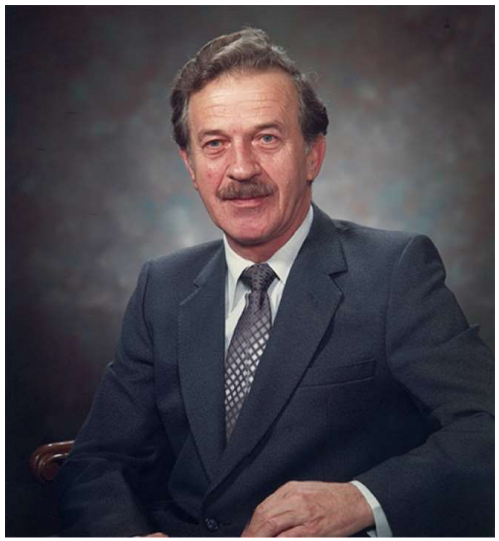


Physicist and Professor Franc Grum

Metric Follies
or
The Folly of Metrics

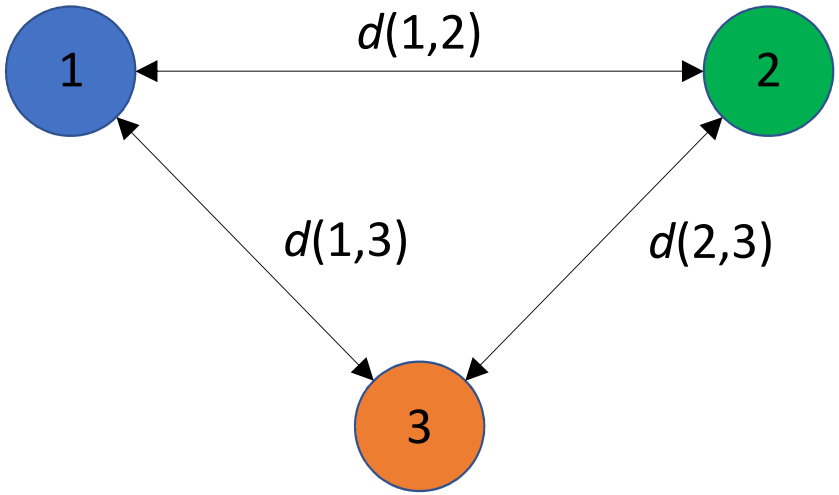
Franc Grum Memorial Lecture

Ian Ashdown, P. Eng. (Ret.), FIES
Senior Scientist
SunTracker Technologies Ltd.

Metric Definition

- *metric, n.*

  A function that defines a concept of distance between any two members of the set, satisfying four specific conditions:



$$d(x, y) \geq 0$$
$$d(x, y) = 0 \rightarrow x = y$$
$$d(x, y) = d(y, x)$$
$$d(x, y) \leq d(x, z) + d(z, y)$$

Metric Examples (Radiometry)

Metric	Example Unit
Length	meter (m)
Area	square meter (m^2)
Solid angle	steradian (sr)
Radiant flux	watt (W)
Radiant energy	joule (J)
Radiant intensity	W / sr
Irradiance	W / m^2
Radiance	W / sr-m^2
Spectral radiant flux	W / nm

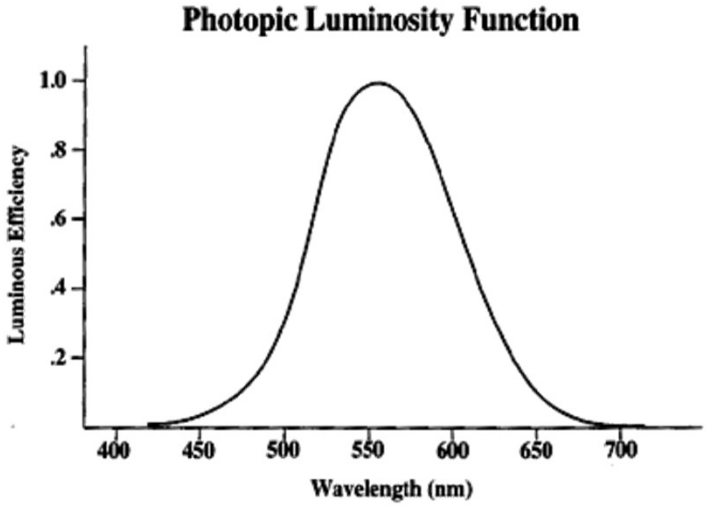
- Physically-based
- SI units

Metric Examples (Photometry)

Metric	Example Unit
Luminous flux	lumen (lm)
Luminous intensity	candela (lm / sr)
Illuminance	lm / m^2
Luminous exitance	lm / m^2
Luminance	cd / sr-m^2

- V(λ) luminous efficiency function based on photopic vision of CIE Standard Observer

- Psychophysically-based
- CIE 1924 V(λ)
- SI units

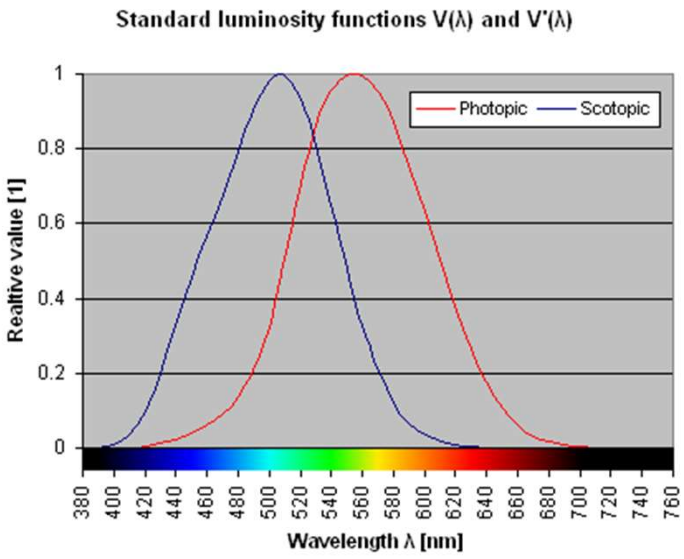


Metric Examples (Photometry)

Metric	Example Unit
Luminous flux	lumen (lm)
Luminous intensity	candela (lm / sr)
Illuminance	lm / m^2
Luminous exitance	lm / m^2
Luminance	cd / sr-m^2
Scotopic luminous flux	scotopic lumen (lm)

- V'(λ) luminous efficiency function based on scotopic vision of CIE Standard Observer
- Luminous efficiency K_m = 683 lm/W
- Scotopic luminous efficiency K'_m = 1700 lm/W

- Psychophysically-based
- CIE 1924 V(λ)
- CIE 1951 V'(λ)



