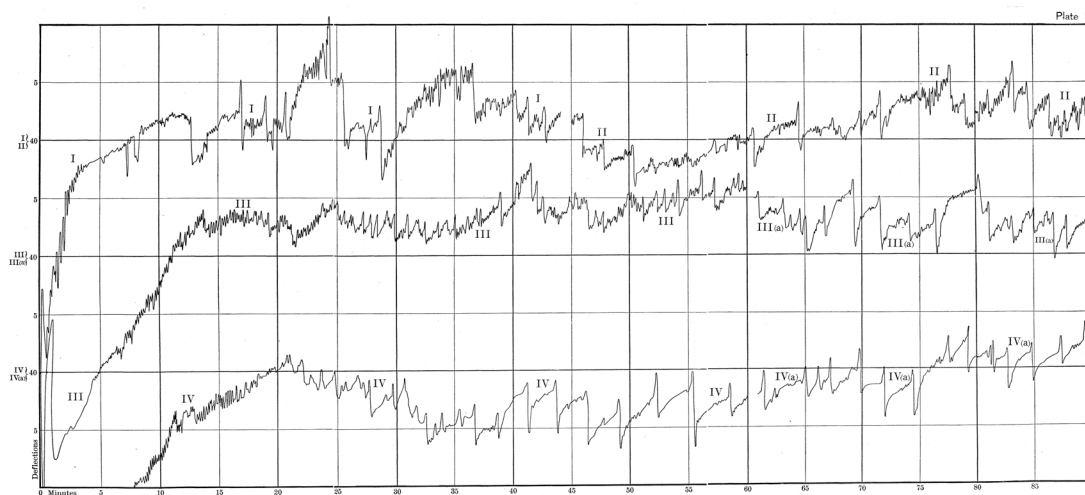


Photopic and Scotopic lumens - 2: A Bit of History

Is there a good reason to consider the historical development of our current definition of the lumen? The answer is not obvious. In our hurtling, warp-speed, instant-this and instant-that world, it may seem that we have no time for history; it is all we can do to come to grips with the latest whiz-bangery. And in the press of commerce we may come to agree with Henry Ford when he famously said “History is bunk.” But the Spanish-born American philosopher George Santayana (1853-1952) warned us: “Those who cannot remember the past are condemned to repeat it.” We can be more specific: A clear idea of where the lumen comes from and how it came to be defined deepens our understanding of this fundamental concept, helps us use it correctly, protects us from fads and humbug, gives us the hard-won clarity achieved by early workers in this field, and generates a healthy skepticism about the universal use of the lumen. Thus, a bit of history.

The need to develop something like the lumen

During the early part of the 19th century, visual photometry was used for the important commercial task of assessing the “illuminating power” of commercial illuminants: gas, various oils, and kerosene. The source in question was compared to a standard by visual photometry. In this process, light from the standard and test sources fell on different sides of a split screen and, other factors being held constant, the distance between the screen and the sources was varied until the brightness on both sides of the screen appeared equal. The ratio of the square of the two distances gave the power of the test source relative to that of the standard. The standard light source was invariably some form of flame: in England and The United States the standard was the “Parliamentary Candle” of 1860; in France the Carcel lamp burning rape seed oil was the standard; in Germany the Vereinskerze (“Association Candle”) was the standard. Late in the century, the English candle was replaced with a special lamp invented by Vernon-Harcourt that burned pentane, and the German candle was replaced by the Hefner lamp burning amyl acetate.



Data taken by Sharp and Turnbull in 1894 of the constancy of standard light sources. The data plotted here is for the English Parliamentary candle. The *radiometric* intensity is plotted as a function of time. It was assumed (reasonably) that variations in the luminous output tracked variations in radiant (physical) output. Sharp and Turnbull evaluated the other common light standards as well. All were shown to be relatively stable over the time required to make visual photometric measurements

This process worked well enough as long as the color of light of the two sources was similar. Contemporary reports stated that a repeatability of 2% could be achieved by experienced observers.

