

Radiometry and Photometry

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Week 15

- Course Website: <http://courses.washington.edu/me557/optics>

- Reading Materials:

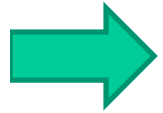
- Week 15 reading materials are from:

<http://courses.washington.edu/me557/readings/>

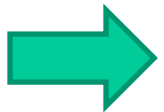
- HW #2 due Week 16
- Set up a schedule to do Lab 2 (those who haven't done the lab, you can do some designs projects relating to LED and detectors and send them to me before 6/25)
- Prism Design Project memo and presentation due next two weeks (here are things you need to send me, video of your oral presentation with demo, PPTs, memos)
- Final Project proposal: Due Today (please follow the instruction on what you need to include in your proposal)
- Final Project Presentation on 6/7 (We will not do the final presentation on 6/7, but instead you will send me the videos of your oral presentations and demos along with your PPTs on 6/8)
- Final project report and all the missing HW's must be turned in by 6/19 5PM
- Please send all these appropriate assignment and project materials to abong@uw.edu according to the due dates.

Again, I need videos of your oral presentations and demos besides your PPTs and reports or memos.

Last Week

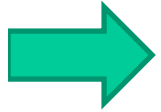


- Photodetectors
 - Photoemmissive Cells
 - Semiconductor Photoelectric Transducer
(diode equation, energy gap equation, reverse bias voltage, quantum efficiency, responsivity, junction capacitance, detector angular response, temperature effect, different detector operating mode, noises in detectors, photoconductive, photovoltaic, photodiode, PIN, APD, PDA, PSD, CCD, CMOS detectors)
 - Thermal detectors (IR and THz detectors)



- Radiometry and photometry

Last Week



- Photodetectors
 - Photoemissive Cells
 - Semiconductor Photoelectric Transducer
(diode equation, energy gap equation, reverse bias voltage, quantum efficiency, responsivity, junction capacitance, detector angular response, temperature effect, different detector operating mode, noises in detectors, photoconductive, photovoltaic, photodiode, PIN, APD, PDA, PSD, CCD, CMOS detectors)
 - Thermal detectors (IR and THz detectors)



- Radiometry and photometry
 - Intensity and phase modulating optical techniques

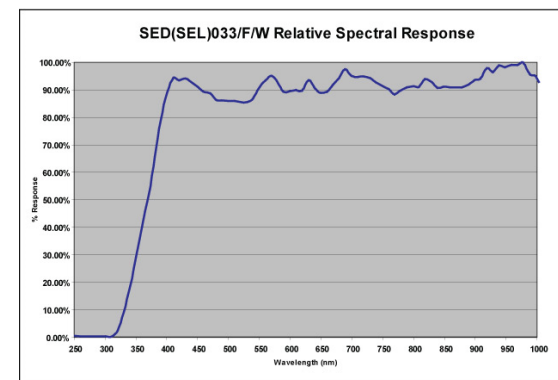
Materials Covered

- Radiometry
 - Radiant Flux
 - Radiant Intensity
 - Irradiance
 - Radiance
- Photometry
 - luminous Flux
 - luminous Intensity
 - Illuminance
 - luminance

Conversion from radiometric and photometric

Radiometry

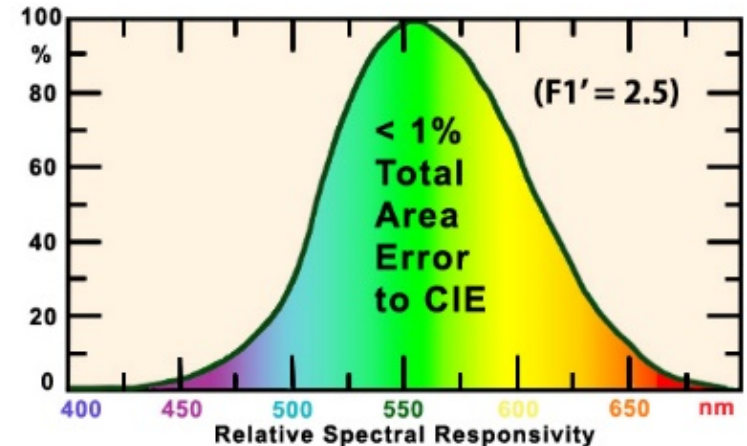
Radiometry is the **detection and measurement of light waves in the optical portion of the electromagnetic spectrum** which is further divided into **ultraviolet, visible, and infrared light.**



Example of a typical radiometer

Photometry

All light measurement is considered radiometry with photometry being a special subset of radiometry weighted for a typical human eye response.



Example of a typical photometer

Human Eyes

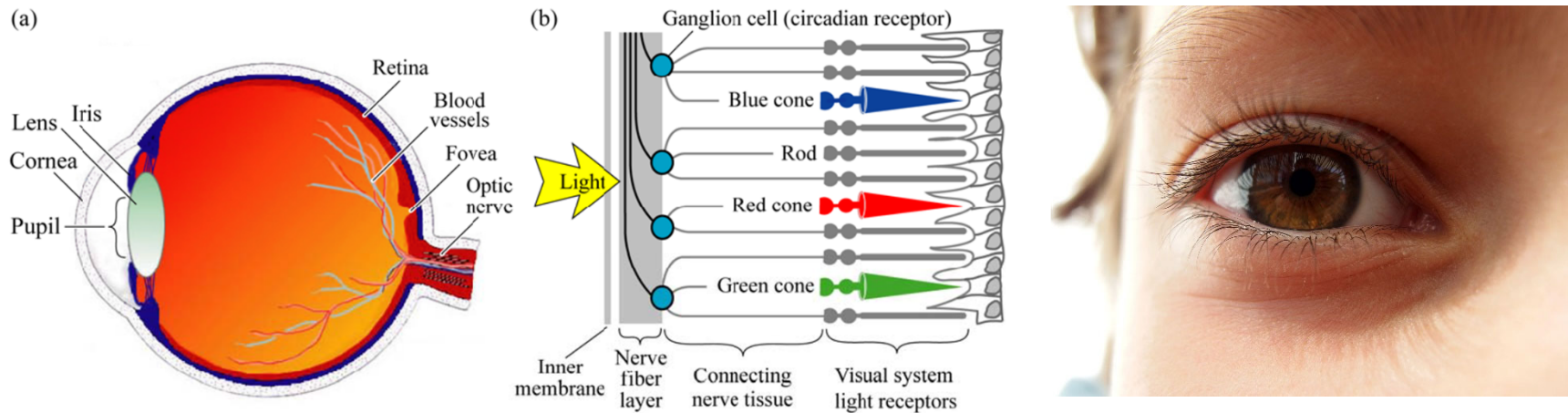
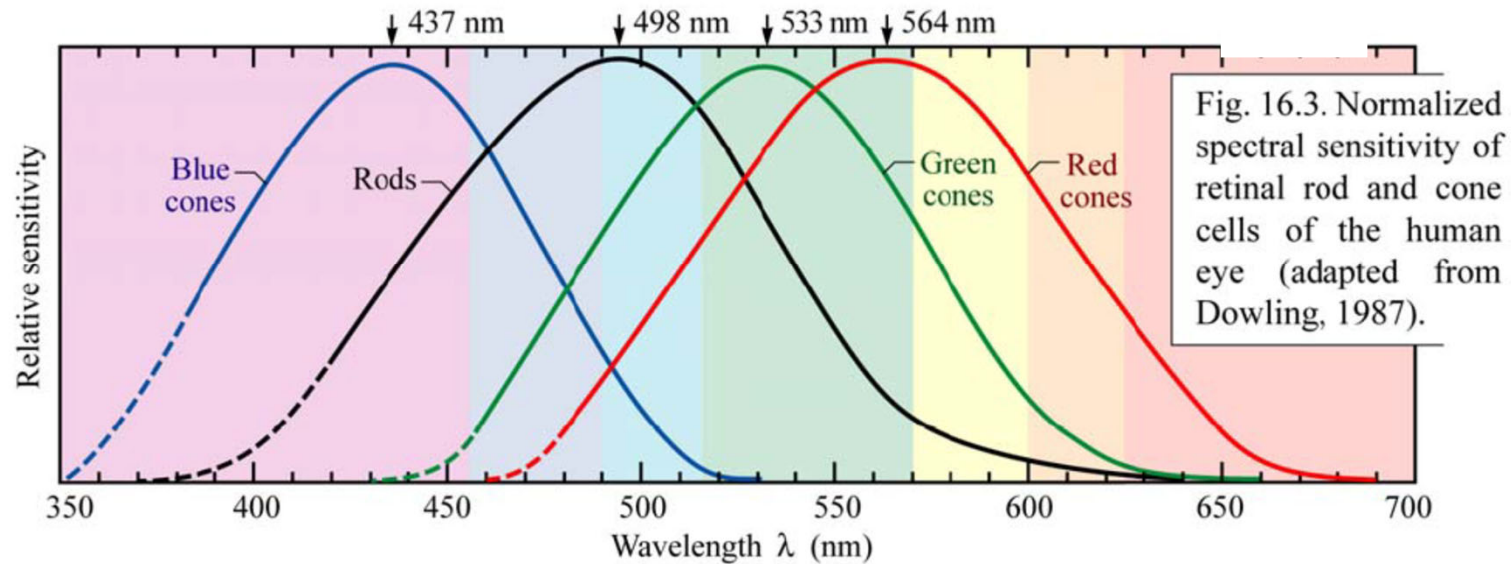


Figure shows a schematic illustration of the human eye (Encyclopedia Britannica, 1994).

The inside of the eyeball is **clad by the retina**, which is the light-sensitive part of the eye. The illustration also shows the **fovea, a cone-rich central region of the retina which affords the high acuteness of central vision**.

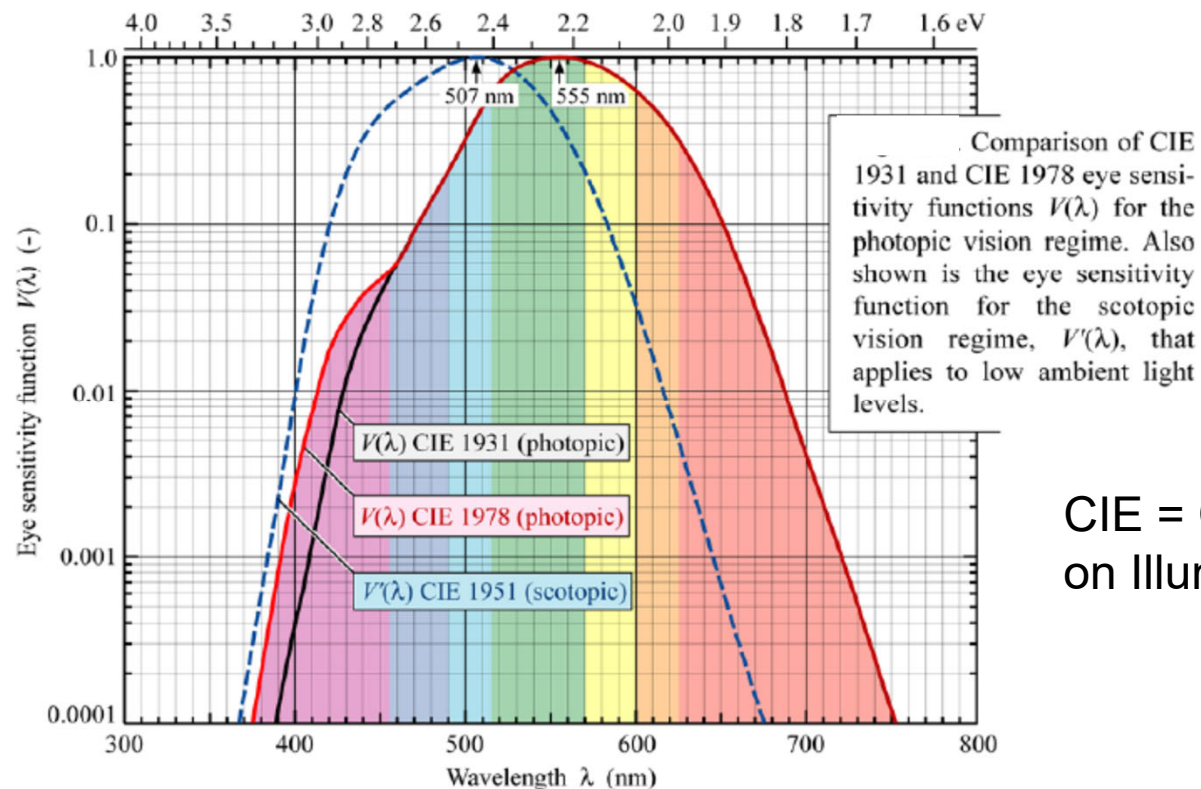
Figure also shows the cell structure of the retina including the **light-sensitive rod cells and cone cells**. Also shown are the ganglion cells and nerve fibers that transmit the visual information to the brain. Rod cells are more abundant and more light sensitive than cone cells. Rods are sensitive over the entire visible spectrum.