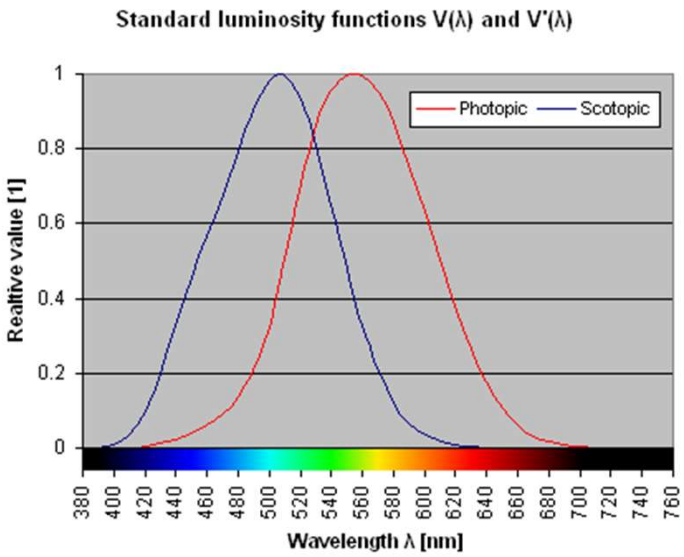
Metric Examples (Photometry)

Metric	Example Unit
Luminous flux	lumen (lm)
Luminous intensity	candela (lm / sr)
Illuminance	lm / m^2
Luminous exitance	lm / m^2
Luminance	cd / sr-m^2
Scotopic luminous flux	scotopic lumen (lm)
Mesopic luminous flux	mesopic lumen (lm)

- Valid between *about* 0.034 and 3.4 cd/m^2

  CIE 191:2010, Recommended System for Mesopic Photometry Based on Visual Performance

- Psychophysically-based
- CIE 1924 V(λ)
- CIE 1951 V'(λ)



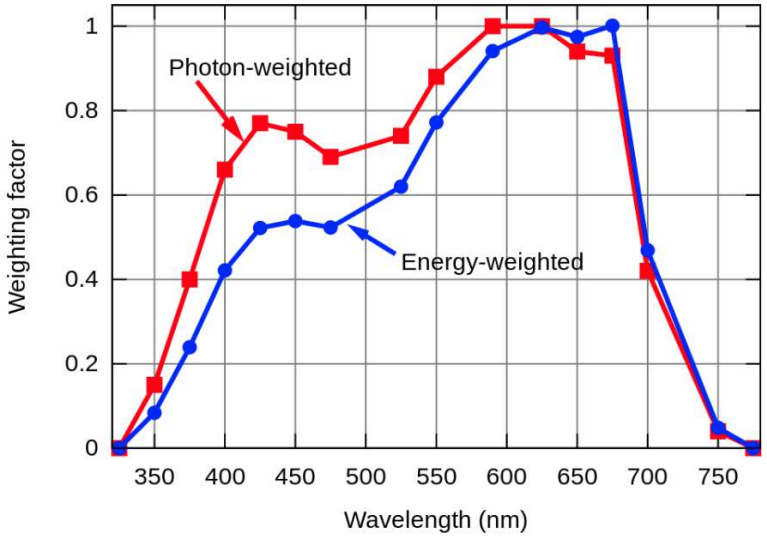
Metric Examples (Horticulture)

Metric	Example Unit
Photon (quantum) flux	μmol / sec
Photon flux density	μmol / m^2-sec
Photon intensity	μmol / sr-sec
Photon efficacy	μmol / J

- Ultraviolet (280 nm – 400 nm)
- Photosynthetic (400 nm – 700 nm)
- Far-red (700 nm – 800 nm)
- Spectral (per unit wavelength)

ANSI/ASABE S640 JUL2017, Quantities and Units of Electromagnetic Radiation for Plants (Photosynthetic Organisms)

- Biologically-based
- Stark-Einstein law



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ANSI/ASABE S640 JUL2017, Quantities and Units of Electromagnetic Radiation for Plants (Photosynthetic Organisms)

- Biologically-based
- Stark-Einstein law
- Blue
- Green
- White
- Red

WHAT ARE THESE "COLORS" ???

Metric Examples (Horticulture)

Metric	Example Unit
Photon (quantum) flux	µmol / sec
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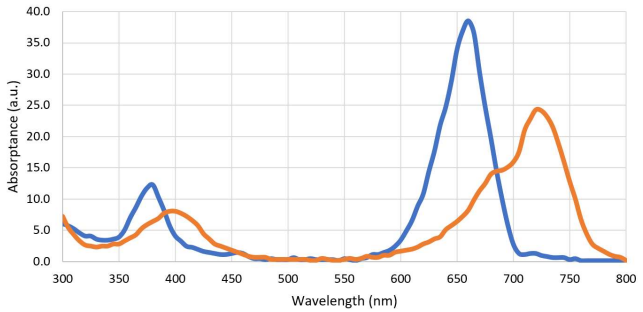
ANSI/ASABE S640 JUL2017, Quantities and Units of Electromagnetic Radiation for Plants (Photosynthetic Organisms)

- Biologically-based
- Stark-Einstein law
- Blue
- Green
- White
- Red
- Red to far-red ratio (R:FR)