But new light sources appeared in the second half of the century including electric arc and gas discharge lighting, gas mantle lighting, and electric incandescent lighting. These sources produced light of a very different color from that of the standard sources and it proved to be very difficult to match the brightnesses of the two halves of visual photometer screen when their color was substantially different. This, and the generally high level of uncertainty in standard visual photometry, made clear the need for what came to be called a “physical basis” for photometry.

The differing visual effectiveness of different wavelengths

The lumen is a unit of light with a definition that was conceptualized at the opening of the 20th century. It attempts to provide—and to some extent, achieves—a universal quantification of the *visual effectiveness of radiation* that could account for widely different light-colors. The concept that radiation has a characteristic that gives it varying visual power or effectiveness only slowly became clear. A very early direct reference to the differing "strengths of colors" appears in Newton’s Opticks of 1704:

But its further to be noted, that the most luminous of the prismatic Colours are the Yellow and Orange. These affect the Senses more strongly than all the rest together, and next to these in strength are the Red and Green. The Blue compared with these is a faint and dark Colour, and the Indigo and Violet are much darker and fainter, so that these compared with the stronger Colours are little to be regarded.

Wavelength linked to light-color

But neither Newton nor anyone else at that time associated these “prismatic colours” with changing wavelengths of light. Newton and nearly everyone else conceived of light as a rain of luminous particles—no wavelength were involved since light was a particle. With the rise of the wave theory of light early in the 19th century, it was Thomas Young who first made an explicit link of color and wavelength when in 1800 he used Newton’s data of a century before to calculate the wavelength of light of various colors.



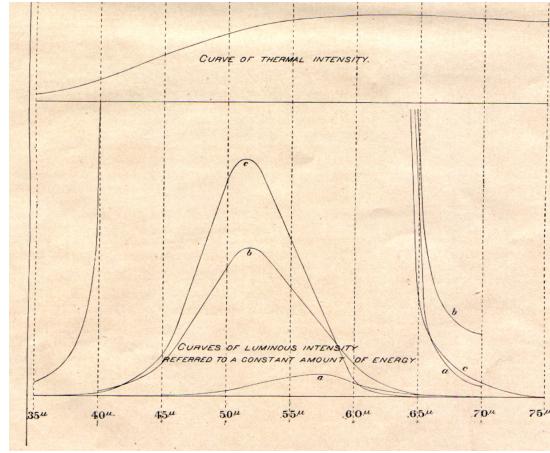
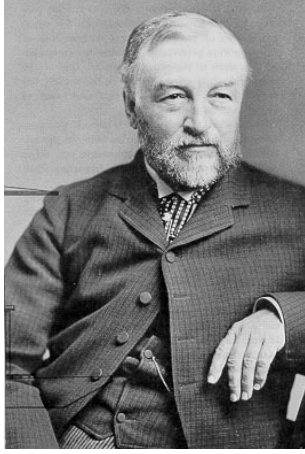
Colours.	Length of an Undulation in parts of an Inch, in Air.	Number of Undulations in an Inch.	Number of Undulations in a Second.
Extreme - - -	.0000266	37640	463 millions of millions.
Red - - - - -	.0000256	39180	482
Intermediate - - - -	.0000246	40720	501
Orange - - - - -	.0000240	41610	512
Intermediate - - - -	.0000235	42510	523
Yellow - - - - -	.0000227	44000	542
Intermediate - - - -	.0000219	45600	561 (≈2 ¹⁹ nearly)
Green - - - - -	.0000211	47460	584
Intermediate - - - -	.0000203	49320	607
Blue - - - - -	.0000196	51110	629
Intermediate - - - -	.0000189	52910	652
Indigo - - - - -	.0000185	54070	665
Intermediate - - - -	.0000181	55240	680
Violet - - - - -	.0000174	57400	707
Extreme - - - - -	.0000167	59750	735
Mean of all, or White	.0000225	44440	547

Thomas Young (1773-1829) and his data. In 1801 and 1803, Young demonstrated light interference and proposed a wave theory of light to account for this phenomenon. Assuming that light was a wave in a “luminiferous ether,” he went back to data that Newton had reported in 1704 on the appearance of colored rings when light passed through a lens in contact with a flat piece of glass. Young assumed these rings were caused by interference and calculated the wavelengths that light of different colors would have to have to produce them. His wavelengths are in complete agreement with modern values.

