

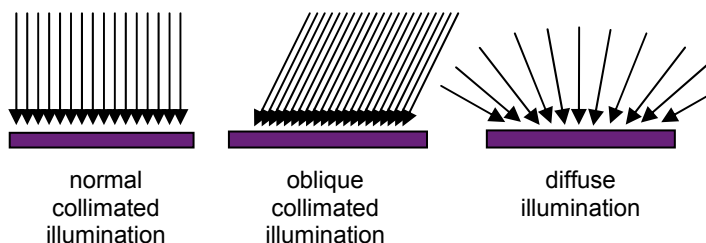
Flux and Irradiance

In examining terminology for illumination, it is useful to separate the spatial considerations from the spectral concerns. In many cases, the spatial and spectral issues are independent and can be separated without losing any generality. In other cases, the spatial and spectral issues cannot be separated physically, but it is useful to separate them conceptually. The commonly used spatial quantities are **flux**, **irradiance**, **intensity**, and **radiance**.

Flux, Φ , is the optical power or rate of flow of radiant energy.

Irradiance, E , is the flux per unit area striking a surface. Occasionally, the flux per unit area leaving a surface, called **exitance**, M , is important. However, the geometry is the same as for irradiance, so it will not be treated separately here. Furthermore, when exitance is used, it is often the flux leaving a nonphysical surface such as the exit port of an integrating sphere or the real image in an imaging system, where it is identical to the irradiance onto the surface.

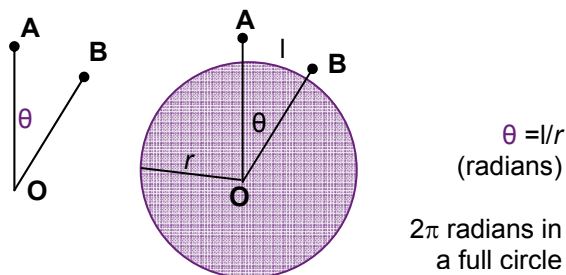
The irradiance quantity itself says absolutely nothing about the directionality of the flux. For example, if the three cases in the figure below all have the same flux per unit area striking the surface, then they all have the same irradiance. Because of this ambiguity, specifications for illumination systems often qualify the irradiance quantity with an added description of the desired directional properties.



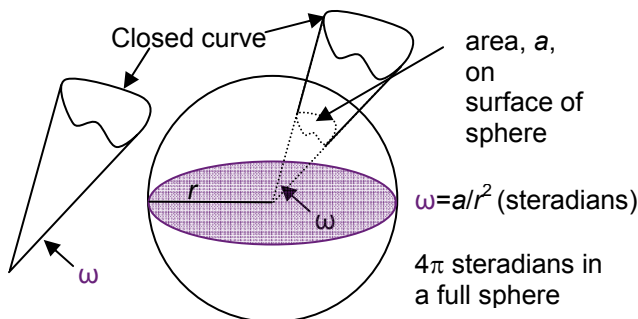
Solid Angle

The definition of intensity involves the concept of a **solid angle**. A solid angle is a 3D angular volume that is defined analogously to the definition of a plane angle in two dimensions.

A **plane angle**, θ , made up of the lines from two points meeting at a vertex, is defined by the arc length of a circle subtended by the lines and by the radius of that circle, as shown below. The dimensionless unit of plane angle is the **radian**, with 2π radians in a full circle.



A solid angle, ω , made up of all the lines from a closed curve meeting at a vertex, is defined by the surface area of a sphere subtended by the lines and by the radius of that sphere, as shown below. The dimensionless unit of solid angle is the **steradian**, with 4π steradians in a full sphere.



Intensity, Radiance, and Projected Solid Angle

Intensity, I , is the flux per unit **solid angle**. It is the amount of flux from a point source contained in a small angular volume. A source can be considered a point source for this application if the irradiance falls off as the **inverse square** of the distance from the source. Intensity, for a given source, can vary with direction.

