Fracturing the Fraction:

Efficacy in Applied Lighting

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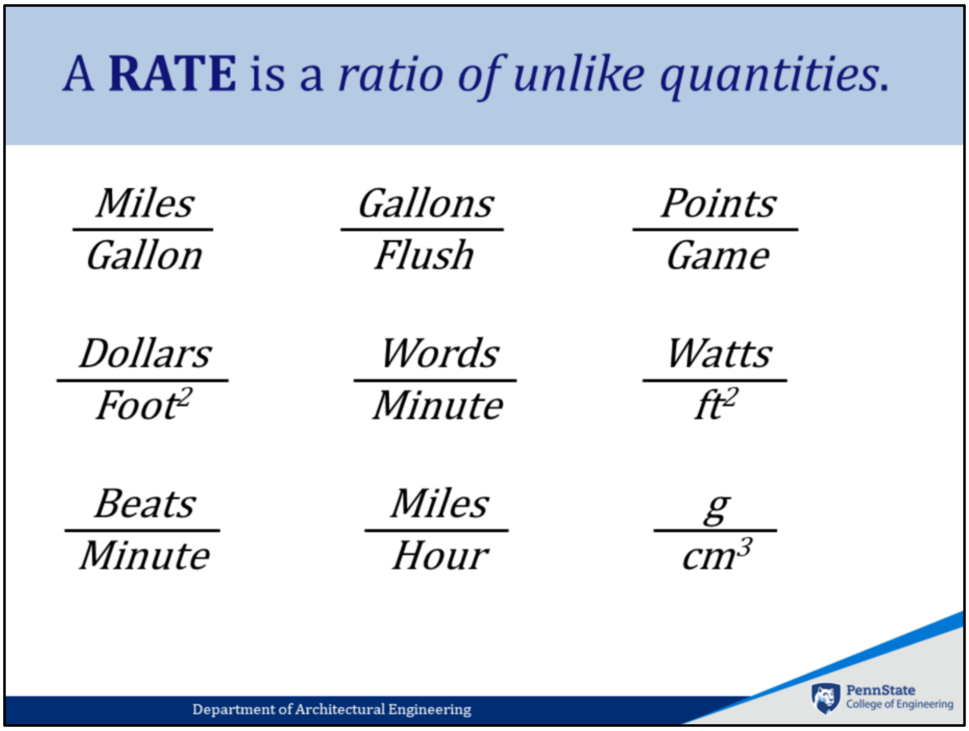
A **RATE** is a *ratio of unlike quantities.*
$\frac{Miles}{Gallon}$ $\frac{Gallons}{Flush}$ $\frac{Points}{Game}$