Early data

Nearly a century later in 1888, Samuel Langley noted that

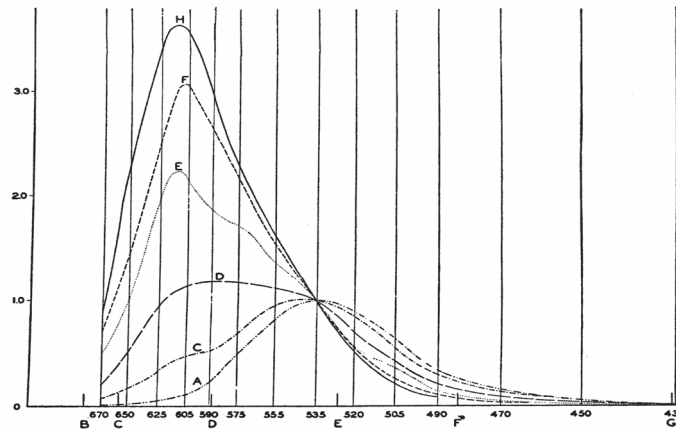
There is on the part of some physicists a failure to recognize how totally different optical effects may be produced by one and the same amount of energy according to the wave length in which this energy is exhibited ... There was nowhere in any physical work known to me any exact or even approximately exact statement of the relative ocular effects of a given amount of energy in different parts of the spectrum.



Samuel Pierpont Langley (1834-1906) and his data. He used a heliostat to track the sun and provide a powerful beam of sunlight that entered an otherwise dark room. The beam was dispersed by a prism and so nearly monochromatic light could be directed at the small type of a table of logarithms. Observers were to read the table and the amount of light required to just barely read the numbers was determined. Thus, Langley's test was threshold conspicuity of small type. Some of his data was plotted and reported. Two of his observers were evidently operating at very low light levels, while a third was operating at higher levels. For comparison, he showed the curve of the radiant power in the beam as a function of wavelength.

To provide such data, Langley built and used an apparatus to determine the relative “ocular effect” of light of different wavelengths. Langley decided to use the *threshold conspicuity* of the small type in a table of logarithms as the measure of “ocular effect”. His data showed the clear peak of conspicuity in the mid-wavelength region of the visible spectrum and that the peak shifted depending on whether high or low light levels were use.

In 1892 Arthur König did more careful and extensive work. König was Helmholtz's most gifted student and did all of his work at Berlin University. König used carefully made apparatus and several observers to determine the “luminosity” of various wavelengths of light through the spectrum, at different illuminance levels. Unlike Langley, König determined the *relative brightness* produced by various wavelengths of light by comparing the light at each wavelength through the spectrum to a fixed standard.



Arthur König (1856-1901) and his data. In 1892 König carefully determined the relative brightness of spectral colors at different illuminance levels. He used 14 wavelengths throughout the spectrum, determining the relative brightness of each wavelength at 9 illuminance levels. The 9 levels ranged from about 6 times the absolute threshold to about 260,000 times higher—a very large range spanning photopic and scotopic adaptation. Shown here is one data set for a color normal observer: the relative brightness of different wavelengths at 6 illuminance levels from A (the highest) to H (the lowest). Contrary to modern practice, König plotted the long wavelengths at the left. The photopic (curve A), scotopic (curve H), and mesopic (curves C-F) relative brightness curves are clearly apparent.

Like other data, König's was the result of comparing the brightnesses of two halves of a field, each half exhibiting a different wavelength of light. Though the data of Langley and König exhibited differences, there were very similar in general form and clearly showed the relationship between wavelength and visual effect or power.