There are three types of cone cells, namely cone cells sensitive in the red, green, and blue spectral range. The approximate spectral sensitivity functions of the rods and three types of cones are shown in the figure above

Eye sensitivity function

The conversion between radiometric and photometric units is provided by the **luminous efficiency function** or **eye sensitivity function**, $V(\lambda)$. The CIE 1978 $V(\lambda)$ function, which can be considered the most accurate description of the eye sensitivity in the photopic vision regime



Scotopic and Photopic Filter

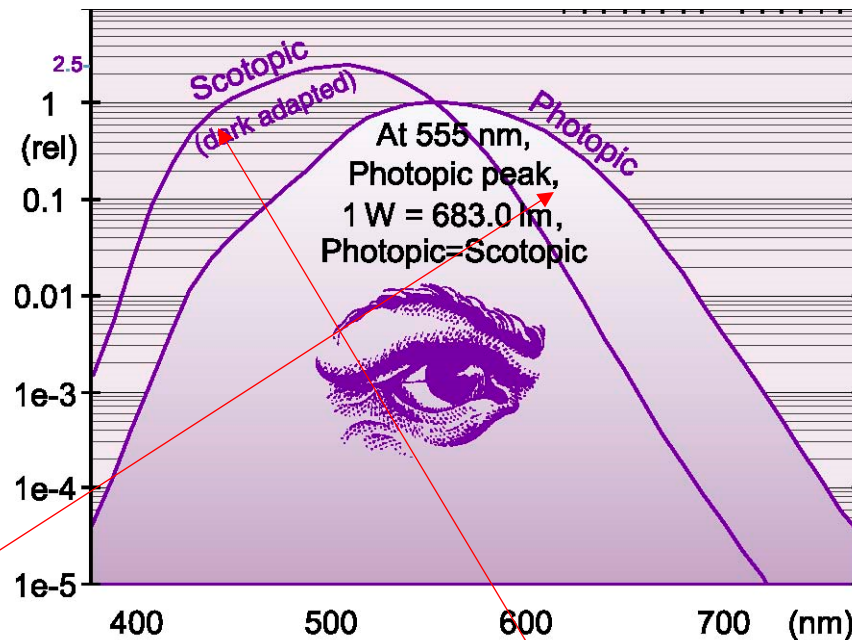


Fig. 2.3 CIE Photopic and Scotopic sensitivity curves.

Use of a **photopic correction filter** is important when measuring the **perceived brightness of a source to a human**. The filter weights incoming light in proportion to the effect it would produce in the human eye. Regardless of the color or spectral distribution of the source, the photopic detector can deliver accurate illuminance and luminance measurements in a single reading. **Scotopic vision refers to the eye's dark-adapted sensitivity (night vision).**

Definitions, Units and Symbols

- **Radiometry** – deals with the detection and measurement of electromagnetic radiation across the total spectrum
- **Photometry** – subfield of radiometry; radiometric power scaled by the spectral response of the human eye

In spec. sheet, this is what you see because of the application we use these light for

Radiometric			Photometric		
Quantity	Symbol	Units	Quantity	Symbol	Units
Radiant Power	Φ_e	W	Luminous Flux	Φ_v	lumens (lm)
Radiant Intensity	I_e	W/sr	Luminous Intensity	I_v	lm/sr
Irradiance	E_e	W/m ²	Illuminance	E_v	lm/m ²
Radiance	L_e	W/m ² -sr	Luminance	L_v	lm/m ² -sr

“e” = “energetic”

“v” = “visual”

The table summarizes the most common radiometric and photometric quantities.

Conversion

To convert between radiometric and photometric units, one needs to know the **photopic spectral luminous efficiency curve $V(\lambda)$** , which gives the spectral response of the human eye to various wavelengths of light. The original curve, which is shown earlier, was adopted by the **Commission on Illumination (CIE)** as the standard in 1924 and is still used today even though modifications have been suggested. Empirical data shows that the curve has a **maximum value of unity at 555nm**, which is the wavelength of light at which the human eye is **most sensitive**, and trails off to levels below 10^{-5} for wavelengths below 370nm and above 780nm.

The **lumen (lm)** is the photometric equivalent of the watt, weighted to match the eye response of the “standard observer”. Yellowish-green light receives the greatest weight because it stimulates the eye more than blue or red light of equal radiometric power:

1 watt at 555 nm = 683.0 lumens



QUANTITY	RADIOMETRIC	PHOTOMETRIC
Radiant Power	W	Lumen (lm) = cd·sr
Radiant Intensity (Power Per Unit Solid Angle)	W/sr	Candela (cd) Power
Irradiant (Power Per Unit Area)	W/m ²	Lux (lx) = cd·sr/m ² = lm/m ²
Radiance (Unit Area Per Unit Solid Angle)	W/m ² ·sr	cd/m ² = lm/m ² ·sr = nit

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1cd (candle) = π lumens

Candle already have angle factor into it!!!!!!

Conversion

The conversion between photometric units which take into account human physiology and straight radiometric units is given by the following: $(\text{photometric unit}) = (\text{radiometric unit}) \times (683) \times V(\lambda)$ where $V(\lambda)$ is the 'Photopic Response,' shown earlier and basically tells us how efficiently the eye picks up certain wavelengths of light. The Photopic response is a function of the wavelength of light and so to convert from radiometric units to photometric units first requires knowledge of the light source. If the source is specified as having a certain color temperature we can assume that its spectral radiance emittance is the same as a perfect black body radiator and use Planck's law.

Conversion

A non-linear regression fit to the experimental data yields the approximation,

$$V(\lambda) = 1.019e^{-285.4(\lambda - 0.559)^2},$$

where the wavelength is in micrometers.

According to the definition for a candela, there are 683 lumens per watt for 555nm light that is propagating in a vacuum. Hence, for a monochromatic light source, it is fairly simple to convert from watts to lumens; simply multiply the power in watts by the appropriate $V(\lambda)$ value, and use the conversion factor from the definition for a candela.

For example, the photometric power of a 5mW red (= 650nm) laser pointer, which corresponds to $V(\lambda) = 0.096$, is $0.096 \times 0.005W \times 683lm/W = 0.33lm$, whereas the value for a 5mW green (= 532nm) laser pointer is $0.828 \times 0.005W \times 683lm/W = 2.83lm$. Thus, although both laser pointers have the exact same radiant flux, the green laser pointer will appear approximately 8.5 times brighter than the red one assuming both have the same beam diameter.

Conversion

Conversion from radiometric to photometric units becomes more complex if the light source is not monochromatic. In this case, the mathematical quantity of interest is

$$\Phi_V = K_m \int_{\lambda=380}^{\lambda=830} \Phi_E(\lambda) V(\lambda) d\lambda$$

where Φ_V is the luminous flux in lumens, K_m is a scaling factor equal to 683 lumens per watt, $\Phi_E(\lambda)$ is the spectral power in watts per nanometer, and $V(\lambda)$ is the photopic spectral luminous efficiency function. Note that the integration is only carried out over the wavelengths for which $V(\lambda)$ is non-zero (i.e. $\lambda = 380 - 830\text{nm}$). Since $V(\lambda)$ is given by a table of empirical values, it is best to do the integration numerically.

Converting to Photometric Units

- Power (Watts) is converted to luminous flux (lumens) via the relation:

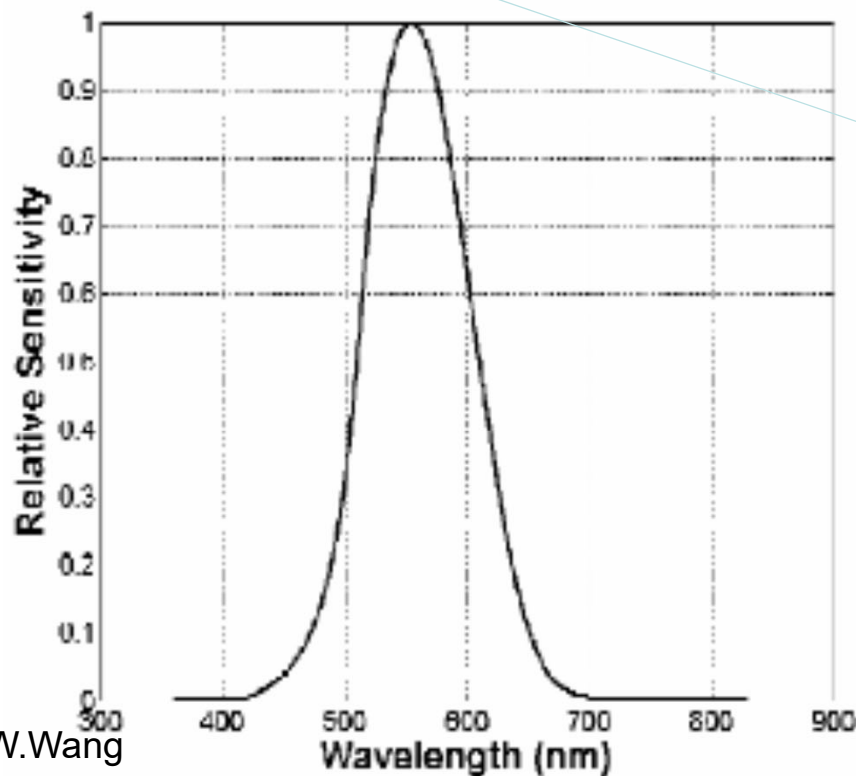
$$\Phi_v = K \int_{380}^{780} P_e(\lambda) V(\lambda) d\lambda$$

Φ_v = flux (lumens)

P_e = Power

V = photopic response function of the human eye

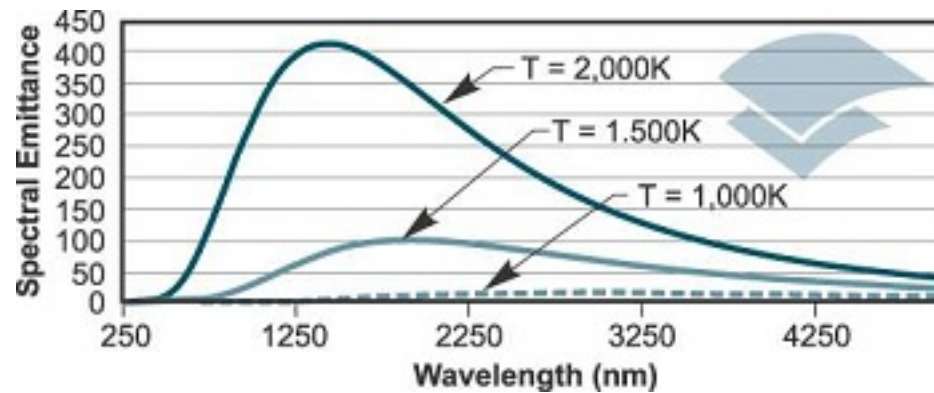
K = constant (683 lm/W for photopic)



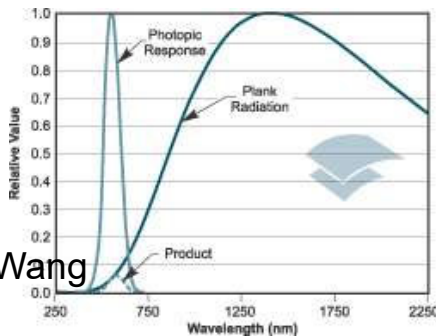
Radiometric power is converted to luminous flux via the integral equation. $V(\lambda)$ is the spectral response of the human eye in daylight, otherwise known as the photopic curve. The unit of luminous flux is the lumen.

