48-410 Acoustics and Lighting
Fall 2008

Monday, Wednesday, 12:30~13:20
DH A310 (lectures)
Hunt Lower Level (Software Sessions)

Lecture 1: Physics of Light

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Office Hours: Wed 18:00~19:00

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Pittsburgh, Pennsylvania

Class Plan

- Light Energy
- Efficacy
- Photometry
  - Luminous Flux
  - Luminous Intensity
  - Illuminance
  - Luminance

References

The Design of Lighting. Tregenza, P. and D. Loe. E and FN Spon. 1998. Chapter 1 (pg. 3-8)

Hyperphysics (©C.R. Nave, 2006) – Photometry.
http://hyperphysics.phy-astr.gsu.edu/hbase/HFrame.html

ERCO Guide - Dimensions, units
http://www.erco.com/guide_v2/guide_2/lighting_te_94/dimensions_1603/en/en_dimensions_intro_1.htm
Chapter 2.2 - Terms and Units, in ERCO Handbook of Lighting Design
http://www.erco.com/~klickmeister/km_ls_download/ls_download.pl?_startseite=en=30_media/20_handbook

Reminder

Email me project groups and selected space
Project interim report due Sep 24, final report due Oct 13

What is light?

....ray optics, electromagnetic, quantum

Reflection
- Mirroring
- Absorption
- Phase Change
  - Coherence
  - Interference
- Scattering
  - Subsurface
  - Atmospheric

Refraction
- Fermat's Principle (Snell's Law)
- Dispersion
  - Aberrations

Diffraction
- Single, Double, Multiple, Crossed Slits
- Fresnel

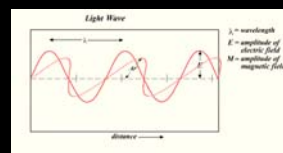
Polarization
- Linear, Elliptic, Circular

Lighting Phenomena

Photometry
Photometry is the science of measuring visible light in terms of the *perceived brightness*; light power units that are weighted according to the sensitivity of the human eye (photopic vision).

Ray (Geometric) Optics
Light propagation is described as discrete ideal narrow beams that propagate according to geometric rules.
Incident Rays
Reflected Rays
Refracted Rays

Electromagnetic Theory
Light described as a combination of electric and magnetic waves perpendicular to each other



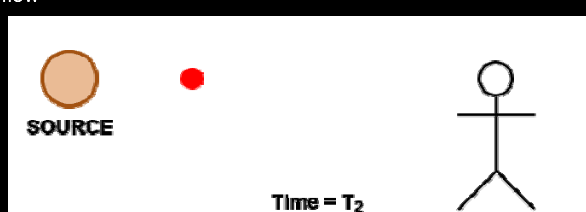
Quantum Theory
Light described as discrete packets of energy (photons) emitted by black bodies

$$E = hf = \frac{hc}{\lambda}$$

Light Energy

What is Light?

Consider particle theory (Isaac Newton, *Hypothesis of Light 1675*)
- corpuscles (particles of matter)
- emitted in all directions from a source
- time rate flow



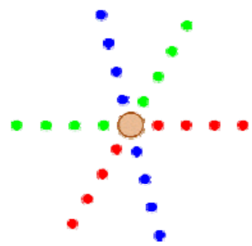
Quantum Theory (Max Plank 1900)
- blackbody radiation, black body emitting discrete packets of energy
- each photon has energy proportional to frequency

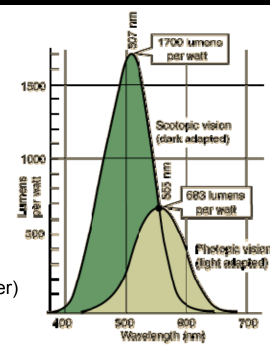
$$E = hf = \frac{hc}{\lambda}$$ where Planck's constant $h = 6.626\ 0693(11) \times 10^{-34}\ \mathrm{J \cdot s}$

Luminous Flux, F [lm]

