Physics of Light

- Radiometry vs. photometry
- Lambertian surfaces
- Luminance
- Spectral sensitivity of the human eye
- Black body radiation

Radiometry vs. photometry

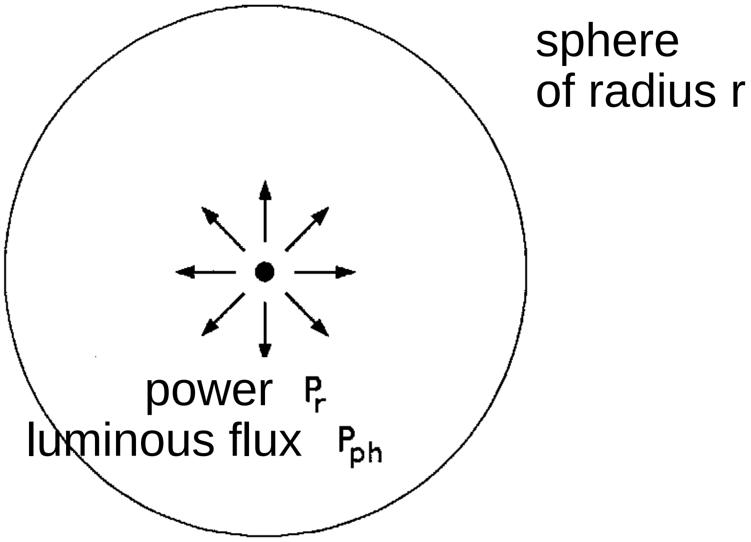
Radiometry:

considers electromagnetic radiation at all wavelengths

Photometry:

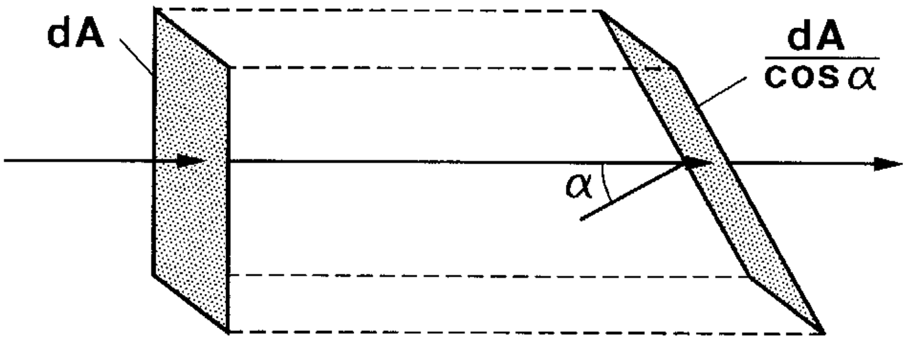
radiometric quantities weighted by the „luminous efficiency curve“ of the human eye

Point Source



Radiometry:	Photometry:
irradiance	illumination
$I_r = \dfrac{P_r}{4\pi r^2}$	$I_{ph} = \dfrac{P_{ph}}{4\pi r^2}$
unit: W/m^2	unit: $\dfrac{lm}{m^2} = lx$

Illumination vs. Incident Angle



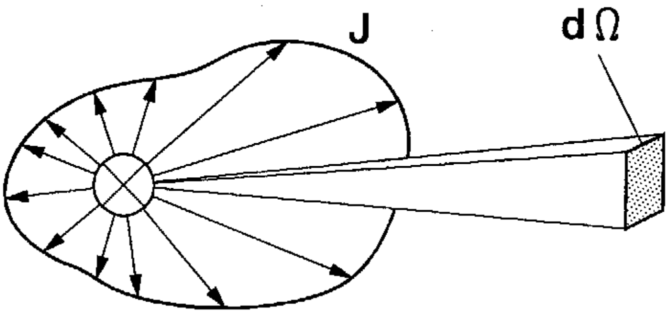
$$I(0) \cdot dA = \frac{I(\alpha) \cdot dA}{\cos\alpha}$$