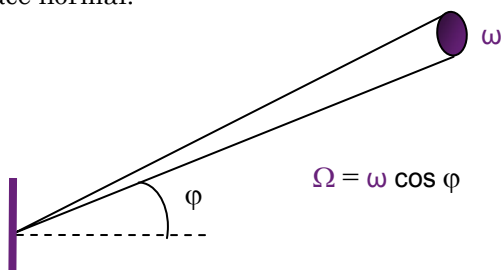
The term “intensity” is used in many disciplines, some even closely related to optics, to mean things other than flux per unit solid angle. Use caution and rely on context to determine the meaning of the word in a particular situation.

Radiance, L , applies to extended sources and surfaces. It is the flux per unit solid angle per unit **projected area** of the source or surface. The projected area is the projection of the area onto a surface normal to the direction of view and is equal to the actual area times the cosine of the angle between the surface normal and the direction of view. Radiance can vary with position on a surface, and like intensity, it can vary with direction. A source or surface with constant radiance in all directions is called Lambertian. A **Lambertian source** or surface has intensity that varies with the cosine of the angle with the surface normal.

In many cases, the angle of view changes over the extent of the receiver. These cases require an alternate definition of radiance: radiance is the flux per unit area per unit **projected solid angle**. (In fact, this is the more general definition and covers the simpler case where the entire surface of the extended source is at essentially the same angle as the direction of view.)

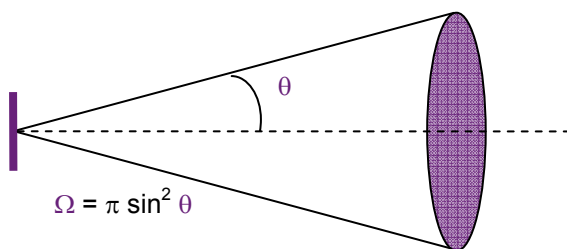
Solid Angle and Projected Solid Angle

The relationship between solid angle and projected solid angle can be confusing. Projected solid angle has meaning primarily for a small Lambertian source, which has intensity that varies as the cosine of the angle with the surface normal. The **projected solid angle**, Ω , is the **solid angle**, ω , weighted by the cosine of the angle with the surface normal.



When the solid angle is large enough so that the angle with the surface normal is not the same over the entire solid angle, the total projected solid angle must be computed by integrating the incremental projected solid angles. See the reference by Bartell for a more detailed explanation.

For some special cases, the integration results in simple expressions, such as for a large circular cone that is normal to a surface and subtends a half angle, θ .



A hemisphere has 2π steradians (solid angle) but π projected steradians (projected solid angle).

Spectroradiometric and Radiometric Quantities

In the spectral dimension of illumination, the most general view looks at the spectral density—the amount of radiation per unit wavelength interval. In terms of the four spatial quantities already considered, the spectral quantities are **spectral flux**, Φ_λ ; **spectral irradiance**, E_λ ; **spectral intensity**, I_λ ; and **spectral radiance**, L_λ . These quantities, usually written with a subscript to indicate that they are integrable, must be integrated to determine the amount of radiation in a particular spectral band. For example, the **total radiant flux**, Φ (in units of watts), in the band between wavelength λ_1 and wavelength λ_2 is

$$\Phi(\lambda_1, \lambda_2) = \int_{\lambda_1}^{\lambda_2} \Phi_\lambda(\lambda) \cdot d\lambda.$$

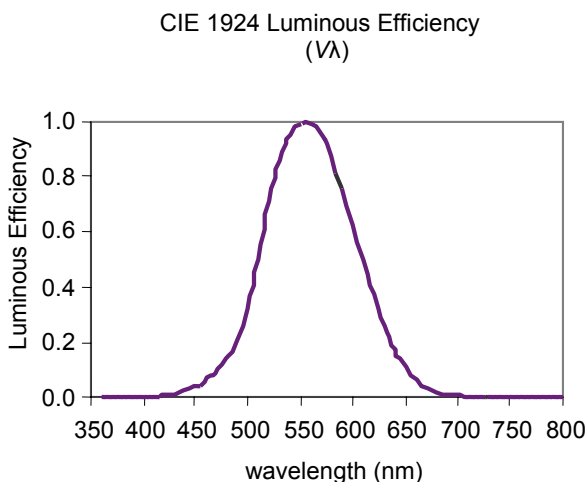
Similar expressions can be written for the **total irradiance**, E (watts/m²); **total radiant intensity**, I (watts/sr); and **total radiance**, L (watts/m²·sr).

