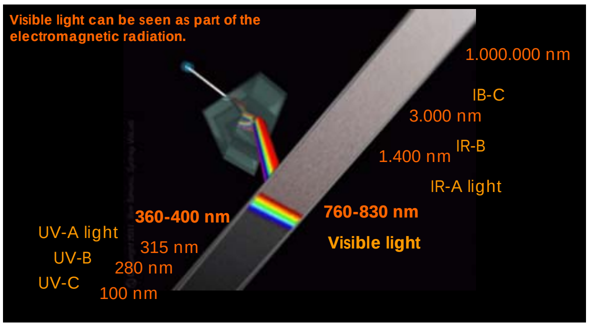
Photometry

Prof. Grega Bizjak, PhD
Laboratory of Lighting and Photometry
Faculty of Electrical Engineering
University of Ljubljana

Light as part of the EM spectrum

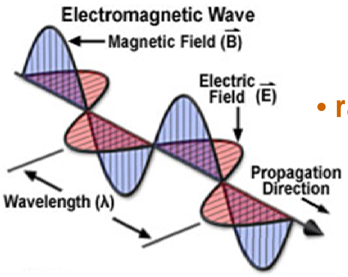


Physical measurement of light

In optics, radiometry is the field that studies the measurement of electromagnetic radiation, including visible light.

Physical measurement of light

Four main radiometric quantities are:



- radiant flux,
- radiant intensity,
- irradiance,
- radiance.

Energy and power delivered by source

The total energy delivered by a source is called **radiant energy (J)** and when observed per unit time, is called **radiant power**.

Φ_e watt (W)

Radiant intensity

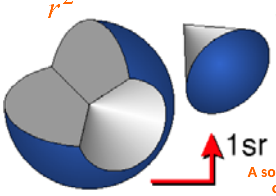
The radiant flux emitted in a given direction is called **radiant intensity**.
The direction is represented by a solid angle.

$$I_e = \frac{\phi_e}{\omega}$$

I_e watt per steradian (W/sr)

Solid angle

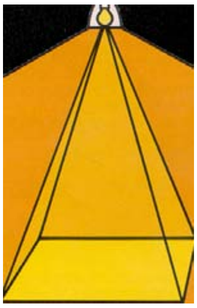
$$\omega = \frac{A}{r^2}$$



A **solid angle** is equal to the area of the segment of unit sphere. In case of non-unit sphere, the area should be divided by square of radius. The units of solid angle can be called **steradian (sr)**.

A solid angle equals the area of a segment of unit sphere in the same way a planar angle equals the length of an arc of unit circle.

Irradiance

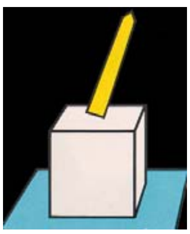


Irradiance is radiant flux per unit area received by real or imaginary surface.

$$E_e = \frac{\phi_e}{A}$$

E_e watt per square meter (W/m^2)

Radiance



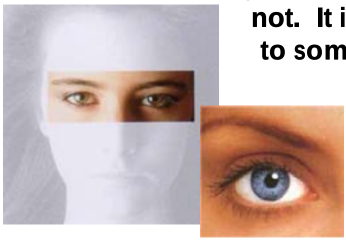
Radiance is a radiant flux per unit projected area leaving a surface in a given direction (defined by solid angle)

$$L_e = \frac{\phi_e}{\omega \cdot A \cdot \cos\theta}$$

L_e watt per steradian per square metre ($W/sr\ m^2$)

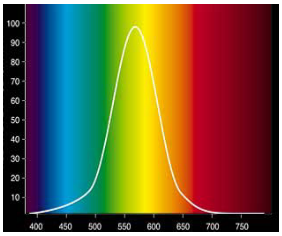
Human eye – the visual organ

Radiometry deals with all wavelengths in a same way but human eye does not. It is sensitive only to some wavelengths (visible light).