$\frac{Dollars}{Foot^2}$ $\frac{Words}{Minute}$ $\frac{Watts}{ft^2}$
$\frac{Beats}{Minute}$ $\frac{Miles}{Hour}$ $\frac{g}{cm^3}$
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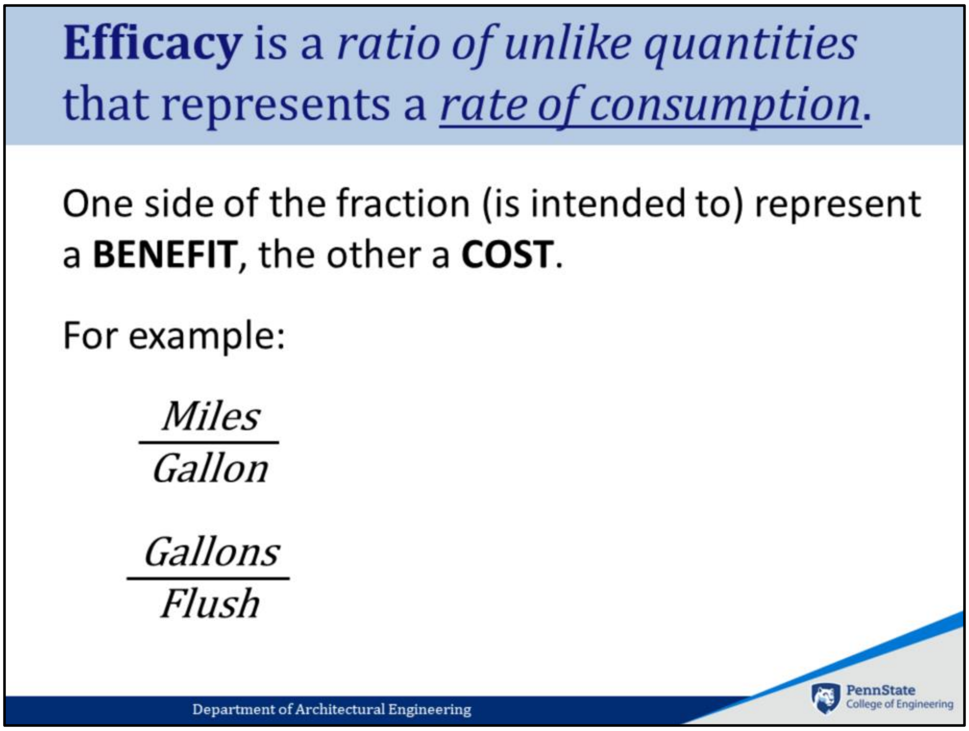
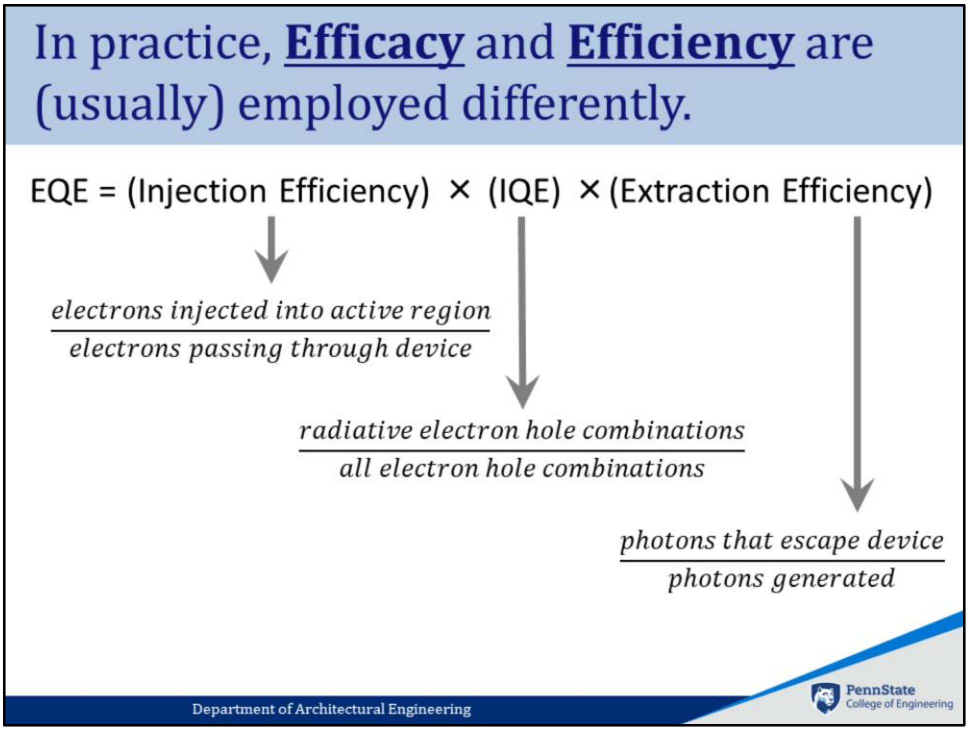