Photometry measures the response of the human eye to light. Although not everyone has exactly the same response, the standardized **CIE 1924 luminous efficiency function** works very well for most people. (The CIE is the International Commission on Illumination.) This function, shown on the following page, is designated $V(\lambda)$. The values for this function, in 5-nm increments, are given in the Appendix. Not coincidentally, this function is identical to the **CIE color matching function**, \bar{x} . The unit of **luminous (photopic) flux** is the **lumen**. The luminous flux is found from the spectral flux and the $V(\lambda)$ function from the following relationship:

$$\text{luminous flux} = 683 \int \Phi_\lambda(\lambda) \cdot V(\lambda) \cdot d\lambda.$$

The factor of 683 in this equation comes directly from the definition of the fundamental unit of luminous intensity, the **candela**.

Photometric Quantities



Notes on notation:

- The photopic quantities of flux, irradiance, intensity, and radiance are called **luminous flux**, **illuminance**, **luminous intensity**, and **luminance**, respectively.
 - These quantities are sometimes notated with a subscript “ v ” (for visual), as Φ_v , E_v , I_v , and L_v . But often the subscript is omitted since the meaning is usually clear from the context, and it could be confused with the subscript notation often reserved for integrable quantities.
 - The designations Φ , E , I , and L are common but not universally standard. Another set of symbols sometimes used is P , H , J , and N , respectively, for radiometric quantities; P_λ , H_λ , J_λ , and N_λ for spectral quantities; and F , E , I , and B for the corresponding photometric quantities.
 - Solid angle and projected solid angle are not always distinguished by ω and Ω , respectively.
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Matrix of Basic Quantities

SPECTRAL				
		Radio-metric	Spectral	Photopic
S P A T I A L	Flux	Power	Power/ wavelength interval	Luminous flux
		Watts (W)	Watts/nm	Lumens (lm)
	Flux/ area	Irradiance	Spectral irradiance	Illuminance lm/m ² or lux
		W/m ²	W/m ² nm	
	Flux/ solid angle	(Radiant) intensity	Spectral intensity	(Luminous) intensity lm/sr or candela (cd)
		W/sr	W/sr nm	
	Flux/ area· solid angle	Radiance	Spectral radiance	Luminance lm/m ² ·sr or cd/m ² or nit
		W/m ² ·sr	W/m ² ·sr nm	

The table above shows the four spatial quantities and the three spectral categories that are discussed in the preceding pages. These create 12 distinct cells that cover the vast majority of specifications for illumination systems.

With two exceptions, both used mainly in the United States, work in illumination is almost always done in SI units. The two exceptions (both deprecated) are:

Illuminance

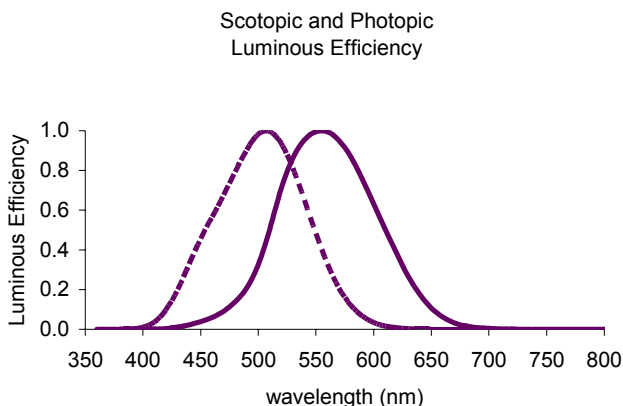
1 footcandle (lm/ft²) = 10.764 lux (lm/m²)

