

Less Light, More Dark

A Proposal to Protect Darkness by Regulating Light

By Soft Lights

Chapter 2 - Vocabulary of Light

Geometry

Geometry is the branch of mathematics concerned with questions of shape, size, relative position of figures, and the properties of space.¹

Radian

The ratio of the circumference of a circle to the diameter is a constant called pi, written using the Greek letter π . Pi has no units because it is a ratio of two measurements with the same units.

$$\frac{C}{d} = \pi$$

The diameter of a circle is double the radius, so we can rewrite the above ratio as:

$$\frac{C}{2r} = \pi$$

This means that the ratio of the circumference to the radius is (multiply both sides by 2):

$$\frac{C}{r} = 2\pi$$

Since division tells us how many of the denominator fit into the numerator, this means that a circle has 2π radii in the circumference. If we take the inverse, then we find that one of these radii as compared to the entire circle, is equal to:

$$1 \text{ radian} = \frac{1}{2\pi}$$

Since 1 radian is a ratio of length to length, there are no units. A radian is a unit of angular measure and can be treated as a percentage of the arc of an entire circle. Therefore, 1 radian measures an angle, just like degrees. There are 360 degrees in a circle and there are 2π radians in a circle.

Figure 1 shows a radius of a circle and an arc of that same length. This angle, which is a fractional part of a whole circle and there has no units, is known as 1 radian.

¹ <https://en.wikipedia.org/wiki/Geometry>

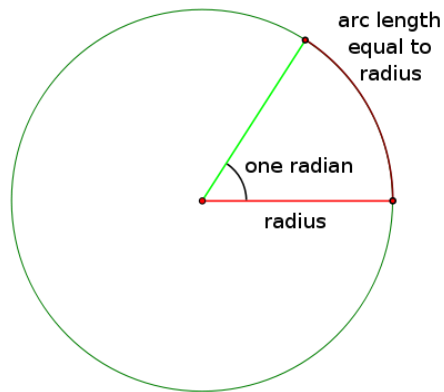


Figure 1 - Diagram of Radian²

Steradian

A steradian is the same idea as a radian, but in three dimensions instead of two. A steradian (abbreviated as “sr”) is another name for square radians, abbreviated as “rad²”. This is called a solid angle and is an area in two dimensions.

The circumference of a circle is: $C = 2\pi r$. Also, the circumference of a circle is 2π radians. Since these are the same thing, we can set them equal: $2\pi r = 2\pi \text{ radian}$. Divide both sides by 2π to get: $r = 1 \text{ radian}$. Therefore, whenever we see ‘r’ for radius, we can replace the ‘r’ with ‘1 radian’.

The surface area of a sphere is: $SA_{\text{sphere}} = 4\pi r^2$. If we use 1 radian for the radius, we get:

$$SA_{\text{sphere}} = 4\pi (1 \text{ rad})^2 = 4\pi \text{ rad}^2 = 4\pi \text{ steradian} = 4\pi \text{ sr}$$

Since there are 4π steradians in the surface area of a sphere, then 1 steradian is the inverse.

$$1 \text{ steradian} = \frac{1}{4\pi}$$

A steradian is a unit of solid angular measure. Figure 2 shows 1 steradian.

² https://en.wikibooks.org/wiki/High_School_Trigonometry/Radian_Measure

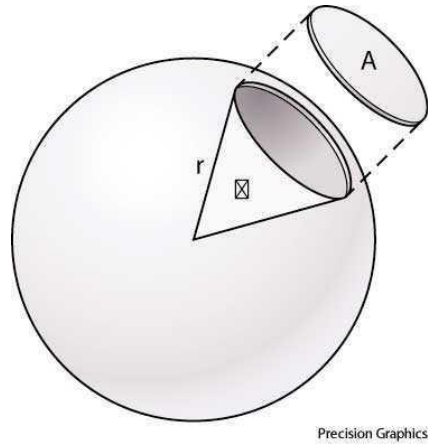


Figure 2 - 1 Steradian³

Radiometry

Radiometry is a set of techniques for measuring electromagnetic radiation, including visible light.⁴

Joule

The joule is equal to the energy transferred to an object when a force of one newton acts on that object in the direction of the force's motion through a distance of one meter.⁵

Watt

A watt is 1 joule per second.⁶

Radiant Flux

Radiant flux (or radiant power) is the radiant energy emitted, reflected, transmitted or received, per unit time, measured in watts.⁷

For example, the radiant flux of an incandescent light bulb might be 60 watts. The radiant flux for the human visible part of the spectrum is just 6 watts while the other 54 watts are emitted as heat radiation.