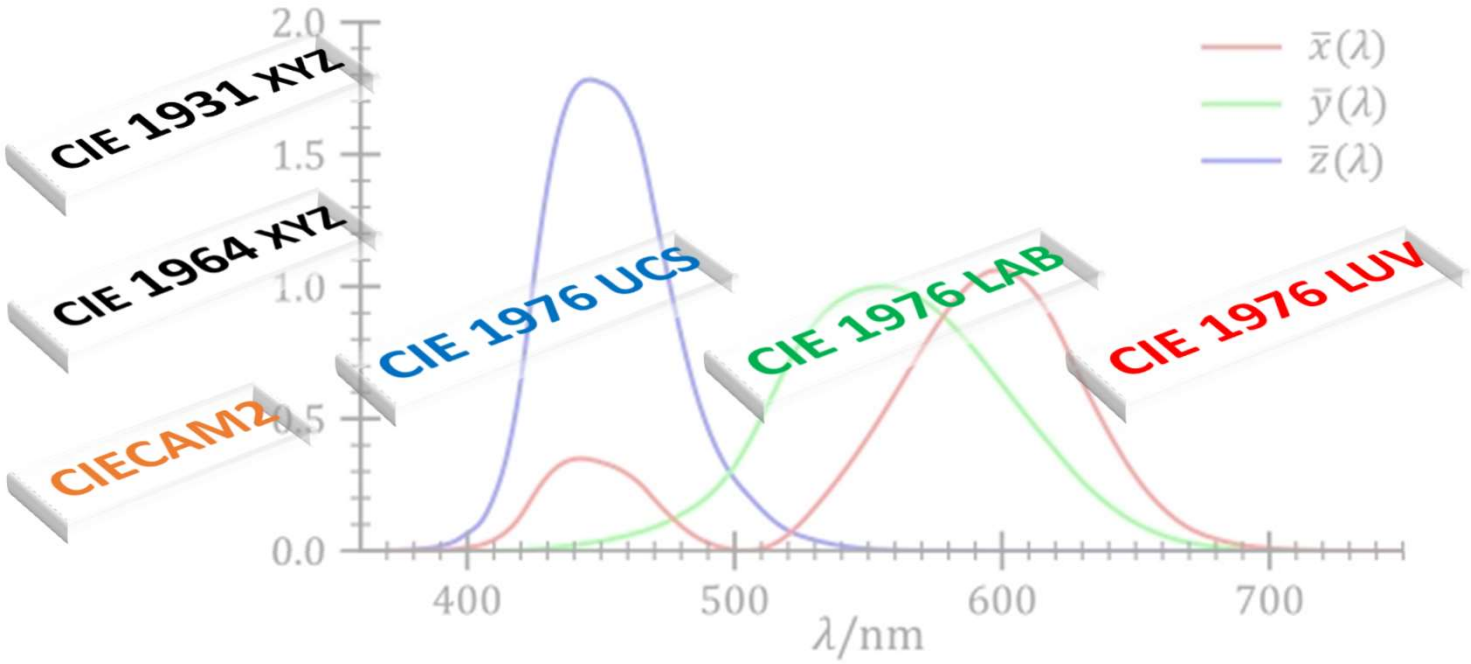


- Blue to red ratio (B:R)

Metric Examples (Colorimetry)

- Psychophysically-based

CIE Standard Colorimetric Observer



CIE 1931 XYZ

CIE 1964 XYZ

CIECAM2

CIE 1976 UCS

CIE 1976 LAB

CIE 1976 LUV

Munsell

Pantone

OSA-UCS

Swedish NCS

RGB CMYK HSL HSV

Metric Examples (Color Differences)

- MacAdam Ellipses
  - Just Noticeable Difference (JND)
  - CIE Illuminant C (average daylight)
  - One trained observer
  - 25 thousand trials

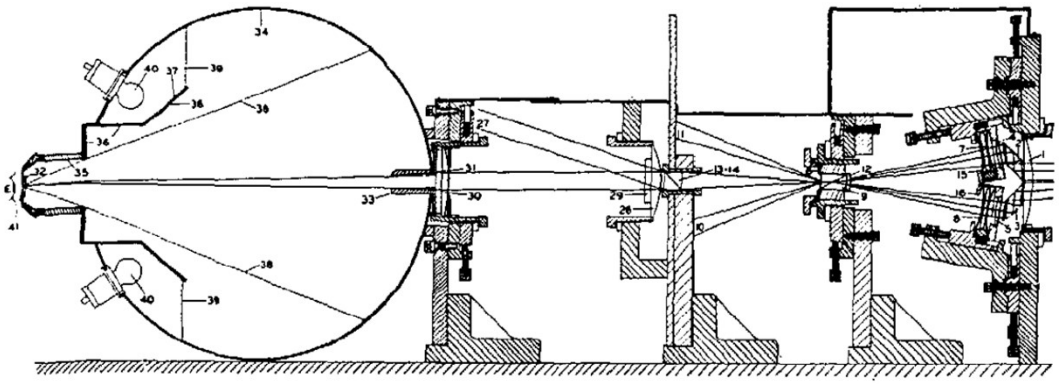
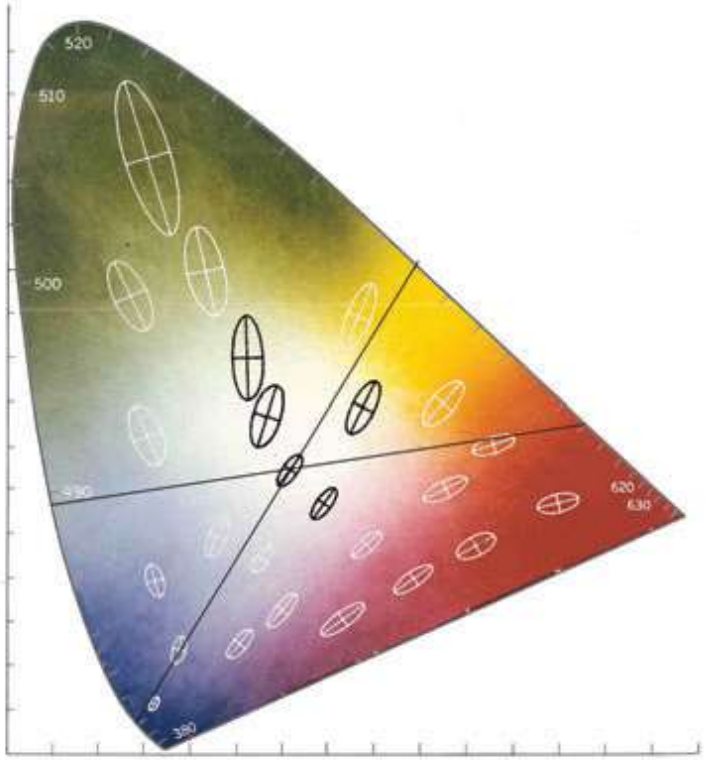


FIG. 2. Vertical cross section of chromaticity discrimination apparatus.

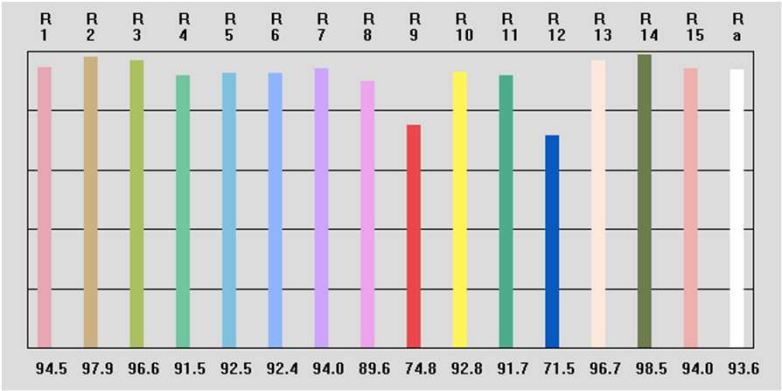
- Psychotically-based

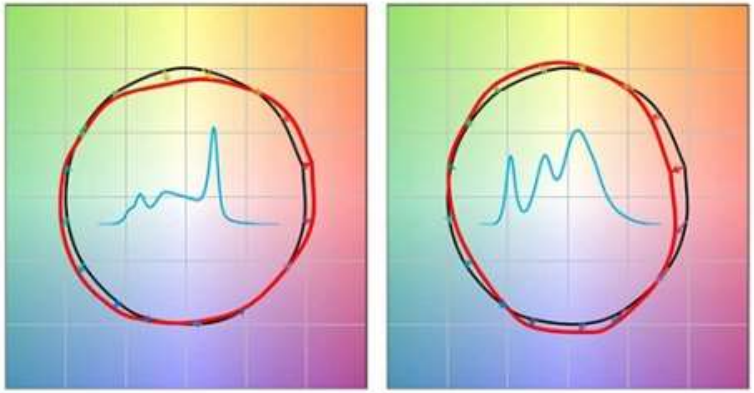


Metric Examples (Color Rendering)