Luminance

1 footlambert (candela/πft²) = 3.426 nit (candela/m²)

Photopic and Scotopic Vision

The human visual system responds to light over a wide dynamic range, in excess of 6 orders of magnitude. To achieve this dynamic range, the mechanisms for high-light-level vision and low-light-level vision are different. The high-level region, called the **photopic region**, is active at luminance levels above about 3 cd/m^2 . The low-level region, called the **scotopic region**, is active below approximately 0.01 cd/m^2 . The region between pure photopic and pure scotopic is called the **mesopic region**, where the visual response is a mixture of the two. The **photopic efficiency**, usually designated $V(\lambda)$, peaks at 555 nm, while the **scotopic efficiency**, usually designated $V'(\lambda)$, peaks at 507 nm.



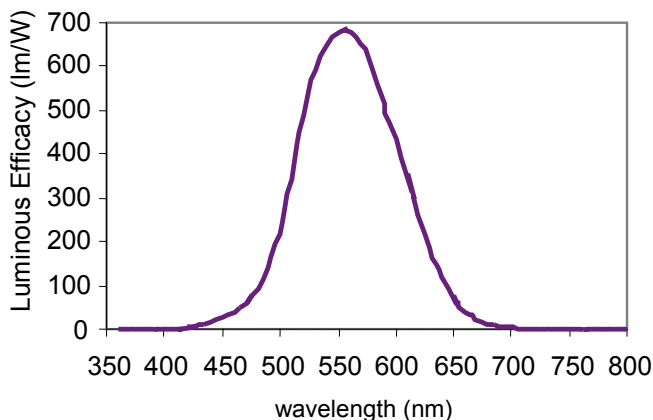
The values for photopic efficiency and scotopic efficiency, both in 5-nm increments, are given in the Appendix.

Luminous Efficacy

Luminous efficacy, quantified in lumens per watt, is a measure of the ability of a light source to produce a visual response from its power. In the photopic region, luminous efficacy peaks at 683 lumens per watt at 555 nm. In fact, the lumen is defined in terms of the power at 555 nm (frequency of 540×10^{12} Hz). Specifically, the definition (adopted in 1979) is in terms of the candela (lumen per steradian).

The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation at a frequency of 540×10^{12} Hz and that has a radiant intensity in that direction of 1/683 Watt per steradian.

Luminous Efficacy (photopic)



It is usually clear from the context whether the power is the radiated power (as in the discussion above) or, often for lamps, the “wall-plug” power.

Typical Values of Illumination Quantities

Irradiance and Illuminance			
Direct sunlight	1000	W/m ²	(250-2500nm)
Direct sunlight	100,000	lux	
Shade	10,000	lux	
Overcast day	1,000	lux	
Office space	300–600	lux	
Full moon	0.2	lux	
Quarter moon	0.01	lux	
Moonless clear night	0.001	lux	
Luminous Intensity			
Automobile headlight	5,000–20,000	cd	
Household flashlight	100–1,000	cd	
100-W tungsten lightbulb	100	cd	
LED traffic signal	250–700	cd	
Single LED	1 mcd–25	cd	
Radiance and Luminance			
Sun	2 x 10 ⁷	W/m ² sr	(250-2500nm)
Sun	2 x 10 ⁹	nit	
Frosted lightbulb	100,000	nit	
Fluorescent lamp	5,000	nit	
Computer screen	100	nit	
Wavelength Ranges for Illumination			
UV-C*	250 to 280	nm	
UV-B	280 to 315	nm	
UV-A	315 to 400	nm	
Visible	~360–400 to ~760–800	nm	
Near-infrared (NIR) [†]	760 nm to 1.1	μm	

* Actual definition of UV-C is 100 to 280 nm. However, the range from 100 to 250 nm is not of interest for illumination systems.

[†] Actual definition of NIR is to 1.4 μm. However, 1.1 μm is the upper limit for silicon-based detectors.