Efficacy represents the ability to produce a desired result. It is a ratio of unlike quantities, where one side of the fraction represents the “benefit”, and the other side of the fraction represents the “cost”.

In miles-per-gallon, the benefit is the number of miles driven, and the cost is the gallons consumed. In gallons per flush, the benefit is “the flush” (removal of waste), and the cost is gallons consumed.

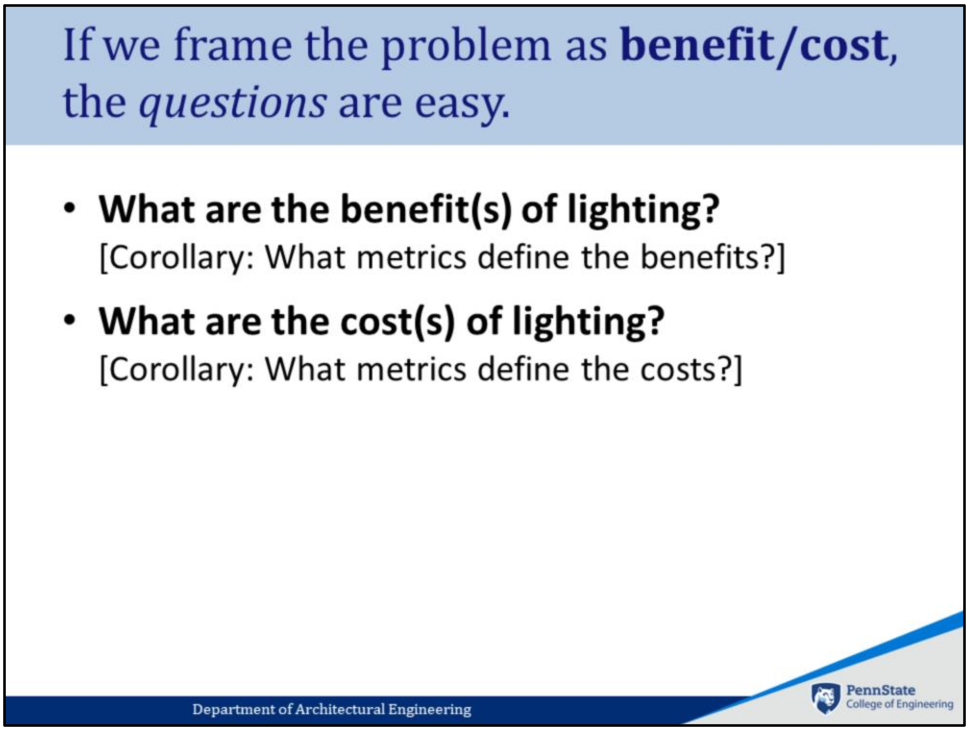
Parenthetically, I say “is intended to”, because the measures (or metrics) that are used in the numerator and denominator are highly relevant. A minivan may have less miles/gallon than a compact car, but if the minivan is used for a family of six, then the (people)(miles)/gallon may look pretty good. Thus, car-pooling and public transportation have the potential to be more effective than incremental improvements in miles/gallon. Gallons per flush begs the question of what gallons? If graywater is used—such as water redirected from sinks and showers—then the number of gallons per flush may not be relevant.

The general point, and a key aspect of my talk, is to probe the quantities and metrics on each side of the fraction. Is *lumens* an appropriate proxy for *benefit*? Is *watts* an appropriate proxy for *cost*?

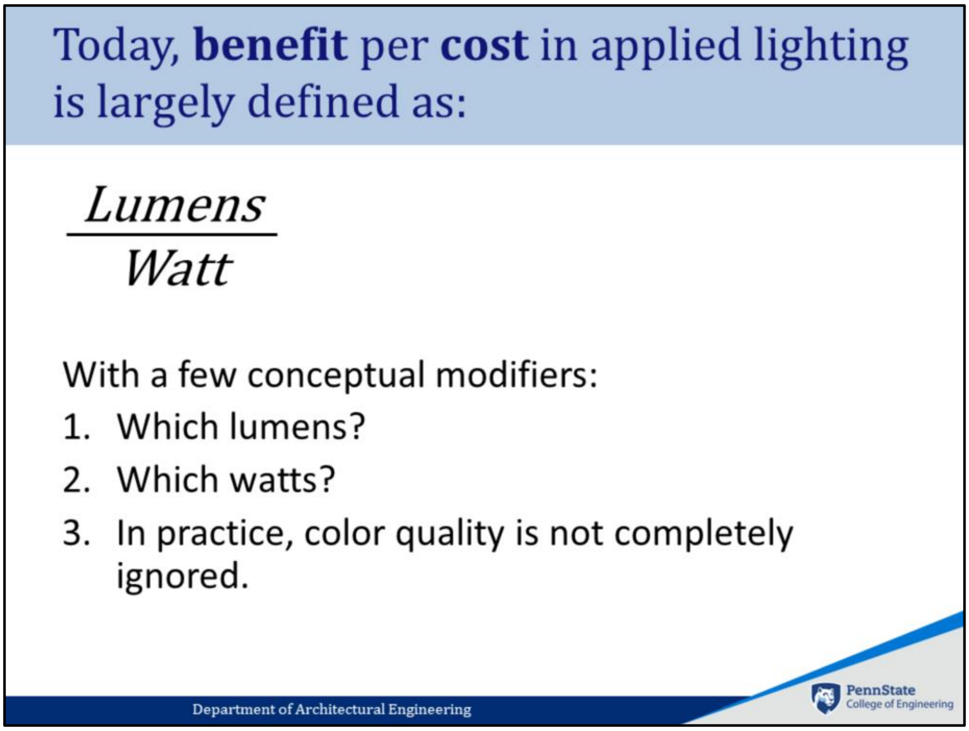


Efficiency is presented as a product of ratios of like quantities. This equation illustrates components of external quantum efficiency for LEDs.