- CIE Colour Rendering Indices (CRI)
  - 14 parameters
- IES TM-30-18 / CIE 224:2017
  - 32 parameters
- Television Lighting Consistency Index (TLCI – EBU 2014)
  - Camera rather than human observer

- Psychophysically-based
- Light sources
- 20+ other proposals





Metric Examples (Indoor Glare)

- CIE Unified Glare Rating (UGR – CIE 117)
  - $UGR = 8log\left[\frac{0.25}{L_b}\sum\frac{L^2\omega}{p^2}\right]$
- Subjective de Boer rating scale

- Psychophysically-based
- View-dependent
- Age-dependent

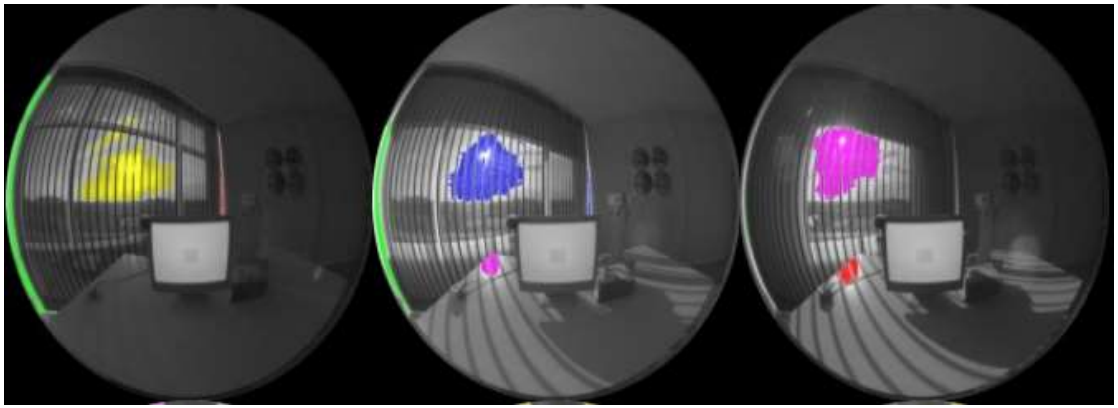
De Boer Glare Rating Scale	
De Boer Glare Index	**Subjective Evaluation Of Glare**
1	Unbearable
2	-
3	Disturbing
4	-
5	Just Admissible
6	-
7	Satisfactory
8	-
9	Just Noticeable

UGR	Discomfort Degree
30	Just intolerable
28	Uncomfortable
25	Just uncomfortable
22	Unacceptable
19	Just unacceptable
16	Perceptible
13	Just perceptible
10	Imperceptible

Metric Examples (Daylight Glare)

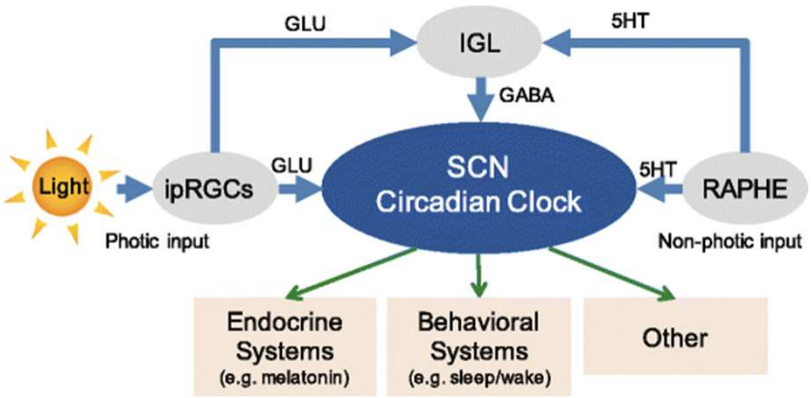
- Daylight Glare Probability (DGP)
  - $DGP = c_1 E_v + c_2 log\left(1 + \sum \frac{L_{s,i}^2 \omega_{s,i}}{E_v^{a_1} P_i^2}\right) + c_3$
  - $DGP_{low} = DGP \frac{e^{(0.024E_v - 4)}}{1 + e^{(0.024E_v - 4)}}$, E_v < 300 lux
- Subjective de Boer rating scale
- Radiance *evalglare* tool has 12 user-defined parameters

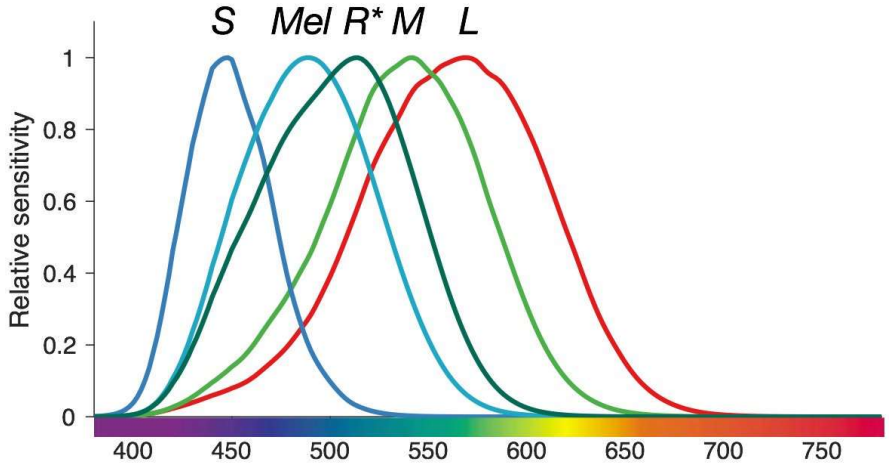
- Psychophysically-based
- View-dependent
- Age-dependent



Metric Examples (Circadian)

- Intrinsically photosensitive retinal ganglion cells (ipRGCs)
- Melanopsin sensitive to blue and green light
- ipRGCs project to suprachiasmatic nucleus (SCN)
- SCN triggers pineal gland to secrete melatonin

