Photometry Webinar Level 1

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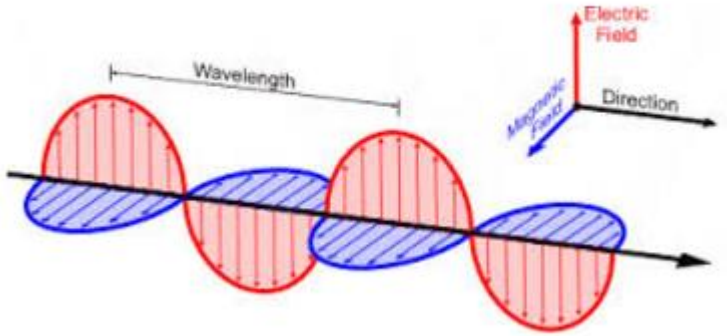
Outline

- Wave nature of light
- Particle nature of light
- Far-Red radiation
- UV radiation
- Blackbody radiation
- Refractive index and Snell's law
- **P**hoto-synthetic **P**hoton **F**lux **D**ensity (PPFD)
- Colour temperature and CRI index
- Scotopic/Photopic ratio (S/P ratio)
- Radiometric and Photometric units

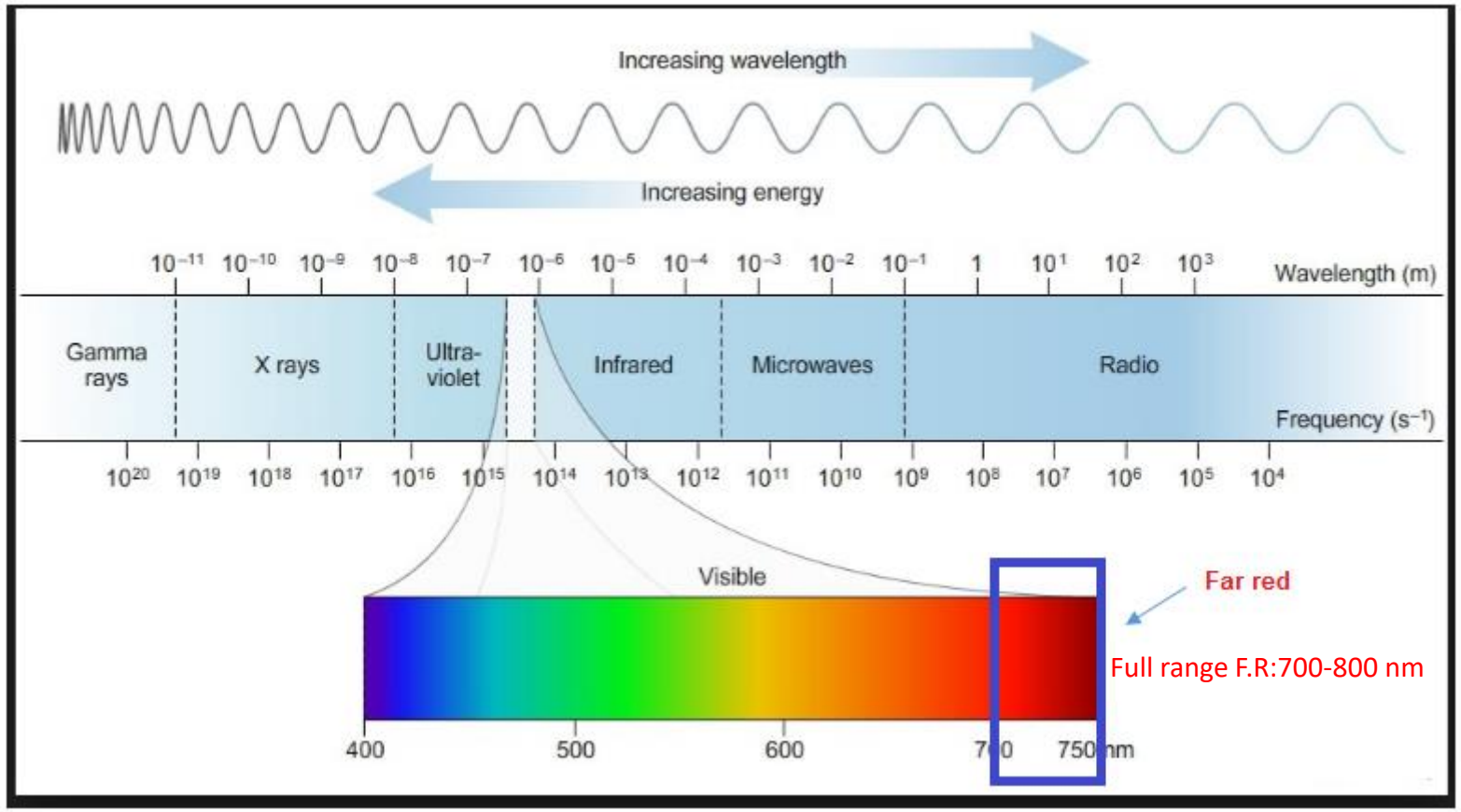
Electromagnetic wave

- Electromagnetic energy has a wave aspect and a particle aspect.
- As a wave, it contains an electric field vector and a magnetic field vector perpendicular to each other and also perpendicular to the direction of propagation.



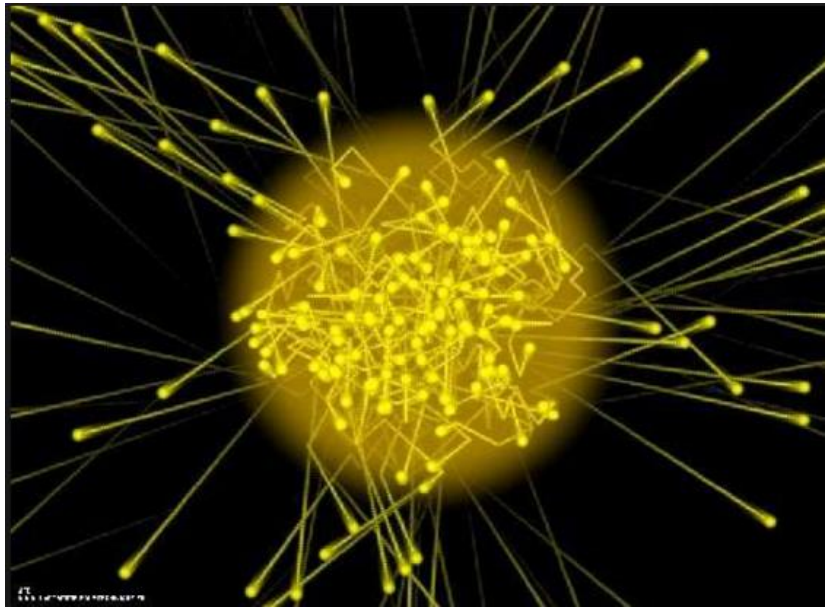
- The wavelength of electromagnetic spectrum ranges from 0.01 nm for gamma radiation to 100 km for radio waves.
- Visible light (400-700 nm) is only a small fraction of the electromagnetic spectrum which can be detected by the human eye.
- The wavelength and frequency of an electromagnetic wave are related by $\lambda = c/\nu$ where ν is the frequency in Hertz (Hz), and c is the speed of light which is 3×10^8 m/s (300,000 km/s).

