Describing the "Strength" of Visible Light

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Issue 5
March 4, 2025

ABSTRACT AND INTRODUCTION

In many types of technical work it is necessary to describe (and quantify) the "strength" of visible light. The matter is complicated by the fact that there are many distinct concepts of the strength of light, each involving a distinct quantity having its own dimensionality and unit of measure.

In this article I describe these circumstances and the way in which the strength of light is described for each.

1 BACKGROUND

1.1 Introduction

In the discussions of describing the "strength" [1] of light, several pivotal underlying concepts are encountered with which the reader may not be familiar. In this section, I will briefly review these concepts.

1.2 Light

Light is electromagnetic radiation, conceptually the same as radio waves, but having a frequency in a range many times greater than that used in radio communication, that range of frequencies being recognized by the human visual system. Said anther (and more common) way, its wavelength is many times less than that of the waves used in radio communication. The boundaries of this visible range are not sharply defined, but we often arbitrarily consider it as being 400-700 nm (nanometers). That would be a frequency range from 750 THz to 428 THz (respectively).

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[1] I use the rather vague term "strength" here rather than, for example, "intensity" or "brightness", since all those terms have specific meanings applicable to only one of the various quantities we encounter in the matter of light measurement and description.

1.3 "Visible" light

It is common to refer to this kind of electromagnetic radiation as "visible light". Rigorously, that term is tautological: only electromagnetic radiation that is visible is formally considered to be "light".

But in actual practice, two kinds of electromagnetic radiation that, because of their wavelengths, are not visible are still often spoken of as "light", namely "infrared light" and "ultraviolet light." The former has wavelength a bit greater than the maximum for the radiation to be visible (which is the red end of the spectrum of visibility); the latter has wavelength a bit less than the maximum for the radiation to be visible (which is the violet end of the spectrum of visibility) [2].

1.4 Dimensionality

Dimensionality[3] is the property of a physical quantity that shows how it relates to the seven fundamental physical quantities: *length*, *mass*, *time*, *electric current*, *thermodynamic temperature*, amount of *substance*,[4] and *luminous intensity*. Any physical quantity can be described in terms of one or more of these seven quantities.

For example, the width of an object is a quantity with dimensionality *length*. The area of a geometric figure is a quantity with dimensionality *length squared*. The velocity of a moving object is a quantity with dimensionality *length per (unit* [5]*) time*.

We can write the dimensionality of a quantity in an algebraic form. For example, we can write the dimensionality of velocity, "length per (unit) time", this way: s/t, where s represents length, t represents time, and the word "per" in the verbal description is represented by the division sign ("/"). We can write the dimensionality of area, "length squared", as s^2. We can write the dimensionality of electric

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[2] The terms may seem to be backward; "infra" means "below", thus "less", while the wavelength of infra-red light is greater than the limit for visible light. The key is that infra-red radiation is less in **frequency** than the lower limit for visible radiation. Similarly, ultraviolet radiation ("ultra" means "beyond", thus "greater"), and ultraviolet light is greater in **frequency** than the upper limit for visible radiation.

[3] Often called by mathematicians "dimension". As that word has a quite different common meaning, I will use here the admittedly more-clumsy term *dimensionality* to avoid any misunderstanding.

[4] This is the property that relates to the notion, in chemistry, of "one mole" of a substance. It is related to the matter of the molecular weight of the substance.

[5] The word "unit" is often included for clarity, but is not needed for the technical definition. When I get into more complicated expressions of dimensionality, I often eliminate the word "unit".

charge, "current-time"[6], this way: *it*, where *i* represents current and *t* represents time. However, in the symbolic form we often use a dot to represent multiplication, as for example *i•t*, in order to avoid any misunderstanding that the adjacent symbols form a word.

Now consider the quantity "number of eggs in this box". It does not work in terms of any of the seven fundamental physical quantities. It works in terms of just a number (sometimes called a "counting number" to emphasize this). Such a quantity is said to be *dimensionless*.

The unit in which a quantity is described must have a dimensionality consistent with the dimensionality of the quantity. There are of course many different legitimate units for any given quantity. Length may be reckoned in units of inch, foot, yard, meter, fathom, furlong, or many others, but not in the unit kilogram, or volt, or square foot.

In modern engineering and scientific work, it is preferred to use only the units of the International System of Units (SI, from the first two initials of its name in French), the "modern metric system".