³ <https://www.yourdictionary.com/steradian>

⁴ <https://en.wikipedia.org/wiki/Radiometry>

⁵ <https://en.wikipedia.org/wiki/Joule>

⁶ <https://en.wikipedia.org/wiki/Watt>

⁷ https://en.wikipedia.org/wiki/Radiant_flux

Radiant Intensity

Radiant intensity is the radiant flux emitted, reflected, transmitted or received, per unit solid angle and is measured in watts per steradian.⁸

For example, if a 60-watt incandescent light bulb radiates in all directions of space and has a radiant flux of 60 watts, then we must divide the 60 watts by the total surface area to get the amount of energy within 1 steradian.

$$\frac{60 \text{ watts}}{4\pi \text{ steradian}} = 4.78 \frac{\text{watts}}{\text{steradian}}$$

The 4.78 watts/steradian measures the intensity of the radiation, not just the total amount.

Photometry

Photometry is the science of measuring the human visible portion of the electromagnetic spectrum.⁹

Figure 3 is a diagram of the electromagnetic spectrum. The higher energy, shorter wavelengths are towards the left and the lower energy, longer wavelengths are towards the right. Photometry measures the slice of the electromagnetic spectrum that is between 400 nanometers and 700 nanometers that is visible to the human eye.

⁸ https://en.wikipedia.org/wiki/Radiant_intensity

⁹ [https://en.wikipedia.org/wiki/Photometry_\(optics\)](https://en.wikipedia.org/wiki/Photometry_(optics))

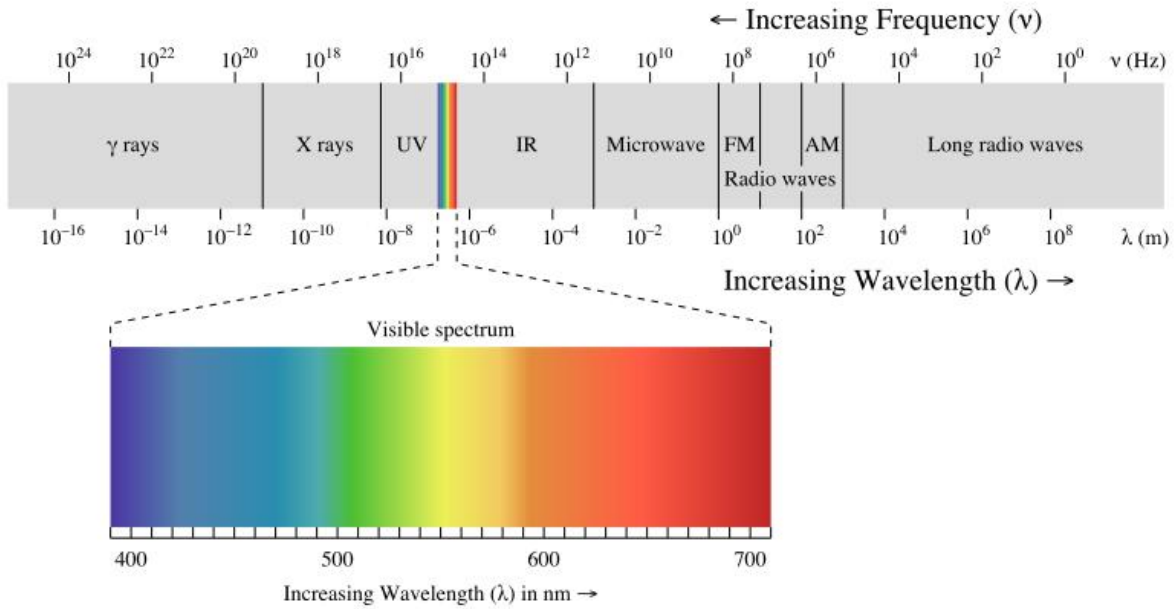


Figure 3 - Visible Light on the Electromagnetic Spectrum¹⁰

Since photometry deals with the human visible part of the spectrum and how a human perceives the light, we must know about the sensitivity of the receptors of the human eye.

For daytime, humans use mostly the cone cells of the eye to see. This is called photopic vision and is most sensitive at 555 nanometers. For nighttime vision, humans use mostly rod cells. This is called scotopic vision and is most sensitive at 507 nanometers. Mesopic vision is the transition between photopic and scotopic vision. Figure 4 shows rods and cones under a scanning electron microscope.