- Time rate flow of *visible* light energy
- Wavelength-weighted power emitted by a light source
- Light energy in *all directions* and *all visible wavelengths*
- Units ➔ Lumens [lm]
- Efficacy = ratio of luminous flux to radiant flux (i.e. efficacy = lumens / watts)
- Maximum efficacy ➔ 683 lm/W

$$\Phi_v = \int_{\Lambda} \Phi_\lambda V(\lambda) d\lambda$$





Φ_λ radiant flux at wavelength λ

$V(\lambda)$ standard luminosity function (visual response of a standard observer)

Λ visible spectrum from 380nm to 780nm

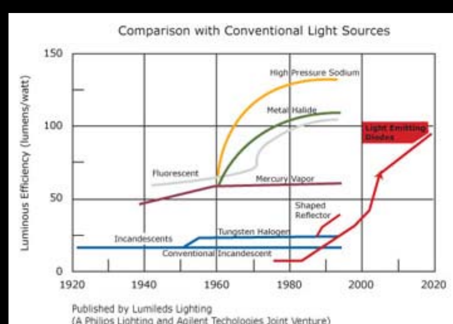
At 555nm, 1 lumen = 1/683 W of radiant flux
In practice, the lumen output of lamps are usually given

Luminous Efficacy, [lm/W]

- Relationship between light output and electrical input (lumens/watt)
- Depends on the physical efficiency of the lamp and the spectral distribution
- Varies between manufacturers, rated wattage, and other equipment (ballasts)

Lamp		Efficacy (lm/W)
Edison lamp	(1879)	1.4
Carbonized bamboo	(1879)	2.0
Carbonized cellulose	(1891)	3.0
Metalized (Gem)	(1905)	4.0
Drawn Tungsten	(1911)	10.0
60W Tungsten C.C.	**(1968)**	**14.7**
Filament Lamp	(1970)	10 – 18
Tungsten Halogen	**(1980)**	**17 – 22**
Mercury Vapor		32-63
Fluorescent Lamp	**(1938)**	**65 -100**
Metal Halide Lamp		**85 -120**
High Pressure Sodium Lamp		80 -140
Low Pressure Sodium Lamp		**120 – 200**
White LED	(2004)	60-98
White LED	(08 Prototype)	131
White LED	(Projected)	200

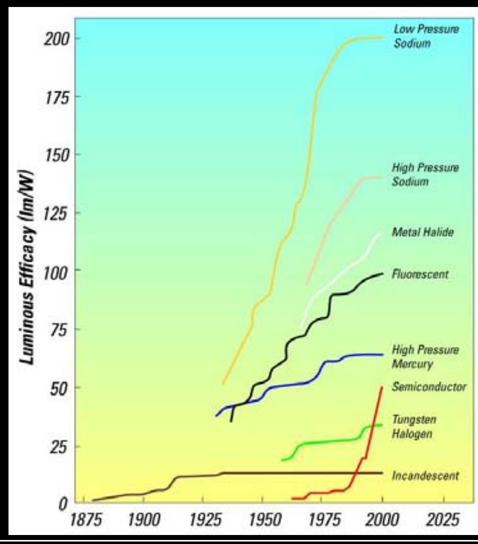
Typical Lamp Efficacies



…note ranges, NOT absolute values

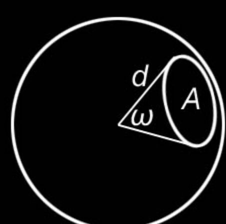
Luminous Efficacy, [lm/W]

…note ranges, NOT absolute values



Luminous Intensity, I [cd]

- Angular (not surface) density of Luminous Flux
- Light energy per unit angle
- Unit angle ➔ steradian [sr]



Solid angle ω.
Its size is A/d^2 steradians

A steradian describes a solid angle, the spatial equivalent of the radian. One steradian is the solid angle at which the area on the surface of a sphere is equal to the radius squared. It is a ratio, and its use in the definition of the candela simplifies calculations.