Units for derived quantities are formed from one or more of the basic units. These compound units can be written with the symbols for the units in the same algebraic form as that in which we represented dimensionality. In the case of units, we do not commonly use the dot to indicate multiplication, but rather a hyphen, in both verbal and symbolic forms: electric charge is measured in the SI unit *coulomb*, which corresponds to the ampere-second, or A-s.

Although counting numbers are dimensionless, they are not necessarily unitless. For example, we have the unit "dozen". In inventory control and the like, where for consistency every quantity must have a named unit, often the contrived basic unit "each" is used for items described by counting numbers.

The quantity *angle* is an interesting case. Angle does not correspond to any of the seven fundamental physical quantities. In fact, angle can be thought of as working by counting "revolutions". Thus angle is a dimensionless quantity.

Angle is nevertheless not unitless. Common units for measuring angle are the *revolution*, the *degree* (1/360 of a revolution) and the *radian* ($1/2\pi$ revolution). All are "dimensionless units".

The unit *radian* is defined thus: if we construct two lines outward from the center of a circle of radius *r*, so that the length of the

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[6] Meaning "current times time".

circumference which they embrace is *r*, then the angle between them is one radian.

1.5 Solid angle

If we look through the viewfinder of a camera, we are able to see a certain amount of space. We can ssometimes describe it in terms of two angles. Perhaps the amount of space we can see is 30 degrees horizontally and 20 degrees vertically. But how do we in general describe the entire amount of space we can see (independent of its shape). The quantity we use is *solid angle*. If we have a cone or pyramid that continues on indefinitely, how do we describe “what amount of space does it include, overall”? We do that in terms of the included *solid angle* of its apex.

Solid angle is preferably measured in terms of the unit *steradian*.[7] If we have a cone or pyramid, and with its apex as the center we construct a sphere having radius r, and the region of the sphere surface embraced by the cone or pyramid has an area r^2, then the included solid angle of the apex of the cone or pyramid is one steradian.

2 RADIOMETRY AND PHOTOMETRY

Measurement and description of the “strength” of electromagnetic radiation (in several situations) constitutes the field of *radiometry*. Visible light is electromagnetic radiation, and thus the concepts of radiometry apply to it just as to other forms of electromagnetic radiation—at least when we are not interested in the strength of the light from the perspective of human perception, but only with respect to the laws of physics.

When we are interested in the strength of light from the perspective of human perception, we enter the separate but parallel field of *photometry*.

The quantities and units of photometry parallel those of radiometry, with the important difference that photometric concepts reflect the differing “sensitivity” of the human eye at different wavelengths. At any given wavelength, there is a standardized relationship between the corresponding radiometric and photometric quantities (based on the response of the “average human eye” at that wavelength).

If we have light containing light at multiple wavelengths (perhaps even over a continuous spectrum), we can determine the photometric quantity by multiplying the radiometric quantity by the sensitivity of

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[7] The particle *ster* comes from the Greek and means “solid”. Recall that the term “stereophonic sound” was based on the concept that this was “solid sound”.

the eye (both are functions of wavelength) over the entire range of visible wavelengths, and summing the results (actually, since continuous functions are involved, the final process is actually *integration*).

3 QUANTITIES, DIMENSIONALITIES, AND UNITS

The reader unfamiliar with this topic may be mystified by my mention of “different circumstances” of “the strength of light”, and the consequent matter of different dimensionality of the corresponding quantities. Perhaps a homey metaphor will help illuminate this.

Suppose we are interested in the flow of water through a channel. We may be interested in qualifying the following aspects of that flow:

a. The linear rate at which the water flows across a certain plane (perhaps in meters per second)

b. The volume rate of flow across a certain plane (perhaps in cubic meters per second).

c. The total linear flow across a certain plane during some given event (perhaps when the channel is open to flow into a basin between certain times of the day). This might be expressed in meters.

d. The total volume flow across a certain plane during some given event (perhaps in cubic meters).

We can see from the units that these four quantities have different dimensionalities, as follows (respectively):

a. Length per unit time

b. Volume (length squared) per unit time.

c. Length

d. Volume

In the next section we will see of many different quantities that all fall in the general field of “the strength of light”.

4 PHOTOMETRIC QUANTITIES AND UNITS

4.1 Introduction

As with our analogy of water flow, there are several different circumstances to which the general notion of the “strength” of light apply. Each has it own dimensionality and its own SI unit.

I will in many cases also mention the most common of the many non-SI units for the quantity.