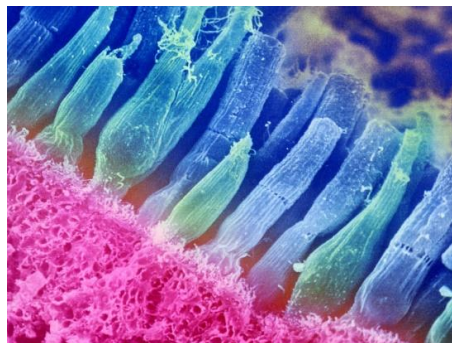


Figure 4 - Rod and Cone cells.¹¹

¹⁰ <https://www.lumitex.com/blog/light-brightness>

¹¹ <https://www.npr.org/sections/health-shots/2018/12/21/678342879/scientists-find-a-brain-circuit-that-could-explain-seasonal-depression>

The photopic scheme is used when the light is greater than 3 candela per square meter ($> 3 \text{ candela/m}^2$). The scotopic scheme is used when the light is less than 0.003 candela per square meter ($< 0.003 \text{ candela/m}^2$).¹²

Figure 5 illustrates some of the vocabulary we need for understanding photometry.

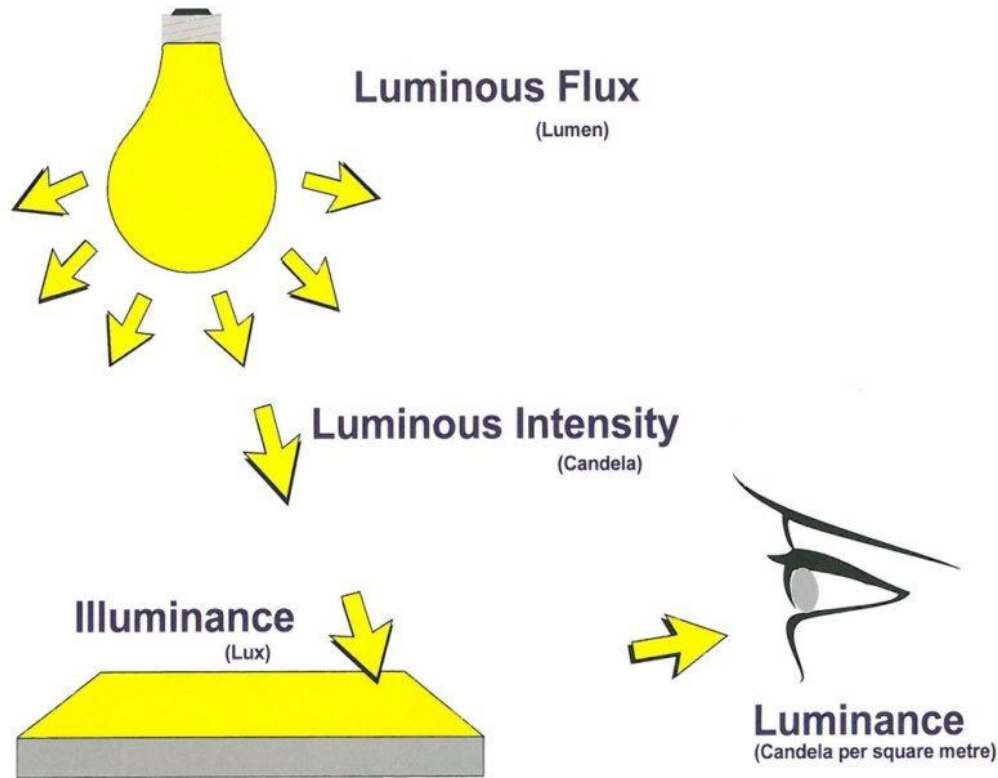


Figure 5 – Photometry Vocabulary¹³

Lumen (Unit of Luminous Flux)

A lumen is defined as the amount of visible light emitted per unit of time. Lumen is analogous to watt but narrowed to just the portion of energy that represents visible light. The lumen is specifically tied to human vision. So, lumen is an amount of visible light energy per unit of time.

A lumen is equal to $1/683$ of a watt at 100% 555 nanometer green. Taking the inverse means that there are 683 lumens in 1 watt at the 100% 555nm wavelength. For comparison, there are 0 lumens in 1 watt at 100% 700nm infrared wavelength because there is no visible light at that wavelength. Using the photopic spectral luminous efficiency function of weighting

¹² <https://www.ecse.rpi.edu/~schubert/Light-Emitting-Diodes-dot-org/Sample-Chapter.pdf>

¹³ <https://www.fireflier.com/led-101/>

for the visible spectrum leads to most of the weight being given to 555nm and only 0.4% to infrared.¹⁴

Luminous Flux

Luminous flux (or luminous power) is the same as radiant flux, except that luminous flux is adjusted to reflect the varying sensitivity of the human eye to different wavelengths of light and is measured in lumens.¹⁵

A 60 watt incandescent light bulb produces about 870 lumens of luminous flux. Luminous flux radiates in all directions of a sphere, as shown in Figure 6.

