More light on obscure units

Are you in a muddle over light units?

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This covers the basic concepts underlying light measurements, deliberately cutting out the dull listing of units and tabulation of conversion factors, relating to four physical quantities: flux, intensity, luminance/radiance and illuminance/irradiance. The treatment emphasizes this physical character of light units, to make them tangible to engineers.

If you are not in a muddle over light units, switch over to another article now. If you are let me take you out of the jungle, to basic concepts with a physical meaning. But first, a glance at the jungle.

One of the units of photometry is called the nit. Page 578 of the Concise Advanced Learner's Oxford Dictionary defines the nit so:

> nit[1]/nit/n egg of a louse or other parasitic insect (e.g. as found in the hair of persons who seldom wash).
> nit[2]/nit/n=nitwit.

Neither nice nor helpful. Another, more often encountered unit for light measurement is the candle. Romantic perhaps, but not very practical. We also have noxes, stibs and apostilbs, sea-mile candles, foot-lamberts, carcels, lumens, luxes, heffners and other talbots, without mentioning the radiometric unit of watts per steradian per metre square per nanometre used by c.r.t specialists. How then do we get out of this jungle? Simple. By going straight to the basic concepts of light measurements.

These concepts are but four, relating to four physical qualities: flux, illuminance-/irradiance, intensity and luminance/radiance. Equipped with these you will be able to put into the right place every single one of the two dozen or so existing units. Articles dealing with stage illumination, with camera sensitivity, with the light performance of l.e.ds, c.r.ts, incandescent and other light sources, with photodiodes, phototransistors and other light receivers will become clear, catalogues will become intelligible, and comparisons of components from different sources possible.

Luminous flux

The first and truly fundamental concept is that of *luminous flux;* the remaining three derive from it. The idea of flux is closely associated with that of flow: think of the flow and you "feel" the flux. For example the flow of people in Oxford Street. How many per hour? Think of the water flow of a mountain stream. How many gallons per minute? Think of your Company's cash flow. Try to remember now the shaft of light you once saw pouring through a stained glass window. Finally, imagine a torch shining on a pitch-dark night – this is light flow – and you will have grasped the notion of light flux.

Light is a form of energy. The luminous flux is the time-rate of the flow of this energy through a certain area or out of a certain solid angle. For instance, in the case of the shaft of light, this will be the "energy" time-rate of the light beam traversing a particular fragment of the stained glass window or the whole of it; in the case of the torch, the total flux is the "power" radiated into the light cone of the torch, out of its apex.

Photometric units are designed to convey a sense of strength of human responses to light and NOT to give an objective measure of the power carried by a beam of light. Whence " " in the previous paragraph. Being physiologically dependent, photometric units of flux are colour-related. Radiometric units are not. They alone represent genuine power – without inverted commas! They alone have licence to use the watt as a unit of flux. The practical consequences of the unequal sensitivity of the human eye to various colours is that even though two fragments of stained glass, one green, the other red, may be transmitting equal amounts of true power (such as would be measured in absolute terms and hence expressed in watts) their photometrically assessed fluxes will be different, the human eye being more sensitive to green than to red light. The photometric unit of luminous flux is the lumen. For pure colorimetric green light 1 lumen corresponds to 1.47 milliwatts. For red light some ten times more is required to produce the same physiological sensation and so, here, 1 lumen corresponds to 15 milliwatts. Green and red colours as used above correspond to monochromatic radiation of 550 and 650nm wavelength respectively. An internationally agreed lumen/watt relationship called the visibility curve for the whole range of colours was established many years ago based on an "average eye", the result of numerous measurements made on a large sample of humans, Fig. 1. This curve gives an immediate answer to a common question of the type: "My gallium arsenide diode emits 0.7mW. How many lumens is that?" As GaAs l.e.ds emit at a wavelength of 900nm, the answer is zero. This is how it should be, as the infra-red radiation produces no visual effects.

Illuminance – Irradiance

The magazine you are reading is illuminated. So is the theatre stage (though sometimes dimly), the shop window display and the road. What they all have in common is the fact that they all receive light shed onto them. To the contrary of, for example, a television screen which is self-luminous. This distinction must be clearly perceived and firmly rooted in the mind for the remaining three of the basic four to be understood.

Illuminance is the area-density of light falling from an external source onto a surface. Hence it is represented by lumens per square metre. The unit used in photometry is lux, with one lux representing an illuminance of one lumen per square metre: 1 lux=1 lumen/1m^2.