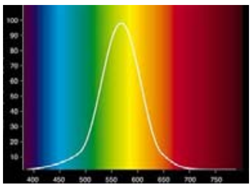
Not all “watts” are the same

Perception of a “watt” at 555 nm is different (brighter) as perception of a “watt” at other wavelength. So if we need to measure the perception of light radiometry is not the right scale.



Not all “watts” are the same

If we consider eye's response to light as a function of wavelength we get “lumens” from “watts”



1W at 400 nm is equal to 0,270 lm
1W at 500 nm is equal to 220,609 lm
1W at 600 nm is equal to 430,973 lm
1W at 700 nm is equal to 2,802 lm
1W at 800 nm is equal to 0,000 lm

1W at 555 nm is equal to 683,000 lm

Photometry

When light needs to be measured "through the human eye" e.g. in lighting engineering, the photometry should be used instead of radiometry.

Photometry units

From four main radiometric quantities we get four main photometric ones:

- radiant flux ⇨ luminous flux
- radiant intensity ⇨ luminous intensity
- irradiance ⇨ illuminance
- radiance ⇨ luminance

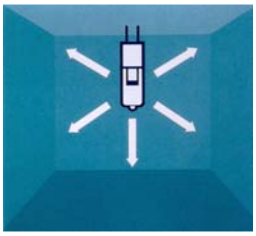
Luminous flux

Φ lumen (lm)

Luminous flux is measure for power delivered by a lighting source and which we can see.

It is only a part of its radiant power (flux) or its consumed power.

Luminous flux



Luminous flux can be calculated from radiant flux with help of:

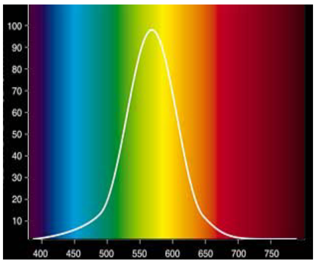
$$\Phi = K_m \cdot \int_0^\infty \frac{d\Phi_e}{d\lambda} \cdot V(\lambda) \cdot d\lambda$$

Where K_m equals 683,002 lm/W and represents luminous flux (lm) at radiant flux of 1W at 555 nm.

Φ lumen (lm)

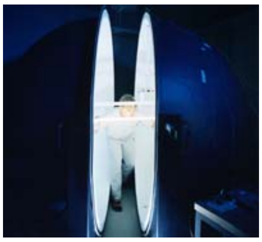
1 W at 555 nm at photopic vision equals 683 lm
1W at 507 nm at scotopic vision equals 1700 lm

Luminous flux



$V(\lambda)$ is luminous efficiency function, normalized to a peak value of unity at 555 nm and describes the average visual sensitivity of the human eye. It is a standard function established by the CIE.

Luminous flux

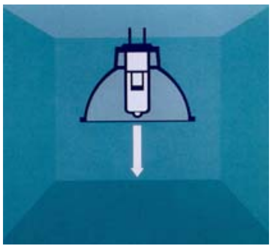


Φ lumen (lm)

Some characteristic values:

- Incandescent lamp 100W 1300 lm
- fluorescent lamp 58 W 5200 lm
- high pressure sodium lamp 100W 10.000 lm
- low pressure sodium lamp 90W 13.500 lm

Luminous intensity

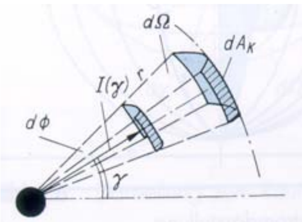


Luminous intensity is a measure of the luminous flux emitted by a light source in a particular direction per unit solid angle.

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

I candela (cd)

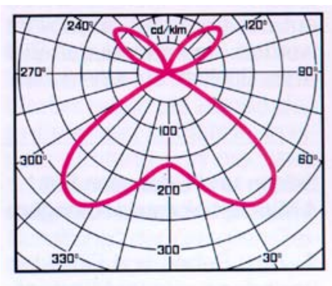
Luminous intensity



The **candela (cd)** is the SI base unit defined as the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540 THz and that has a radiant intensity in that direction of 1/683 W/sr.