Example

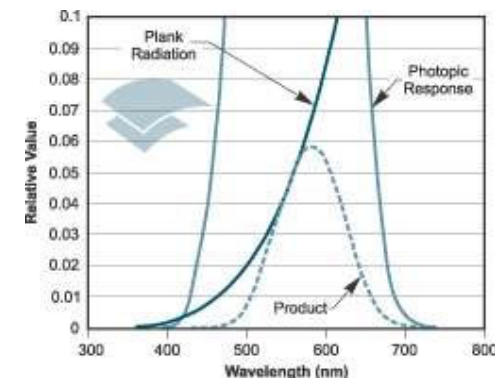
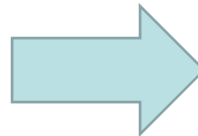
Artificial sources in general do not have the same spectral distribution as a perfect black body but for our purposes we shall consider them equal. The graph above depicts the spectral radiance of several black body radiators. If we consider the Photopic evaluation of a black body radiation at a temperature of $T=2045\text{K}$.



Integration of the product of the light emittance by the Photopic function provides the conversion from a Radiometric signal to a Photometric.

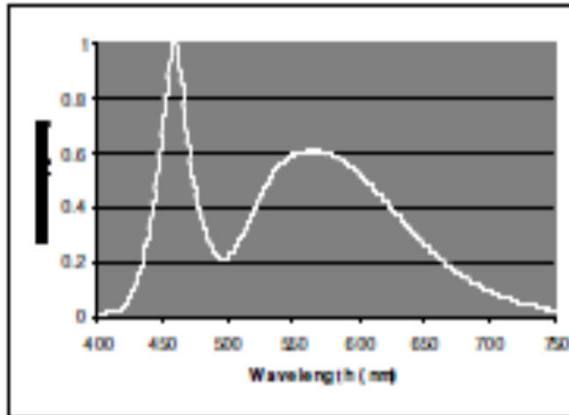


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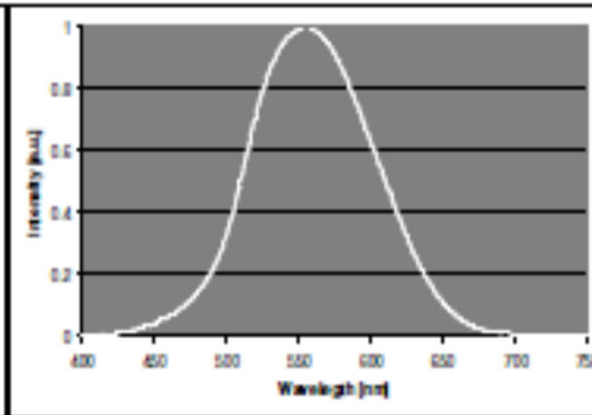


Convert Radiometric to Photometric

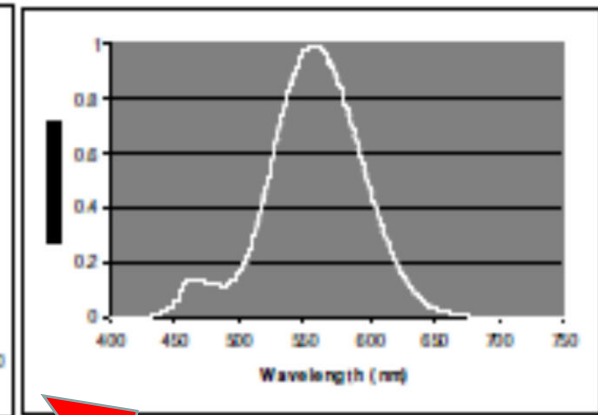
$$P_e(\lambda) \quad V(\lambda) \quad \longrightarrow \quad \Phi_v(\lambda)$$



White LED



photopic spectral



luminous flux

$$\Phi_v = K \int_{380}^{780} P_e(\lambda) V(\lambda) d\lambda$$

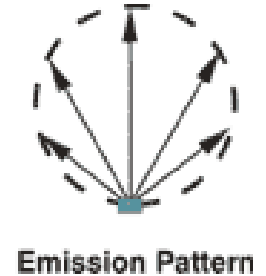
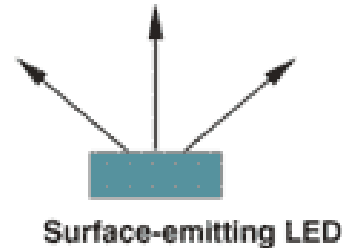
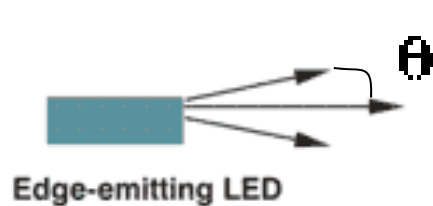
Like transformation
or transfer function

Recall

LED

There are two basic types of LED structures: edge emitters and surface emitters.

$$P = P_0 \cos \theta$$



output power is high (emitting spot is very small, typically 30-50 μm)

narrow emission spectra (FWHM is typically about 7% of the central wavelength)

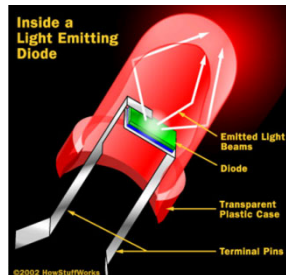
Narrow beam pattern

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simple structure, are relatively inexpensive, offer low-to-moderate output power levels, and are capable of low-to-moderate operating speeds

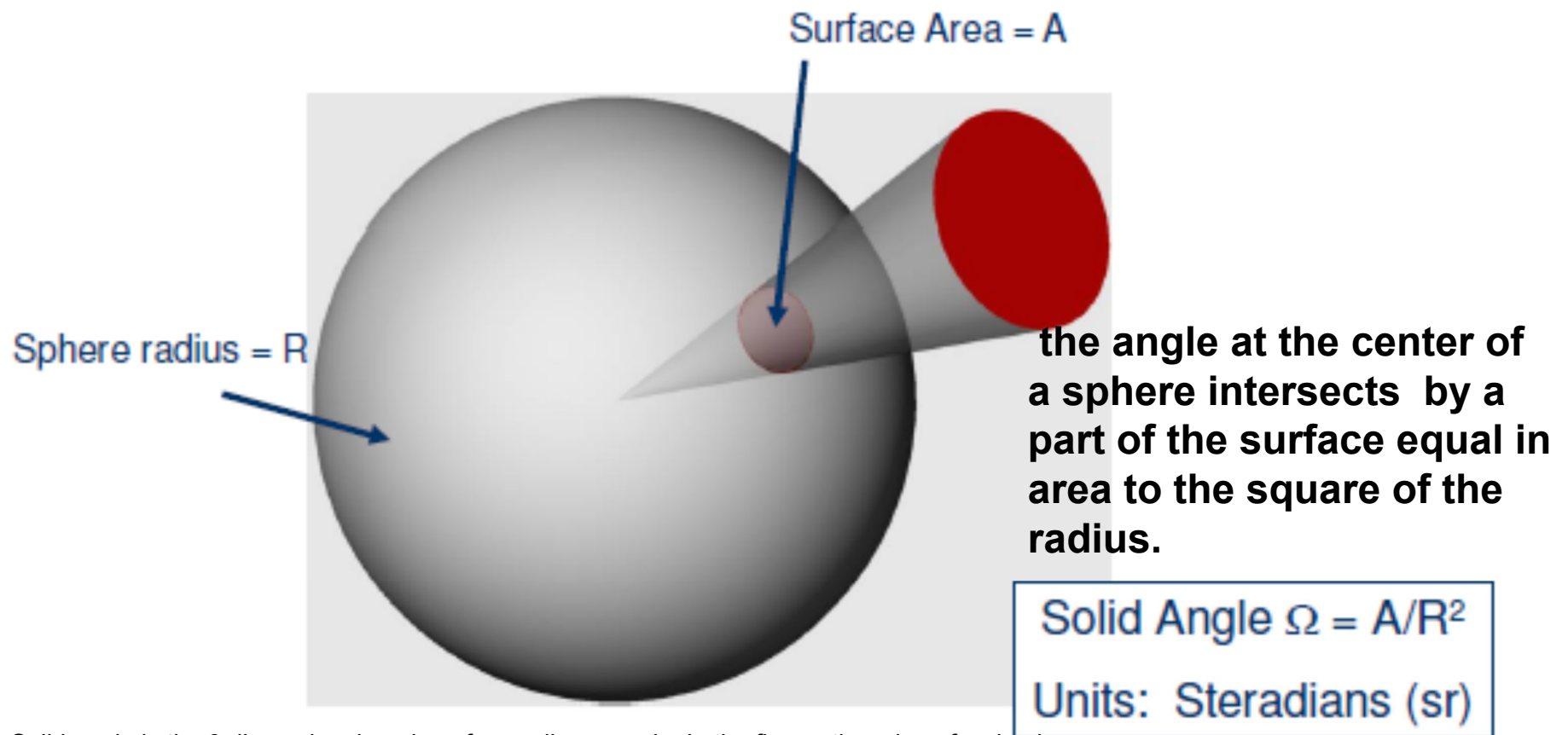
output power is as high or higher than the edge-emitting LED, but the emitting area is large, causing poor coupling efficiency to the optical fiber

emit light in all directions



Solid Angle

Radiant Intensity and luminous Intensity



Solid angle is the 3 dimensional analog of an ordinary angle. In the figure, the edge of a circular disk, the bright red circle, is projected to the center of a sphere. The projection intersects the sphere and forms a surface area A. Solid angle is the area A on the surface of a sphere of radius R divided by the radius squared. The units of solid angle are steradians. Note that it is a dimensionless quantity.

