Energy Efficient Artificial Lighting

MSc Architecture, Energy & Sustainability
Module ADP033
Daylighting & Energy Efficient Artificial Lighting

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2012/13

Structure

I Lamps

II Luminaires

III Light and Health

IV Lighting Design

V Lumen Method

I *Lamps*

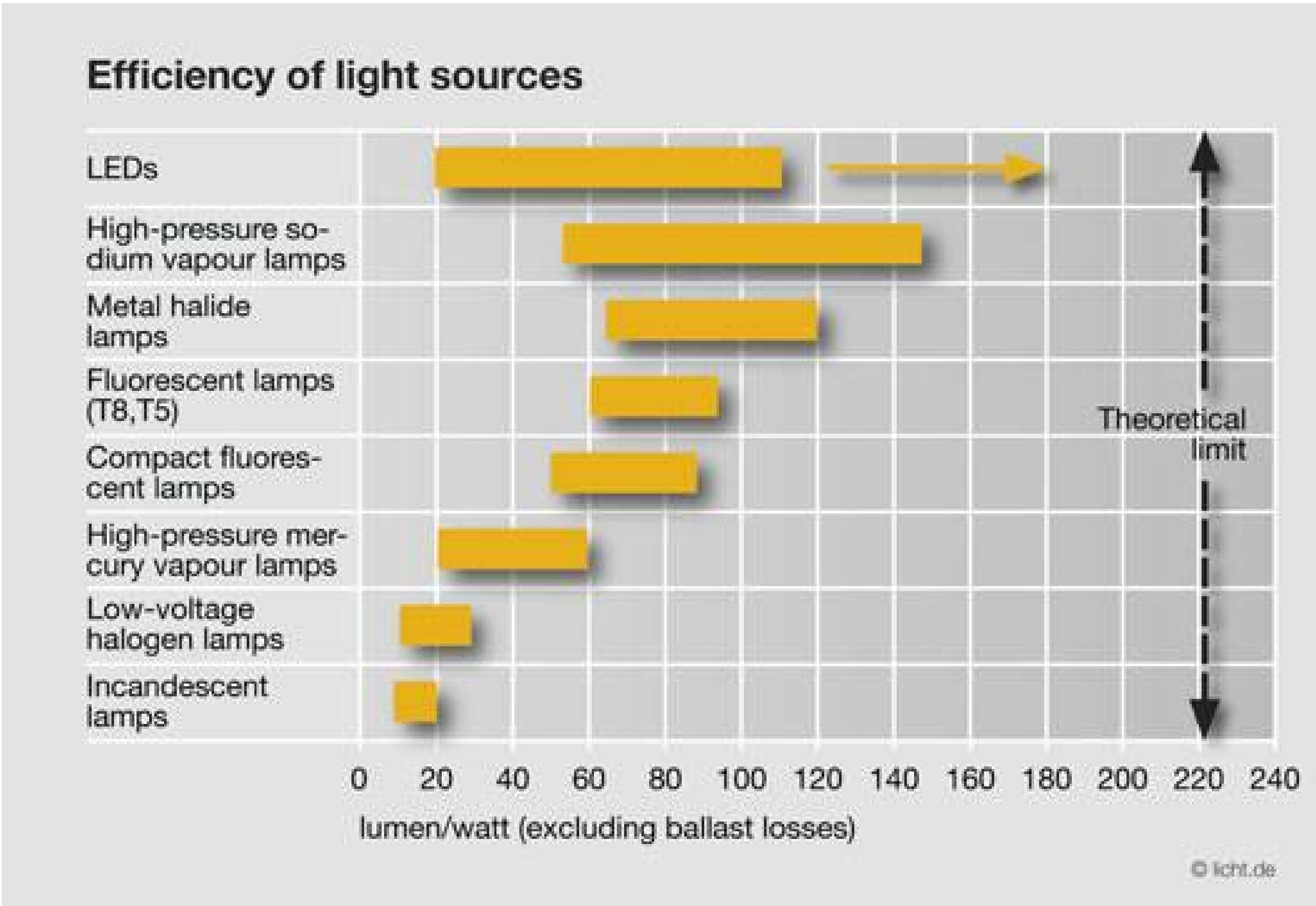
Terminology - Lamp

Terminology - Luminaire

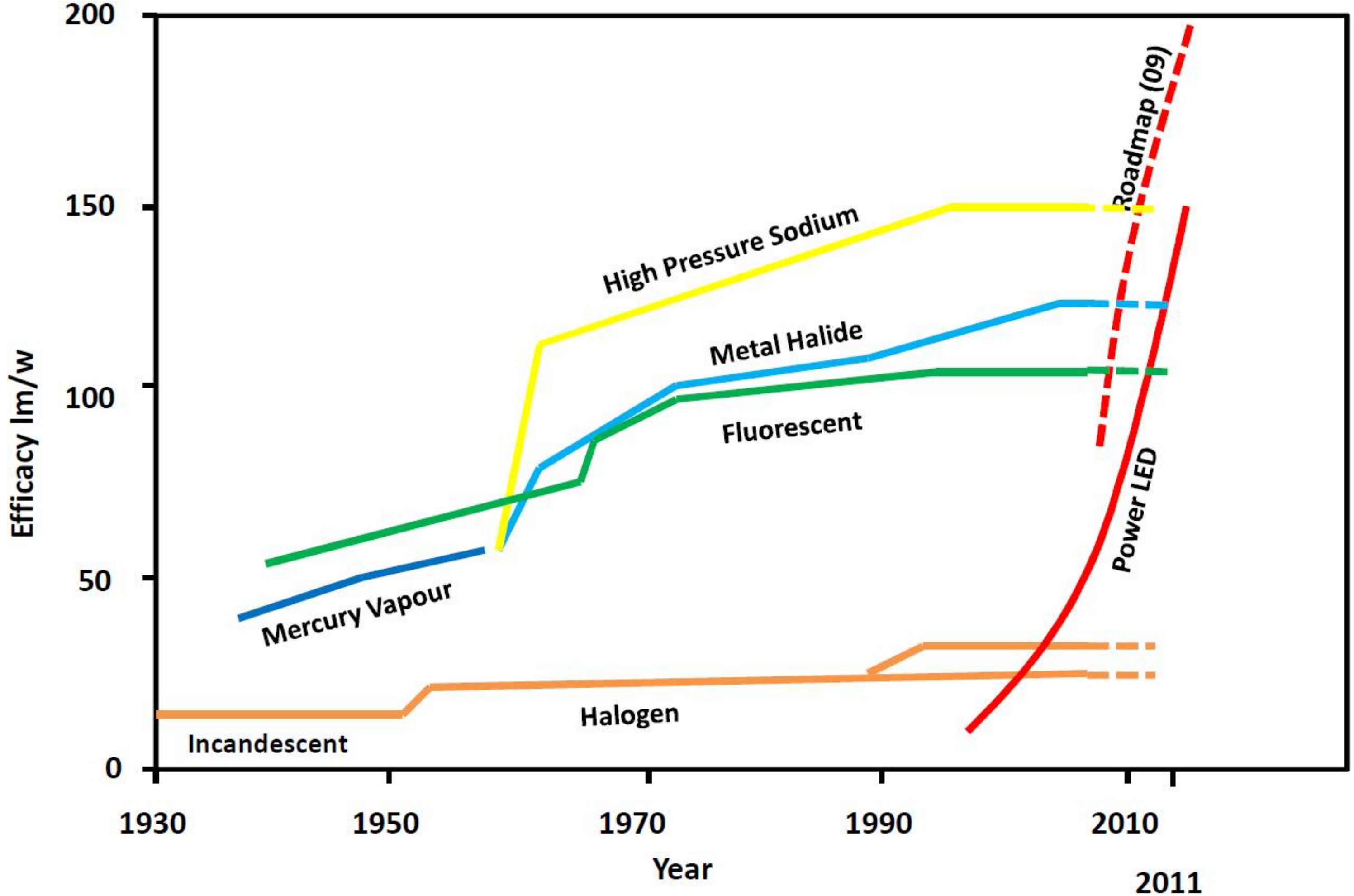
US English: Light fixture; British English: Light fitting;
International Electrotechnical Commission (IEC): Luminaire