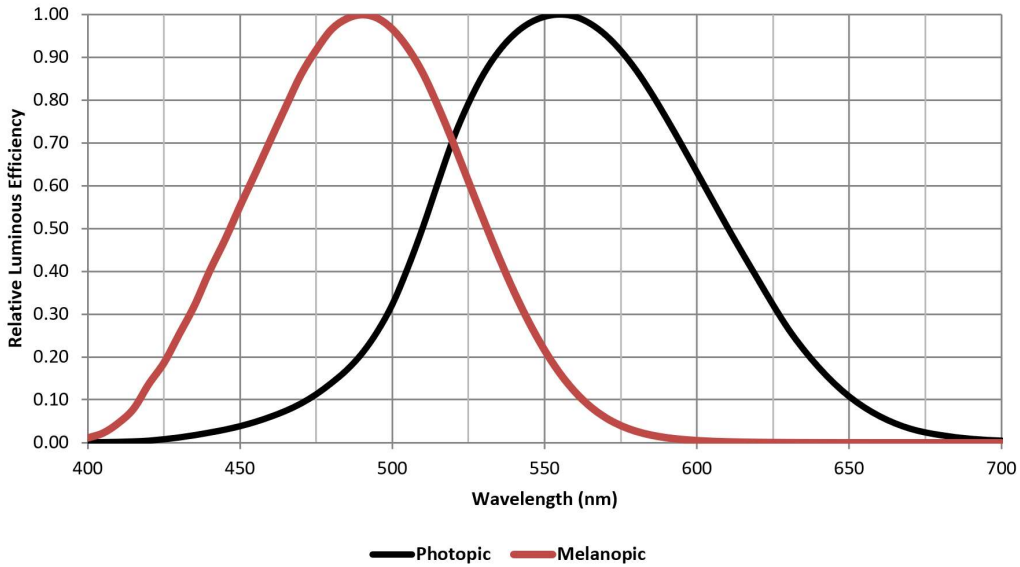




Metric Examples (EML)

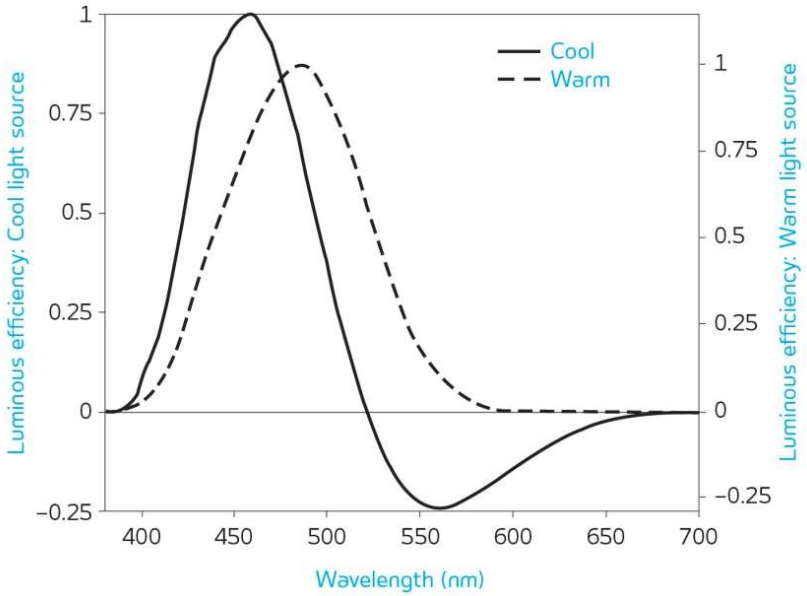
- Equivalent Melanopic Lux (EML)
  - Melanopic weighting
  - Based on light source SPD
  - Scaled by vertical photopic illuminance
- Time-independent
- Age-independent
- WELL Building Standard v2 with 2019 Addenda
  - 200 EML at workstations between 9:00 AM and 1:00 PM

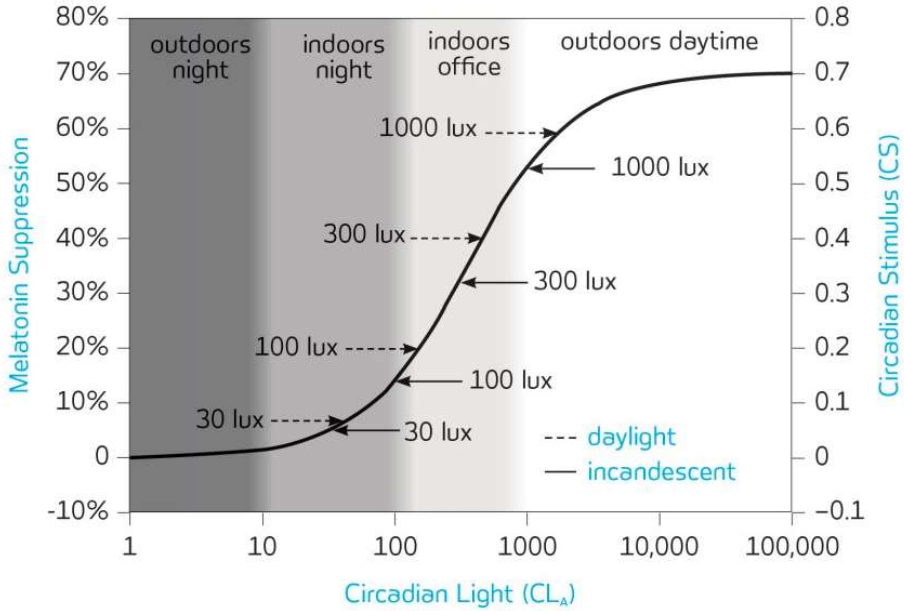
CIE S 026/E:2018, CIE System for Metrology of Optical Radiation for ipRGC-Influenced Response to Light



Metric Examples (CS)

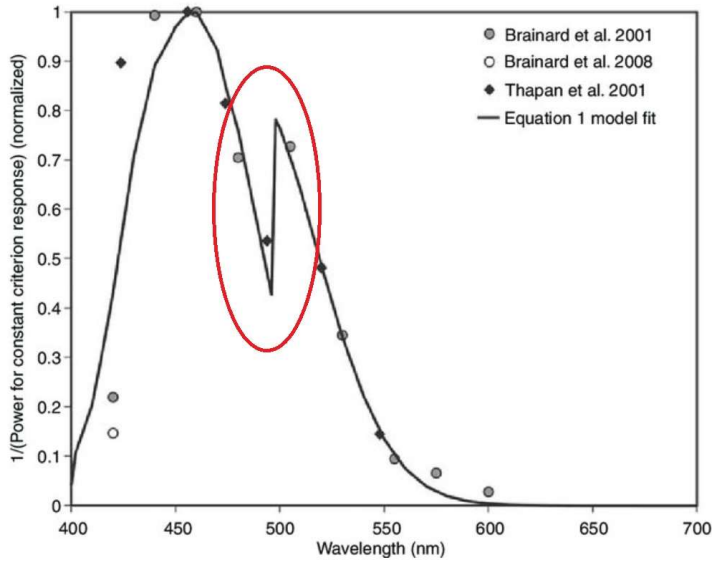
- Circadian Light (CL_A)
- Circadian Stimulus (CS)
- Age-independent