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

Luminous intensity



As **luminous intesity** depends on direction it can be presented with a help of **polar diagrams**.

Luminous intensity

Some characteristic values:

- Candle
  0,6 do 1,0 cd
- Incandescent lamp 100W
  110 cd
- high pressure sodium lamp 70W
  500 cd
- Sun (outside the atmosphere)
  $3 \cdot 10^{27}$ cd

Illuminance

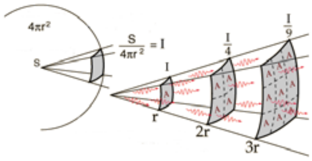
Illuminance is the total luminous flux incident on a surface, per unit area.

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

E lux (lx)

Photometric law of distance

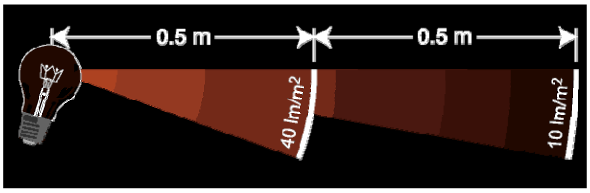
Luminous intensity or luminous flux per solid angle is constant in a given direction (solid angle). If the distance from the source increases the (illuminated) area increases with the square of the distance. So the luminous flux per unit area (illuminance) decreases with the square of the distance.



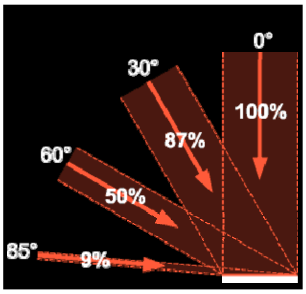
$$E = \frac{I}{r^2}$$

Photometric law of distance

Double the distance, four times smaller the illuminance.



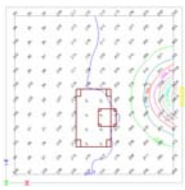
Cosine law



Illuminance *E* upon a surface with arbitrary orientation is related to illuminance upon a surface perpendicular to the beam E_0 by following equation where θ denotes the angle between the beam and the surface's normal.

$$E = E_0 \cdot \cos\,\theta$$

Illuminance



Illuminance is a photometrical quantity which is most frequently used. Especialy in light planning.

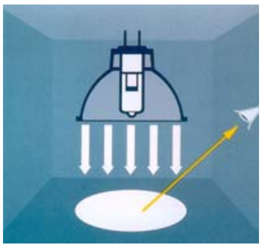
Standards for indoor lighting list minimum values of needed illuminance for different kinds of working places.

Illuminance

Some characteristic values:

- outside on a sunny summer day at 12:00 100.000 lx
- outside in a shade of tree 10.000 lx
- workingplace in office 500 lx
- Incandescent lamp 100W on 1m distance 110 lx
- Street lighting, pedestrian area 3 lx
- outside in a moonlight 0,05 lx

Luminance



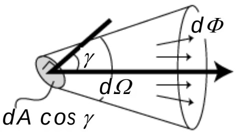
Luminance is a photometric measure of the luminous intensity per unit area of light travelling in a given direction. It describes the amount of light that passes through or is emitted from a particular area, and falls within a given solid angle.

L candela per square metre (cd/m^2)

Luminance

Luminance is defined by:

$$L = \frac{d^2\Phi}{dA \cdot \cos\gamma \cdot d\omega}$$



Where $d\Phi$ is the luminous flux inside the solid angle $d\omega$. dA is the area of the surface (source) and γ is the angle between the surface normal and the specified direction.

Luminance

Luminance can also be defined by:

$$L = \frac{dI}{dA \cdot \cos\gamma}$$

when we observe the luminance of the source with given luminous intesity and area;

$$L = \frac{dE}{\cos\gamma \cdot d\Omega}$$

when we observe the luminance of the illuminated area.