Terminology - Bulb

Luminous Efficacy

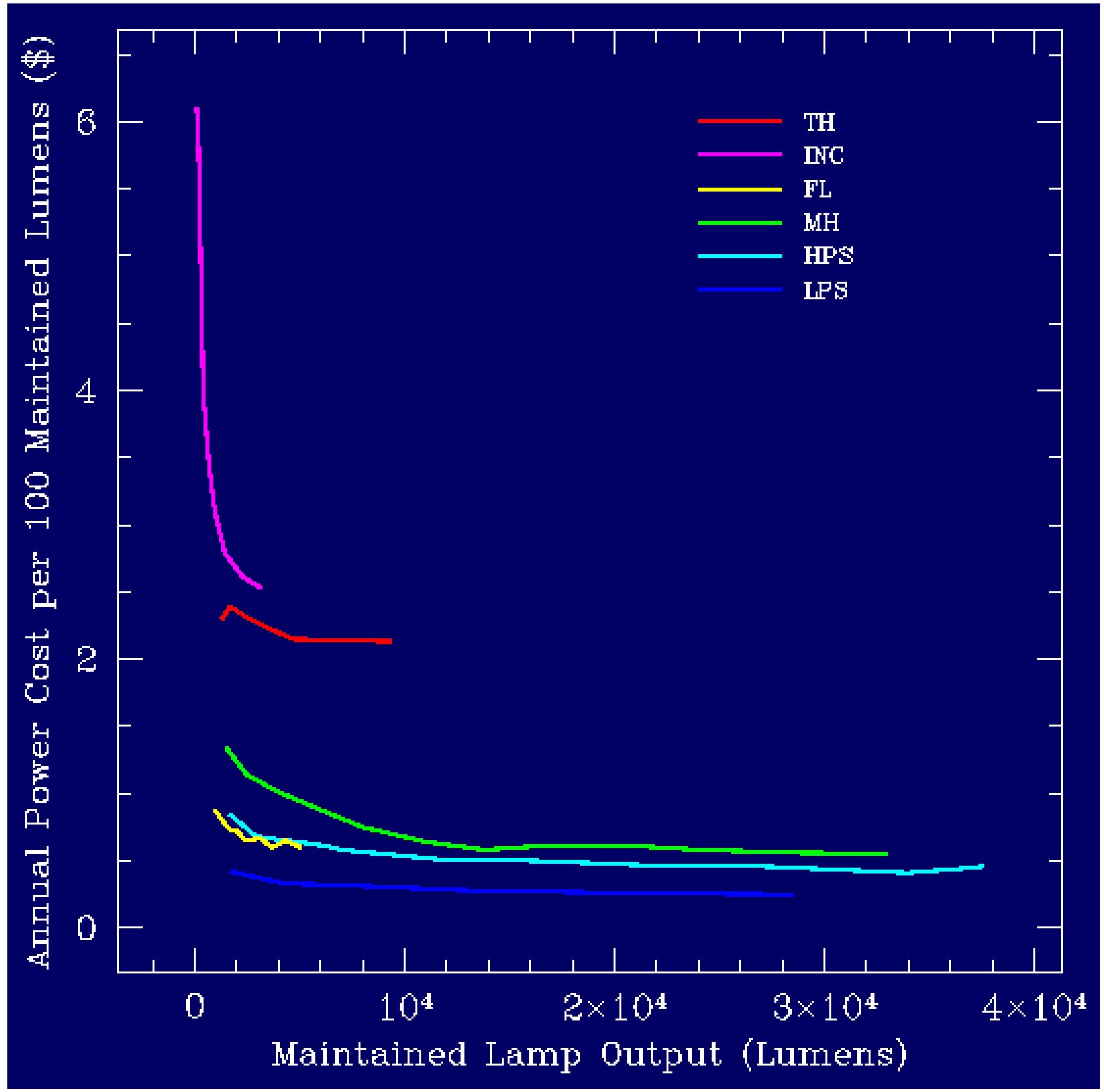


Luminous Efficacy



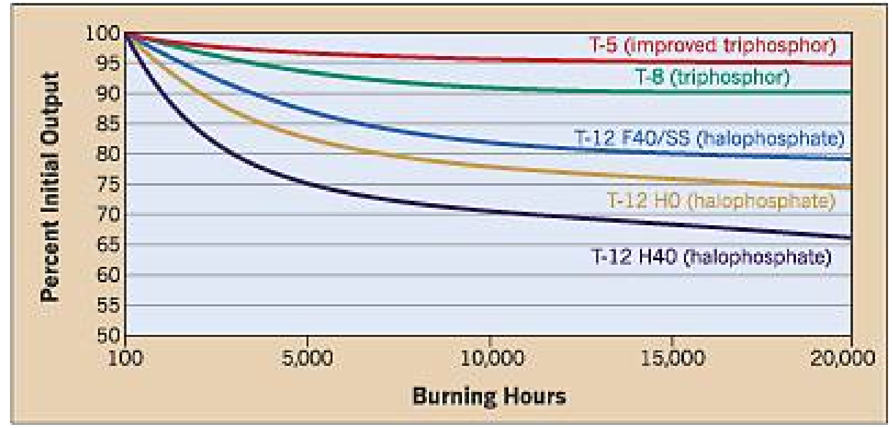
Light Output