When light from more than one source falls onto an area, the individual fluxes are added.*

The radiometric conceptual (not numerical!) equivalent of the lux is the watt per square metre (W/m^2). Here, the area density of incident flux is called *irradiance.* You will have noticed the identity of the basic concept linking illuminance and irradiance. It is obvious from Fig. 2, right, that the more the surface is tilted with regard to the incident rays, the larger the area lit by the same flux and the smaller the illuminance/irradiance. This is what is expressed by saying the sun is hotter midday than morning and evening.

Before going onto the next item of the basic four it is of utmost importance to emphasize that neither illuminance (lux) nor irradiance (W/m^2) gives the slightest idea on how bright an area appears to us. Consider the example of Fig. 2. The illuminance of a black matt table top will be exactly the same whether or not it is covered with a snow-white table cloth. This fits the definition of illuminance which, like irradiance, is concerned with the area density of the on-coming and not the outgoing radiation.

Just how strong a lux is and what practical magnitude a watt/m^2 is can be judged from these few examples

- moonlit landscape receives 0.01lux
- comfortably lit desk is illuminated by 300lux
- St Tropez sunbather receives 1.5 × 10^5 lux
- 2mW helium-neon laser (red) produces an illuminance of a few thousand lux, or an irradiance of 200W/m^2.

Intensity

Few real light sources radiate with the same vigour in all directions. Some, such as the earlier-mentioned torch, are directional by design. Some, meant to be omnidirectional, fail in this respect through unavoidable manufacturing or exploitational constraints. Such is the case of a spherical light bulb, Fig. 3, in which the unavoidable contact-bearing base impedes the light preparation into a part of the surrounding space. Clearly, to characterize the strength of the radiation in a certain direction, a directional quantity is required – *luminous intensity.* The luminous intensity

* Laser light requires a specialized treatment.

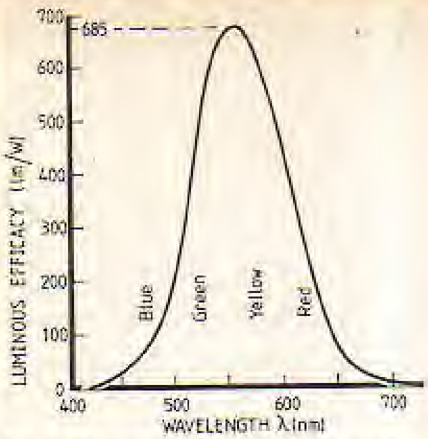


Fig. 1. "My gallium arsenide diode emits 0.7mW. How many lumens is that?" As GaAs l.e.ds emit at 900nm the answer, from the internationally agreed curve, is zero. Which is how it should be as the infra-red radiation produces no visible effect.

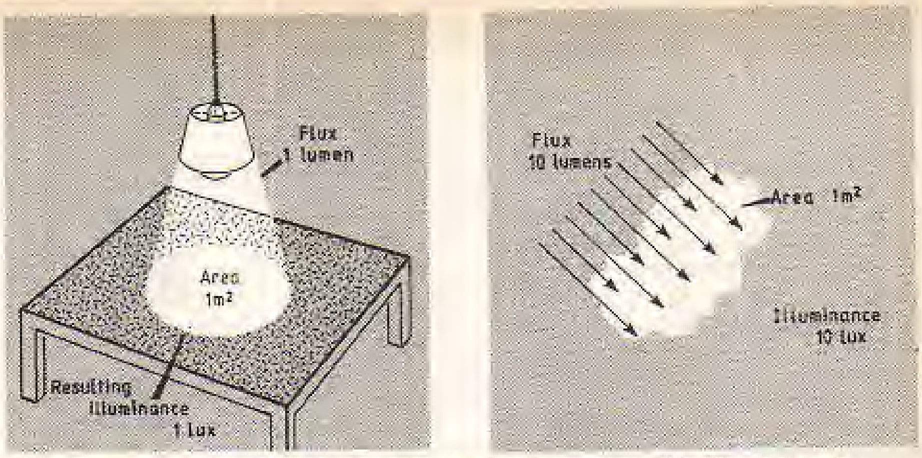


Fig. 2. The area-density of light falling onto a surface is represented by illuminance, i.e. lumens per square metre, for both divergent light and parallel light.

Fig. 3. As few real light sources radiate equally in all directions a directional quantity is needed to characterize strength of radiation in a particular direction. Candelas are lumens per unit solid angle.