Electromagnetic spectrum

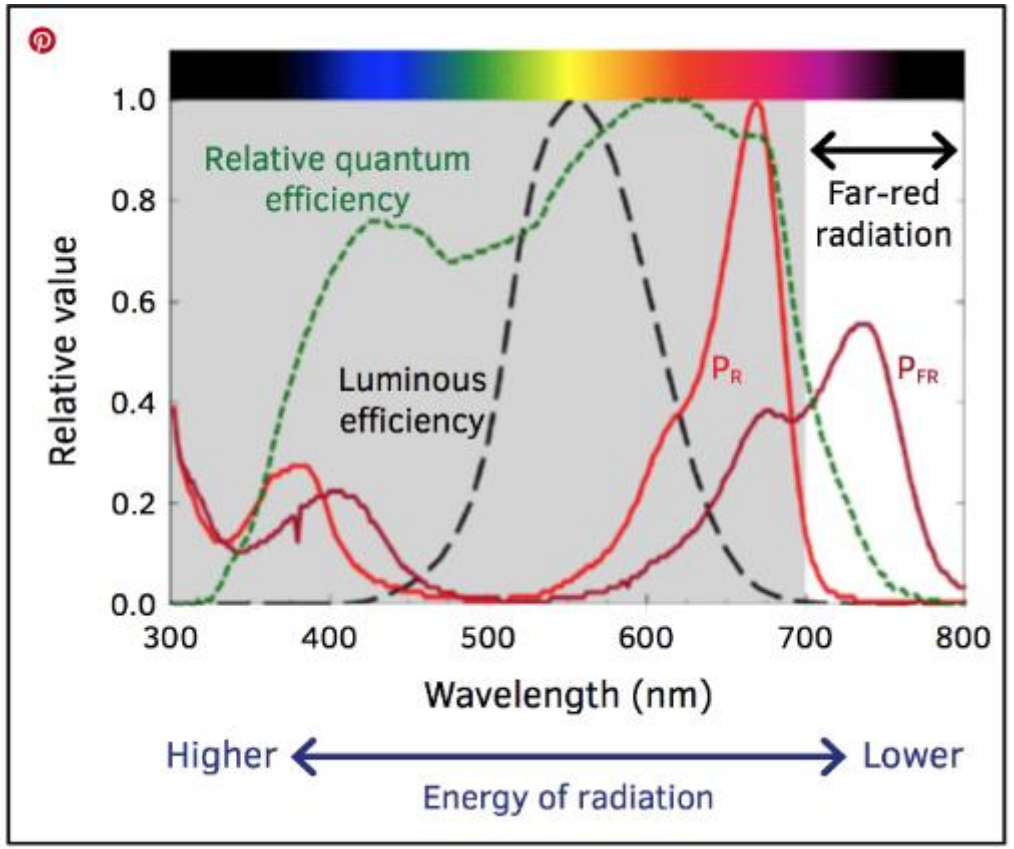


Particle nature of light

- As a particle, a quantized bundle of energy is called photon and its energy is inversely proportional to wavelength. **$E=hc/\lambda$** where h is the Plank's constant (6.63×10^{-34} joules.sec), c is the speed of light (3×10^{8} m/sec), λ is the wavelength (meter) and E in the energy (joules). The quantity c/λ is the frequency ν , so **$E=h\nu$** as well.
- When the wavelength λ increases, the energy of the photon decreases.
- When the wavelength λ decreases, the energy of the photon increases.



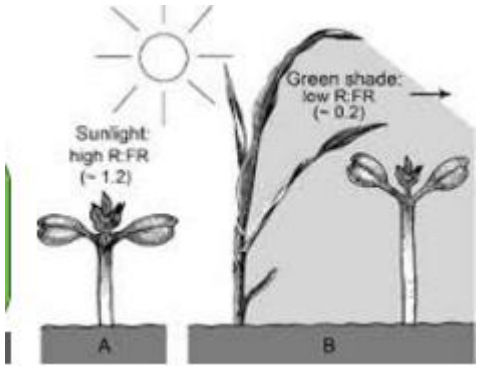
Far Red radiation



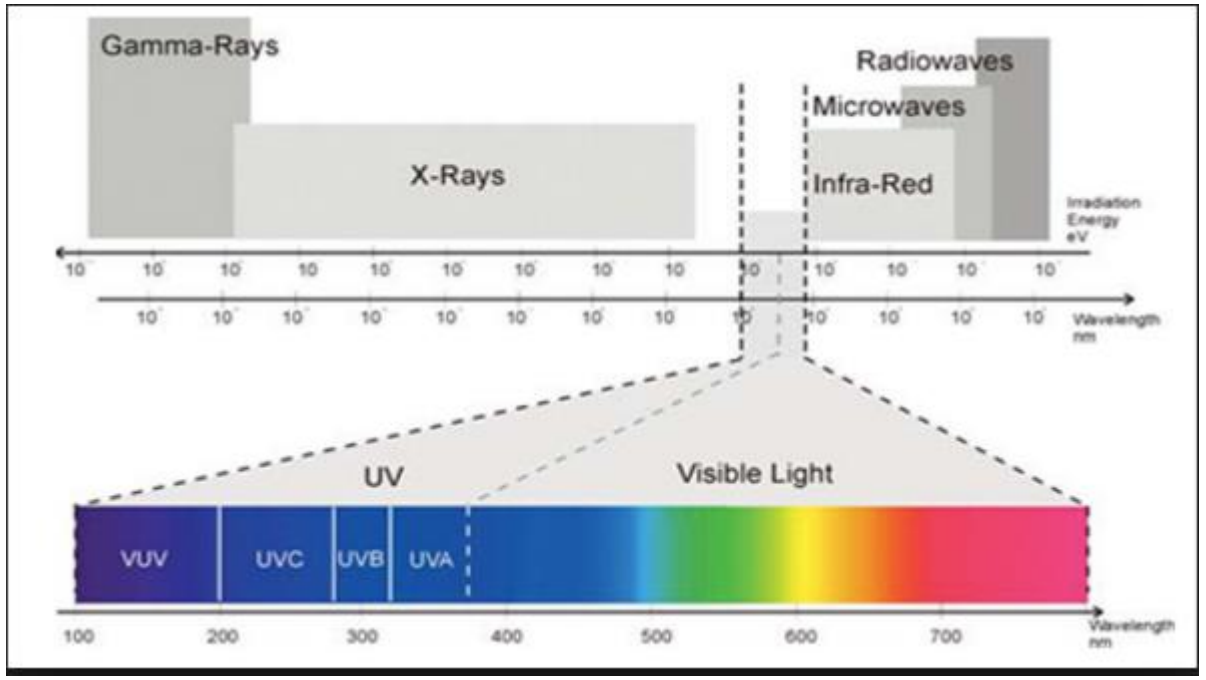
- Far red radiation is between 700-800 nm immediately outside the visible radiation.
- Reference: http://www.gpnmag.com/article/a-closer-look-at-far-red-radiation/