Metric Examples (CS)

$$CL_A = \begin{cases} 1622\left[\int Mc_\lambda E_\lambda \mathrm{d}\lambda + \left(a_{\mathrm{b-y}}\left(\int \frac{S_\lambda}{mp_\lambda} E_\lambda \mathrm{d}\lambda - k\int \frac{V_\lambda}{mp_\lambda} E_\lambda \mathrm{d}\lambda\right) - a_{rod}\left(1 - e^{\frac{-\int V'_\lambda E_\lambda \mathrm{d}\lambda}{\mathrm{RodSat}}}\right)\right)\right] \\ \qquad if \int \frac{S_\lambda}{mp_\lambda} E_\lambda \mathrm{d}\lambda - k\int \frac{V_\lambda}{mp_\lambda} E_\lambda \mathrm{d}\lambda \geq 0 \\ 1622\int Mc_\lambda E_\lambda \mathrm{d}\lambda \quad if \int \frac{S_\lambda}{mp_\lambda} E_\lambda \mathrm{d}\lambda - k\int \frac{V_\lambda}{mp_\lambda} E_\lambda \mathrm{d}\lambda < 0 \end{cases}$$

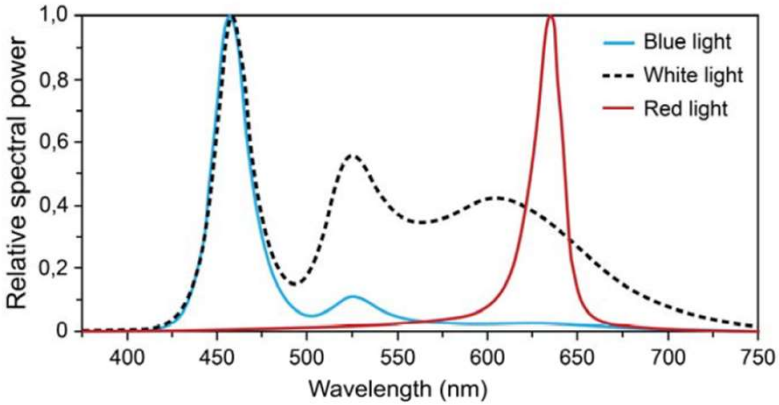


Rea, M., et al. 2012. "Modelling the Spectral Sensitivity of the Human Circadian System," Lighting Research & Technology 44(4):386-396.

- UL RP 24480, Recommended Practice and Design Guideline for Promoting Circadian Entrainment with Light for Day-Active People.

Circadian Lighting Research

- "Non-visual layer of light" … support[s] office occupants' entrainment and alertness during the daytime.
- Subjective measures of sleep, alertness, and vitality/energy
- Objective measure (wrist actigraphy)
- 13-hour daily exposure



Figueiro, M., et al. 2019. "Light, Entrainment, and Alertness: A Case Study in Offices," CIR x046:209, Proc. 29th CIE Session.

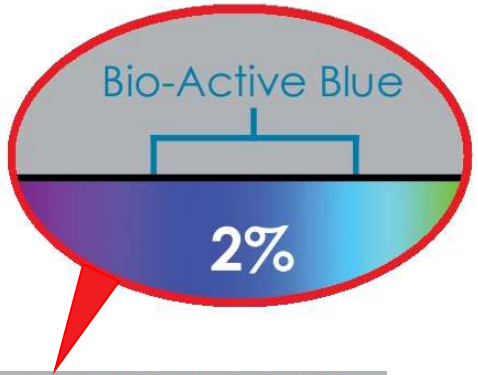
Circadian Lighting Research

- Color changes at dawn and dusk entrain circadian rhythms
- Sample references (of over 150):

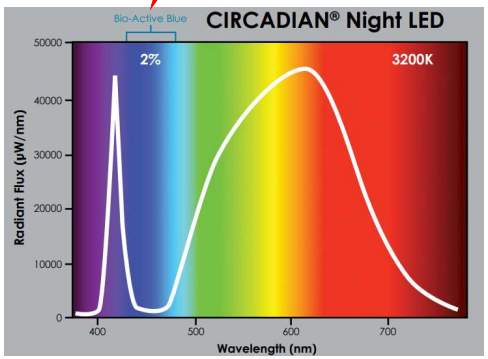
- Dacy, D. M., et al. 2005. "Melanopsin-expressing Ganglion Cells in Primate Retina Signal Color and Irradiance and Project to the LCN," Nature 443:749-754.
- Krüll, F., et al. 1985. "On the Circadian Rhythm of Animals in High Polar Latitudes," Naturwissenschaften 72(4):197-203.
- Patterson, S., et al. 2019. "An S-Cone Amacrine Cell in the Primate Retina Sets the Circadian Clock at Sunrise and Sunset," Investigative Ophthalmology & Visual Science Vol. 60(9):1373.
- Patterson, S., et al. 2019. "Reconciling Color Vision Models with Midget Ganglion Cell Receptive Fields," Frontiers in Neuroscience 13:865.
- Pauers, M. J., et al. 2006. "Diel Changes in the Color of Sunlight and its Potential Role in Entrainment of Circadian Rhythms," Investigative Ophthalmology & Visual Science 47(13):2668.
- Pauers, M., et al. 2012. "Changes in the Colour of Light Cue Circadian Activity," Animal Behaviour 83(5):1143-1151.
- Rani, S., and V. Kumar. 2000. "Phasic Response to the Photoperiodic Clock to Wavelength and Intensity of Light in the Redheaded Bunting, *Emberiza bruniceps*," Physiology & Behavior 69(3):277-283.
- Revell, V. L., et al. 2010. "Predicting Human Nocturnal Nonvisual Responses to Monochromatic and Polychromatic Light with a Melanopsin Photosensitivity Function," Chronobiology International 27(9-10):1762-1777.
- Poul, H. 1999. "Spectral Composition of Light as a Zeitgeber for Birds Living in the High Arctic Summer," Physiology & Behavior 67(3):327-337.
- Snodderly, M., et al. 2017. "Influences of Sunrise and Morning Light on the Visual Behavior of Four Sympatric New World Primates (Ateles, Callicebus, Lagothrix, and Pithecia)," Journal of Vision 17:659.
- Spitschan, M., et al. 2017. "Chromatic Clocks: Color Opponency in Non-image-forming Visual Function," Neuroscience & Biobehavioral Reviews 78:24-33.
- Van Diepen, H. C., et al. 2015. "A Colorful Clock," PLOS Biology 13(5):e1002160.
- Walmsley, L., et al. 2015. "Colour as a Signal for Entraining the Mammalian Clock," PLOS Biology 13(4):e1002127.