The concept of the lumen emerges

In 1907 Perley Nutting advanced the idea of defining light as the product of a “visibility function” derived from the data of Langley and König, and the spectral power of a light source. Nutting outlined the modern idea of the lumen in his famous paper “The Luminous Equivalent of Radiation,” published in the Physical Review Journal in 1907.

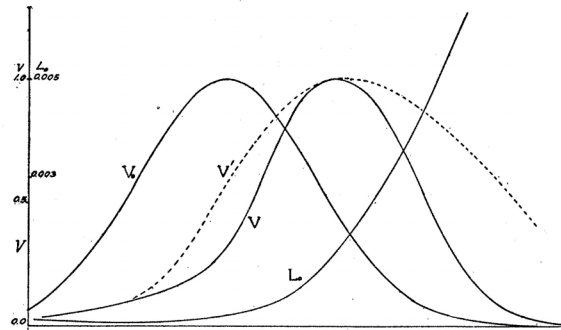


Fig. 2.

Perley G. Nutting (1873-1949) and his functions. In 1907, Nutting reduced and averaged the data of Langley and König to produce an average “visibility function” for low light levels. In the figure, taken from his 1907 paper, V_0 is the visibility function, L_0 is the radiant power distribution of the source used by König, and V is the wavelength-by-wavelength product of the two. The area under the curve V is the total “luminosity” of the source. It was recognized that the proposed system needed a visibility function for high light levels, but the data was difficult to obtain since at low light levels color sensation was muted or absent, but at high levels it was quite pronounced.

Nutting outlined the idea for a “physical definition of light”:

The same amounts of radiation in watts per unit wave-length in different parts of the spectrum, affect the eye in different degrees. Hence, other things being equal, the sensibility of the eye is a function of the wave-length, say $V(\lambda)$, call this *visibility* of the radiation. For any arbitrary spectral distribution of radiation $E(\lambda)$ then, the product EV will give a third function of wave-length, say $L(\lambda)$, which we may call the luminosity or optical intensity of the radiation. The determination of the visibility function $V(\lambda)$ is the first step toward the solution of this general problem.

Nutting noted that Langley and König’s data showed two types of responses: low and high adaptation states and, noting that only two of the 50 data sets available were for the high state, chose the data for the lower state for his visibility function, $V(\lambda)$. Nutting then formulated the entire system. Notice that Nutting’s function E is the spectral radiance (radiant equivalent of luminance) and his function L is spectral luminance.

Suppose the spectral *energy* $E(\lambda)$ of the radiation be given in watts per s.-m. per unit solid angle ω . From this suppose the spectral *luminosity* $L(\lambda)$ derived in arbitrary units (say *lumens*) per s.-m. per unit solid angle by means of the subsidiary visibility $V(\lambda)$. Then

$$\text{Specific Emission} = \int_0^{\infty} E \, d\lambda \text{ in watts per unit solid angle.}$$

$$\text{Total Emission} = \int_s d\omega \int_0^{\infty} E \, d\lambda \text{ in watts.}$$

$$\text{Specific Illumination} = \int_0^{\infty} L \, d\lambda \text{ in lumens per unit solid angle.}$$

$$\text{Total Illumination} = \int_s d\omega \int_0^{\infty} L \, d\lambda \text{ in lumens.}$$

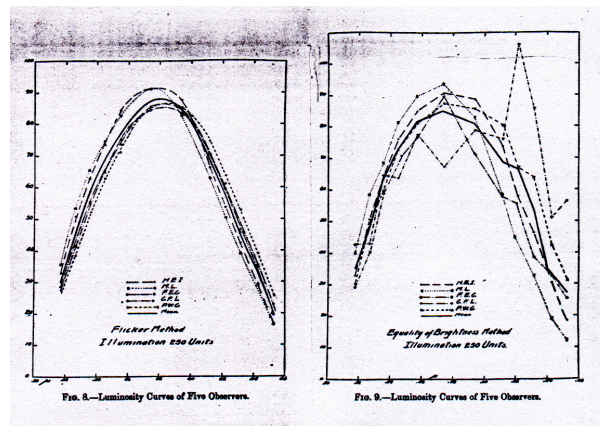
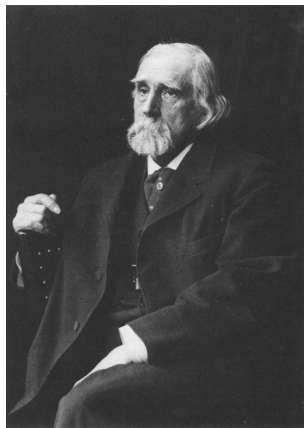
$$\text{And since} \quad L = E V,$$