More on Far Red radiation

- Far red radiation is transmitted by leaves but red is heavily absorbed.
- Plants hidden under a canopy receive enough far red but very little red.
- Hence plants use far red radiation to detect if they are in a shadow and this is called shade avoidance response.
- Red/FR is an important parameter for plants because this ratio decreases if the plant is under a shadow of another plant.



UV radiation



- UVA: 320-400 nm, UVB:290-320 nm, UVC: 200-290 nm, VUV<200 nm

Downward Solar Radiation at the Top of Atmosphere (TOA) and Ground

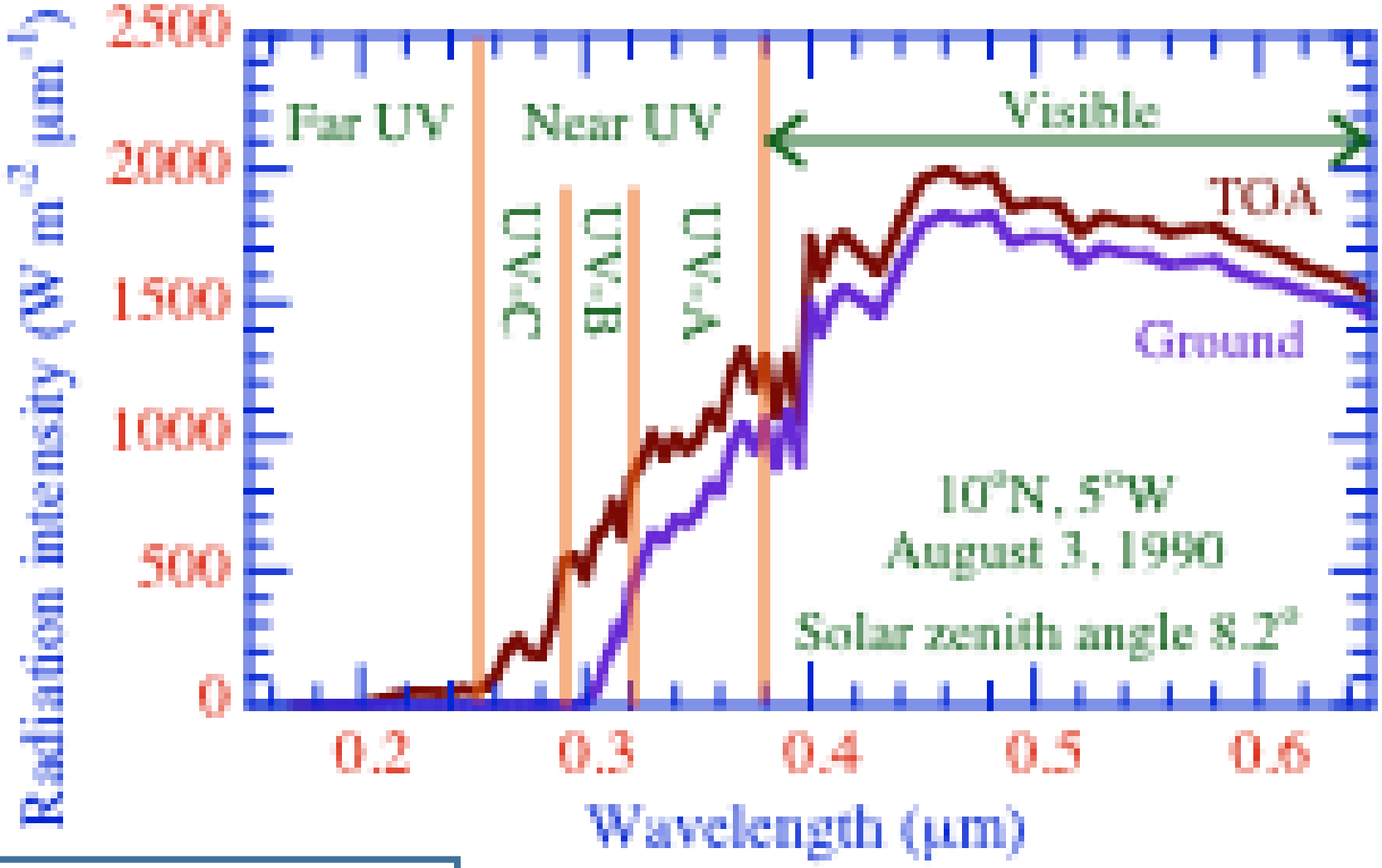


Figure from Air pollution and global warming by Mark Jacobson

Emission Spectra of the Sun and Earth

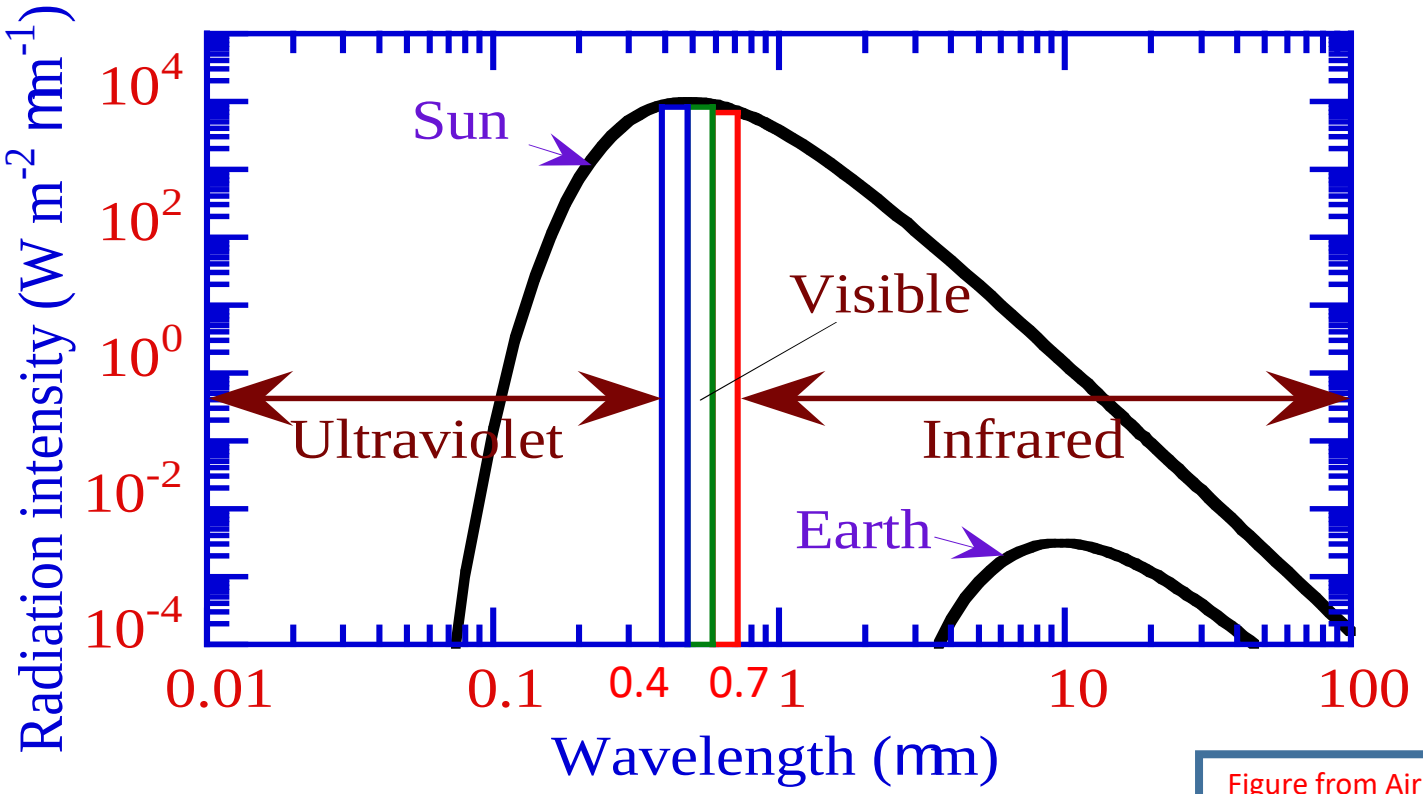


Figure from Air pollution and global warming by Mark Jacobson

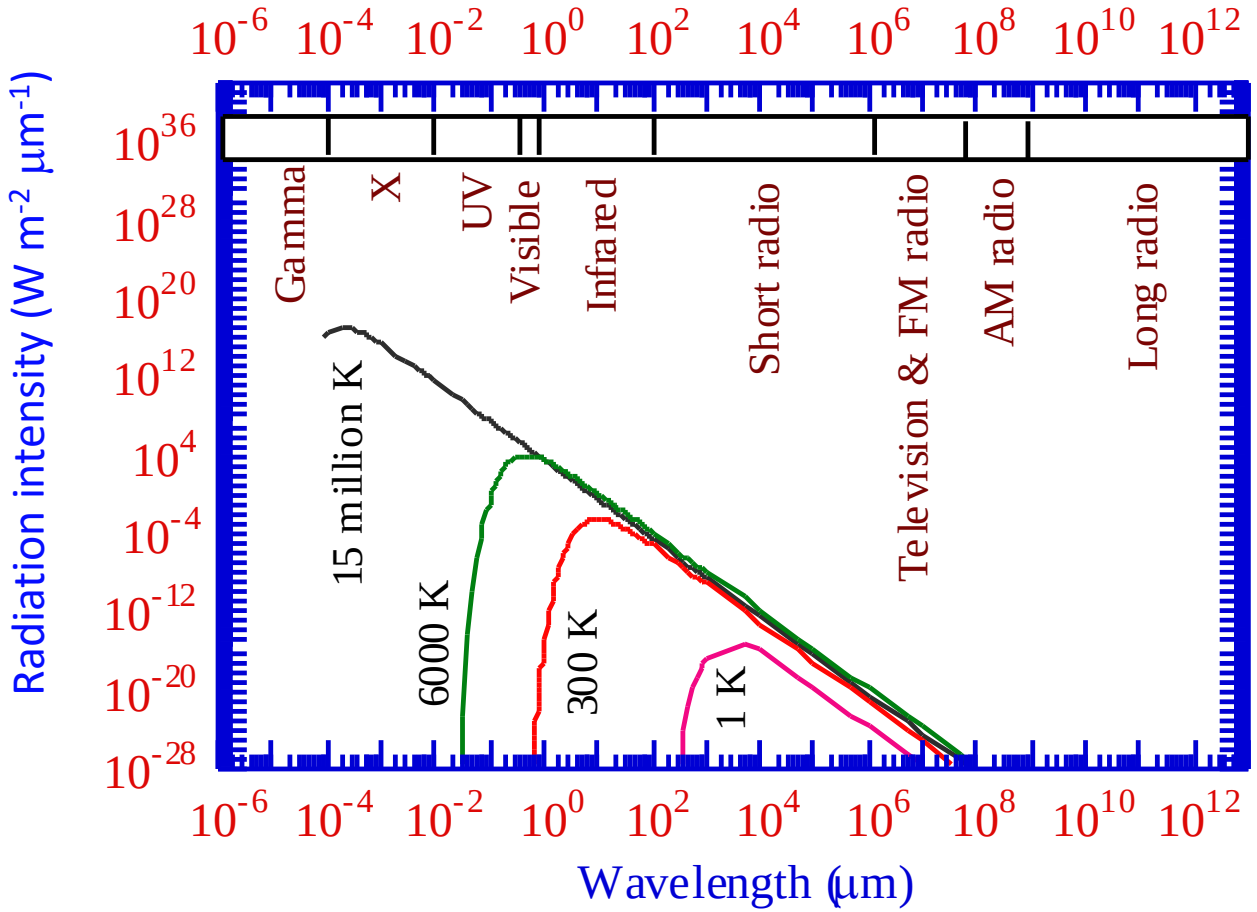
Visible range: 0.4-0.7 μm (400-700 nm)

Blackbody: A body which is a perfect absorber of emission. No incident radiation is reflected by a black body. It is also a perfect emitter of radiation. Both the Sun and the Earth are approximated to be blackbodies. Sun is nearly a 5800 K blackbody.