UL Verified Mark

- Manufacturer claims employee benefits:
  - 55% reduction in excessive sleepiness
  - 50% increase in alertness
  - 67% reduction in mistakes
  - 28% reduction in obesity



Less than 2% blue light content at night

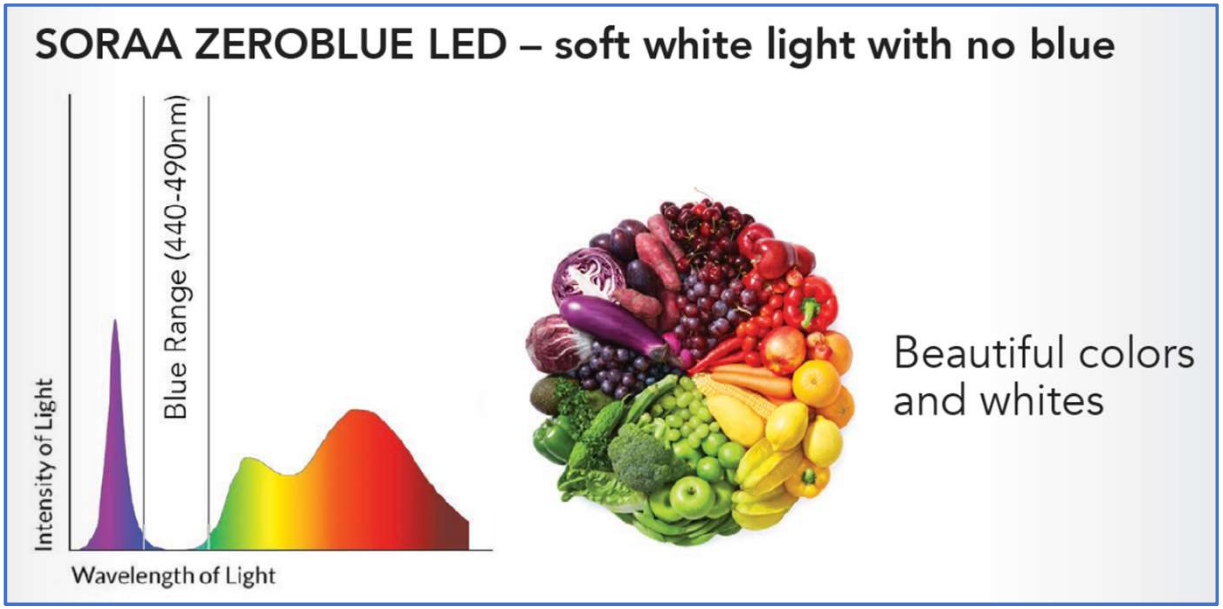


Circadian ZircLight, Inc.

UL Verify ID A097099

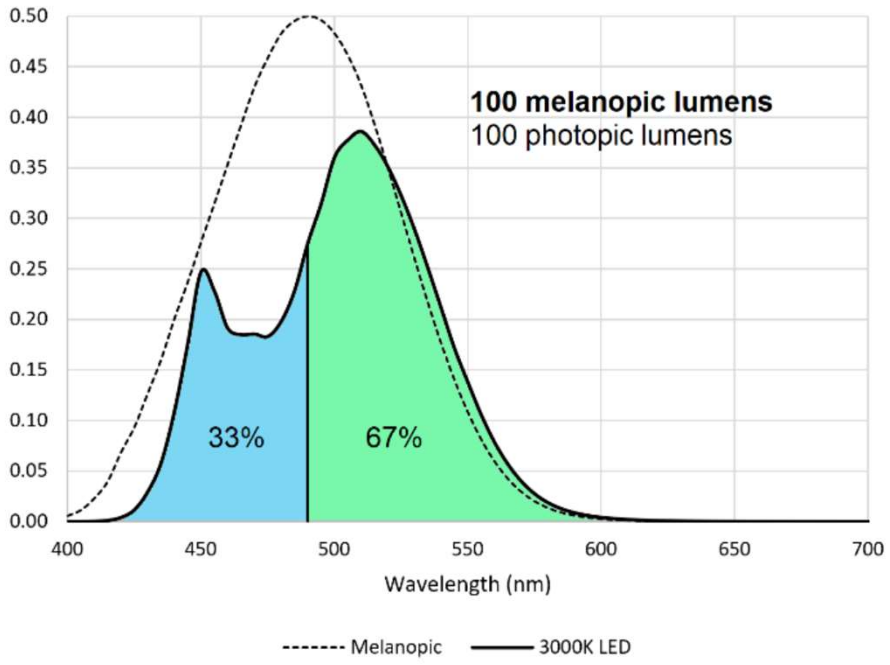
Melanopic Blue

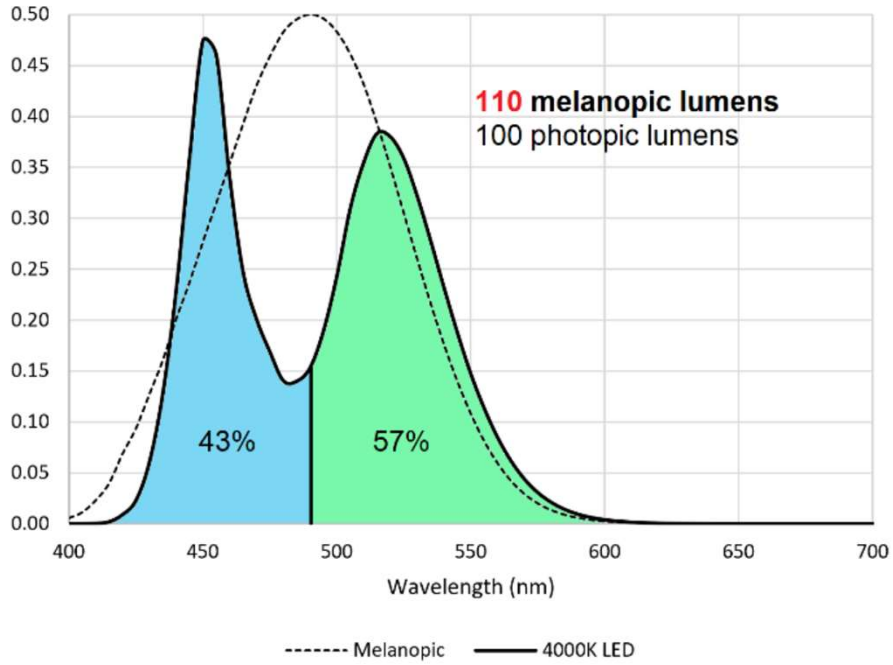
- "Soraa ZEROBLUE™ have no blue content in the spectrum … so there is no overexposure to blue light in the evening which can negatively impact our sleep cycles and longer-term health."