Radiometry:	Photometry:
irradiance	illumination
$I_r(\alpha) = I_r(0) \cdot \cos\alpha$	$I_{ph}(\alpha) = I_{ph}(0) \cdot \cos\alpha$

Typical Illumination Levels

direct sunlight	100 000 lux
open shade	10 000 lux
overcast/dark day	10 - 100 lux
twilight	1 - 10 lux
full moon	0.1 lux
starlight	0.001 lux
well illuminated office	500 lux
television studio	5000 - 10000 lux

Nonuniform Light Distribution



Sphere around light source of radius r = 1

Area of patch on surface of the sphere: „solid angle“ Ω

Radiometry	Photometry
radiant intensity	luminous intensity
$J_r = \frac{dP_r}{d\Omega}$	$J_{ph} = \frac{dP_{ph}}{d\Omega}$
unit: $\frac{W}{sr}$	unit: $\frac{\ell m}{sr} = cd$

Solid Angle

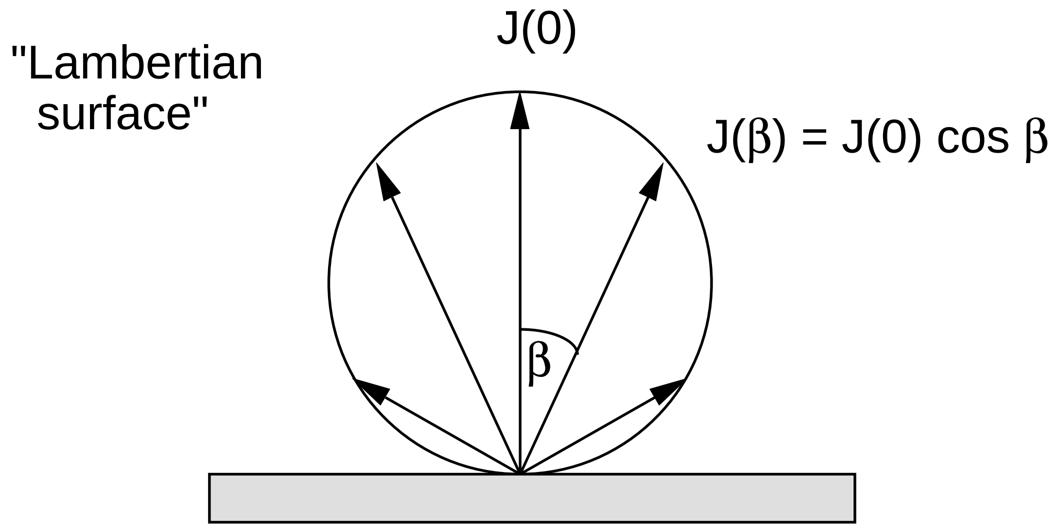
Definition: Ratio of the area of a patch on the surface of a sphere to the sphere‘s squared radius

unit: steradian (sr)