4.2 Luminance and illuminance—a caution

I will shortly speak of *luminance* and *illuminance*. These are two separate and quite different properties. Be careful not to confuse them as a result of their similar names.

4.3 Luminous flux

Luminous flux is the quantity that characterizes the total strength of a body of light. That body of light could be, for example, the total luminous output of a lamp, or the portion of that total luminous output that passes out through a nearby window, or the total amount of sunlight falling on a region of specified area.

The SI unit of luminous flux is the *lumen* (lm). The lumen is not one of the fundamental SI units. (It probably should have been, as it is at the root of the photometric food chain—see a further discussion of this under *Luminous intensity*.)

Luminous flux is parallel to the concept of *power* in radiometry, and has the same dimensionality (but a different unit).

At any given wavelength, there is a known relationship between the luminous flux of a body of light (in lumens) and the power in the body of light (in watts). In fact, the modern definition of the lumen is (indirectly) based on that relationship at a wavelength of 555 nm, where 1 lumen is equivalent to 1/683 watt.[8]

A common non-SI unit of luminous flux is the *spherical candlepower*.[9]

4.4 Luminous intensity

The strength of light emission in a particular direction from an emitter of very small size (from the perspective of the viewer)—a “point source”—is the *luminous intensity* in that direction. Its dimensionality is *luminous flux per (unit) solid angle*. It is in effect the solid-angular density of luminous flux. Luminous intensity is one of the seven fundamental physical quantities (but see below).

The SI unit of luminous intensity is the *candela* (cd). The candela corresponds to *one lumen per steradian* (lm/sr). The candela is one of the fundamental SI units.[10]

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[8] This actually occurs through the definition of the *candela*, the unit we will encounter next.

[9] A hypothetical lamp exhibiting a *luminous intensity* (see the next section) of one *candlepower* in every direction is said to have a total luminous output of one *spherical candlepower*.

Luminous intensity is parallel to the concept of *radiation intensity* in radiometry.

It may at first seem peculiar that solid angle is involved in the concept if luminous intensity, Couldn't we just speak of the amount of luminous flux emitted in a the direction of interest? In fact, **no** flux flows in "a certain direction"—that is, along any particular line from the source. That is because a line is infinitely thin, and as such cannot constitute a "conduit" for any amount of luminous flux, any more than an infinitely-thin pipe could convey any amount of water.

To have flux, we must have something for it to flow through, a non-zero solid angle. It can be as small as we wish to contemplate, even "infinitesimal", but not of zero size.

Thus the indicator of the strength of emission (in a particular direction) is the ratio of the amount of luminous flux to the solid angle through which it flows, where the solid angle we think of is arbitrarily small (usually infinitesimal) and centered on the direction of interest.

Note that the concept of *luminous intensity* does not involve distance from the emitter. It describes the emission, not the effect the emission produces at some distant point. (It of course is a factor on the effect produced at a distant point, as we'll see shortly under *illuminance*.)

A common non-SI unit of luminous intensity is the *candlepower* (cp). This is sometimes called *beam candlepower* to distinguish it from *spherical candlepower*, used as a unit of luminous flux, as well as to imply that it is stated as an average over the "beam" of an emitter.

Luminous intensity is one of the seven fundamental physical quantities identified under the SI. It really shouldn't be since (at the present time) it is directly relatable to power, and thus to the a combination of certain other fundamental physical quantities. But before 1979, it had an independent definition in terms of a certain physical phenomenon, qualifying it to be a fundamental quantity.

As a formally-defined "fundamental physical quantity", it wasn't the best choice among the photometric quantities. *Luminous flux* would have been a more logical choice, since it is at the bottom of the "photometric food chain". However, when the fundamental quantities were being selected, it was much more practical to measure luminous intensity with an instrument than luminous flux, so *luminous intensity* got the mantle out of pragmatism. Today it keeps that mantle out of "seniority".

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[10] The unit *candela* is essentially equivalent to the older unit, the *candle* (generally expressed as *candlepower*).

In the case of a source of finite area (not a point source), but where its dimensions are still small compared to the distance to the location from which its emission is observed, we may speak of an *equivalent luminous intensity*. (Such a source is, from the perspective of its effect at that distant location, "essentially a point source".)

4.5 Luminance

Luminance tells us the "strength" of the light emission from a luminous source whose size (from the perspective of the viewer) is not insignificant—an "extended source"—as observed from a site along a particular direction from the surface. We can think of this as the "brightness"[11] of the surface.

Such a source may be self-luminous (think of the translucent shade of a table lamp) or illuminated by incident light (as for most objects we see).