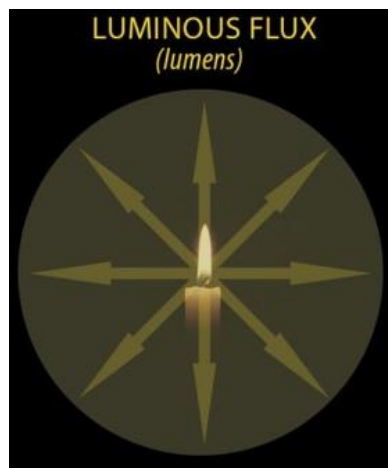


Figure 6 - Luminous Flux is measured in all directions in lumens¹⁶

Candela (Unit of Luminous Intensity)

The candela is analogous to radiant intensity, but candela is used for luminous intensity (see below) and is weighted by the luminosity function for visible light and is dependent on the perception of the human eye.¹⁷ Candela is equivalent to watts per steradian.

1 candela is how bright the eye perceives 1 candle per steradian. Because candela is measured per solid angle, 1 candela near the candle is still 1 candela 10 meters away. Candela measures the amount of visible light energy at the source.

The candela measurement unit uses a weighted luminosity function for visible light. The weighting function uses 555nm (yellow-green) for peak sensitivity of photopic vision, and

¹⁴ [https://en.wikipedia.org/wiki/Photometry_\(optics\)](https://en.wikipedia.org/wiki/Photometry_(optics))

¹⁵ https://en.wikipedia.org/wiki/Luminous_flux

¹⁶ <https://www.ledwatcher.com/light-measurements-explained/>

¹⁷ <https://en.wikipedia.org/wiki/Candela>

507nm (blue-green) for peak sensitivity of scotopic vision. Candela refers to photopic vision. Scotopic Candela refers to scotopic vision.

A 25-watt incandescent light bulb is about 135 candela, or 135 candles per steradian.¹⁸

Luminous Intensity

Luminous intensity is analogous to radiant intensity but is based on the luminosity function which uses only the visible spectrum of radiation and is measured in candela. Figure 7 shows that luminous intensity is measured per solid angle.



Figure 7 - Luminous Intensity is measured in one solid angle in candelas.¹⁹

Lux (Unit of Illuminance)

Lux is a measure of the luminous flux per unit area (square meters).²⁰

Whereas luminous flux measures how much human visible light energy is emitted in total from a source, lux will measure how much of that energy falls onto a flat surface and will depend on how far the detector is from the source.

Illuminance

Illuminance is the amount of light hitting an area of surface and is measured in lux. Illuminance does not depend on the type of surface the light is landing on. Figure 8 shows light energy landing on a two-dimensional flat surface.

¹⁸ <https://store.hp.com/us/en/tech-takes/what-is-candelas-per-square-meter>

¹⁹ <https://www.ledwatcher.com/light-measurements-explained/>

²⁰ <https://en.wikipedia.org/wiki/Lux>

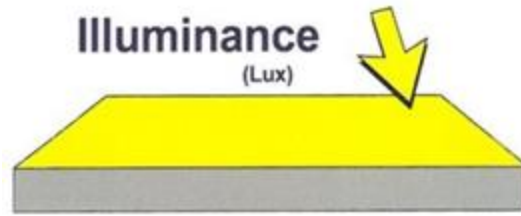


Figure 8 - Illuminance is measured in lux.²¹

Candela per Square Meter or Nit (Unit of Luminance)

Nit is the name sometimes used for candela per square meter.

Candela per square meter allows us to measure how much light energy is falling onto the human eye through a solid angle and is therefore a measure of brightness.

Luminance

Luminance is a measure of the human-perceived brightness of an object through a given solid angle and is measured in candela per square meter or nits. Luminance is dependent on the type of surface that the light is reflected off.

Since luminance is measured through a given solid angle, we can describe the amount of energy being emitted at the source and landing on the eye. The distance between the observer and the source of light will not change the luminance value.

Luminance refers to photopic vision (daylight). Scotopic luminance refers to scotopic vision (darkness).



Figure 9 - Luminance is measured in candela per square meter or nit²²

²¹ <https://www.fireflier.com/led-101/>

²² <https://www.fireflier.com/led-101/>

Comparison of Light Measurements

Each of these four lighting measurements are per unit of time.