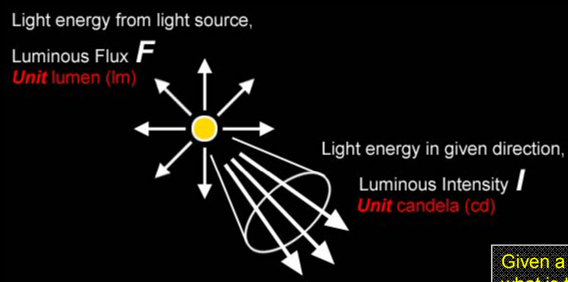
How many steradians does a sphere subtend?

Total surface area of a sphere = $4\pi r^2$

i.e. Solid angle of a sphere = $4\pi r^2 / r^2$
= 4π sr

Luminous Intensity, I [cd]

- Luminous intensity is the luminous flux emitted from a source per unit *solid angle*
- Units ➔ Candela [cd], (SI Unit)
- candela initially defined as the brightness of a standard candle
- later defined as source that emits monochromatic radiation of frequency 540 x 10^{12} hertz and that has a radiant intensity in that direction of 1/683 watt per steradian
- recall at 555nm, 1 lumen = 1/683 W of radiant flux
- thus, 1 cd = 1 lm / sr



Given a 1 cd uniform point light source, what is the total lumen output?

Point source = 4π sr 1 cd = 1 lm/sr
Total Output = 4π lm

Luminous Intensity, I [cd]

Qn 1: Is luminous intensity affected by distance?

Qn 2: If a point light source outputs 2000 lm, what is the luminous intensity of the lamp?

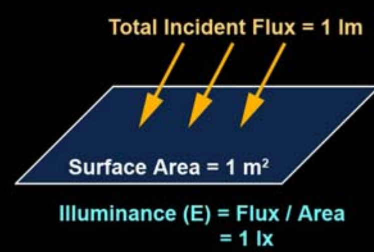
Qn 3: If a 60 W point light source has a luminous intensity of 150 cd, what is the efficacy of the lamp?

Illuminance, E [lx]

- Surface density of incident Luminous Flux
- Light energy per unit area (Differential flux per differential area)
- Units ➔ lux [lx]
- 1 lx = 1 lm / m^2

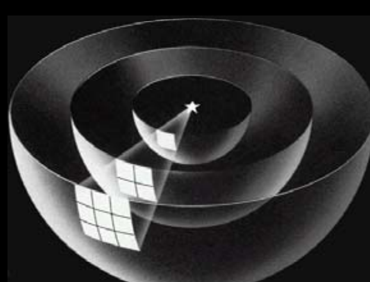
From a candle 1m away	1 lx
Corridors and Stairs	50 lx
On desks in a general office	500 lx
Workbenches	1 000 lx
Surgical Tables	5 000 lx
On the ground from overcast sky	10 000lx
On the ground from sun and bright summer sky	100 000 lx

Typical Illuminance Values

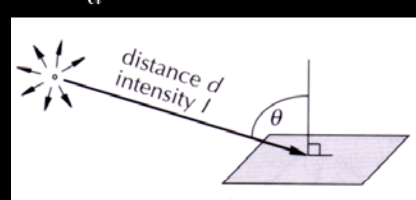


Illuminance, E [lx]

- Consider Luminous Intensity is angular density
- Inverse square law



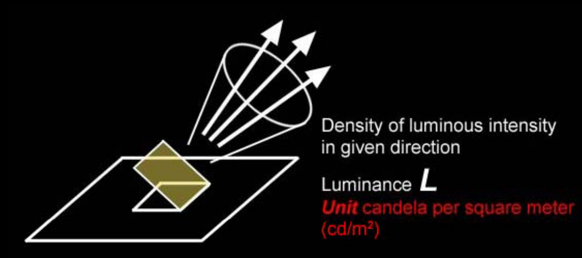
$$E = \frac{I \cos\theta}{d^2}$$



No real lamp is a point source, but equation may be used with negligible error when the dimensions of the source are small relative to the distance (>1:5)

Luminance, L [cd/m²]

- Photometric measure of the density of luminous intensity in a given direction
- Objective brightness
- Amount of light that passes through or is emitted from a particular area, and falls within a given solid angle
- Units ➔ candelas/ m^2 [cd/ m^2]



Qn: Does luminance vary over distance?

