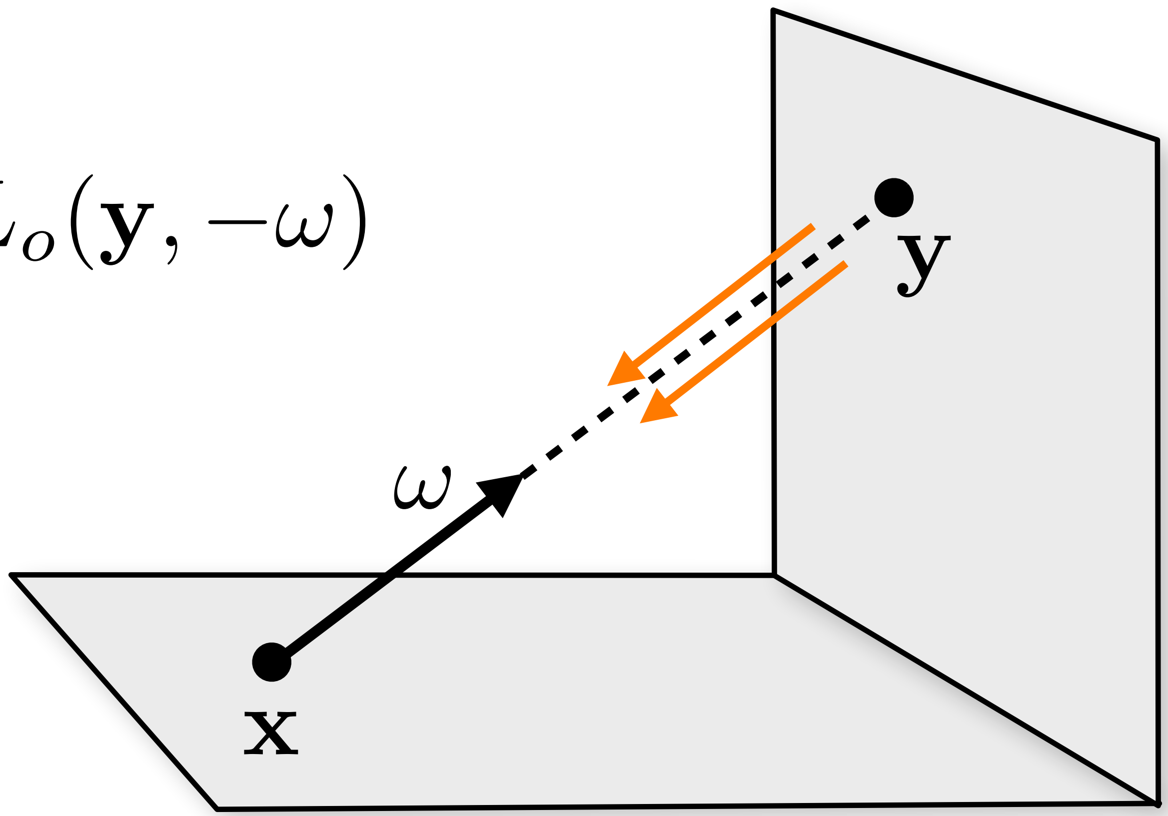


$$E = \frac{\Phi}{A/\cos\theta} = \frac{\Phi}{A}\cos\theta$$

Radiance

- fundamental quantity for ray tracing
- remains constant along a ray (in vacuum only!)
- incident radiance L_i at one point can be expressed as outgoing radiance L_o at another point

$$L_i(\mathbf{x}, \omega) = L_o(\mathbf{y}, -\omega)$$



Radiance

- expressing *irradiance* in terms of radiance:

$$L(\mathbf{x}, \vec{\omega}) = \frac{d^2\Phi(A)}{\cos\theta dA(\mathbf{x}) d\vec{\omega}} \qquad E(\mathbf{x}) = \frac{d\Phi(A)}{dA(\mathbf{x})}$$

$$L(\mathbf{x}, \vec{\omega}) = \frac{dE(\mathbf{x})}{\cos\theta d\vec{\omega}}$$

$$L(\mathbf{x}, \vec{\omega}) \cos\theta \, d\vec{\omega} = dE(\mathbf{x})$$

$$\int_{H^2} L(\mathbf{x}, \vec{\omega}) \cos\theta \, d\vec{\omega} = E(\mathbf{x})$$

Integrate radiance over hemisphere

Radiance

- expressing *flux* in terms of radiance:

$$\int_{H^2} L(\mathbf{x}, \vec{\omega}) \cos\theta \, d\vec{\omega} = E(\mathbf{x}) \qquad E(\mathbf{x}) = \frac{d\Phi(A)}{dA(\mathbf{x})}$$

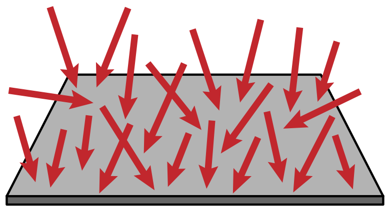
$$\int_A E(\mathbf{x}) \, dA(\mathbf{x}) = \Phi(A)$$

$$\int_A \int_{H^2} L(\mathbf{x}, \vec{\omega}) \cos\theta \, d\vec{\omega} dA(\mathbf{x}) = \Phi(A)$$

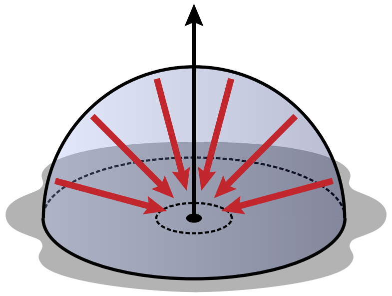
Integrate radiance over hemisphere and area

Overview of Quantities

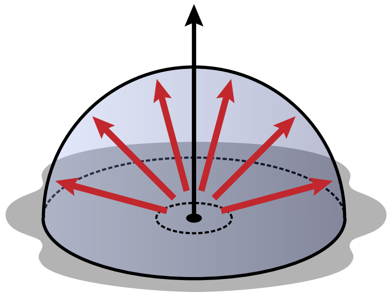
- flux: $\Phi(A)$ $\left[\frac{J}{s} = W\right]$



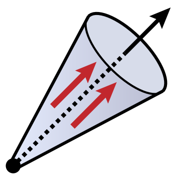
- irradiance: $E(\mathbf{x}) = \frac{d\Phi(A)}{dA(\mathbf{x})}$ $\left[\frac{W}{m^2}\right]$



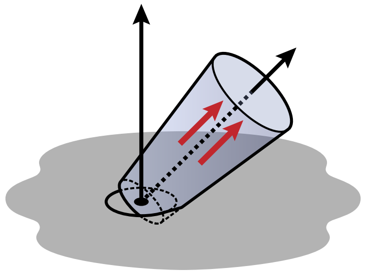
- radiosity: $B(\mathbf{x}) = \frac{d\Phi(A)}{dA(\mathbf{x})}$ $\left[\frac{W}{m^2}\right]$



- intensity: $I(\vec{\omega}) = \frac{d\Phi}{d\vec{\omega}}$ $\left[\frac{W}{sr}\right]$



- radiance: $L(\mathbf{x}, \vec{\omega}) = \frac{d^2\Phi(A)}{\cos\theta \, dA(\mathbf{x}) \, d\vec{\omega}}$ $\left[\frac{W}{m^2 sr}\right]$



Next time:

- Appearance modeling (how light interacts with different materials)

What is a Flame?

Ben Ames (https://vimeo.com/40271657)