Type of Measurement	Units	How Measured	Comments
Luminous Flux	Lumen	Spherical Total	Lumens is unchanged by distance or angle
Luminous Intensity	Candela	Per Solid Angle	Candela is unchanged by distance
Illuminance	Lux	Per Flat Area	Lux changes by distance
Luminance	Candela/m ² (nit)	Per Solid Angle	Luminance is unchanged by distance

Luminous Efficacy

Luminous efficacy is found by dividing the luminous flux by the radiant flux.²³ This information can be used to indicate the percentage of emitted radiation that is in the visible part of the spectrum.

A 60-watt incandescent that emits 8700 watts/steradian of energy, but only 870 lumens of visible light energy, has a luminous efficacy of 10%.

Spectral Power Distribution

Spectral power distribution (SPD) describes the power per unit area per unit wavelength of an illumination.²⁴ Figure 10 shows the SPD of six different sources of light. The intensity of each visible wavelength is measured relative to the other wavelengths of human visible light.

The Incandescent shows a smooth increase from very little blue to lots of red. The Cool White LED shows a large spike of blue wavelength and very little red.

²³ https://en.wikipedia.org/wiki/Luminous_efficacy

²⁴ https://en.wikipedia.org/wiki/Spectral_power_distribution

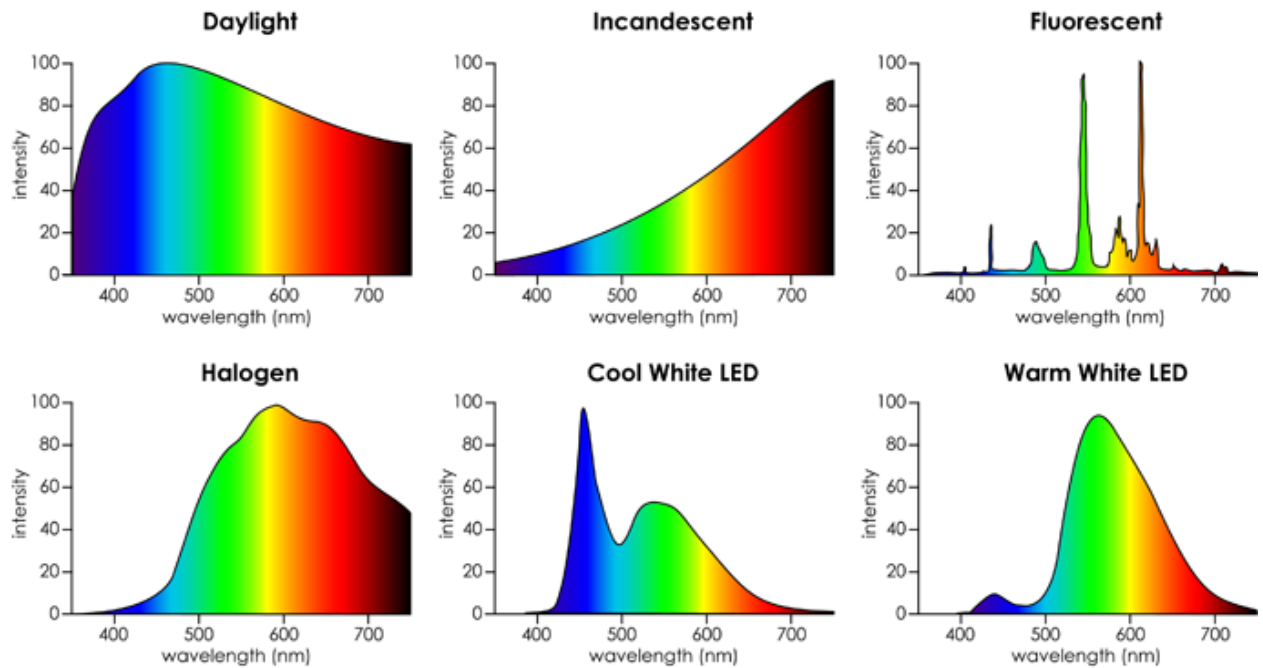


Figure 10 - Spectral Power Distribution of Different Sources²⁵

Color Temperature

The color temperature of a light source is the temperature of an ideal black-body radiator of a color comparable to that of the light source.²⁶

Figure 11 shows the color of the sun as it goes through the phases of sunrise to noon to sunset. At sunrise, the color is an orange/red, but by noon, the high energy blue wavelengths are most abundant.