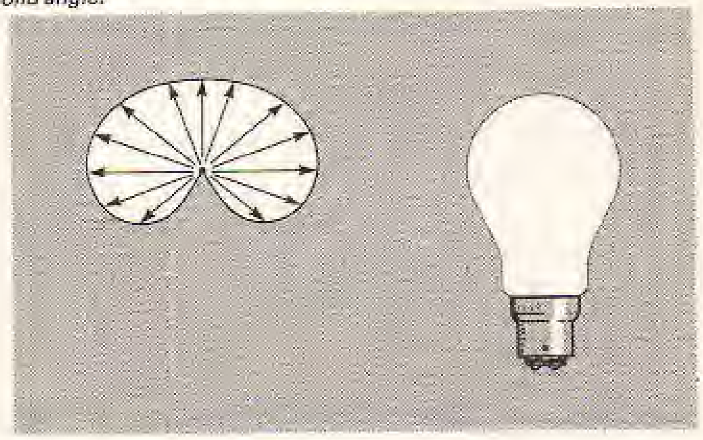
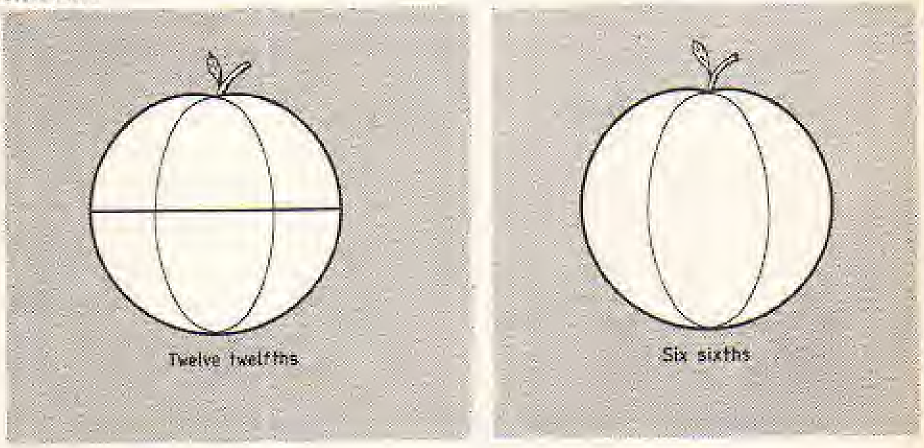


Fig. 4. Cutting an apple into twelfths as shown gives a solid angle that approximates to one steradian.



represents the flux flowing out of a source in a given direction per unit angle.

Because light source beam radiation three-dimensionally a flat angle unit such as the degree will not do here. A space angle unit must be used instead: the steradian. As the unit of flux is a lumen, the luminous intensity will be measured in lumen/steradian. For brevity a single word has been internationally agreed, the candela, to stand for one lumen/steradian.

The choice of a steradian for a unit of spatial angle is unfortunate: a steradian is a very large chunk of space and as such it does not impart well the sense of directionality. Steradians are seldom used in other fields and it will certainly help to describe an easy way of visualizing their size. To form a steradian, take an organe or an apple and cut it into six as if sharing it equitably between six people. Then make a fourth, horizontal cut through the middle, Figs 4 & 5. You have 12 equal portions. Each one of them contains at its apex a space angle of one steradian (within a 4% error). A corner of a room contains approximately 1.5 steradians.

Within the context of light intensity measurments it might be even more helpful to visualize the spatial angle not as the hollow of a three-sided structure, but as the interior of the tip of a cone. A hypothetical cornet with a rounded off "filler" surface having an area just equal to r^2 would make exactly one steradian at its tip.

In radiometry, the third basic concept corresponds to the power radiated into a unit solid angle. This is named radiant *intensity* and is measured in watt/steradian. The intensity concept is valid only for sources small with regard to the surrounding space, aptly called point sources. As long as the linear dimension of the radiating element is some ten times smaller than the distances of interest around them, one can call them point sources and use the intensity concept. This is mostly the case with bulbs, candles, l.e.ds or c.r.t. spots but not with large panels.

Finally, the value of both luminous intensity and radiant intensity in a given direction is independant of the distance from the source at which it is measured, as seen from the sketch of Fig. 6.