The dimensionality of luminance is *luminous intensity per unit area*, which is also *luminous flux per unit solid angle per unit area*. Note that the *unit area* of concern here relates to the "projected" area as seen from the direction in which we are describing the luminance, not necessarily the actual surface area.

In terms of the SI, there is no unique name for the unit of luminance. Rather that unit is the *candela per square meter*[12] (cd/m^2) It can also be expressed as the *lumen per steradian per square meter* (lm/sr-m^2)[13].

We can perhaps best understand the concept and dimensionality of *luminance* with reference to Figure 1.

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[11] But formally, *brightness* has a slightly different meaning than *luminance*.

[12] This compound unit does have its own name, the *nit*, but that name is not actually a part of the SI and is not too widely used.

[13] Less ambiguously presented as lm•sr^{-1}•m^{-2}.

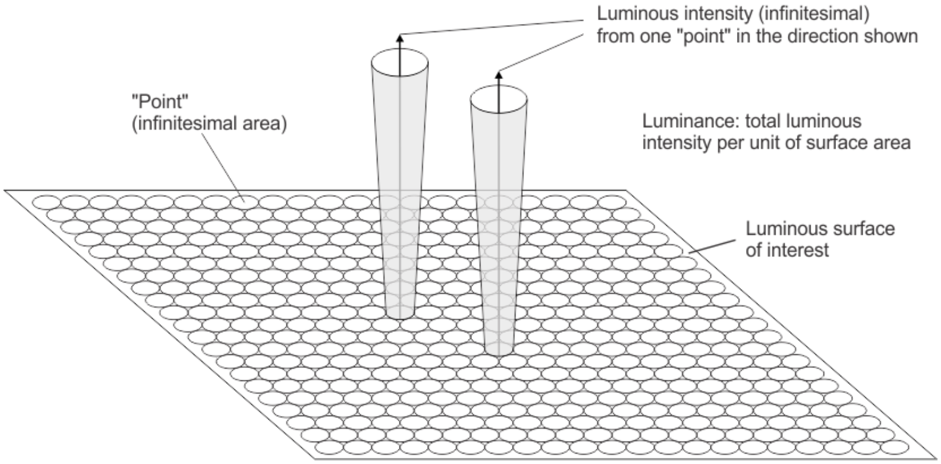

Figure 1. Concept of luminance

We imagine that the luminous surface is populated with a very large number of point sources (shown here as having finite size for graphic practicality), each emitting with a certain *luminous intensity* (in terms of *lumens per steradian*) in the direction of interest (which to avoid complication we assume to be along a direction perpendicular to the surface). (That luminous intensity, from one “point”, is infinitesimal.)

The *luminance* of the surface, as seen by a human observer at that direction is the product the luminous intensity of these point sources (in that direction) and how many of them there are per square meter. So luminance is *luminous intensity* (in the direction of interest) per unit *area*.

(Although the luminous intensity from one “point” is infinitesimal, there are an ”infinite” number of them within any finite region, so the sum of their luminous intensities over that region is finite.)

In radiometry we are rarely concerned with emission from an extended source, and so the radiometric quantity that is parallel to luminance is not often encountered.

A common non-SI unit of luminance is the *foot-lambert*. The name has an odd historical provenance; it is not, as it name might suggest, the product of the foot and the lambert.

Note that for an illuminated reflective surface that exhibits “ideal diffuse reflection” (a so-called *Lambertian* surface–see section A.3 in Appendix A), its luminance will be the same from any angle of observation.

Note that luminance is a property of the emission from a surface, not its effect at some distance. If we measure the luminance of a surface with a valid instrument located at different distances (and in the same direction) from the surface, the results will be the same.

4.6 Luminous exitance

Luminous exitance describes the total amount of luminous flux leaving an extended surface per unit area of the surface. It does not relate to observation from any particular direction.

The SI unit of luminous exitance is the *lumen per square meter*.

4.7 Luminous flux density

Luminous flux density tells us the amount of luminous flux per unit area as light crosses some plane in space perpendicular to the direction of flow. Its dimensionality is *luminous flux per unit area*.

The SI unit of luminous flux density is the *lux*, which corresponds to the *lumen per square meter*.

It is parallel to the concept of power flux density (PFD) often encountered in the general study of electromagnetic radiation.

The luminous flux density at a location distant from the emission from a point source is proportional to the luminous intensity of the source in the direction toward the location and inversely proportional to the square of the distance from the source to the location (the "inverse square law").