²⁵ https://www.ledrise.eu/blog/human_centrig_lighting/

²⁶ https://en.wikipedia.org/wiki/Color_temperature

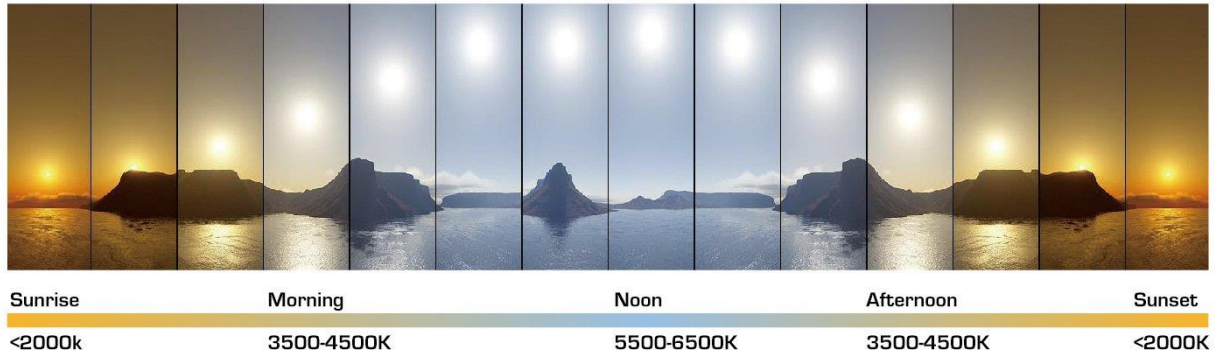


Figure 11 - Color Temperature²⁷

The color of the sun can be measured using Color Temperature, which is a mapping of colors to a reference called a black body radiator. The black body radiator is only theoretical and does not exist, but heating a piece of iron would be very similar. We use the Kelvin temperature scale for this measurement.

Figure 12 shows an iron bar that is heated to high temperatures. The iron bar emits different wavelengths of light depending on the temperature, measured in Kelvins. We can then map these colors to the temperature of the iron.

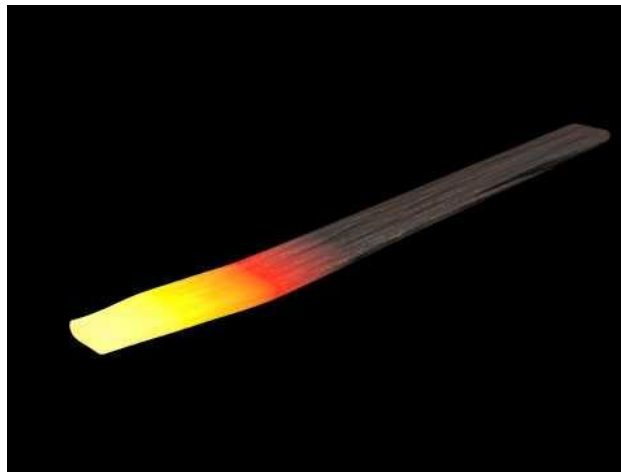


Figure 12 - Hot Iron Bar²⁸

Figure 13 shows a mapping of color temperature to typical lighting sources.

²⁷ <https://www.ledrise.eu/blog/innovative-sunlike-natural-spectrum-leds-by-seoul-semiconductor/>

²⁸ <https://www.youtube.com/watch?v=LDSVIZX-Lmc>

Temperature	Source
1,700 K	Match flame
1,850 K	Candle flame, sunset/sunrise
2,700–3,300 K	Incandescent lamps
3,000 K	Soft (or Warm) White compact fluorescent lamps
3,200 K	Studio lamps, photofloods, etc.
3,350 K	Studio "CP" light
4,100–4,150 K	Moonlight ^[2]
5,000 K	Horizon daylight
5,000 K	tubular fluorescent lamps or cool white/daylight compact fluorescent lamps (CFL)
5,500–6,000 K	Vertical daylight, electronic flash
6,200 K	Xenon short-arc lamp ^[3]
6,500 K	Daylight, overcast
5,500–10,500 K	LCD or CRT screen
15,000–27,000 K	Clear blue poleward sky
These temperatures are merely characteristic; considerable variation may be present.	