It's possible to start with efficacy, and multiply by an efficiency, yielding a more specific version of efficacy. For example, consider luminaire efficacy in lumens/watt, that is, the number of lumens exiting the luminaire divided by the input watts to the luminaire. To get to application efficacy, we multiply by the ratio of the lumens striking the target plane, divided by the lumens exiting the luminaire, which is an efficiency (that is, the ratio expressing how efficiently lumens are delivered to the target plane). Thus, (efficacy) x (efficiency) is a legitimate operation. This also underscores why "efficacy" should also have an appropriate modifier, as in "luminaire efficacy" or "application efficacy".

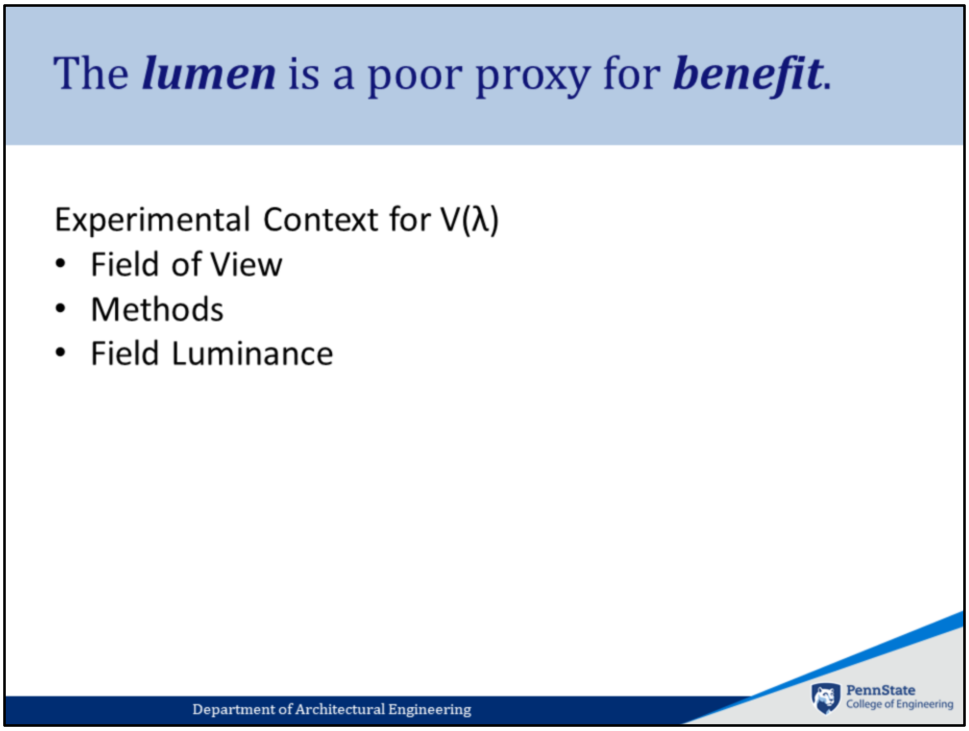


I'm arguing the need to thoughtfully define the numerator and denominator. Just because the question is easy, doesn't mean the answer is.