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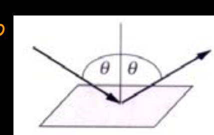
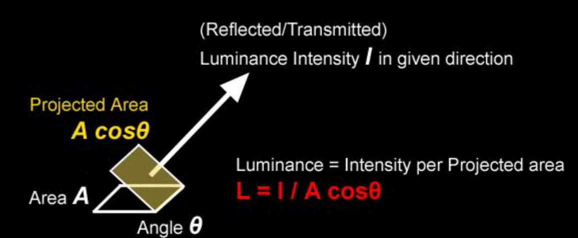
Specular Reflectance

- Fraction of light that is reflected back by surface is reflectance, ρ
- ρ ranges from 0 (perfect black) to1 (perfect mirror)
- Angle of incidence = angle of reflectance





Similar to the issue of errors in assuming point sources, the size of bright patches relative to the distance of other surfaces that it illuminates must be sufficiently small.

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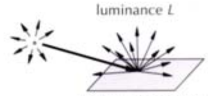
Diffused (Lambertian) Reflectance

Diffused - Light is evenly scattered in all directions by surface (Brightness NOT flux!)

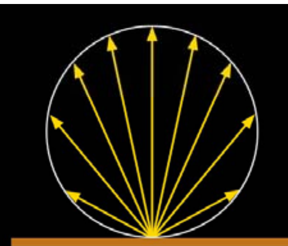
This is more accurately described as **Lambertian** - Light is scattered such that brightness of surface is the same in all directions

With a diffuse reflector, as in Figure 1.5, luminance (cd/m^2) is directly proportional to illuminance and reflectance:

$$L = \frac{E\rho}{\pi} \qquad (1.3)$$



Arrows represents magnitude of Luminous Intensity



Recall that lumianace is intensity per projected area. How does luminance vary over different directions in each case?

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Typical Reflectance Values

Typical reflectances under diffuse daylight

Ground:		Carpet (cream)	0.4
Snow (new)	0.8	Wood (light veneers)	0.4
Sand	0.3	Wood (medium colours)	0.2
Paving	0.2	Wood (dark)	0.1
Earth (dry)	0.2	Quarry tiles	0.1
Earth (moist)	0.1	Window glass	0.1
Green vegetation	0.1	Carpet (deep colours)	0.1
Other external materials:		*Paint colours, with Munsell ref:*	
White glazed tile	0.7	White N9.5	0.85
Portland stone	0.6	Pale cream 5Y9/2	0.81
Medium limestone	0.4	Light grey N8.5	0.68
Concrete	0.4	Strong yellow 6.25Y8.5/13	0.64
Brickwork (buff)	0.3	Mid-grey N7	0.45
Brickwork (red)	0.2	Strong green 5G5/10	0.22
Granite	0.2	Strong red 7.5R4.5/16	0.18
Window glass	0.1	Strong blue 10B4/10	0.15
Tree foliage	0.1	Dark grey 5Y4/0.5	0.14
		Dark brown 10Y3/6	0.10
Materials used internally:		Deep red-purple 7.5RP3/6	0.10
White paper	0.8	Black N1.5	0.05
Stainless steel	0.4		
Cement screed	0.4		

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Summary

F = efficacy x watts [lm]

I = Flux per steradian
= F / steradians [cd]

E = Flux per Area
= F / area [lx]

E = I cosθ / d^2 [lx]

L = Intensity per projected Area
= I / A cos θ [cd/m^2]

L = E ρ / π [cd/m^2] (Lambertian)