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Radiometric			Photometric		
Quantity	Symbol	Units	Quantity	Symbol	Units
Radiant Power	Φ_e	W	Luminous Flux	Φ_v	lumens (lm)
Radiant Intensity	I_e	W/sr	Luminous Intensity	I_v	lm/sr
Irradiance	E_e	W/m ²	Illuminance	E_v	lm/m ²
Radiance	L_e	W/m ² -sr	Luminance	L_v	lm/m ² -sr

OSRAM

Steradian

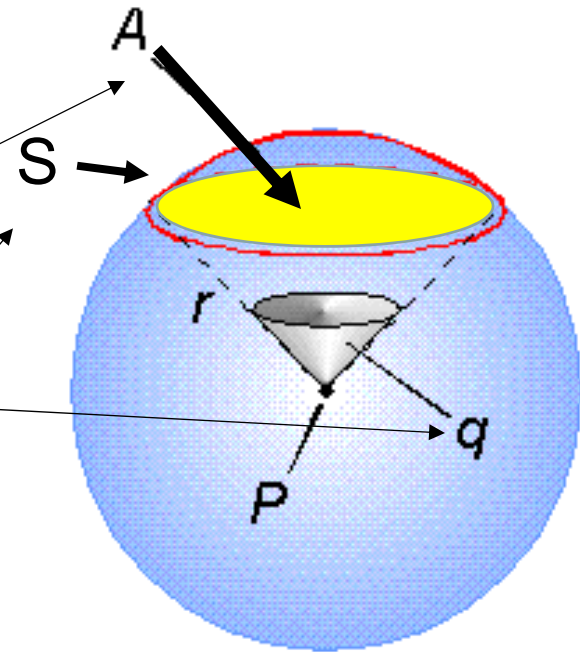
The steradian (symbolized sr) is the Standard International (SI) **unit of solid angular measure**. There are **4π , or approximately 12.5664, steradians in a complete sphere**.

A steradian is defined as **conical in shape, as shown in the illustration**. Point P represents the center of the sphere. The solid (conical) angle q , representing one steradian, is such that the area A of the subtended portion of the sphere is equal to r^2 , where r is the radius of the sphere.

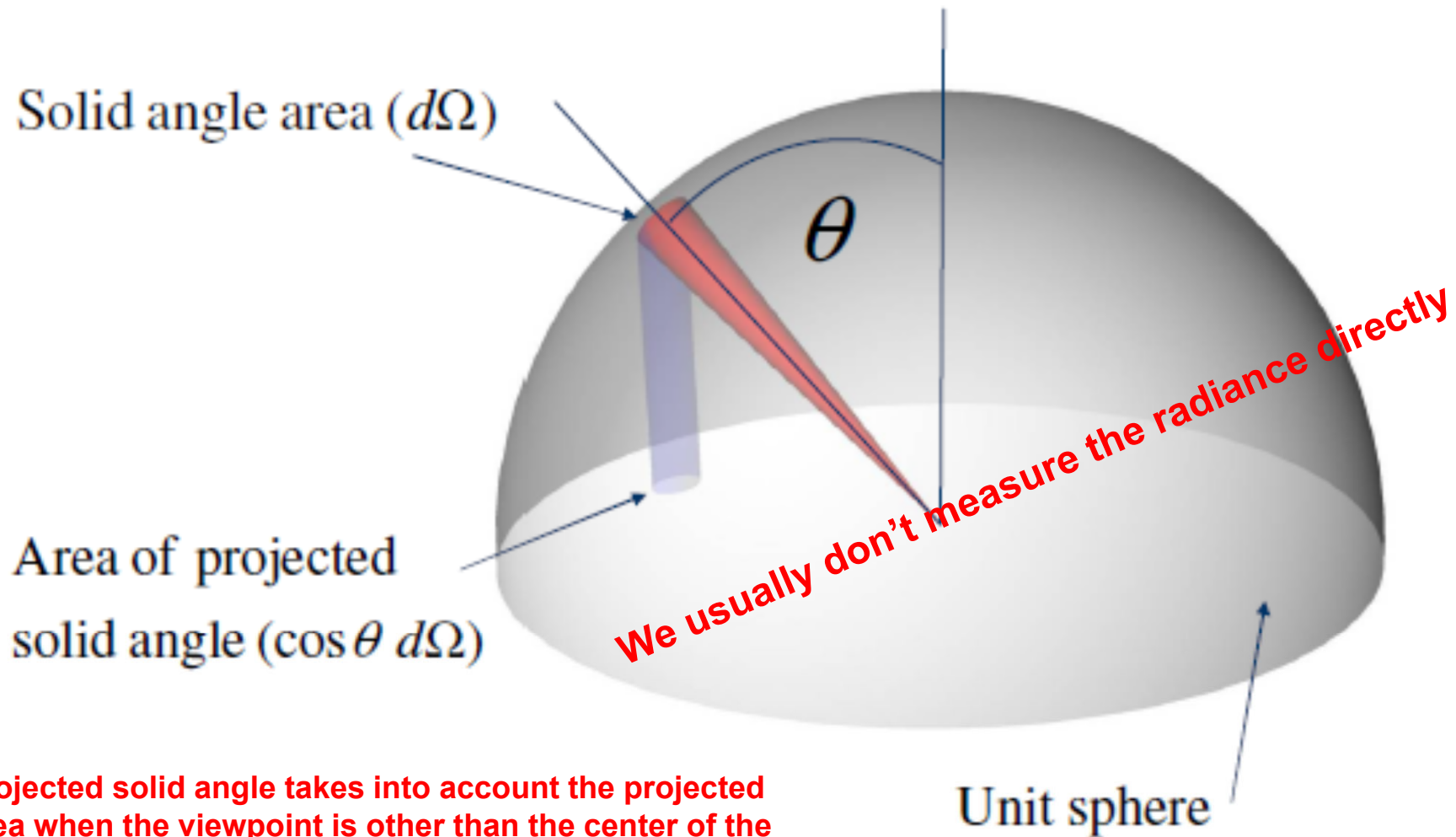
A general sense of the steradian can be envisioned by considering a sphere whose radius is one [meter](#) ($r = 1\text{m}$). Imagine a cone with its apex P at the center of the sphere, and that intersects the surface in a circle (shown as a red ellipse, the upper half of which is dashed). Suppose the flare angle q of the cone is such that the area A of the spherical segment within the circle is equal to one meter squared ($A = 1\text{ m}^2$). Then the flare angle of the cone is equal to 1 steradian ($q = 1\text{ sr}$). The total surface area of the sphere S is, in this case, 12.5664 square meters (4π times the square of the radius).

Based on the foregoing example, the geometry of which is independent of scale, it can be said that a solid angle of 1 sr encompasses about 1/12.5664, or 7.9577 percent, of the space surrounding a point.

The number of steradians in a given solid angle can be determined by dividing the area on the surface of a sphere lying within the intersection of that solid angle with the surface of the sphere (when the focus of the solid angle is located at the center of the sphere) by the square of the radius of the sphere.



Projected Solid Angle



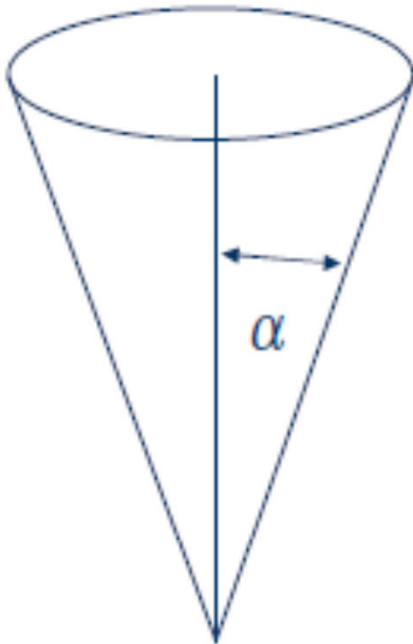
Projected solid angle takes into account the projected area when the viewpoint is other than the center of the sphere. The element of solid angle is shown in red. The area of projected solid angle is shown in blue.

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Radiometric			Photometric		
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Radiant Power	Φ_e	W	Luminous Flux	Φ_v	lumens (lm)
Radiant Intensity	I_e	W/sr	Luminous Intensity	I_v	lm/sr
Irradiance	E_e	W/m ²	Illuminance	E_v	lm/m ²
Radiance	L_e	W/m ² ·sr	Luminance	L_v	lm/m ² ·sr

ISRAM

Projected Solid Angle



As an example, the projected solid angle for a cone of half angle alpha is calculated.

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$$d\Omega = \sin \theta d\theta d\phi$$

$$d\Omega_{proj} = \cos \theta d\Omega$$

$$\Omega_{proj} = \int_0^{2\pi} \int_0^{\alpha} \cos \theta \sin \theta d\theta d\phi$$

$$\Omega_{proj} = \pi \sin^2 \alpha$$

We use these angles
integral because most of
these light source we use
have this kind of radiation
pattern (e.g. point source)

OSRAM

Lambertian Source

LED Example

- Brightness (luminance) is independent of angle

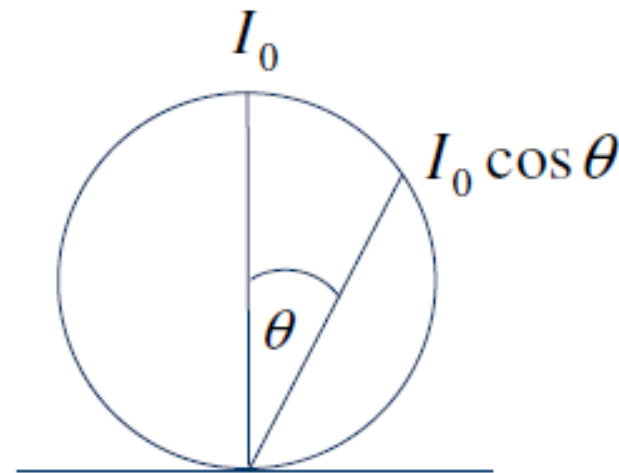
$$L(\theta) = L(0)$$

- Intensity falls off as $\cos \theta$

$$I(\theta) = I_0 \cos \theta$$

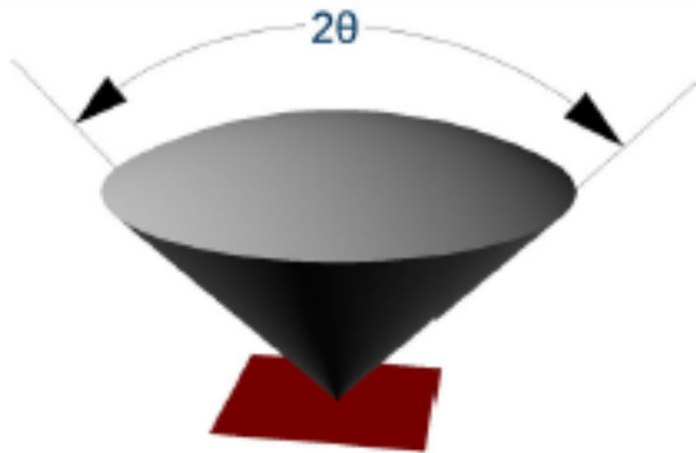
- Many LEDs are very nearly Lambertian sources

A Lambertian source is defined as one in which the brightness (or luminance) is independent of angle, in other words the off-axis luminance is the same as on-axis. Such a source has an intensity vs. angle profile that falls off as the cosine of the angle. Historically, many LED sources have had nearly Lambertian beam distributions, simplifying certain calculations.



Lambertian Source

LED Example



Take the example of calculating the luminous flux within a certain cone angle. Substituting the intensity **distribution of a Lambertian source into the equation makes the integration simple**. For a so-called Lambertian LED, the total lumens is about 3 times the on-axis intensity.