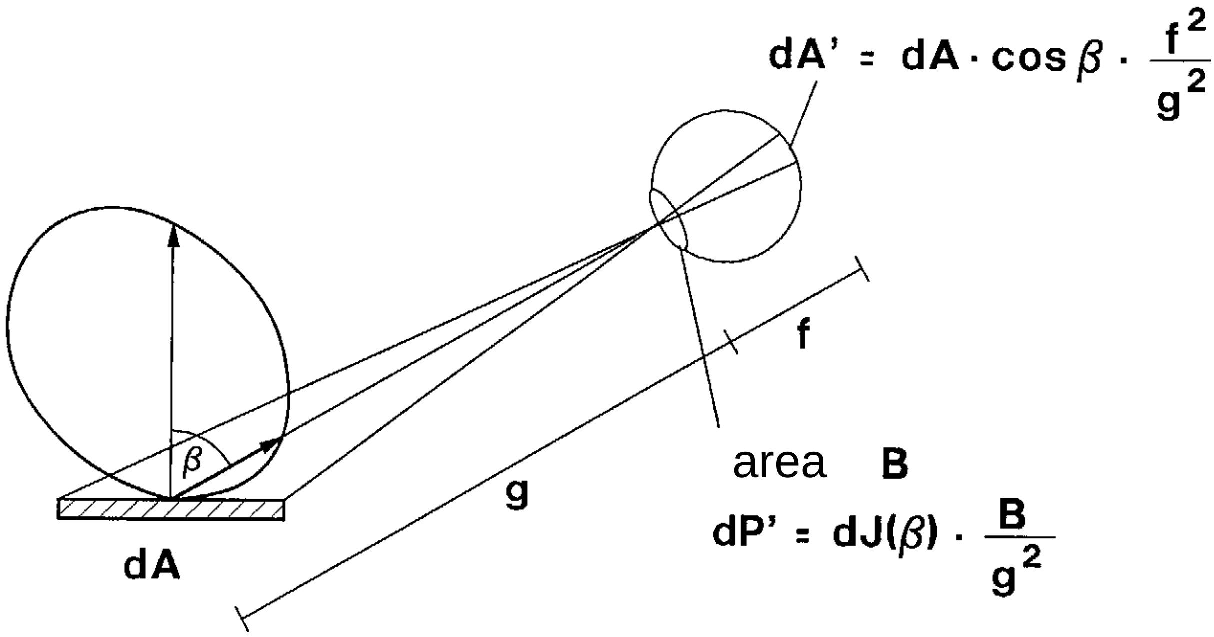
solid angle of complete sphere: 4π sr

1 sr corresponds to a cone with angular diameter of 65.6°

Diffusely Radiating Surfaces



Luminance of a Surface



illumination of image plane:

$$\frac{dP'}{dA'} = \frac{dJ(\beta)}{dA \cdot \cos\beta} \cdot \frac{B}{f^2} = L \cdot \frac{B}{f^2}$$

luminance:

$$L = \frac{dJ}{dA \cdot \cos\beta} = \frac{d^2P}{d\Omega\, dA \cos\beta}$$

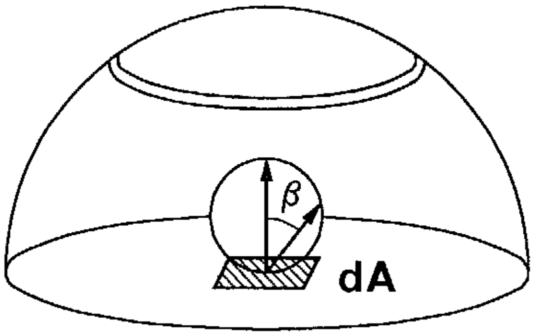
unit: $\frac{\ell m}{sr \cdot m^2} = \frac{cd}{m^2}$

Luminance of a Lambertian Surface

$$L = \frac{dJ(\beta)}{dA \cos\beta} = \frac{dJ(0)\cdot\cos\beta}{dA\cdot\cos\beta} = \frac{dJ(0)}{dA}$$

independent of angle !

Power / Luminous Flux Radiated by Lambertian Surface Element



$$\frac{dP}{dA} = \int_{\text{half sphere}} \frac{dJ(0)}{dA} \cdot \cos\beta \, d\Omega = \pi L$$