Luminance

Some characteristic values:

- **Sun 1.600.000 kcd/m²**
- **Incandescent lamp (filament) 15.000 kcd/m²**
- **Fluorescent lamp 10 kcd/m²**
- **Candle 8 kcd/m²**
- **Moon 2,5 kcd/m²**
- **Indoor wall illuminated with electric lighting 0,04 kcd/m²**

Interrelations of photometric quantities

$$\begin{tikzcd}
\text{Luminous flux } \Phi \text{ (lm)} \arrow[r, ": \Omega"] \arrow[d, ": A"'] & \text{L. intensity } I \text{ (cd)} \arrow[d, ": A"] \arrow[dl, ": r^2"'] \\
\text{Illuminance } E \text{ (lx)} \arrow[r, ": \Omega"'] & \text{Luminance } L \text{ (cd/m}^2\text{)}
\end{tikzcd}$$

Measurement basics

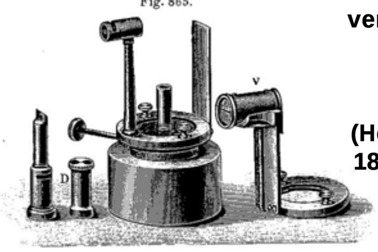
- If we want to measure a quantity we first need an unit and its definition: candela (cd) is a SI unit ...
- The unit needs to be realized so that we get the representation of the unit (e.g. experimental setup) and standards.
- Afterwards unit can be disseminated to the users (e.g. through the calibrations).

Photometrical standards for candela

First unit for luminous intensity was based on candle and also named candle. Different candles were used (English, German ...)

Photometrical standards for candela

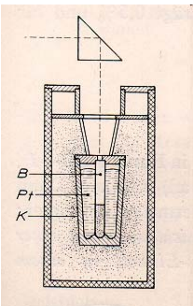
Fig. 865.



Hefnerlampe.

As candles were not very uniform later lamps burning liquid fuel like Hefner lamp (Hefner-Alteneck 1884) were used.

Photometrical standards for candela



In 1937 new definition was adopted based on the black body radiator at the temperature of freezing platinum (2041,4 K) and the unit was called “new candle”. The definition was internationally ratified in 1948 and the name was changed to candela. The definition was changed again in 1967.

Photometrical standards for candela

Today's definition of candela was adopted in 1977 and slightly changed in 1979:

1 candela (cd) is the luminous intensity, in a given direction, of a (light) source that emits monochromatic radiation of frequency 540×10^{12} hertz and that has a radiant intensity in that direction of 1/683 watt per steradian

Photometrical standards for candela

Unfortunately the definition is not suitable for realization so today the candela is realized with a help of cryogenic radiometer which is a measuring device. With help of lasers it is transferred further to standard illuminance photometers.

Photometrical standards for candela

The candela can be further transferred to standard incandescent lamps and maintained with a set of lamps and illuminance photometers.

With the help of illuminance meters it can also be disseminated to other standards.

Photometrical standards - Lumen

Photometrical standards for lumen are also realized in form of standard incandescent lamps.

Photometrical standards - lux

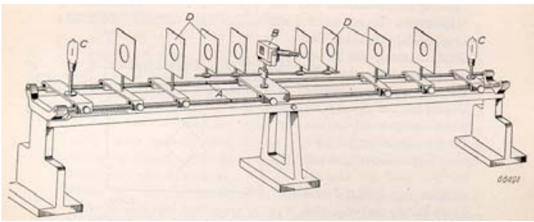
The unit for illuminance – lux – is maintained with help of measuring devices – illuminance photometers (lux meters), which are calibrated against standard lamps.

Photometrical standards - cd/m^2

Photometrical standard for unit of luminance (candela per square meter) is made with help of integrating sphere and stabilized lamp. Part of the sphere is replaced by a “window” with uniform luminance.