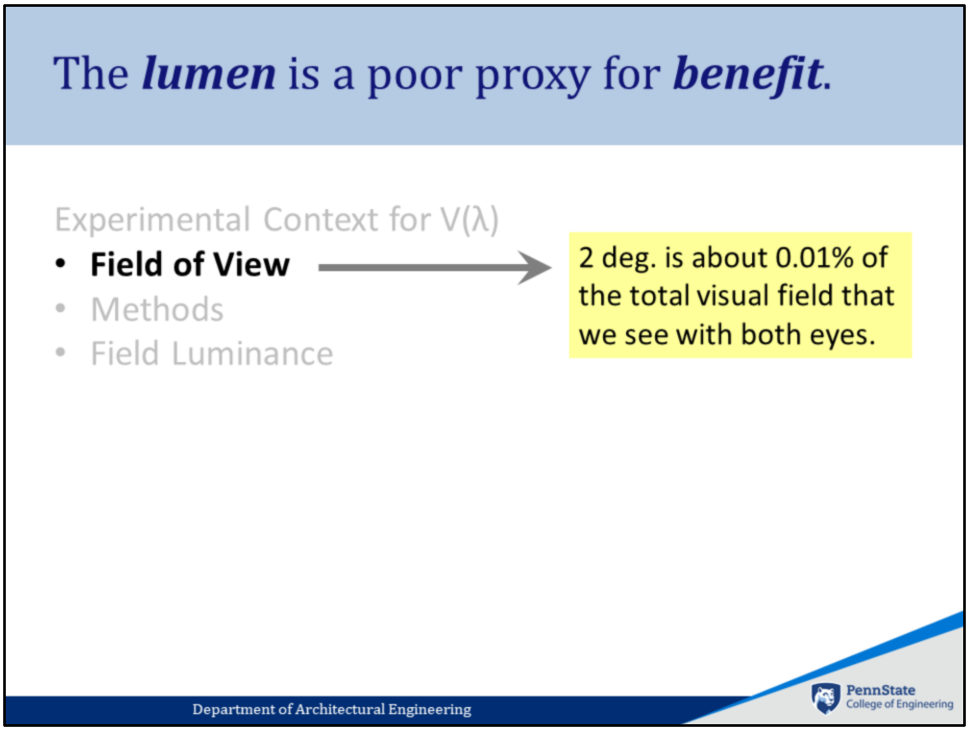


Regarding which lumens and which watts, we can consider luminous efficacy (lamp), system efficacy (lamp + ballast), luminaire efficacy, and system efficacy. These vary in their consideration of where the lumens are delivered, and whether or not auxiliary gear is considered as a consumer of watts. Luminous efficacy of radiation (LER) is a ration of lumens to radiated optical watts, where both are within the range of 360 to 830 nm.

An owner or designer will have further considerations, such as lifetime, initial cost, dimmabilty, source size and shape, and so on. By way of analogy, we don’t judge the quality of a cake by it’s ingredients. It’s not how much flour, or eggs, or sugar, or flavoring, but the relative proportions of those ingredients that creates a desirable flavor. Similarly, the benefits of lighting minimally include efficacy (in one or more of it’s possibly forms), visibility, color rendering, psychological reinforcement, and circadian stimulation. However, while efficacy is clearly important, it is not generally a top criterion for applied lighting design. Efficacy has to be good enough, but a lower-efficacy solution may meet other design criteria that are deemed more important.

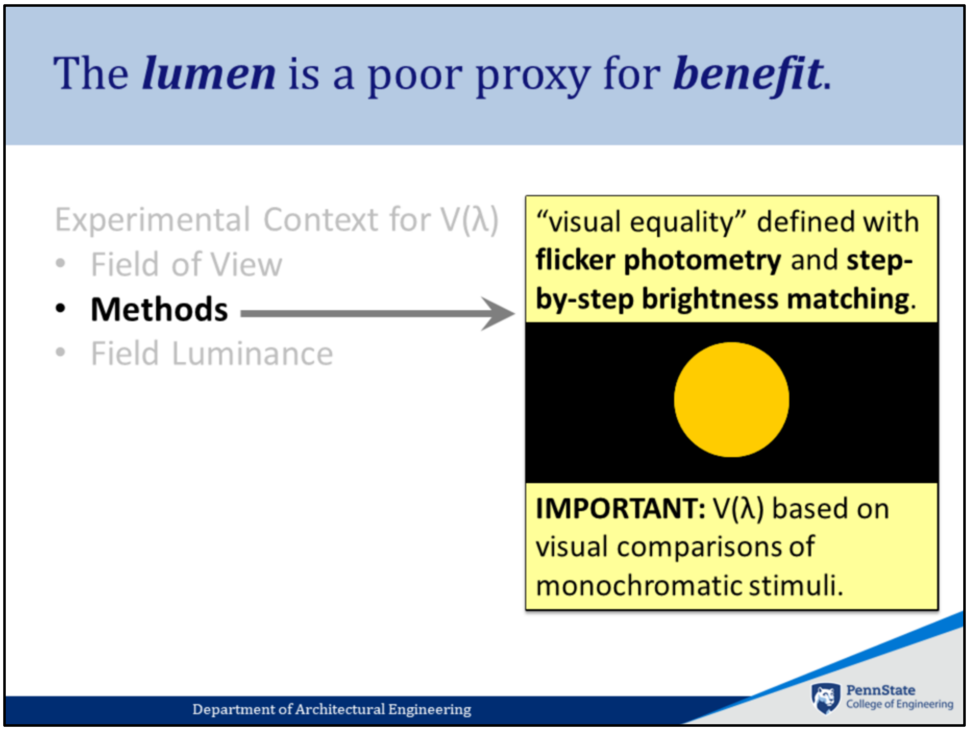


I’m not going to provide an exhaustive rationale, but will instead provide evidence for my assertion by explaining three aspects of the lumen’s experimental context.