Peak emissions: Peak solar emission is at 0.5 μm and peak terrestrial emission is at 10 μm.

Radiation Spectra

Figure from Air pollution and global warming by Mark Jacobson



ε is emissivity, a number between 0 to 1. For a black body, It is 1.

σ is a constant called Stefan-Boltzman constant: 5.67×10^{-8} $Wm^{-2}k^{-4}$

F is Irradiance in Watts/m^2 and is the area under the curve.

Wien's Law

$\lambda_p(\mu m) = 2897/T(K)$

Stefan-Boltzmann Law

$F_b\,(W/m^2) = \varepsilon\sigma T^4$ (where T is in K)

Refractive index and Snell's law

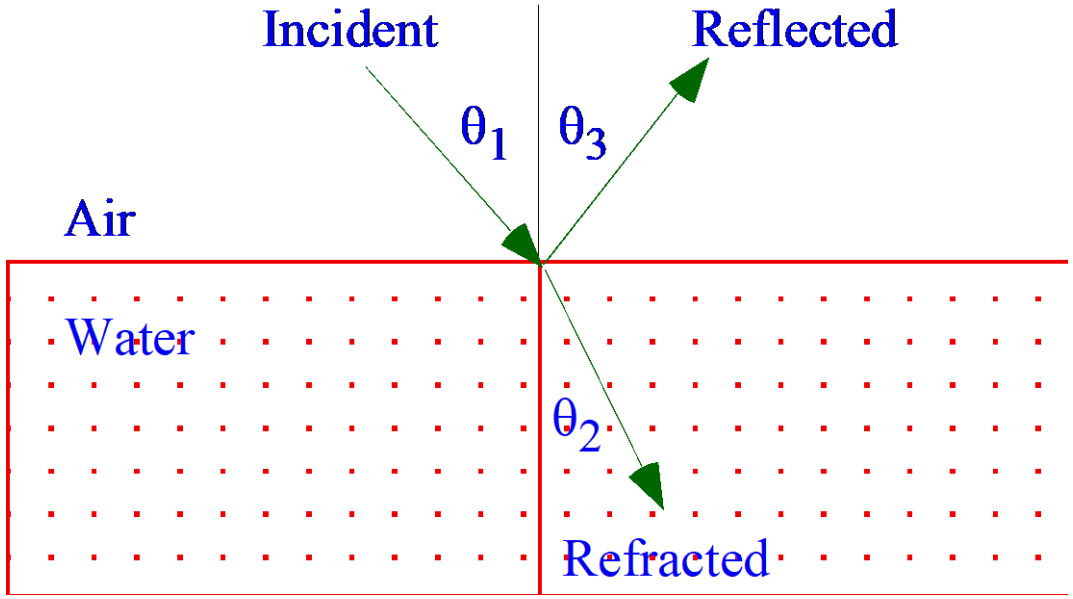
Snell's Law

$$\frac{n_2}{n_1} = \frac{\sin q_1}{\sin q_2}$$

Refractive index

$n_1 = c/c_1$

c = speed of light in vacuum (3×10^8 m/s)



n_1 and θ_1 always refer to refractive index and angle of incidence in the first medium. Refractive index of air is nearly 1.

PPFD (Photosynthetic Photon Flux Density)

- Convert Watts/m^2 (Irradiance) to Photons/m^2/sec using Watt=Joule/sec and $E=nh\nu$ where E is the energy, n is the number of photons, h is Planck's constant 6.63x10^-34) and ν is the frequency of light.
- Unit is μmol/m^2/sec. 1 mol is 6.023x10^23 and refers to Avogadro number which is the number of molecules in the molecular weight of a substance or number of atoms in an atomic weight of a substance. For example for Sodium (Na) the atomic weight is 23 grams so there will be 6.023x10^23 atoms of sodium in 23 grams. μ refers to micro and is 10^-6.
- For plants and the photosynthesis process, the energy of the individual photon is more important than the total energy.
- Red photons have less energy than blue photons so for a fixed optical power, the ppfd of red photon is larger than blue because there needs to be more of them to create that energy.