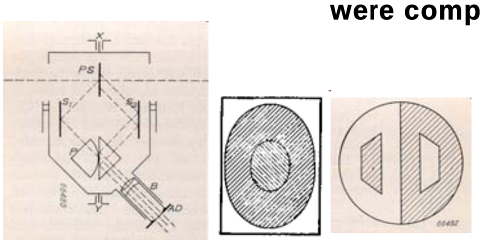
Measuring light

Luminous intensity of unknown source can be measured with help of known source, optical bench and photometer.



Visual photometer

First photometers were made so, that the luminance of two surfaces were compared.



Luminous intensity measurement

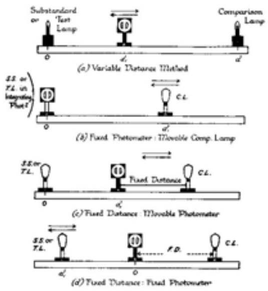
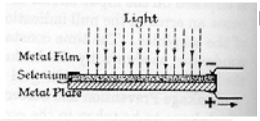


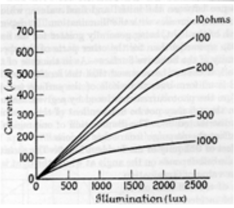
Fig. 123. Methods of Bench Photometry.

The point on an optical bench needs to be found where both surfaces have same luminance. With known distances to the standard and the test lamps and with known luminous intensity of a standard lamp the luminous intensity of the test lamp can be calculated:

$$I_x = \frac{I_n}{r_n^2} \cdot r_x^2$$

Photodetectors

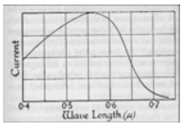


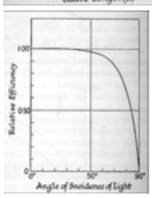


Instead of visual photometers today a photometers based on photodetectors (photovoltaic cells) are used.

If short-circuit or connected to the low resistance ampere-meter, the electrical current is proportional to the illuminance of the cell.

Photodetectors



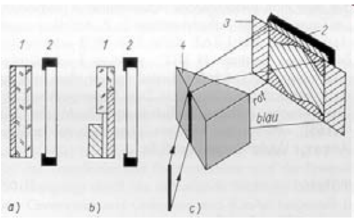


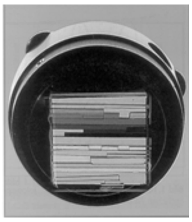
There are two (main) problems connected with the use of (silicon) photodetectors:

- they are not sensitive to different wavelengths as human eye is (luminous efficiency function);
- their relative efficiency does not depend on angle of incidence of light according to cosine law.

Photodetector
– spectral sensitivity correction

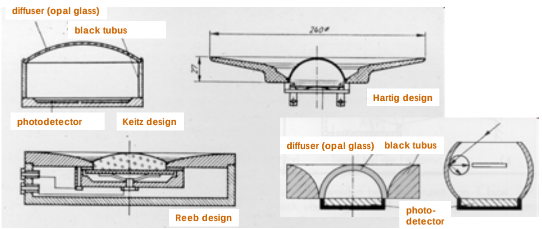
The spectral sensitivity can be corrected with the use of full (b) or pass (a) filters or spectral stencil (c).





Photodetector
– cosine law correction

Also the relative efficiency dependence on angle of incidence of light can be corrected with the help of “stencils” so that resembles the cosine law.



Photodetector
– temperature dependence

The photo-current of photodetectors changes with the temperature:

- cadmium sulfide: 5%/K,
- selenium: 0,5%/K,
- silicon: 0,1%/K.

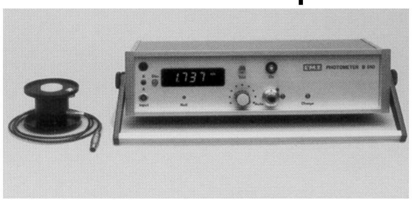
To overcome this problem, the constant temperature of 25 °C is used in photometric laboratories or thermo-stabilized photodetectors are used.