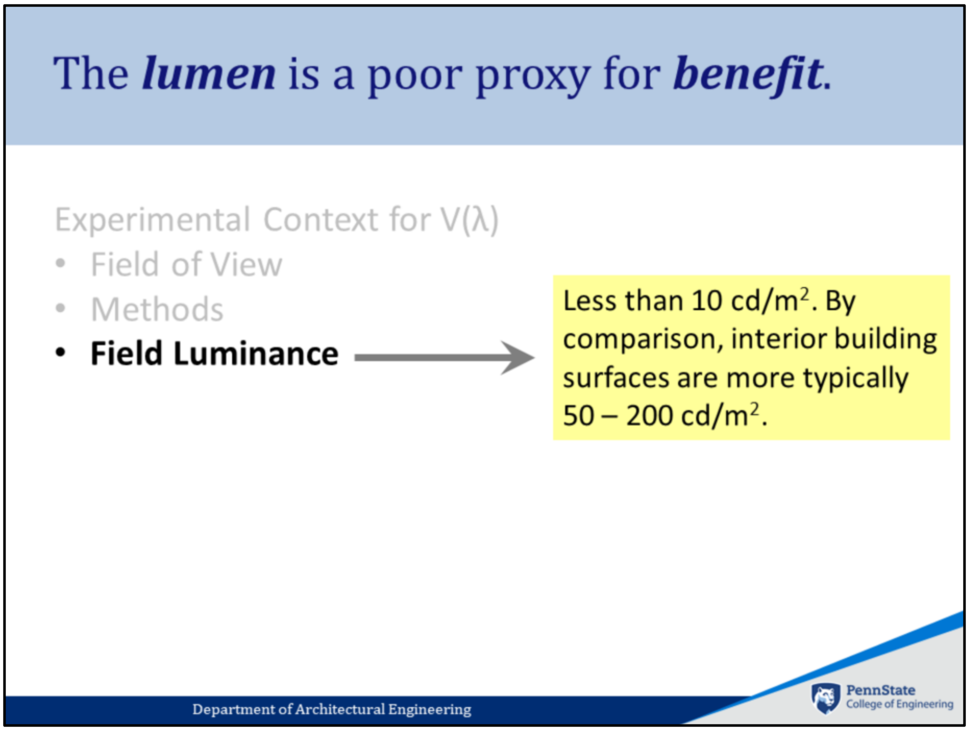


The experiments used to derive the V(λ) function used a field of view between 2 and 3 degrees. A 2 field of view covers only about one hundredth of one percent of the total visual field that we see with both eyes. 2 degrees approximately corresponds to the angle subtended by a quarter US dollar viewed at arms length. This field size is not representative of vision in building interiors, where we use the full field of view. The rationale for restricting the field of view to these small sizes is that light entering the eyes under these conditions will only strike the fovea. The fovea is the central portion of the retina; it is densely packed with L and M cone photoreceptors and contains no S cone or rod photoreceptors. By design, the V(λ) function attempts to segregate the L and M cones and characterize their spectral sensitivity in isolation.

Traditionally, the cones have been thought to provide color vision and resolution of detail. Rods have traditionally been thought to be associated with night vision. Contemporary research suggests that this view is incorrect, and that the rods contribute to visual processes at typical interior lighting levels. This result suggests that it is wrong to apply a photometric system based on small field sizes to full field viewing.