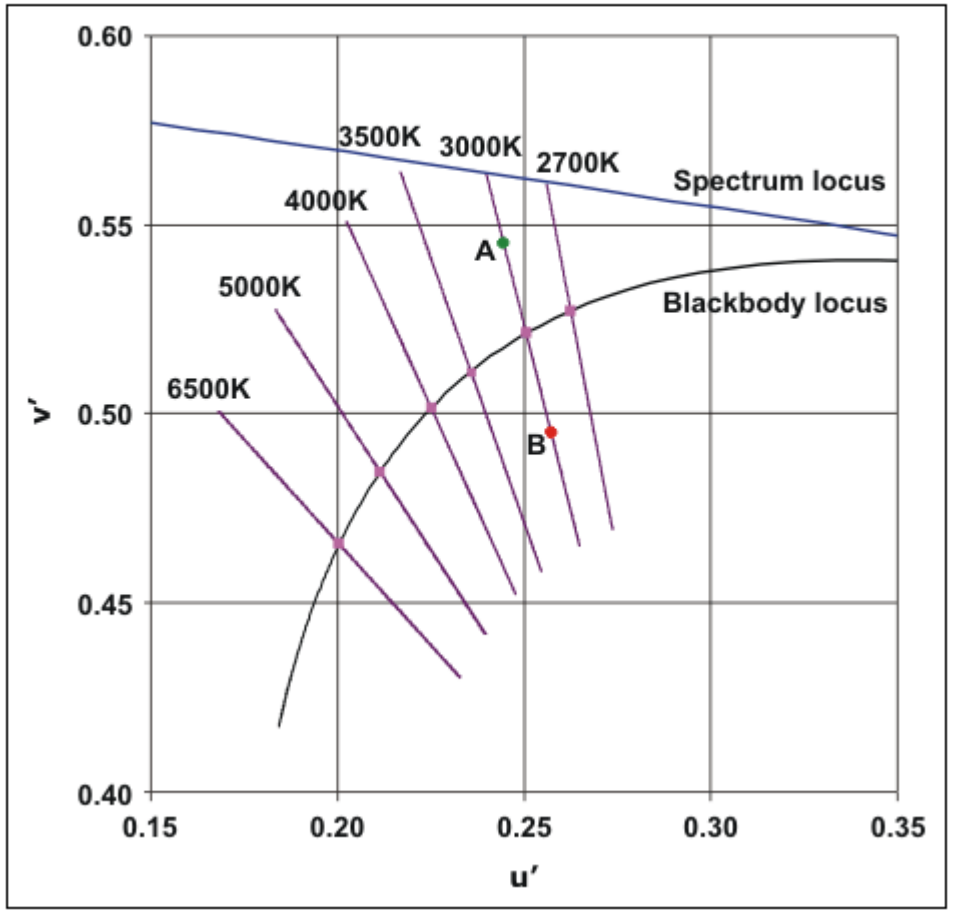
Colour temperature

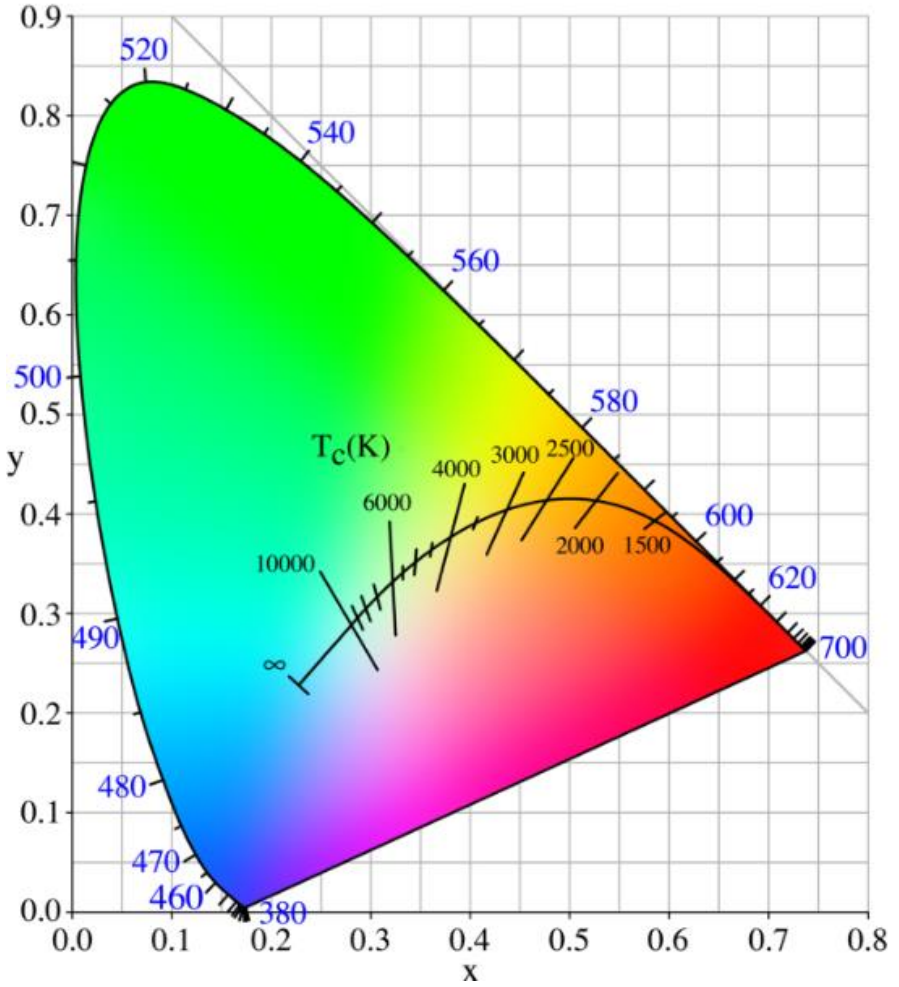
- Colour Temperature (CT): When a blackbody is heated it changes colour at different temperatures. For any colour the corresponding temperature is conventionally expressed in absolute temperature or kelvins (0 C=273 K), using the symbol K. Colour temperatures over **5000 K** are called cool colours (bluish white), while lower colour temperatures (**2700–3000 K**) are called warm colours (yellowish white through red). If you look at a red LED, its actual temperature is not 3000K, but its colour temperature is 3000K.
- Correlated Colour temperature (CCT): The **correlated colour temperature** (CCT) is a specification of the **colour** appearance of the light emitted by a lamp, relating its **colour** to the **colour** of light from a reference source (normally a blackbody) when heated to a particular **temperature**, measured in degrees Kelvin (K).

Chromaticity diagrams
Map human colour perception
in terms of two coordinates x
and y (CIE1931) or u', v' (CIE1976)

More on CCT

The CIE 1976 chromaticity diagram with six isotemperature lines used by manufacturers to represent light emitted by commercially available fluorescent lamps





CRI index

- Effect of an illuminant on the colour appearance of objects by conscious or subconscious comparison with their colour appearance comparison with their appearance under a reference illuminant.
- CRI index is meaningless for monochromatic light and has a value for lights which are continuous

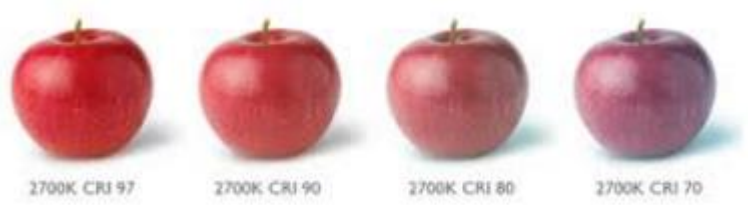
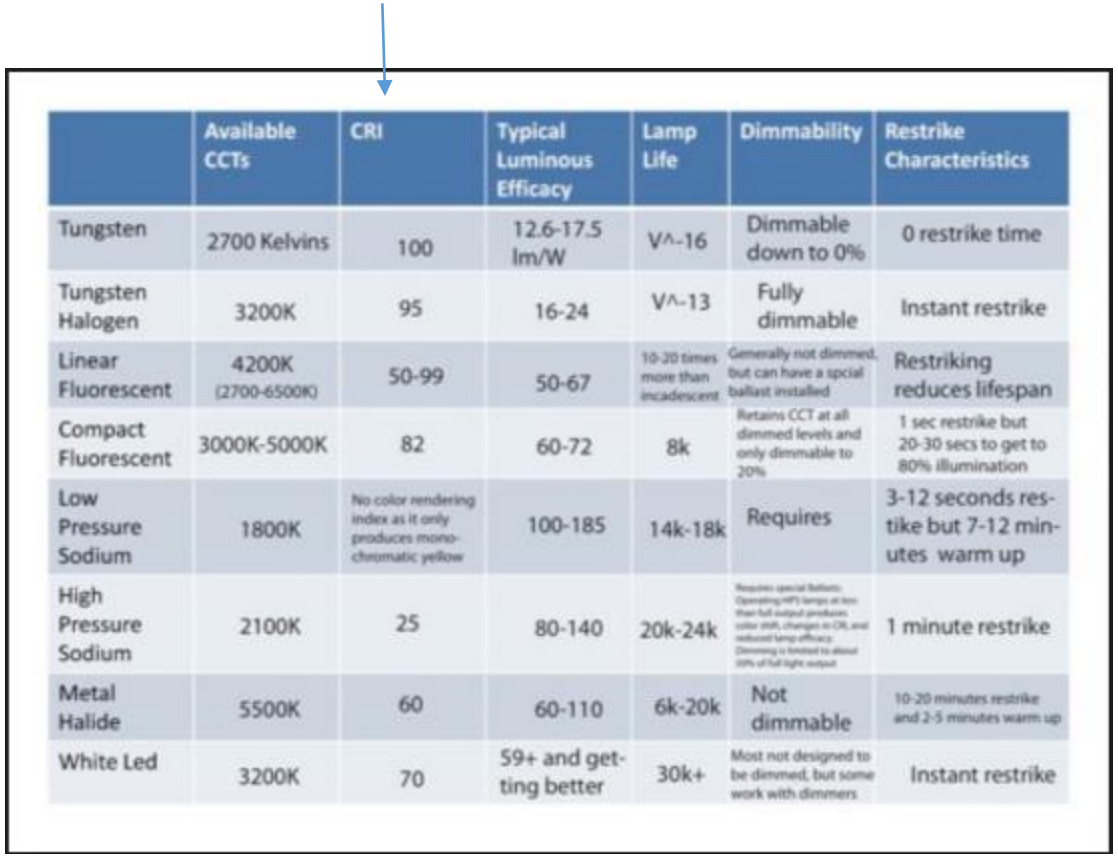