Melanopic Blue

- Melanopic blue and green
- Reduction in melanopic blue versus introduction of actinic radiation

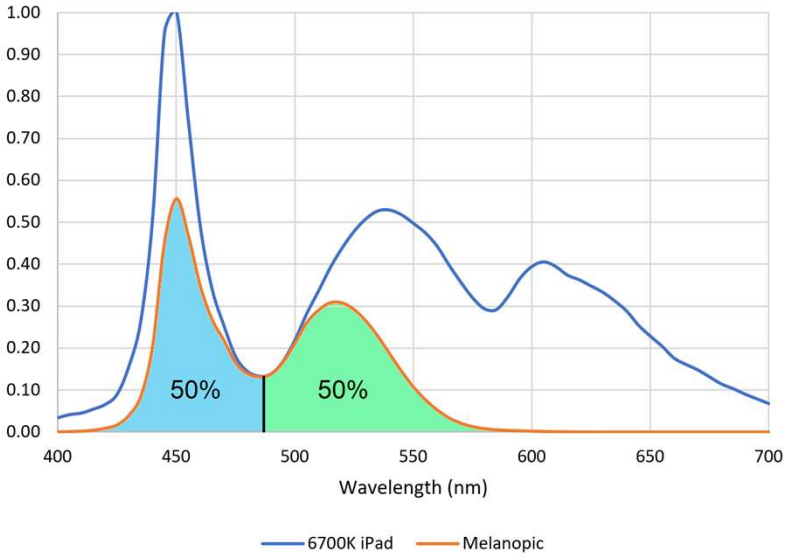




Blue-blocking Strategies

- Blue-blocking glasses

- f.lux computer software

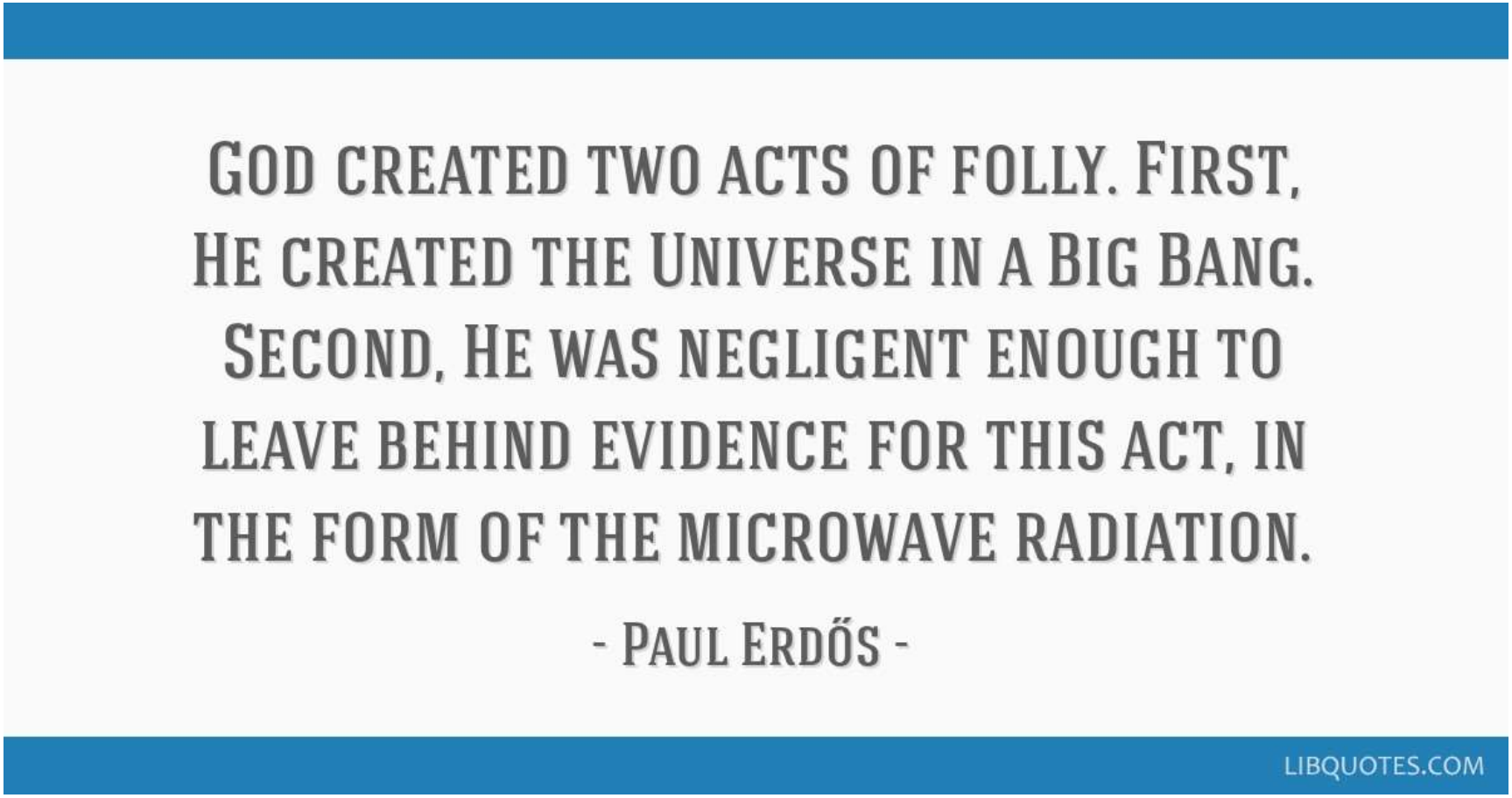


The Folly of Metrics

Metric	Comments
Radiometry	Physical principles
Photometry	CIE Standard Observer
Colorimetry	CIE Standard Observer
Horticulture	Physical principles (apart from ill-defined “colors”)
Color Rendering	Psychophysiology
Visual Glare	Semantic scaling
Circadian	Two competing metrics Open questions regarding usefulness
Blue-blocking	Reduction only due to melanopic green

- Unless they are firmly based on physical principles, adopting lighting metrics for standards can be an act of folly

Thank You


GOD CREATED TWO ACTS OF FOLLY. FIRST,
HE CREATED THE UNIVERSE IN A BIG BANG.
SECOND, HE WAS NEGLIGENT ENOUGH TO
LEAVE BEHIND EVIDENCE FOR THIS ACT, IN
THE FORM OF THE MICROWAVE RADIATION.
- PAUL ERDŐS -
LIBQUOTES.COM