$$\text{Luminous efficiency} = \frac{\int_0^{\infty} E V \, d\lambda}{\int_0^{\infty} E \, d\lambda}$$

Nutting proposed a “purely physical definition of light” and established the concept of a visibility function, derived from basic vision experiments, used to assess the visual effect of the radiant power of a source, and the notion that the sum of the wavelength-by-wavelength visually weighted radiant power defines the lumens of the source.

Flicker photometry and better data for the visibility function

Late in 19th century it had become clear that traditional visual photometry was very unreliable when assessing light of very different colors. This was called “heterochromatic photometry.” Attempts to use it to establish a visibility function failed to provide useful data as differences between observers and repeatability for even a single observer were very poor. In 1893 Ogden Rood extended to photometry a technique he had developed for the study of color. Rood noted that if two fields that differ in brightness *and* color are made to alternate, a flicker in both color and brightness results. At a low frequency of alternation, the differing colors blend into one and the color aspect of the flicker disappears, but the brightness flicker persists to a higher frequency of alternation unless the brightnesses are made equal. In 1895 this idea was incorporated into experimental photometers that produced very consistent data. Instead of viewing both sides of a split screen—as in the equality of brightness method—the flicker photometer gave the observer superimposed, alternating views of two screens, one lighted by the standard source and one lighted by the test source. The frequency of alternation was several cycles per second. At this frequency, the two colors blended into one, but the field appeared to flicker in brightness. The observer made an adjustment (changing distance or aperture size) until the brightness flicker ceased. “Flicker photometry” became the method of choice to compare lights of differing color and to establish visibility functions.



Ogden Rood (1831-1902) and data obtained by his method of flicker. The plot on the left shows data from 5 observers for the determination of a photopic visibility function using flicker photometry. The plot on the right shows the data for the same observers using simple brightness matching photometry.

By 1910, fairly reliable data was available for photopic visibility functions. But there were still some discrepancies between data sets from different workers in different countries. It became clear that if international agreement was to be obtained, a new large measurement project would need to be undertaken to produce a data set that met international standards and upon which the international community could agree and approve for global use. In 1923 this task was undertaken by K.S. Gibson and E.P.T. Tyndall at the National Bureau of Standards in Washington, D.C. Their data and the procedures used to obtain it proved to satisfy the international community and Gibson’s and Tyndall’s recommendation for a standard data set to define a photopic visibility function was adopted by the CIE in 1924.

Learn More

Here are some references to original papers or excellent summary articles on the material discussed here. These papers and articles can be found on-line.

***Physiological Optics at the National Bureau of Standards* by Deane B. Judd. *Applied Optics*. Vol 6. No. 1. January 1967.** Here is an excellent summary of the work done at NBS over the course of more than 40 years. It contains references to more than 120 articles.

***The Luminous Equivalent of Radiation* by P.G. Nutting. *Physical Review*. Vol 24. No. 2. 1907.** The classic paper of Perley G. Nutting that introduced and outlined the ideas that became the modern lumen.

***On the Photometry of Differently Colored Lights and the "Flicker" Photometer* by F.P. Whitman. *Physical Review*. Vol. 3. No. 4. January-February 1896.** Here is the introduction of flicker photometry.

***Energy and Vision* by Samuel P. Langley. *American Journal of Science*. Vol. 36. 1888.** The first clear attempt to measure the relative visual effects of radiant power at different wavelengths. Langley's data was used by Nutting in his original proposal for the lumen.