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Total flux in a 2θ cone:

Radiometric			Photometric		
Quantity	Symbol	Units	Quantity	Symbol	Units
Radiant Power	Φ_e	W	Luminous Flux	Φ_v	lumens (lm)
Radiant Intensity	I_e	W/sr	Luminous Intensity	I_v	lm/sr
Irradiance	E_e	W/m ²	Illuminance	E_v	lm/m ²
Radiance	L_e	W/m ² ·sr	Luminance	L_v	lm/m ² ·sr

$$\Phi = 2\pi \int_0^\theta I(\theta') \sin \theta' d\theta'$$

$$\Phi = 2\pi \int_0^\theta I_0 \cos \theta' \sin \theta' d\theta'$$

$$\Phi = I_0 \pi \sin^2 \theta$$

We use these angles integral because most of these light source we use have this kind of radiation pattern

The total flux of a Lambertian source of 1 cd is π lumens.

Definitions, Units and Symbols

- **Radiometry** – deals with the detection and measurement of electromagnetic radiation across the total spectrum
- **Photometry** – subfield of radiometry; radiometric power scaled by the spectral response of the human eye

Radiometric			Photometric		
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Radiance	L_e	W/m ² -sr	Luminance	L_v	lm/m ² -sr

“e” = “energetic”

“v” = “visual”

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The table summarizes the most common radiometric and photometric quantities.

Radiant Flux (Power) (ϕ) (W)

Radiant flux is the fundamental unit in detector-based radiometry. It is defined as the total optical power of a light source, and is expressed in watts.

To measure radiant flux, the detector must collect all emitted light. Examples of typical flux measurements are shown in Figure 2. Focused lasers and fiber optic cables require only the proper sensor head because the source and detector can be configured so that all radiation is incident within the active area of the sensor. Diverging light sources, such as LEDs and lamps, may require an integrating sphere to capture light radiating in several directions.

Radiant Intensity ($I = d\phi/d\Omega$) (W/sr)

Radiant Intensity is the amount of flux emitted through a known solid angle. It is measured in watts/steradian.

To measure radiant intensity, start with the angle subtended by the detector at a given distance from the source (see Figure 4). Then divide the amount of flux by that solid angle.

Radiant Intensity is a property of the light source and may not be relevant if the spatial distribution of radiation from the source is non-uniform. It is appropriate for point sources (and for close approximations, such as an LED intensity measurements), but not for collimated sources.

Irradiance ($E = \phi/A = 4\pi I / 4\pi r^2 = I/r^2$) (W/m²)

Irradiance is the amount of radiant flux incident on a known surface area. Its international unit of measure is watt/m². However, because many sensor heads have a 1-cm² detector area, it is simpler to use watt/cm².

There are two ways to control the size of the detector area. The first is to use a sensor head with a known detector area. The second is to place an aperture with a known area between the source and the detector. When source radiation does not completely fill the detector, an aperture is the only reliable method of controlling detector area.

Radiance ($L = dI / dA \cos\theta$) (W/sr*m²)

Radiance is the radiant intensity emitted from a known unit area of a source. Units of radiance are used to describe extended light sources, such as a CRT or an EL/O Panel unit for characterizing point sources.

To measure radiance, you need to define the area of the source to be measured, and also the solid angle received. This is usually simulated using an aperture and a positive lens in front of the detector. It is expressed as watts/cm²·ster.

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Radiometric			Photometric		
Quantity	Symbol	Units	Quantity	Symbol	Units
Radiant Power	Φ_e	W	Luminous Flux	Φ_v	lumens (lm)
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Irradiance	E_e	W/m ²	Illuminance	E_v	lm/m ²
Radiance	L_e	W/m ² ·sr	Luminance	L_v	lm/m ² ·sr

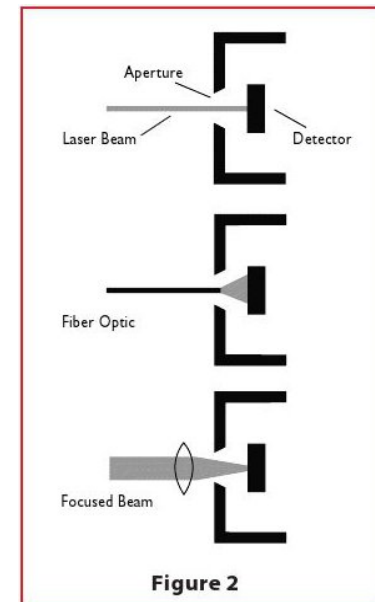


Figure 2

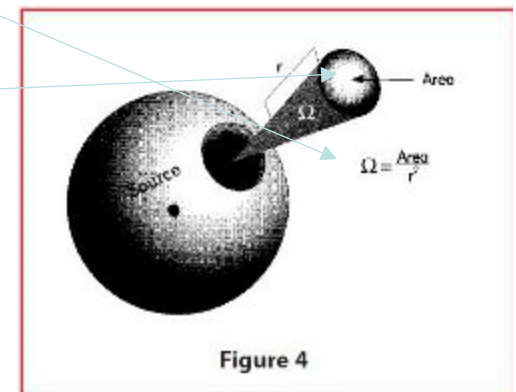


Figure 4

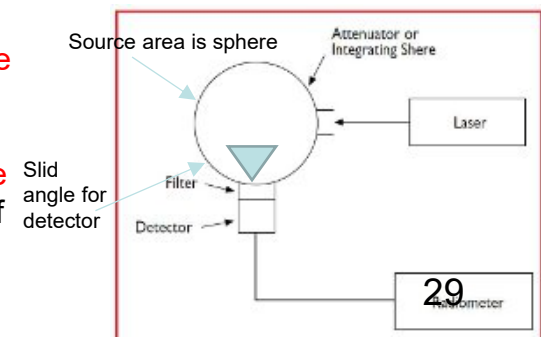
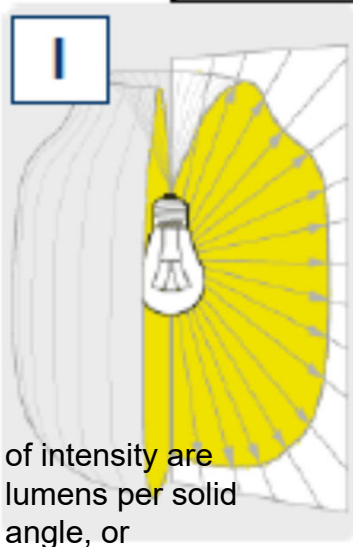


Figure 6

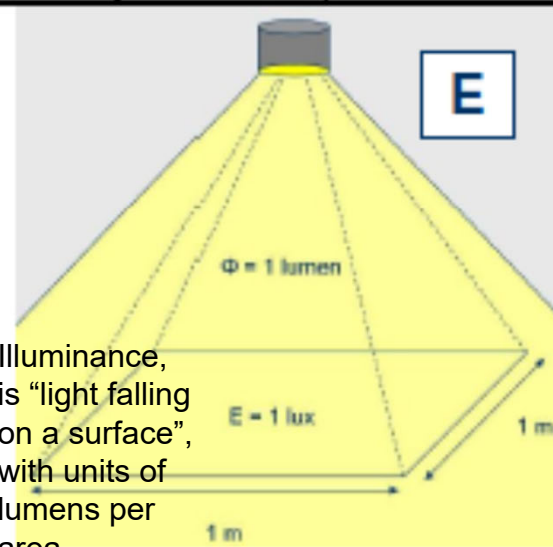
Photometric Units and Symbols

Photometric Units					
Quantity	Symbol	Metric Units	Name	English Units	Name
Luminous Flux	Φ	lumens (lm)	lumens		
Luminous Intensity	I	lm/sr	candela (cd) or candlepower		
Illuminance	E	lm/m ²	lux (lx)	lm/ft ²	Ft-candle
Luminance	L	cd/m ²	nits	cd/π*ft ²	Ft-Lambert

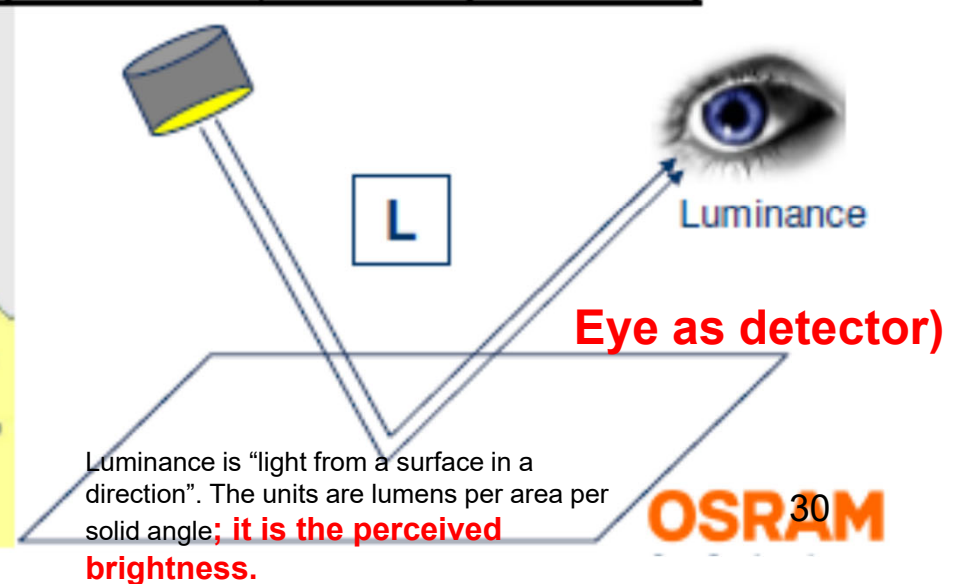


of intensity are
lumens per solid
angle, or
steradians

W.Wang



Illuminance,
is "light falling
on a surface",
with units of
lumens per
area



Luminance is "light from a surface in a
direction". The units are lumens per area per
solid angle; **it is the perceived
brightness.**

OSRAM 30

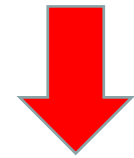
Candle to lumi

you must know the beam angle to do the onversion between millicandelas (or candelas) and lumens for a light source.

conversion 1 candela = 1 lumen/steradian.

To do this, it converts the beam angle you supply into a solid angle in units of steradians.

Unit Conversion Review



QUANTITY	RADIOMETRIC	PHOTOMETRIC
Radiant Power	W	Lumen (lm) = $\text{cd} \cdot \text{sr}$
Radiant Intensity (Power Per Unit Solid Angle)	W/sr	Candela (cd) Power
Irradiant (Power Per Unit Area)	W/m ²	Lux (lx) = $\text{cd} \cdot \text{sr} / \text{m}^2 = \text{lm} / \text{m}^2$
Radiance (Unit Area Per Unit Solid Angle)	W/m ² ·sr	cd/m ² = $\text{lm} / \text{m}^2 \cdot \text{sr} = \text{nit}$

$$1 \text{ cd (candle)} = \pi \text{ lumens}$$

Quantity		Unit		Dimension	Notes
Name	Symbol ^[nb 1]	Name	Symbol	Symbol	
Radiant energy	Q_e ^[nb 2]	joule	J	$\mathbf{M \cdot L^2 \cdot T^{-2}}$	Energy of electromagnetic radiation.
Radiant energy density	w_e	joule per cubic metre	J/m ³	$\mathbf{M \cdot L^{-1} \cdot T^{-2}}$	Radiant energy per unit volume.
Radiant flux	Φ_e ^[nb 2]	watt	W or J/s	$\mathbf{M \cdot L^2 \cdot T^{-3}}$	Radiant energy emitted, reflected, transmitted or received, per unit time. This is sometimes also called "radiant power".
Spectral flux	$\Phi_{e,\nu}$ ^[nb 3] or $\Phi_{e,\lambda}$ ^[nb 4]	watt per hertz or watt per metre	W/ Hz or W/m	$\mathbf{M \cdot L^2 \cdot T^{-2}}$ or $\mathbf{M \cdot L \cdot T^{-3}}$	Radiant flux per unit frequency or wavelength. The latter is commonly measured in W·sr ⁻¹ ·m ⁻² ·nm ⁻¹ .