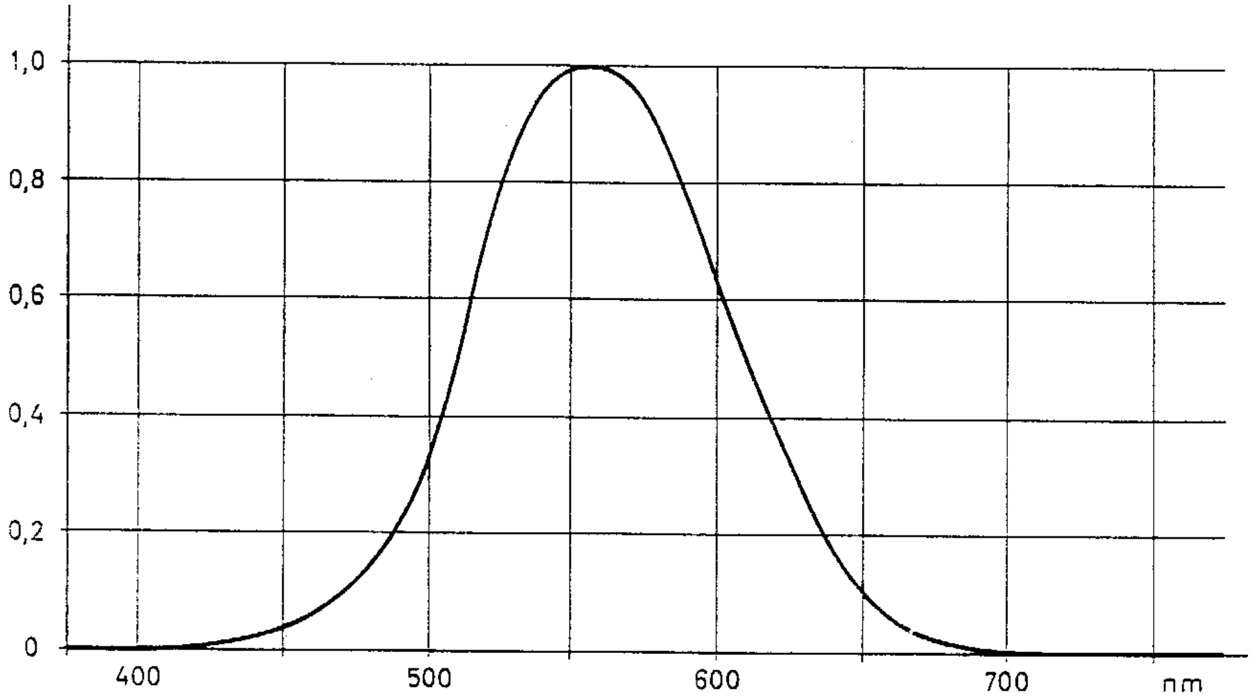
⇨ Ideally reflecting Lambertian surface,

illuminated with 1 lux,

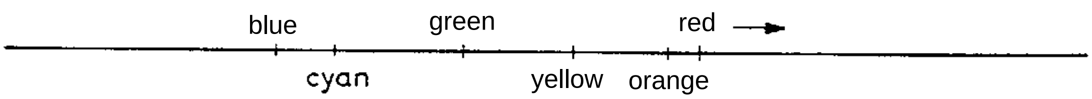
has luminance of $L = \frac{1}{\pi} \cdot \frac{cd}{m^2}$

Spectral Sensitivity of the Human Eye

Luminous efficiency curve V(λ)



wavelength $\lambda \longrightarrow$



Radiometry

$$P_r = \int_{\lambda=0}^{\infty} p(\lambda)\,d\lambda$$

Photometry

$$P_{ph} = C\int_{\lambda=0}^{\infty} V(\lambda)\,p(\lambda)\,d\lambda$$

with $C = 680 \frac{\ell m}{W}$

Blackbody Radiation, I.