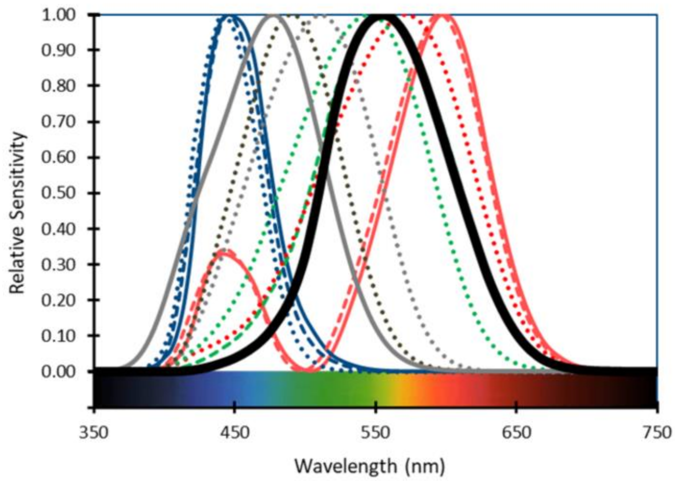


The psychophysical testing procedures used to determine the V(λ) function involved flicker photometry and a step-by step method of brightness matching. A problem arises in that spectral weighting functions depend upon the method of assessment. With flicker photometry, the visual target temporally alternates between a reference light and a chromatic light. The subject is asked to adjust the quantity of a chromatic light until minimum flicker is obtained. With brightness matching, the visual target is a bipartite field. The subject is asked to adjust one of the fields to match the other on some psychophysical attribute (e.g., brightness, color or both). In the step-by-step method of brightness matching, the wavelengths in the two fields are selected to be only a few nanometers apart. In this way, the colors look nearly alike and the subject can make brightness matches without large color differences complicating the task. Flicker photometry and step-by-step brightness matching were used to determine the V(λ) function in part because these methods obey the additivity assumption. The human visual system does not conform to additivity under more complex stimuli, such as polychromatic (white) light that is used for everyday lighting. Flicker photometry and step-by-step brightness matching are inspired techniques that have deepened our understanding of the human visual system, but they do not faithfully characterize vision in real-world conditions. Since additivity fails under normal viewing conditions, flicker photometry and step-by-step brightness matching are inappropriate techniques for determining a spectral weighting function applicable to vision in building interiors.



The field luminances used in the derivation of the V(λ) function were often less than 10 cd·m^2, which is not representative of building interiors. The field luminance in building interiors is more typically in the range of 50 to 200 cd·m^2. Since quantities derived from the V(λ) function are used to assess lighting for buildings, the V(λ) function has been extrapolated and applied outside of the experimental context used for its derivation. We know that the visual system responds differently at different light levels.

There are many other ways to characterize optical radiation.

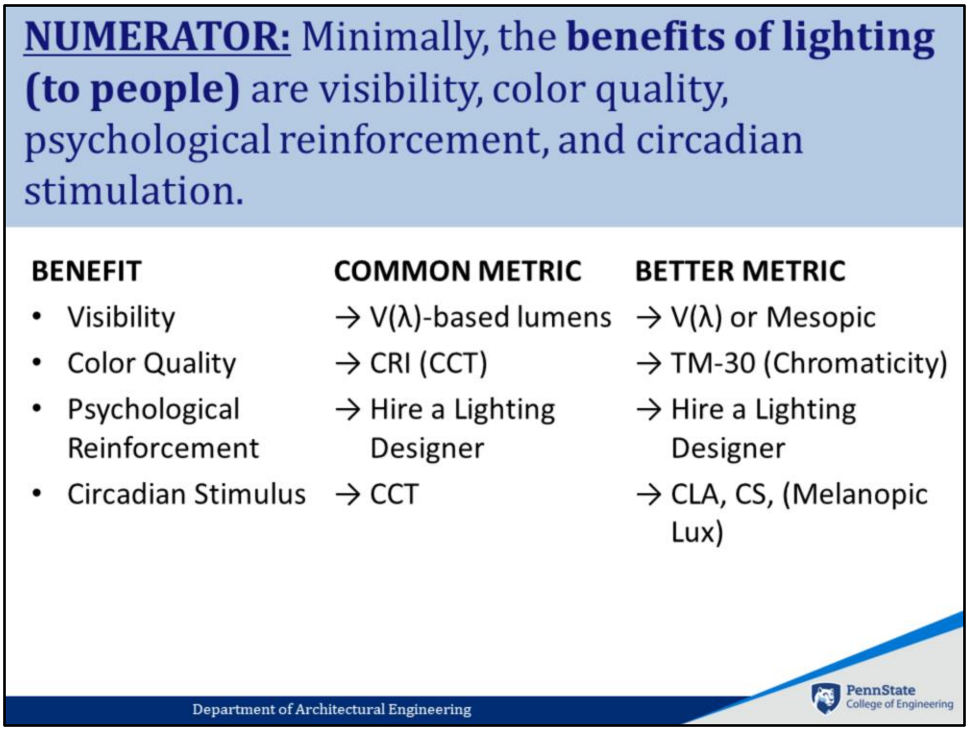


V(λ)

V(λ) and V'(λ)

LC, MC, Rods, Melanopic, SC

10 and 2 deg CMFs



The benefits of lighting include pre-requisites not listed above, especially related to health. For example, the product or application should not result in flicker and should not cause and undue photobiological safety risk (e.g., via the blue-light-hazard).