<u>Radiant intensity</u>	$I_{e,\Omega}$ ^[nb 5]	watt per <u>steradian</u>	W/ <u>sr</u>	$\mathbf{M \cdot L^2 \cdot T^{-3}}$	Radiant flux emitted, reflected, transmitted or received, per unit solid angle. This is a <i>directional</i> quantity.
<u>Spectral intensity</u>	$I_{e,\Omega,\nu}$ ^[nb 3] or $I_{e,\Omega,\lambda}$ ^[nb 4]	watt per steradian per hertz or watt per steradian per metre	$\text{W} \cdot \text{sr}^{-1} \cdot \text{Hz}^{-1}$ or $\text{W} \cdot \text{sr}^{-1} \cdot \text{m}^{-1}$	$\mathbf{M \cdot L^2 \cdot T^{-2}}$ or $\mathbf{M \cdot L \cdot T^{-3}}$	Radiant intensity per unit frequency or wavelength. The latter is commonly measured in $\text{W} \cdot \text{sr}^{-1} \cdot \text{m}^{-2} \cdot \text{nm}^{-1}$. This is a <i>directional</i> quantity.
<u>Radiance</u>	$L_{e,\Omega}$ ^[nb 5]	watt per steradian per square metre	$\text{W} \cdot \text{sr}^{-1} \cdot \text{m}^{-2}$	$\mathbf{M \cdot T^{-3}}$	Radiant flux emitted, reflected, transmitted or received by a <i>surface</i> , per unit solid angle per unit projected area. This is a <i>directional</i> quantity. This is sometimes also confusingly called "intensity".
<u>Spectral radiance</u>	$L_{e,\Omega,\nu}$ ^[nb 3] or $L_{e,\Omega,\lambda}$ ^[nb 4]	watt per steradian per square metre per hertz or watt per steradian per square metre, per metre	$\text{W} \cdot \text{sr}^{-1} \cdot \text{m}^{-2} \cdot \text{Hz}^{-1}$ or $\text{W} \cdot \text{sr}^{-1} \cdot \text{m}^{-3}$	$\mathbf{M \cdot T^{-2}}$ or $\mathbf{M \cdot L^{-1} \cdot T^{-3}}$	Radiance of a <i>surface</i> per unit frequency or wavelength. The latter is commonly measured in $\text{W} \cdot \text{sr}^{-1} \cdot \text{m}^{-2} \cdot \text{nm}^{-1}$. This is a <i>directional</i>

<u>Irradiance</u>	E_e [nb 2]	watt per square metre	W/m^2	$M \cdot T^{-3}$	Radiant flux <i>received</i> by a <i>surface</i> per unit area. This is sometimes also confusingly called "intensity".
<u>Spectral irradiance</u>	$E_{e,v}$ [nb 3] or $E_{e,\lambda}$ [nb 4]	watt per square metre per hertz or watt per square metre, per metre	$W \cdot m^{-2} \cdot Hz^{-1}$ or W/m^3	$M \cdot T^{-2}$ or $M \cdot L^{-1} \cdot T^{-3}$	Irradiance of a <i>surface</i> per unit frequency or wavelength. The terms spectral flux density or more confusingly "spectral intensity" are also used. Non-SI units of spectral irradiance include Jansky = $10^{-26} W \cdot m^{-2} \cdot Hz^{-1}$ and solar flux unit (1SFU = $10^{-22} W \cdot m^{-2} \cdot Hz^{-1}$).
<u>Radiosity</u>	J_e [nb 2]	watt per square metre	W/m^2	$M \cdot T^{-3}$	Radiant flux <i>leaving</i> (emitted, reflected and transmitted by) a <i>surface</i> per unit area. This is sometimes also confusingly called "intensity".
<u>Spectral radiosity</u>	$J_{e,v}$ [nb 3] or $J_{e,\lambda}$ [nb 4]	watt per square metre per hertz or watt per square metre, per metre	$W \cdot m^{-2} \cdot Hz^{-1}$ or W/m^3	$M \cdot T^{-2}$ or $M \cdot L^{-1} \cdot T^{-3}$	Radiosity of a <i>surface</i> per unit frequency or wavelength. The latter is commonly measured in $W \cdot m^{-2} \cdot nm^{-1}$. This is sometimes also confusingly called "spectral intensity".

<u>Radiant exitance</u>	M_e ^[nb 2]	watt per square metre	W/m ²	M·T⁻³	Radiant flux <i>emitted</i> by a <i>surface</i> per unit area. This is the emitted component of radiosity. "Radiant emittance" is an old term for this quantity. This is sometimes also confusingly called "intensity".
<u>Spectral exitance</u>	$M_{e,v}$ ^[nb 3] or $M_{e,\lambda}$ ^[nb 4]	watt per square metre per hertz or watt per square metre, per metre	W·m ⁻² ·Hz ⁻¹ or W/m ³	M·T⁻² or M·L⁻¹·T⁻³	Radiant exitance of a <i>surface</i> per unit frequency or wavelength. The latter is commonly measured in W·m ⁻² ·nm ⁻¹ . "Spectral emittance" is an old term for this quantity. This is sometimes also confusingly called "spectral intensity".
<u>Radiant exposure</u>	H_e	joule per square metre	J/m ²	M·T⁻²	Radiant energy received by a <i>surface</i> per unit area, or equivalently irradiance of a <i>surface</i> integrated over time of irradiation. This is sometimes also called "radiant fluence".
<u>Spectral exposure</u>	$H_{e,v}$ ^[nb 3] or $H_{e,\lambda}$ ^[nb 4]	joule per square metre per hertz or joule per square metre, per metre	J·m ⁻² ·Hz ⁻¹ or J/m ³	M·T⁻¹ or M·L⁻¹·T⁻²	Radiant exposure of a <i>surface</i> per unit frequency or wavelength. The latter is commonly measured in J·m ⁻² ·nm ⁻¹ . This is sometimes also called "spectral fluence".

Hemispherical emissivity

ε

1

Radiant exitance of a *surface*, divided by that of a *black body* at the same temperature as that surface.

Spectral hemispherical emissivity

ε_v
or
 ε_λ

1

Spectral exitance of a *surface*, divided by that of a *black body* at the same temperature as that surface.

Directional emissivity

ε_Ω

1

Radiance *emitted* by a *surface*, divided by that emitted by a *black body* at the same temperature as that surface.

Spectral directional emissivity

$\varepsilon_{\Omega,v}$
or
 $\varepsilon_{\Omega,\lambda}$

1

Spectral radiance *emitted* by a *surface*, divided by that of a *black body* at the same temperature as that surface.

Hemispherical absorptance

A

1

Radiant flux *absorbed* by a *surface*, divided by that received by that surface. This should not be confused with "absorbance".

Spectral hemispherical absorptance

A_v
or
 A_λ

1

Spectral flux *absorbed* by a *surface*, divided by that received by that surface. This should not be confused with "spectral absorbance".

Directional absorptance

A_Ω

1

Radiance *absorbed* by a *surface*, divided by the radiance incident onto that surface. This should not be confused with "absorbance".

Spectral directional absorptance

$A_{\Omega,v}$
or
 $A_{\Omega,\lambda}$

1

Spectral radiance *absorbed* by a *surface*, divided by the spectral radiance incident onto that surface. This should not be confused with "spectral absorbance".

Hemispherical
reflectance

R

1

Radiant flux *reflected* by a *surface*, divided by that received by that surface.

Spectral
hemispherical
reflectance

R_v
or
 R_λ

1

Spectral flux *reflected* by a *surface*, divided by that received by that surface.

Directional
reflectance

R_Ω

1

Radiance *reflected* by a *surface*, divided by that received by that surface.

Spectral
directional
reflectance

$R_{\Omega,v}$
or
 $R_{\Omega,\lambda}$

1

Spectral radiance *reflected* by a *surface*, divided by that received by that surface.

Hemispherical transmittance

T

1

Radiant flux *transmitted* by a *surface*, divided by that received by that surface.

Spectral hemispherical transmittance

T_v
or
 T_λ

1

Spectral flux *transmitted* by a *surface*, divided by that received by that surface.

Directional transmittance

T_Ω

1

Radiance *transmitted* by a *surface*, divided by that received by that surface.

Spectral directional transmittance

$T_{\Omega,v}$
or
 $T_{\Omega,\lambda}$

1

Spectral radiance *transmitted* by a *surface*, divided by that received by that surface.

Hemispherical
attenuation
coefficient

μ

reciprocal metre m^{-1}

L^{-1}

Radiant flux *absorbed* and *scattered* by a *volume* per unit length, divided by that received by that volume.

Spectral
hemispherical
attenuation
coefficient

μ_v
or
 μ_λ

reciprocal metre m^{-1}

L^{-1}

Spectral radiant flux *absorbed* and *scattered* by a *volume* per unit length, divided by that received by that volume.

Directional
attenuation
coefficient

μ_Ω

reciprocal metre m^{-1}

L^{-1}

Radiance *absorbed* and *scattered* by a *volume* per unit length, divided by that received by that volume.

Spectral
directional
attenuation
coefficient

$\mu_{\Omega,v}$
or
 $\mu_{\Omega,\lambda}$

reciprocal metre m^{-1}

L^{-1}

Spectral radiance *absorbed* and *scattered* by a *volume* per unit length, divided by that received by that volume.

- 1.^ [Standards organizations](#) recommend that radiometric [quantities](#) should be denoted with suffix "e" (for "energetic") to avoid confusion with photometric or [photon](#) quantities.
- 2.^ [Jump up to: a b c d e](#) Alternative symbols sometimes seen: W or E for radiant energy, P or F for radiant flux, I for irradiance, W for radiant exitance.
- 3.^ [Jump up to: a b c d e f g](#) Spectral quantities given per unit [frequency](#) are denoted with suffix "v" (Greek)—not to be confused with suffix "v" (for "visual") indicating a photometric quantity.
- 4.^ [Jump up to: a b c d e f g](#) Spectral quantities given per unit [wavelength](#) are denoted with suffix "λ" (Greek).
- 5.^ [Jump up to: a b](#) Directional quantities are denoted with suffix "Ω" (Greek).