Table of CRI Index for different light sources

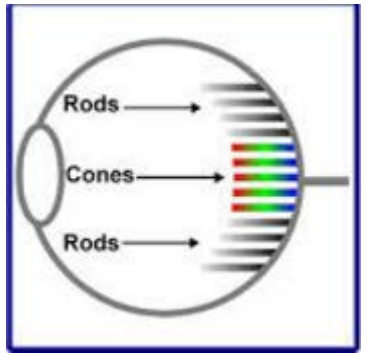


	Available CCTs	CRI	Typical Luminous Efficacy	Lamp Life	Dimmability	Restrike Characteristics
Tungsten	2700 Kelvins	100	12.6-17.5 lm/W	V^-16	Dimmable down to 0%	0 restrike time
Tungsten Halogen	3200K	95	16-24	V^-13	Fully dimmable	Instant restrike
Linear Fluorescent	4200K (2700-6500K)	50-99	50-67	10-20 times more than incadescent	Generally not dimmed, but can have a spcial ballast installed	Restriking reduces lifespan
Compact Fluorescent	3000K-5000K	82	60-72	8k	Retains CCT at all dimmed levels and only dimmable to 20%	1 sec restrike but 20-30 secs to get to 80% illumination
Low Pressure Sodium	1800K	No color rendering index as it only produces mono-chromatic yellow	100-185	14k-18k	Requires	3-12 seconds restike but 7-12 minutes warm up
High Pressure Sodium	2100K	25	80-140	20k-24k	Requires special ballasts. Operating HPS lamps at less than full output produces color shift, changes in CRI, and reduced lamp efficacy. Dimming is limited to about 50% of full light output	1 minute restrike
Metal Halide	5500K	60	60-110	6k-20k	Not dimmable	10-20 minutes restrike and 2-5 minutes warm up
White Led	3200K	70	59+ and getting better	30k+	Most not designed to be dimmed, but some work with dimmers	Instant restrike

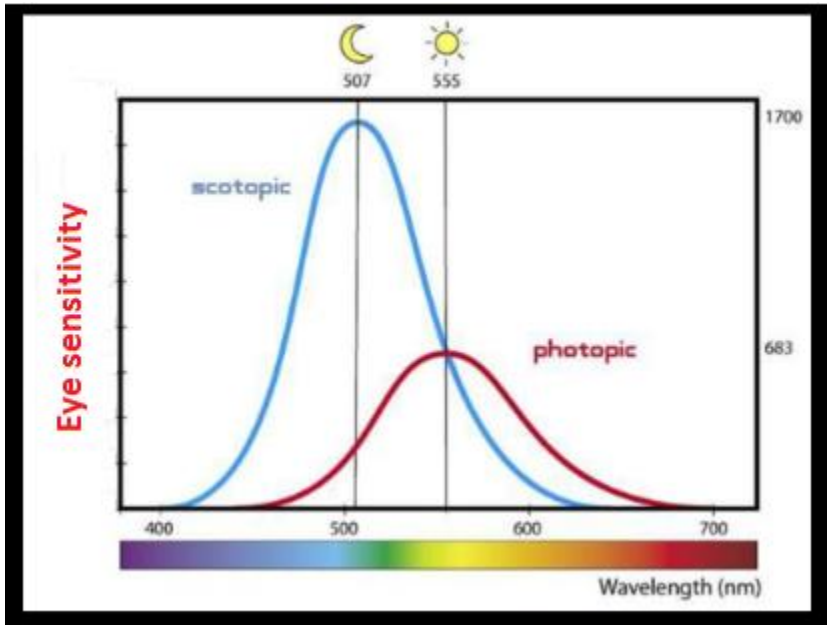
Objects colour appear more natural under illumination of higher CRI index.

S/P ratio

- S/P is the ratio of Scotopic (dark) to Photopic (light) human eye sensitivity functions.
- The higher the ratio, the better the light source in stimulating the eye.
- Larger S/P means better ability to see under both dark and light conditions or large dynamic range.



6 million cones
120 million rods



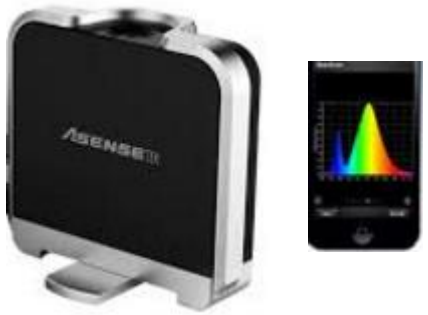
Radiometry and Photometry

- Radiometry is the science of measuring light in any portion of the electromagnetic spectrum. In practice, the term is usually limited to the measurement of infrared, visible, and ultraviolet light using optical instruments. Irradiance is the intensity of light and is measured in watts per square meter.
- Photometry is the science of measuring visible light in units that are weighted according to the sensitivity of the human eye. The photometric equivalent of Irradiance is called Illuminance and is measured in Lumens per square meter (Lux).