Figure 13 - Color Temperature Chart²⁹

Correlated Color Temperature is used when the light source does not emulate a black body radiator. Fluorescent and LED lights do not have smooth curves, so we use CCT to approximate the dominate wavelength. CCT works well because it is a single value (in Kelvin) but CCT hides the true spectral distribution of the wavelengths.³⁰

Spectral G-Index

Spectral G-Index is a variable that was developed to quantify the amount of short wavelength light in a visible light source relative to its visible emission (it is a measure of the amount of blue light per lumen).³¹

The Spectral G-Index value is essentially the sum of the energies of the blue wavelengths of light from 380nm to 500nm divided by the energies of the total human visible

²⁹ https://en.wikipedia.org/wiki/Color_temperature

³⁰ <https://www.lrc.rpi.edu/programs/nlpip/lightinganswers/lightsources/whatisCCT.asp>

³¹ https://en.wikipedia.org/wiki/Spectral_G-index

wavelengths of light. This G-Index concept was developed because of the larger impacts of blue wavelength light on astronomy, light pollution, human eyes, and circadian rhythms.

Figure 14 shows a graph of the Spectral G-Index as compared to an incandescent light and to LED lights with differing spectral distributions. The more blue content in the light, the smaller the G-Index. A G-Index of 1.56 (+/- .15) is the boundary between uncomfortable and/or harmful blue light and softer, more pleasing orange and amber light.

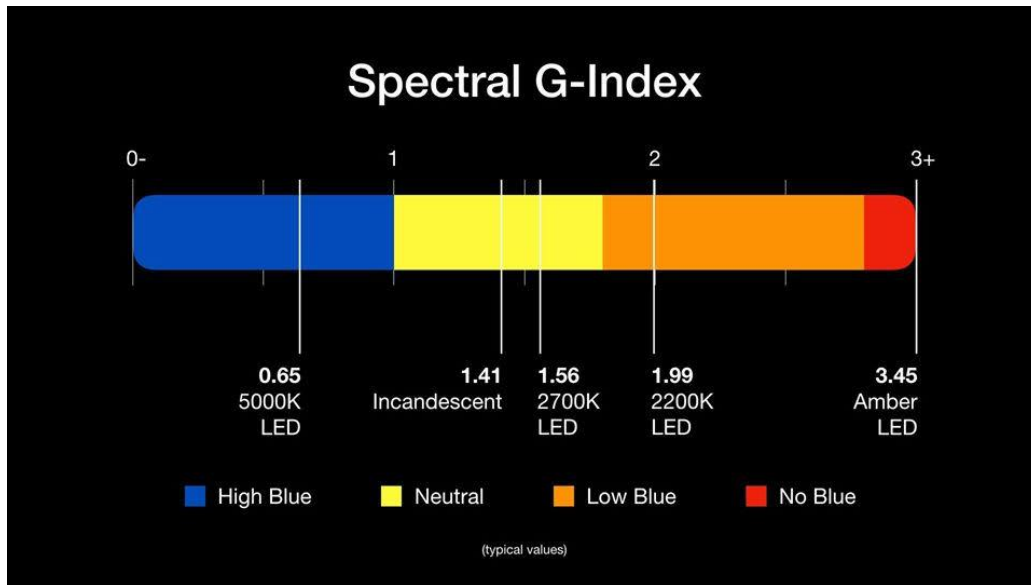


Figure 14 - Spectral G-Index³²

Beam Angle (Apex Angle)

One measures the angle between the axis where the light gives its highest luminous intensity and the axis where that intensity is reduced to 50%. Figure 15 shows an angle θ from the center beam to the angle where the intensity of beam drops by 50%. The Apex Angle is twice angle θ , or 2θ .

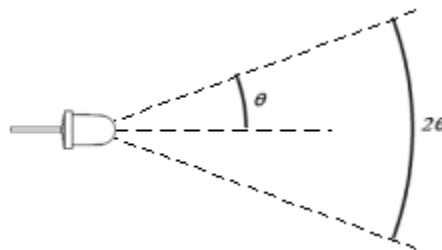


Figure 15 - Beam Angle of LED³³

³² <https://gregyeutter.com/>

³³ https://www.compuphase.com/electronics/candela_lumen.htm

Figure 16 is another example of apex angle.