Quantity Name	Symbol [nb 1]	Unit Name	Symbol	Dimension Symbol	Notes
Luminous energy	Q_v [nb 2]	lumen second	lm ·s	T·J [nb 3]	Units are sometimes called <i>talbots</i> .
Luminous flux / luminous power	ϕ_v [nb 2]	lumen (= cd· sr)	lm	J [nb 3]	Luminous energy per unit time.
Luminous intensity	I_v	candela (= lm/sr)	cd	J [nb 3]	Luminous power per unit solid angle .
Luminance	L_v	candela per square metre	cd/m ²	L⁻²·J	Luminous power per unit solid angle per unit <i>projected</i> source area. Units are sometimes called <i>nits</i> .
Illuminance	E_v	lux (= lm/m ²)	lx	L⁻²·J	Luminous power <i>incident</i> on a surface.
Luminous exitance / luminous emittance	M_v	lux	lx	L⁻²·J	Luminous power <i>emitted</i> from a surface.
Luminous exposure	H_v	lux second	lx·s	L⁻²·T·J	
Luminous energy density	ω_v	lumen second per cubic metre	lm·s·m ⁻³	L⁻³·T·J	
Luminous efficacy	η [nb 2]	lumen per watt	lm/ W	M⁻¹·L⁻²·T³·J	Ratio of luminous flux to radiant flux or power consumption, depending on context.
Luminous efficiency / luminous coefficient	ν			1	

Radiometric Measurement

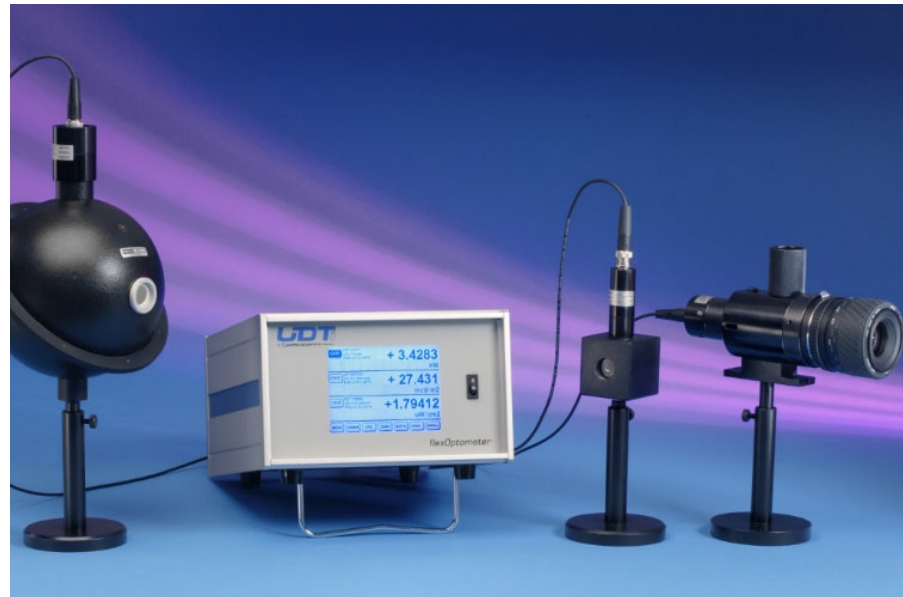
- Radiant Flux Measurements** (in units of watts) are performed with an instrument known as a flux meter or optical power meter. This type of testing is typically used for characterizing the total output of sources such as: Lasers, LEDs, Lamps and Fiber-Optic Systems
- Radiant Intensity Measurements** (in units of W/sr) are performed with an instrument that may be described as an optical intensity meter. This type of testing is typically used for characterizing the output of a relatively small source in a particular direction. Typical devices under test include: LEDs, UV Lamps and IR Lamps
- Irradiance Measurements** (in units of W/m²) are performed with an irradiance meter. This involves the measurement of the radiant flux incident upon a surface, per unit area. Such measurements are important in the following fields: Medical, Biological and Remote Sensing
- Radiance Measurements** (in units of W/m²sr) are performed with a radiance meter. This involves measuring the light emitted in a particular direction by a given spot on the surface of an extended source. Such measurements are important in fields such as: Remote Sensing, Avionics and Night Vision

Radiometers

Radiometers. Radiometers are used to measure the amount of electromagnetic energy present within a specific wavelength range. The measurement is expressed in Watts (W) which is a unit of measurement for power.

Radiometers are usually used to detect and measure the amount of energy outside the visible light spectrum and are used to measure ultraviolet (UV) light or infrared (IR). A typical use for a UV meter is in the museum lighting world where the presence of UV is can be very troublesome. UV energy hastens the ageing process due to its higher energy content so any energy below 400nm needs to be filtered out or eliminated. Another application for a radiometer is in the detection and measurement of infrared or IR. It is used to detect and measure heat on a surface. Technicians use them to safely detect and repair overheating motors or shorted out wiring. Radiometers can measure very quickly because they are simple meters that use only one sensor with a filter designed to just measure the wavelength range they were intended for.

W.Wang



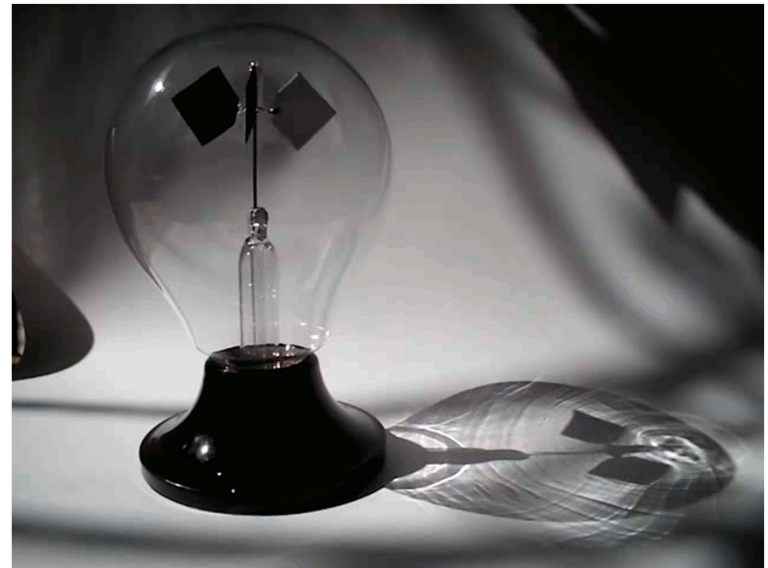
First Radiometer

The radiometer is made from a glass bulb from which much of the air has been removed to form a partial vacuum. Inside the bulb, on a low friction spindle, is a rotor with several (usually four) vertical lightweight metal vanes spaced equally around the axis. The vanes are polished or white on one side and black on the other.

When exposed to sunlight, artificial light, or infrared radiation (even the heat of a hand nearby can be enough), the vanes turn with no apparent motive power, the dark sides retreating from the radiation source and the light sides advancing.

Cooling the radiometer causes rotation in the opposite direction.

W.Wang



Photometric Measurement

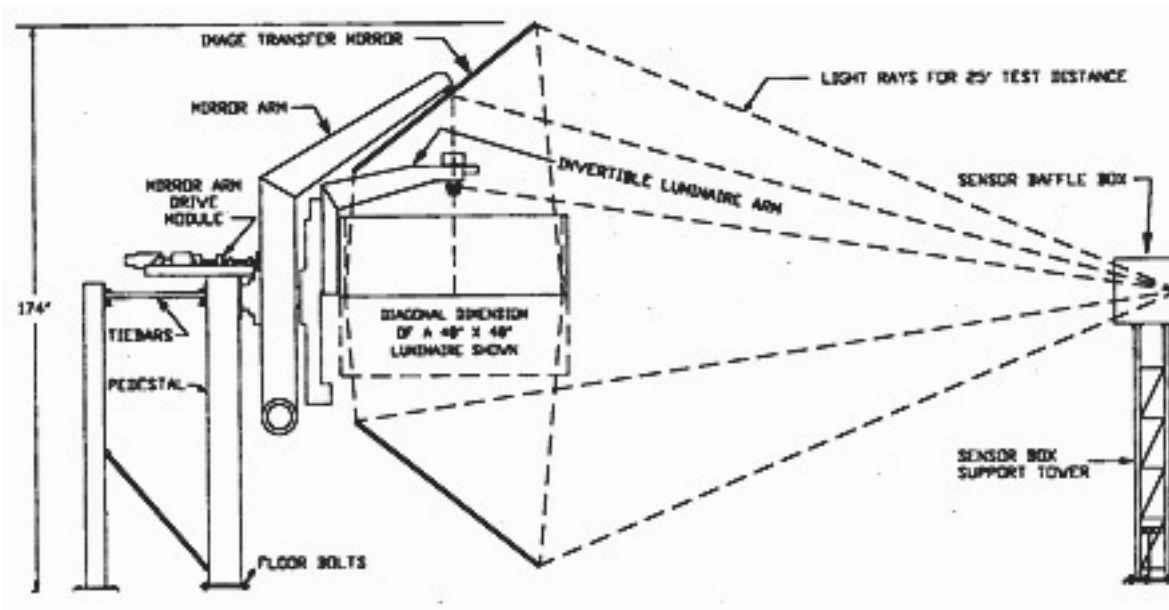
Photometric measurement is based on photodetectors, devices (of several types) that produce an electric signal when exposed to light. Simple applications of this technology include switching luminaires on and off based on ambient light conditions, and light meters, used to measure the total amount of light incident on a point.

More complex forms of photometric measurement are used frequently within the lighting industry. Spherical photometers can be used to measure the directional luminous flux produced by lamps, and consist of a large-diameter globe with a lamp mounted at its center. A photocell rotates about the lamp in three axes, measuring the output of the lamp from all sides.

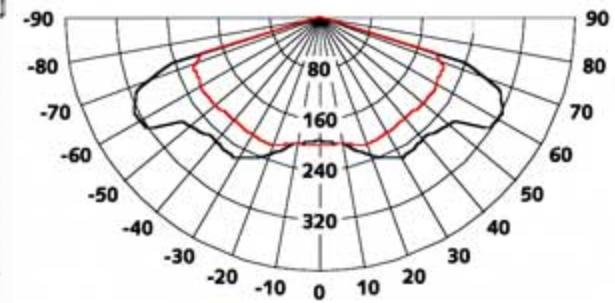
Lamps and lighting fixtures are tested using goniophotometers and rotating mirror photometers, which keep the photocell stationary at a sufficient distance that the luminaire can be considered a point source. Rotating mirror photometers use a motorized system of mirrors to reflect light emanating from the luminaire in all directions to the distant photocell; goniophotometers use a rotating 2-axis table to change the orientation of the luminaire with respect to the photocell. In either case, luminous intensity is tabulated from this data and used in lighting design.

Goniophotometers

A Goniophotometer is a device used for measurement of the light emitted from an object at different angles.[1] The use of goniophotometers has been increasing in recent years with the introduction of LED-light sources, which are mostly directed light sources, where the spatial distribution of light is not homogeneous.[2] If a light source is homogeneous in its distribution of light, it is called a Lambertian source.[3] Due to strict regulations, the spatial distribution of light is of high importance to automotive lighting and its design.



GONIOPHOTOMETER READING



Spherical photometers

Luminous flux measurement is to determine the total visible energy emitted by a light source. An integrating sphere is often used to converge all the power emitted by the source to the detector head.