DENOMINATOR: Using the ***watt*** as a proxy for ***cost*** is imperfect.

- Time *should* be considered, which implies efficacy characterization at the application level, rather than product level.
- Might it be better to account for the source of energy, for example by using CO_2 emissions?
- Should LCA be a part of a product's efficacy?

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I note that this workshop is sponsored by the Department of ENERGY, not the Department of POWER. Lumens (or other lighting benefits) can be generated with minimal environmental impact, or in a manner than is resource intensive. More generally, all aspects of a life cycle analysis (LCA) are relevant to a comprehensive consideration of the costs, these include resource, air, soil, and water impacts.

A family of efficacies could cover common situations.

The below are proposed only as a thought exercise!

$$\frac{Lumen\ Hours}{Lifetime\ Environmental\ Cost}$$

$$\frac{Lumens}{Ton\ CO_2}$$

$$\frac{Circadian\ Stimulus}{Watt}$$

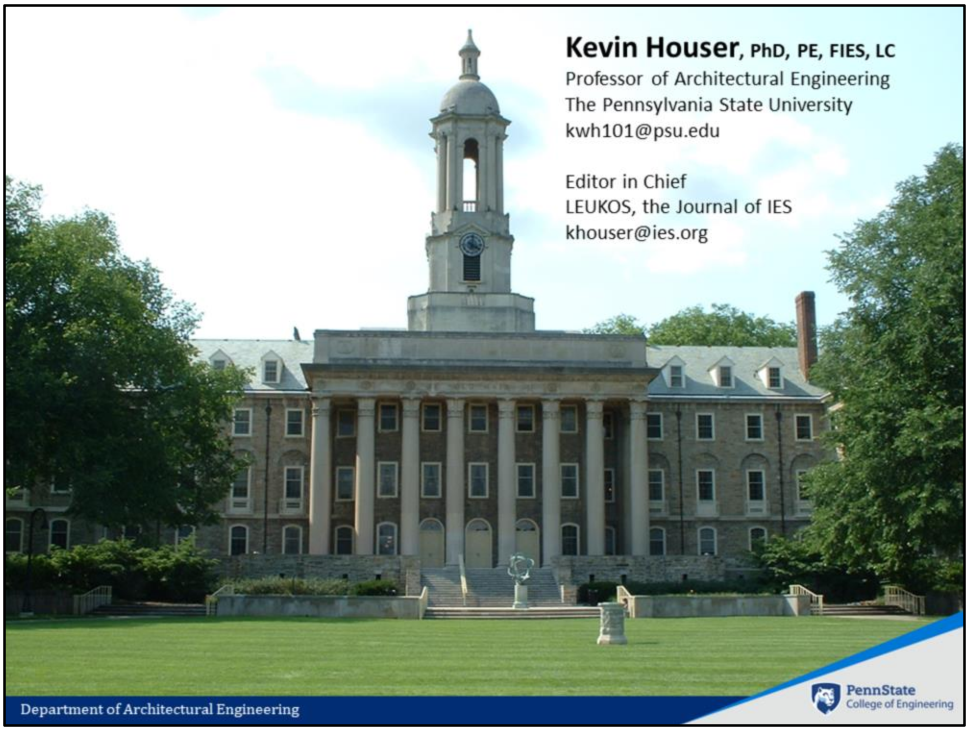
$$\frac{Lumens}{Dollar}$$

$$\frac{Color\ Quality}{Ton\ CO_2}$$

$$\frac{PAR}{Watt}$$

DOE and lighting manufacturer's have done an exceptionally good job of advancing the technical aspects of light generation. The advances in LPW have been impressive and important. However, 'till now, there's been little reconceptualization of the basic problem of efficiency and efficacy. Should we be chasing lumens? Or would it be better to characterize optical radiation using different metrics? As a benefit, lumens is too blunt. I hope, moving forward, DOE will invest in other benefits—not because it's altruistic, but because it will lead to better products of lower energy use. It makes sense to roadmap LED product development to end-user needs.

Human-factors research need not and should not be divorced from product development. Indeed, the most energy-effective products will be responsive to human needs. It makes good sense for the environment and people to create products with the greatest human benefit, with the smallest energy, environmental, and financial costs.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