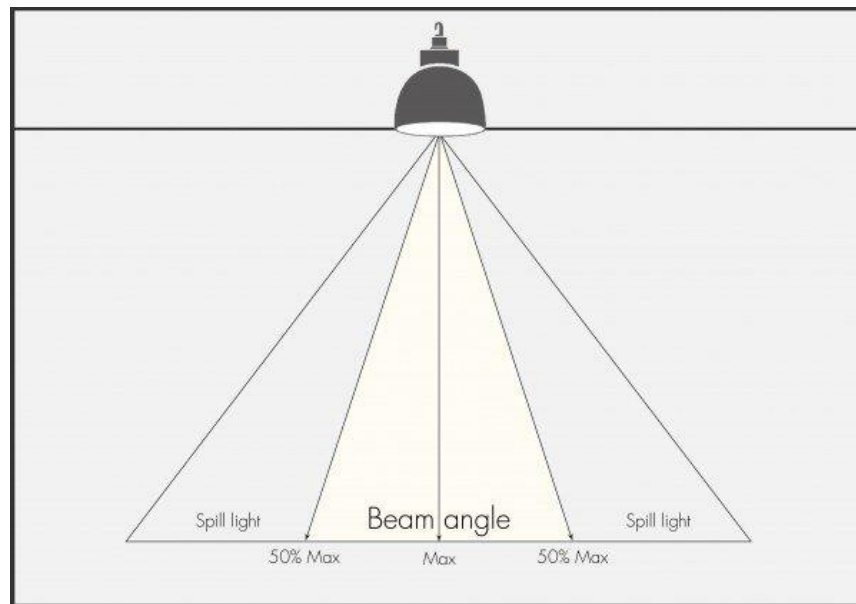


Figure 16 - Beam Angle from Light Above³⁴

Maximum Beam Candlepower (Center-beam intensity)

The luminous intensity along the geometric centerline of a directional light source. The assumption in application is usually that the centerline candlepower is also the maximum candlepower.³⁵

Figure 17 shows a plot of relative intensity for an LED light. The tool used to measure the intensity at each angle is called a goniophotometer. This tool is initially aimed down the center line of the light source, then rotated through a circle around the entire emitter. 0 degrees is the center of the beam and is where the light will be the most intense (most photons). As the goniophotometer is moved in a circle, there will be less and less photons at each degree away from the center beam. The relative intensity (on a scale of 0.0 to 1.0) is plotted against the degrees.

³⁴ <https://www.fireflier.com/led-101/>

³⁵ <https://www.ies.org/definitions/center-beam-candlepower-cbcp/>

Directivity
指向特性

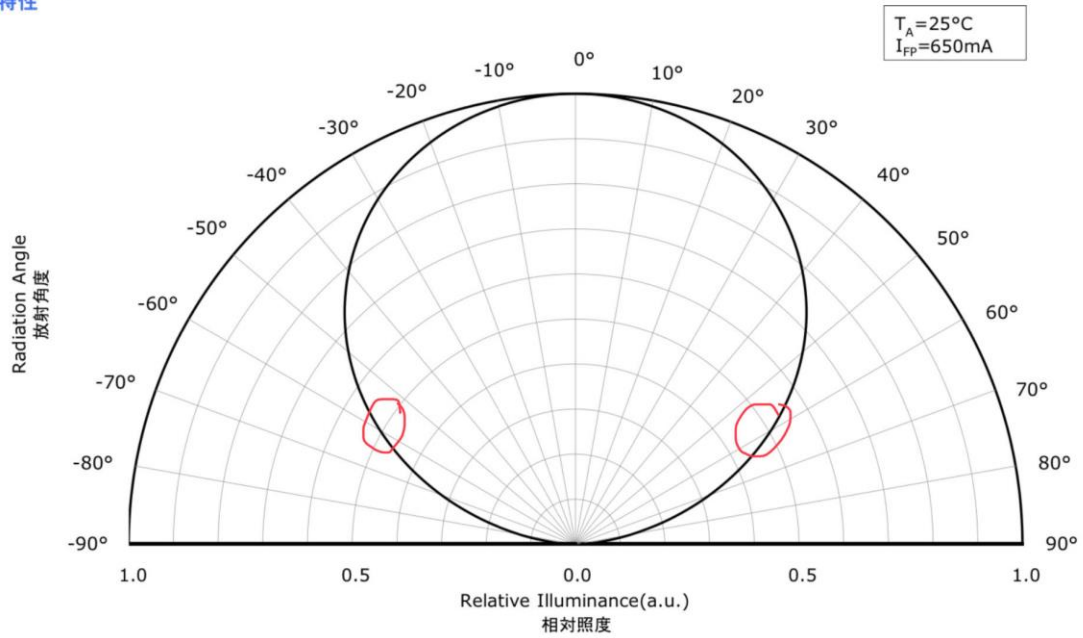


Figure 17 - Beam Angle Plot³⁶

The Beam Angle (or Apex Angle) is defined as the angle at which there is a 50% reduction in light intensity. This is circled in red on Figure 17 at the 0.5 relative illuminance location. For this LED that was measured, the apex angle is 2×60 degrees equals 120 degrees.

³⁶ http://www.nichia.co.jp/en/product/led_product_data.html