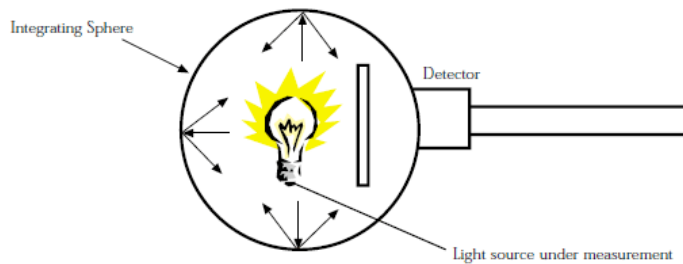
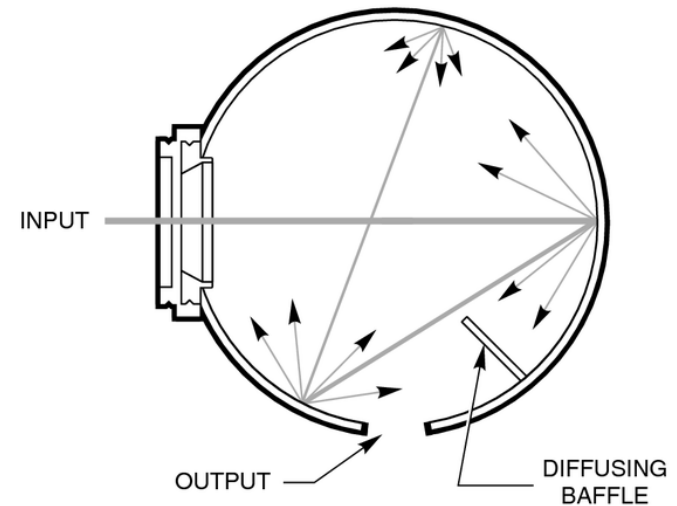
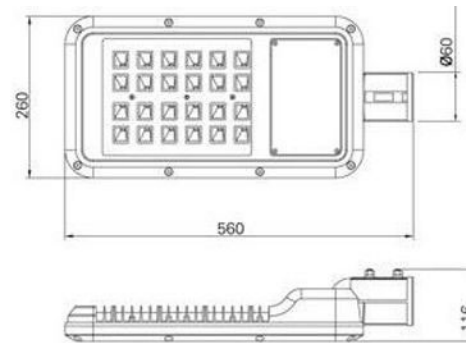


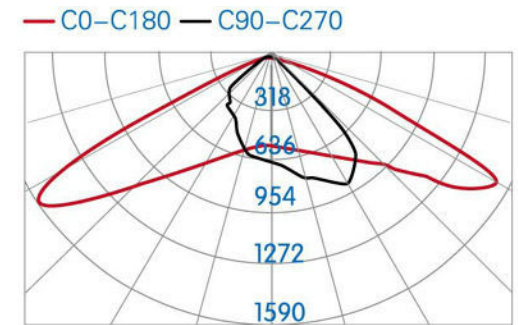
Fig. 3.2.3.3 - Total luminous flux measurement using an integrating sphere



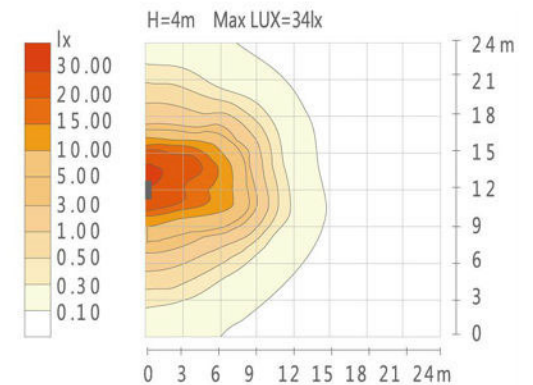
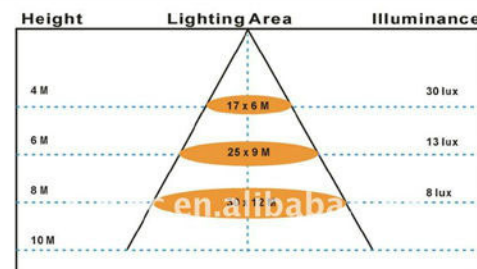
Handheld Photometer



product dimensions



Distribution Curve Flux



Led Street Lamp Varies With Distance Illuminance

Quantity Name	Symbol [nb 1]	Unit Name	Symbol	Dimension Symbol	Notes
Luminous energy	Q_v [nb 2]	lumen second	lm ·s	T·J [nb 3]	Units are sometimes called <i>talbots</i> .
Luminous flux / luminous power	ϕ_v [nb 2]	lumen (= cd· sr)	lm	J [nb 3]	Luminous energy per unit time.
Luminous intensity	I_v	candela (= lm/sr)	cd	J [nb 3]	Luminous power per unit solid angle .
Luminance	L_v	candela per square metre	cd/m ²	L⁻²·J	Luminous power per unit solid angle per unit <i>projected</i> source area. Units are sometimes called <i>nits</i> .
Illuminance	E_v	lux (= lm/m ²)	lx	L⁻²·J	Luminous power <i>incident</i> on a surface.
Luminous exitance / luminous emittance	M_v	lux	lx	L⁻²·J	Luminous power <i>emitted</i> from a surface.
Luminous exposure	H_v	lux second	lx·s	L⁻²·T·J	
Luminous energy density	ω_v	lumen second per cubic metre	lm·s·m ⁻³	L⁻³·T·J	
Luminous efficacy	η [nb 2]	lumen per watt	lm/ W	M⁻¹·L⁻²·T³·J	Ratio of luminous flux to radiant flux or power consumption, depending on context.
Luminous efficiency / luminous coefficient	V			1	

Silicon Detector with Flat Response Filter

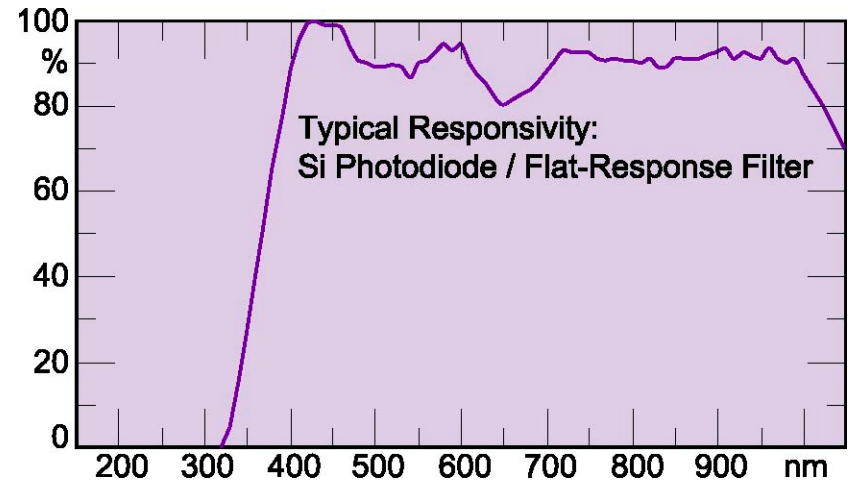
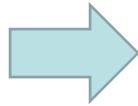
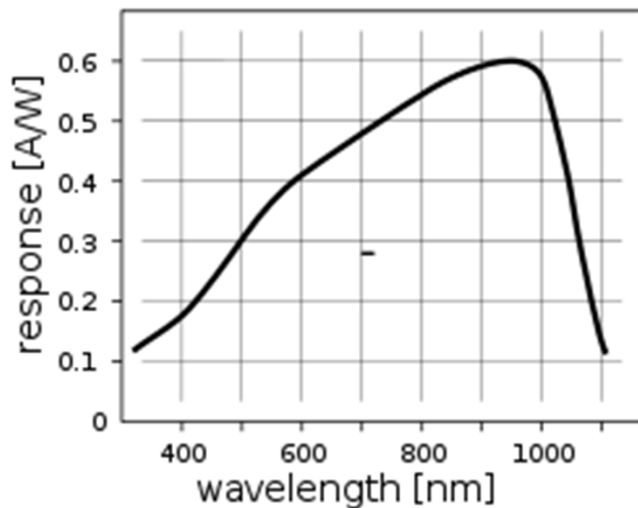


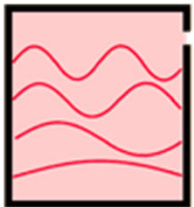
Fig. 2.2 Relative spectral responsivity of a flat response detector.

Since silicon photodiodes are more sensitive to light at the red end of the spectrum than to light at the blue end, radiometric detectors filter the incoming light to even out the responsivity, producing a “flat response”. This is important for accurate radiometric measurements, because the spectrum of a light source may be unknown, or may be dependent on operating conditions such as input voltage.

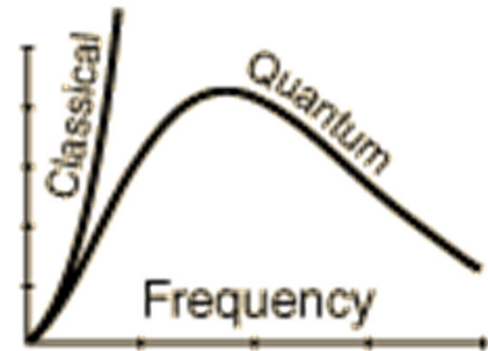
Blackbody Radiation

Blackbody radiation" or "cavity radiation" refers to an object or system which absorbs all radiation incident upon it and re-radiates energy which is characteristic of this radiating system only, not dependent upon the type of radiation which is incident upon it. The radiated energy can be considered to be produced by standing wave or resonant modes of the cavity which is radiating

Radiation modes in a hot cavity provide a test of quantum theory



	#Modes per unit frequency per unit volume	Probability of occupying modes	Average energy per mode
CLASSICAL	$\frac{8\pi\nu^2}{c^3}$	Equal for all modes	kT
QUANTUM	$\frac{8\pi\nu^2}{c^3}$	Quantized modes: require $h\nu$ energy to excite upper modes, less probable	$\frac{h\nu}{e^{\frac{h\nu}{kT}} - 1}$



Blackbody Radiation

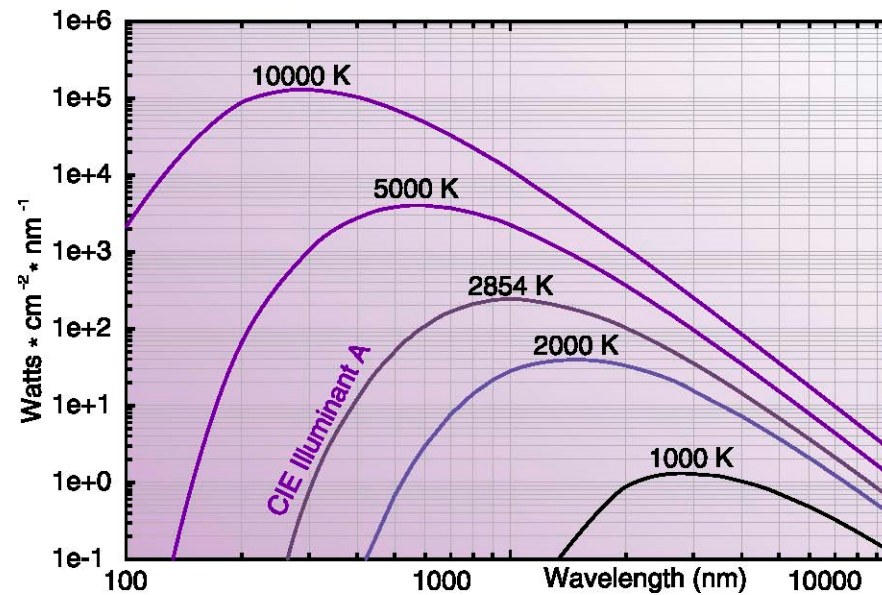


Fig. 5.1 Blackbody radiation at several color temperatures.

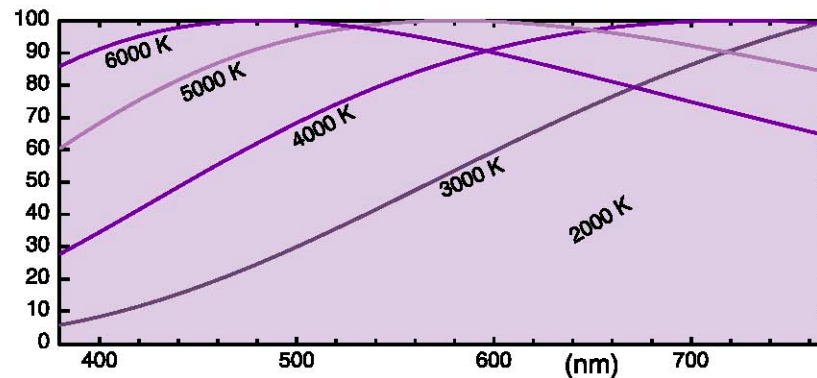


Fig. 5.2 Blackbody radiation plotted on a linear scale in the visible.