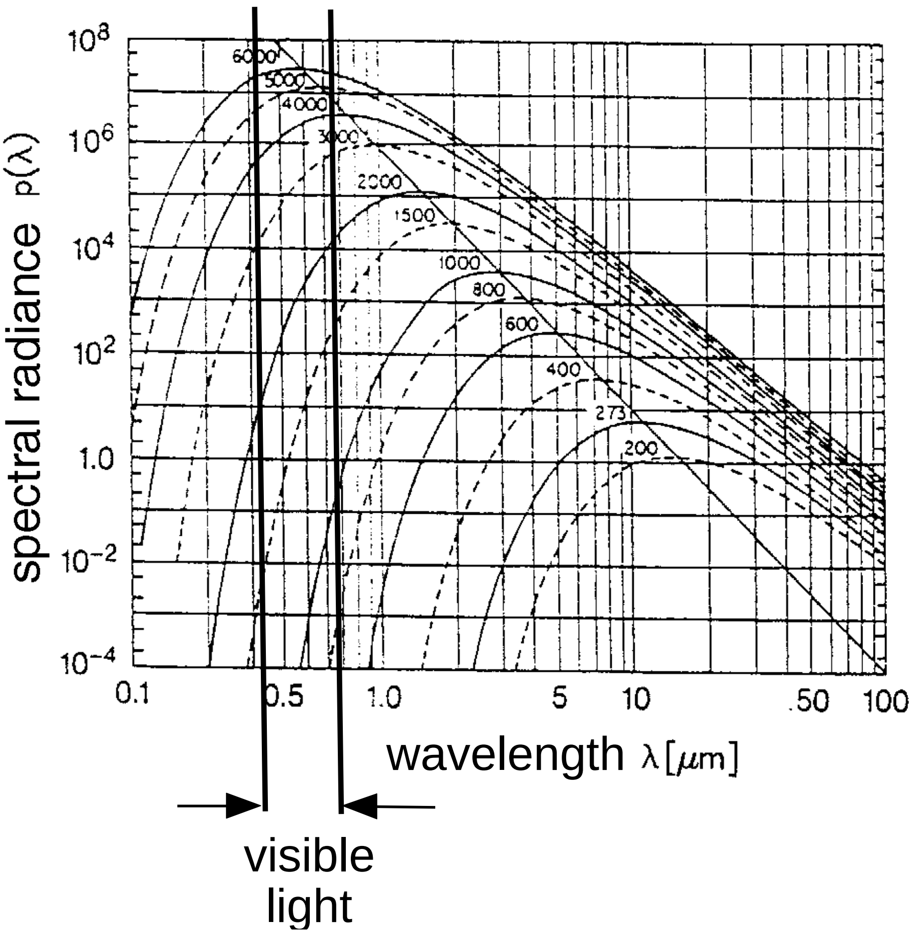
Ideal black body: absorbs all incident radiation

If heated to temperature T

$$\frac{dp(\lambda)}{dA} = \frac{2\pi hc^2}{\lambda^5 (e^{ch/\lambda kT} - 1)}$$ „Planck radiation law"

$c = 2{,}99 \times 10^8$ m/s	speed of light
$k = 1{,}3807 \times 10^{-23}$ J/K	Boltzmann constant
$h = 6{,}6261 \times 10^{-34}$ J·s	Planck's constant

Blackbody Radiation, II.



Blackbody Radiation, III.

Overall radiated power:

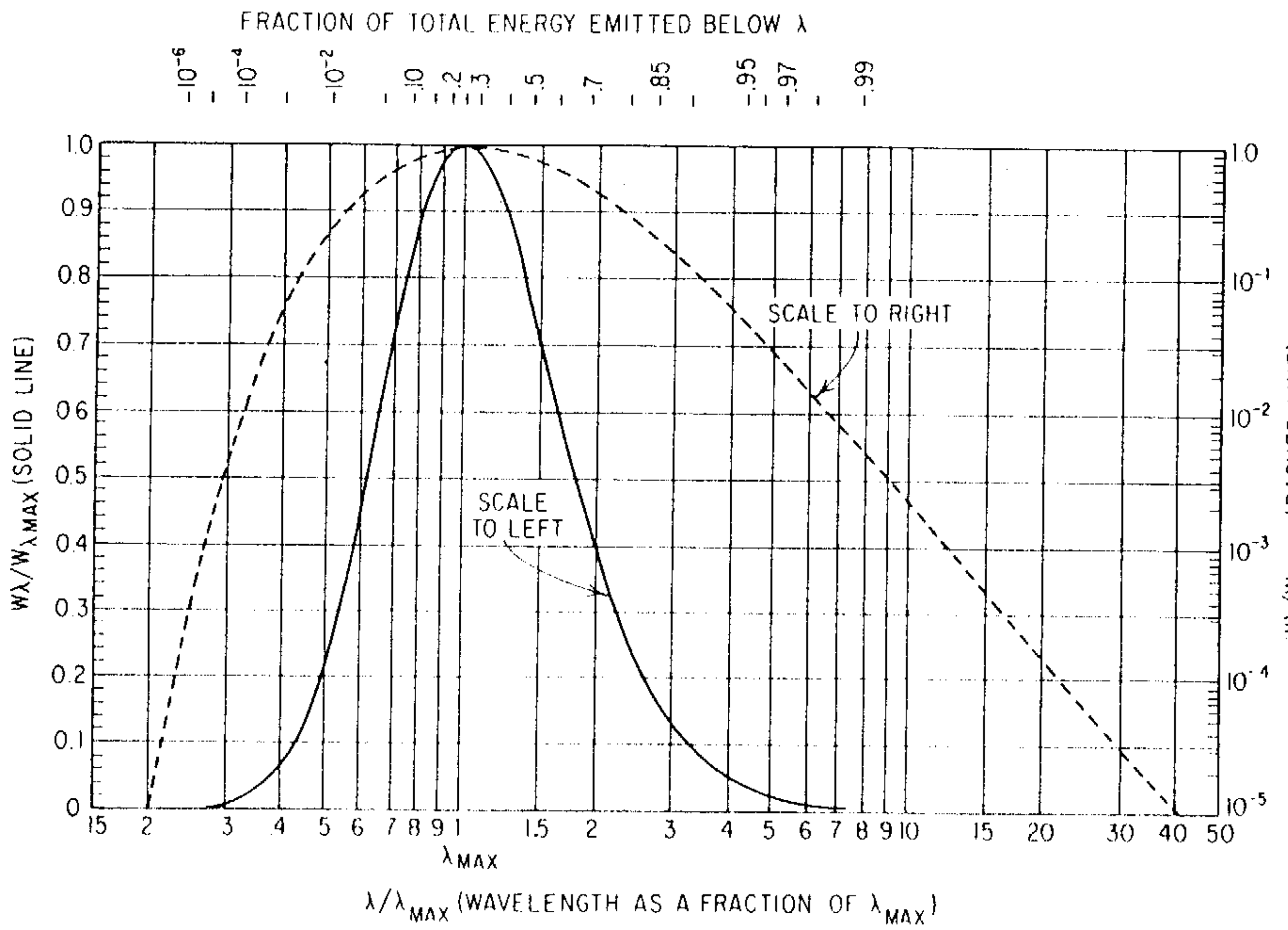
$$\frac{dP_r}{dA} = \int_{\lambda=0}^{\infty} \frac{dp(\lambda)}{dA} d\lambda = \sigma \cdot T^4$$

with $\sigma = \frac{2\pi^5 k^4}{15c^2h^3} = 5{,}6705 \times 10^{-8} \frac{W}{m^2 \cdot K^4}$