Measurement of illuminance

Digital handheld (pocket) lux-meter with detachable photometric head (photodetector) - most widely used photometric device.

Measurement of illuminance

Precision (standard) laboratory lux-meter with thermo-stabilized photometric head.



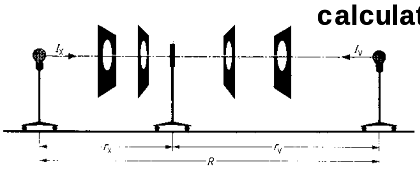
Photodetectors

Photodetector, according to its principle of work, measures illuminance.

It can also be used for measuring the luminous intensity (if the distance is known), luminous flux (if the area is known) or luminance (if the solid angle is known).

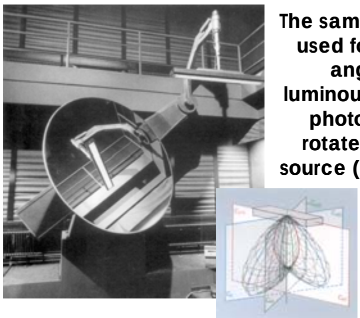
Measurement of luminous intensity

Luminous intensity can be measured on a photometrical bench. If we measure the illuminance (E) and distance (r), the luminous intensity can be calculated using:



$$I = E \cdot r^2$$

Measurement of angular distribution of luminous intensity



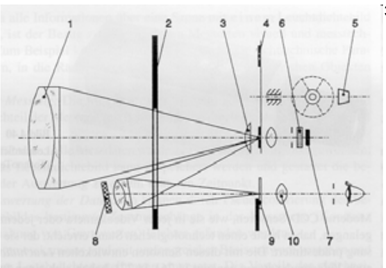
The same principle can be used for measurement of angular distribution of luminous intensity. Just the photodetector needs to rotate around measured source (or vice-versa). The device is called (mirror) goniophotometer.

Measurement of luminance

Luminance can also be measured with the photodetector if we limit the solid angle from which the light comes.

That can be dome with the help of optics: lenses and apertures.

Measurement of luminance



1..lens
2..aperture
3..measuring field lens
4..measuring field aperture
5..wheel with changeable apertures
6..V(λ) filter
7..photodetector
8..mirror system
9..internal display
10..eyepiece

Measurement of luminous flux

Luminous flux can be measured (calculated) with integration of measured illuminance (E) over the area. For light sources an area of (imaginary) sphere with radius (r) around a source is used:

$$\Phi = r^2 \int_0^{4\pi} E(\varphi, \vartheta) \cdot \mathrm{d}\omega$$

$$\mathrm{d}\omega = \sin\vartheta \cdot \mathrm{d}\vartheta \cdot \mathrm{d}\varphi$$

Measurement of luminous flux

Integration can also be done with the help of integration sphere. Due to its high reflectance the inner wall is illuminated with uniform illuminance, which can so be measured only on one spot. Afterwards it only needs to be multiplied with the surface of the sphere.

What is measured daily?

Illuminance:

- illuminance of the interiors and especially
- illuminance of the work places,
- illuminance on outdoor (pedestrian) areas,
- illuminance connected with emergency lighting.

What is measured daily?

Luminous flux:

- luminous flux of lighting sources (producers of lighting sources),
- luminous flux of luminaires (producers of luminaires).

What is measured daily?

Luminous intensity:

- luminous intensity of light sources (producers of light sources),
- angle distribution of luminous intensity of light sources (producers of light sources),
- angle distribution of luminous intensity of luminaires (producers of luminaires).

What is measured daily?

Luminance:

- luminance of roads,
- luminance of illuminated symbols in cockpits (cars, aircrafts ...)
- luminance of interior surfaces (connected with glare).

At the end

- Photometrical quantities are based on spectral responsivity of human eye.
- Four basic quantities: luminous flux, luminous intensity, illuminance and luminance.
- For measurements a photodetector (photocell, photoelement) is used which should be spectrally corrected (and adapted to cosine law).

... and now:

Questions?