It is interesting that this important quantity is only infrequently mentioned in semi-technical literature, although the quantity often appears as an unnamed intermediate result in deriving the formulas for other quantities. Often, when *luminous flux density* is meant, it is inaccurately spoken of as "illuminance" (and indeed these two different quantities are "cousins", but not the same thing).

4.8 Illuminance

Illuminance tells us the "impact" of light falling on a surface. As with *luminous flux density*, its dimensionality is *luminous flux per unit area*. In this case, the concept of "unit area" pertains to the actual area of the surface—not, for example, to the area as projected in the direction from which the light might be coming.

Thus, light with a certain luminous flux density, arriving from an angle of incidence other than 0° (that is, not perpendicular to the surface) constitutes a smaller illuminance than light of that luminous flux density arriving at an angle of incidence of 0° (perpendicular to the surface). (Angle of incidence is measured with respect to the "normal" to the surface at that point—the line perpendicular to the surface.)

As with its cousin, *luminous flux density*, the SI unit of illuminance is the *lux*, which corresponds to *one lumen per square meter*.

The illuminance created on a physical surface at a distant location from the emission from a point source is:

proportional to the luminous intensity of the source in the direction toward the location

inversely proportional to the square of the distance from the source to the location (the "inverse square law"), and

proportional to the cosine of the angle of incidence of the light onto the surface.

The *luminance* (brightness) of an illuminated reflective object, in many cases of interest, is proportional to the total *illuminance* it receives from the light source(s) and also to its *reflectance*. (Information on reflection is found in Appendix A.)

Photographic light meters of the "incident light" type actually measure luminous flux density on the plane of the instrument's sensor, but if properly oriented with respect to the plane of the prospective receiving surface it also tells us the *illuminance* on that surface (our usual interest in photography.

A common non-SI unit of illuminance is the *footcandle*.

4.9 Luminous energy

Not, strictly speaking, one of the concepts of the "strength" of light, but important nevertheless is "light quantity", is *photometric energy*. It is the photometric parallel to *energy* in radiometry. Its dimensionality is *luminous flux times time*. Its SI unit is the *lumen-second* (lm-s).

4.10 Photometric exposure

In photography, the quantity *illuminance times time* generally determines the effect of the light on photographic film (or a digital sensor). As such, it is often called "exposure" (although, unfortunately, that term is used with another meaning as well in the field of photography [14]).

Sometimes this quantity is called *photometric exposure* to clearly distinguish it from that other quantity.

Its SI unit is the lumen-second per square meter (lm-s/m^2) or lux-second.

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[14] That other meaning is the combination of exposure time (shutter speed) and effective relative aperture (effective f-number).

Appendix A
Reflection

A.1 INTRODUCTION

Most objects we observe do not emit light but rather reflect light from another source, such as the sun or a lamp.

Many situations in which we are concerned with describing the “strength” of light relate to the effects of reflection. Here I will spend a little time talking about reflection.

A.2 KINDS OF REFLECTION

Surfaces may exhibit two kinds of reflection. *Specular reflection* is the reflection afforded by a mirror. A light ray striking a specular reflecting surface is reflected as a ray. The angle at which it arrives and the angle at which it leaves (both measured with respect to a line from the point of “impact” and perpendicular to the surface) have the same magnitude but are opposite in direction.

Diffuse reflection is the reflection afforded by most surfaces we encounter. In diffuse reflection, when light strikes a surface, the reflected light departs in every direction on the same side of the plane.

Many real surfaces exhibit “mixed” reflection, a combination of the specular and diffuse types. A piece of shiny metal, or a refrigerator with a glossy finish, are of this category.

A.3 LAMBERT’S LAW

An ideal diffuse surface obeys what is called *Lambert’s law*. Two of its important properties are, for a given illuminance on the surface:

a. The distribution of radiation intensity of the reflected light is not affected by the angle from which the incident illumination comes. (That angle may affect the illuminance on the surface—that pesky cosine at work—but once that is established, the consideration just mentioned applies.)

b. If we consider any tiny area of the surface (which we can treat as a point source), the luminous intensity in any direction is proportional to the cosine of the angle between that direction and a line from the point perpendicular to the surface.

In view of the second of these, we might expect that the luminance (“brightness”) of an illuminated “Lambertian” surface would vary with the cosine of the angle from which we view the surface. However it doesn’t—it is the same for any angle of view. We can see why in Figure 2.