Luminance

The last of the basic four concepts of photometry is that of *luminance*. Imagine you are viewing a tiny, compact filament shining through its bulb of clear glass. The bulb, in fact the filament, it is bright that it hurts your eyes. Then imagine that the glass is opalescent. The device emits now very nearly the same amount of light as before but the eye perceives it unhurt. The total flux is constant to a first approximation, but the opal glass envelope spreads the radiation over a much larger surface which re-diffuses it. Luminance expresses the brightness of the source in a given direction.

The surface area of the source has a large part to play, now. Imagine that the milky spherical bulb containing the filament broke and got replaced by another, twice its diameter, Fig. 7. The new bulb will appear four times less bright, despite the constancy of its wattage and its total flux. To convey these effects of source brightness, the luminance expresses luminous intensity per unit surface area of the source. This is of course the same as the luminous flux per steradian per unit area.

We thus have a unit of luminance:

Candela/metre^2 or lumen/steradian $\times$ metre^2.

It is a unit that characterizes out-going radiation, to be used with objects which emit or re-emit light; a filament, a bulb, an illuminated lamp shade, a working screen or an illuminated table top. An idea of its size: the UK standard for screen luminance in film viewing rooms is 37.5 candelas/m^2 at full illumination.

Luminance is a directional quantity, as is intensity, one of its two constituents. The surface area, the second constituent, must be taken as the projection of the physical radiation area on the plan perpendicular to the direction in case. With certain emitting or re-emitting devices the intensity *versus* viewing angle variation is such that luminance remains constant. This is so because as the observer looks more obliquely at such a source, the projected unit area reduces in the same proportion as the intensity does. Such sources, called lambertian, are exemplified by the moon, flashed opal glass, chalk, good Bristol board. But this directional independence must not be taken for granted, as most devices and materials are not lambertian. Their luminance varies with direction.

Finally, the radiometric sister of luminance is *radiance* and I think that nobody will show puzzlement any longer at the fact that it is usually measured in

$$\mathrm{W/sr} \times \mathrm{m}^2$$

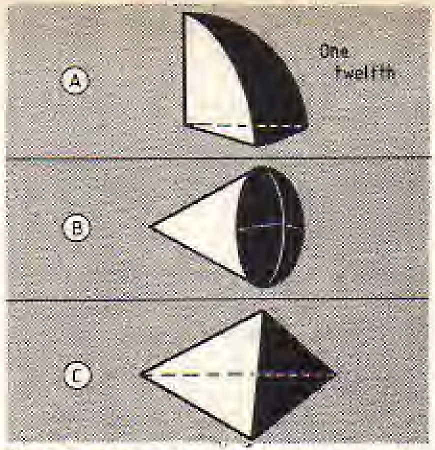


Fig. 5. *Spatial angles may be alternatively visualized as that conical fraction of a sphere whose surface area is equal to the square of its radius.*

and sometimes (I am sure you will know where and why) in

$$\mathrm{W/sr} \times \mathrm{m}^2 \times \mathrm{nm}$$

And yet "watts per steradian per metre square per nanometre" must have sounded puzzling when first met in the opening paragraph of this article.

Final word of guidance. When you come across an unknown exotic unit try to establish, first of all, to which of the basic four denominations it belongs and whether it is photo or radiometric. The subsequent working out of numerical conversion factors should come easily.

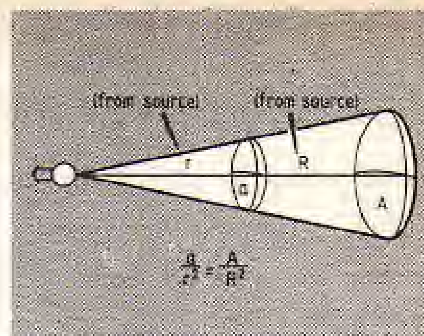


Fig. 6. *Values of both radiant and luminous intensity are independant of source distance.*

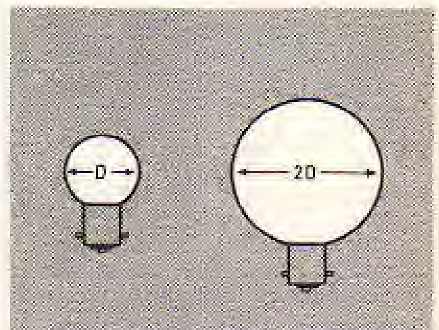


Fig. 7. *Luminance expresses brightness of source. Large bulb appears four times less bright than smaller bulb for the same power and flux. Luminance is luminous intensity per unit surface area (which is the same as flux per steradian per unit area).*