Difference between photometers and spectrometers

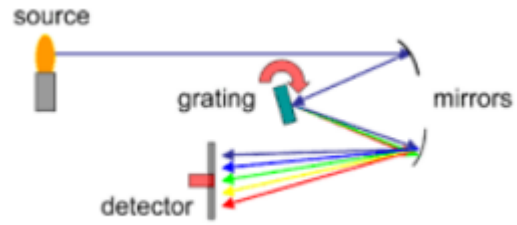
Photometer

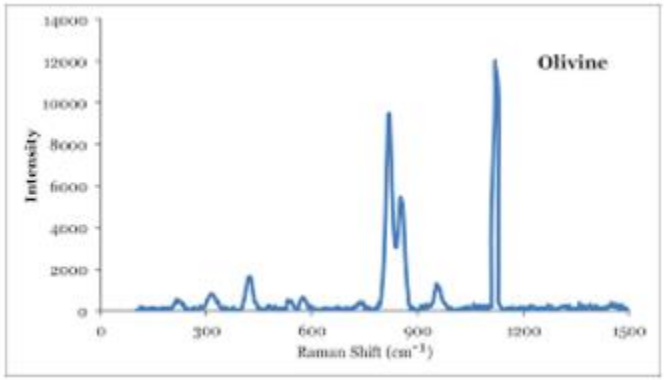
Measures total light output



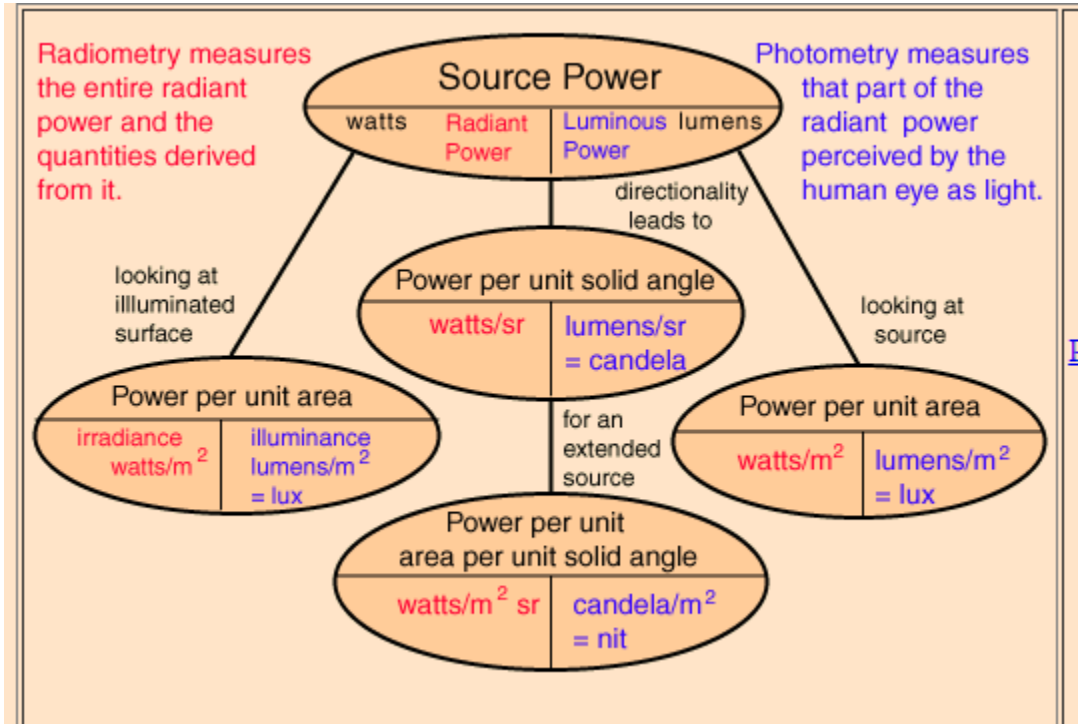
Spectrometer

Measures light output
as a function of wavelength





Photometric and Radiometric Units



Definitions of Candela and Lumen

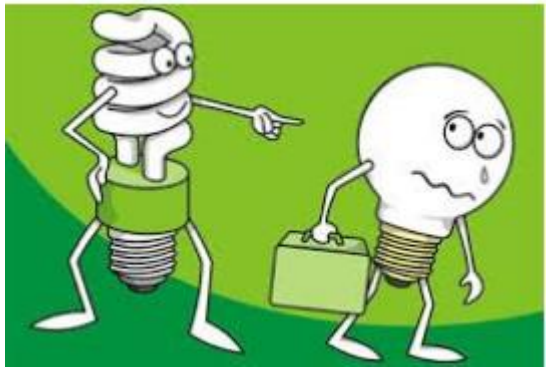
- Candela: the SI unit of luminous intensity. One candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} Hz and has a radiant intensity in that direction of 1/683 watt per steradian.
- Lumen: the SI unit of luminous flux, equal to the amount of light emitted per second in a unit solid angle of one steradian from a uniform source of one candela.
- Luminous efficacy is a measure of how well a light source produces visible light. It is the ratio of **luminous** flux to power, measured in lumens per watt in SI.

one standardized candle emits a luminous intensity of 1.0 cd .

Fig. 16.4. Plumber's candle, as used by plumbers in the nineteenth century to melt lead solder when joining water pipes.

Compact florescence lamp, Incandescent lamp and LED light output

- The wattage of these lamps refer to electrical power consumption. For example a 60 Watt lamp consumes 60 Watts of electrical power.
- The optical power produced is measured in Lumen. For example a 60 Watt lamp could be marked as 900 Lumen.
- Because compact Florence lamps are more efficient than incandescent lamps, they produce more lumen for the same electrical wattage.
- Typically a 60 watt CFL produces 800 Lumen light output. LED will produce double of that light output for the same wattage and Incandescent will produce 10 times less.



Comparison Chart

Comparison Chart
LED Lights vs. Incandescent Light Bulbs vs. CFLs

Energy Efficiency & Energy Costs	 **Light Emitting Diodes (LEDs)**	 **Incandescent Light Bulbs**	 **Compact Fluorescents (CFLs)**
Life Span (average)	**50,000 hours**	**1,200 hours**	**8,000 hours**
Watts of electricity used (equivalent to 60 watt bulb). LEDs use less power (watts) per unit of light generated (lumens). LEDs help reduce greenhouse gas emissions from power plants and lower electric bills	**6 - 8 watts**	**60 watts**	**13-15 watts**
Kilo-watts of Electricity used (30 Incandescent Bulbs per year equivalent)	**329 KWh/yr.**	**3285 KWh/yr.**	**767 KWh/yr.**
Annual Operating Cost (30 Incandescent Bulbs per year equivalent)	**$32.85/year**	**$328.59/year**	**$76.65/year**

Thank You.
Any Questions?