„Stefan-Boltzmann constant“

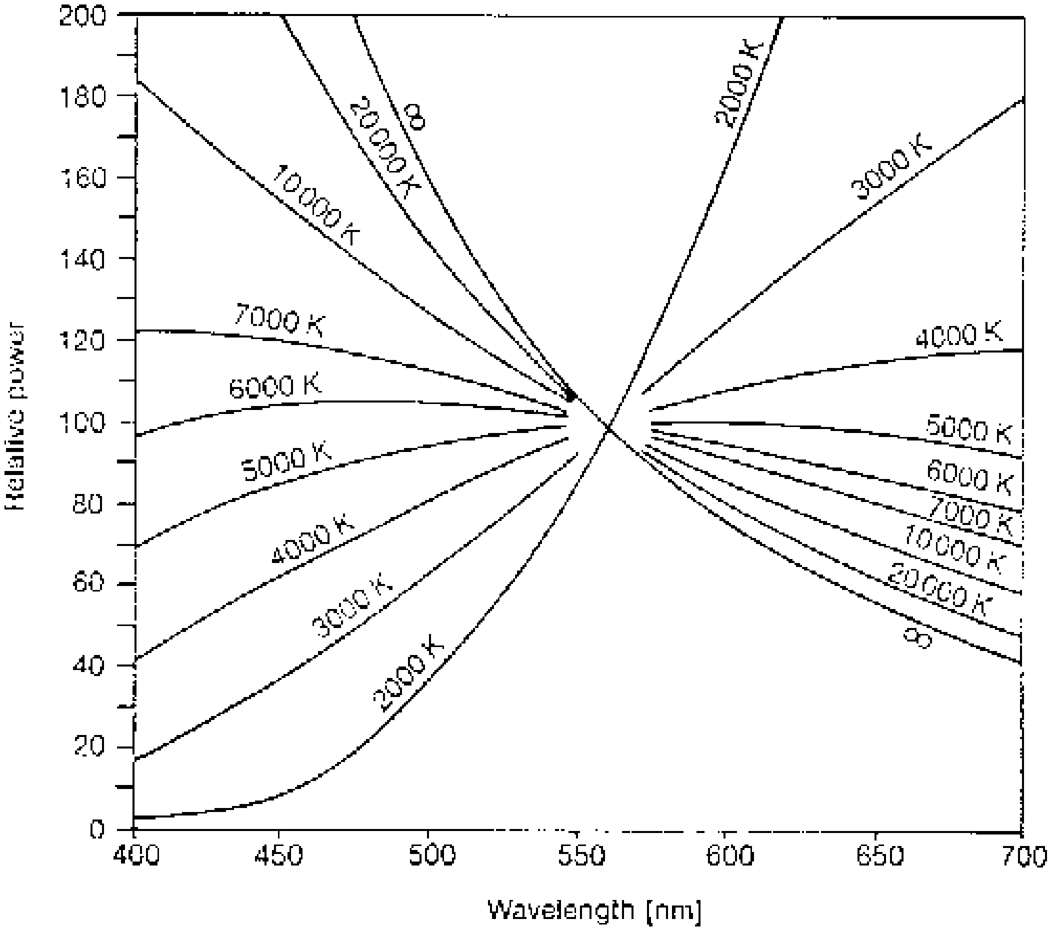
Maximum radiation:

$\lambda_{max} = \frac{2{,}90 \times 10^{-3} m \cdot K}{T}$ „Wien displacement law“


FRACTION OF TOTAL ENERGY EMITTED BELOW λ
10⁻⁶ 10⁻⁴ 10⁻² .10 .2 .3 .5 .7 .85 .95 .97 .99
1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0
Wλ/WλMAX (SOLID LINE)
1.0 10⁻¹ 10⁻² 10⁻³ 10⁻⁴ 10⁻⁵
Wλ/WλMAX (DASHED LINE)
SCALE TO RIGHT
SCALE TO LEFT
.15 .2 .3 .4 .5 .6 .7 .8 .9 1 1.5 2 3 4 5 6 7 8 9 10 15 20 30 40 50
λMAX
λ/λMAX (WAVELENGTH AS A FRACTION OF λMAX)

Blackbody Radiation , V.

Relative power distribution in the range of visible wavelengths:



⟹ „Color temperature“

Gray Body

$$\frac{dp(\lambda)}{dA} = \eta \cdot \frac{2\pi hc^2}{\lambda^5 (e^{ch/\lambda kT} - 1)}$$

η - emissivity

e.g. tungsten at	2000 K	$\eta = 0{,}26$
	3000 K	$\eta = 0{,}33$
	3500 K	$\eta = 0{,}35$

Physics of Light - Summary

- Photometry = radiometry x brightness sensitivity
- Diffuse surfaces equally bright from all angles
- Retinal illumination proportional to luminance
- Spectral sensitivity of the human eye from 380 nm to 780 nm
- Black body radiation