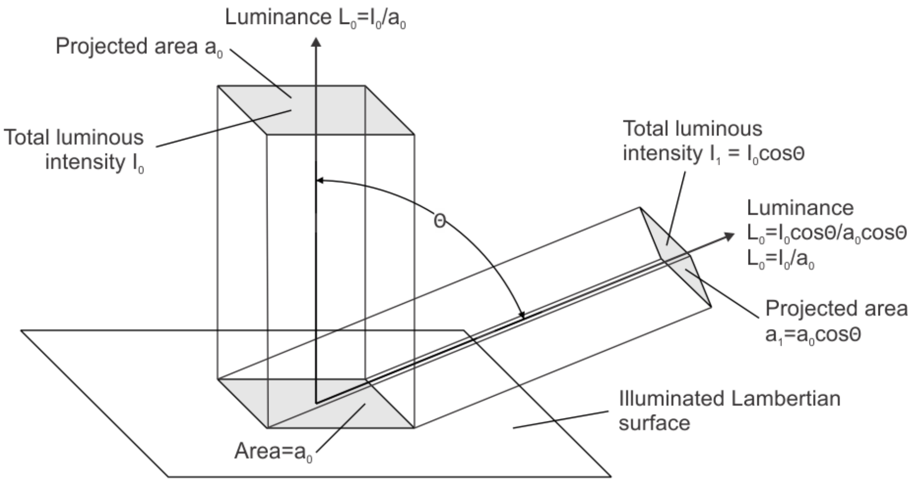

Figure 2. Luminance from different directions of observation

We first consider the illuminance of small region of the surface (with area a_0) as viewed from a direction along a line perpendicular to the surface from that region. The luminance of that region (as seen from that direction), L_0, is the ratio of the total luminous intensity emitted (in that direction), from the region, I_0, to the area of the region, a_0.

Now, consider the observation of that same surface region from a different direction, along a line at an angle Θ from the perpendicular to the surface. Since this is a Lambertian surface, the luminous intensity of the emission from each unit of the actual surface in that direction is $\cos\Theta$ times the luminous intensity of the emission from each unit of surface in the perpendicular direction. That is, for our little region, with area a_0, that total luminous intensity would be $I_0 \cos\Theta$.

But to our observer, the observed illuminance is the ratio of (a) the overall luminous intensity emitted (toward the observer) from that region to (b) the area **as seen by the observer**. That “projected area” is $a_0 \cos\Theta$.

In the overall algebra, these two factors $\cos\Theta$ cancel out, so again the luminance as observed from this “oblique” angle is I_0/a_0, just as before.

Thus we see, for an Lambertian luminous surface, the observed luminance of the surface will be the same for any angle of observation (from the illuminated side of the surface, of course).

A.4 REFLECTANCE

A Lambertian reflective surface will not necessarily reflect all the luminous flux incident on it, and it will not necessarily reflect the same fraction at all wavelengths.[15] The fraction of light reflected by a Lambertian surface, taking the differing response of the eye at different wavelengths into account, is called the *reflectance* of the surface[16] and is represented by the lower-case Greek letter "rho" (ρ).

If we illuminate a Lambertian surface of reflectance ρ with light having illuminance E (in lux), the reflected light will have luminance (brightness) L (in cd/m^2), as follows:

$$L = \frac{1}{\pi} \rho E$$

This relationship is derived by integrating the luminance over the entire hemisphere above the surface (all directions in which the light is reflected), and equating it to the total reflected light per unit area (the *luminous exitance*). The *pi* (π) gets into the deal during the integration process.

If we do this for the most common non-SI units, the *foot-candle* for illuminance (illumination), and the *foot-lambert* for luminance (brightness), the relationship becomes:

$$L = \rho E$$

Where did the π go? It disappeared because the definition of the unit foot-lambert has the $1/\pi$ "built in". Why? To make this important equation not have $1/\pi$ in it, a convenience in calculation!

A.5 SELF-LUMINOUS SURFACES

A particular self luminous surface may fulfill property b (as given in Section A.3) of an illuminated Lambertian surface, and thus will exhibit the constancy of luminance regardless of the direction from which observed (just as for an illuminated Lambertian surface) Such a surface is sometimes described as a "self-luminous Lambertian surface".

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[15] Gray paint, for example, reflects far less than all the light incident on it, and red paint does not reflect the same fraction of the light for all wavelengths.

[16] Also called its *albedo*, especially if we are speaking of astronomical objects, such as planets and their satellites.