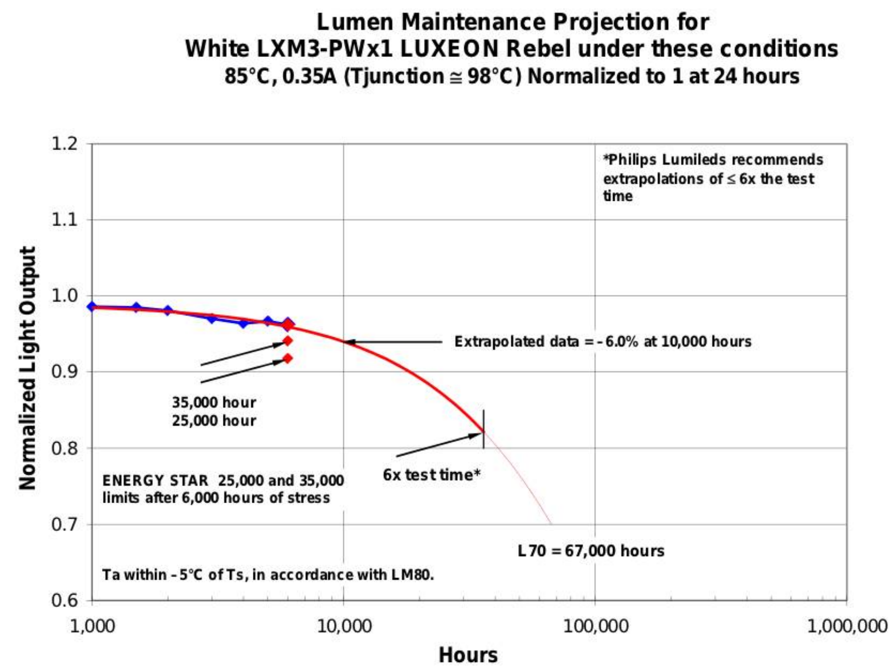
- Luminous flux emitted by the lamp
- Depends on wattage and efficacy
- High wattages only for MH, LPS, HPS



Lumen Depreciation

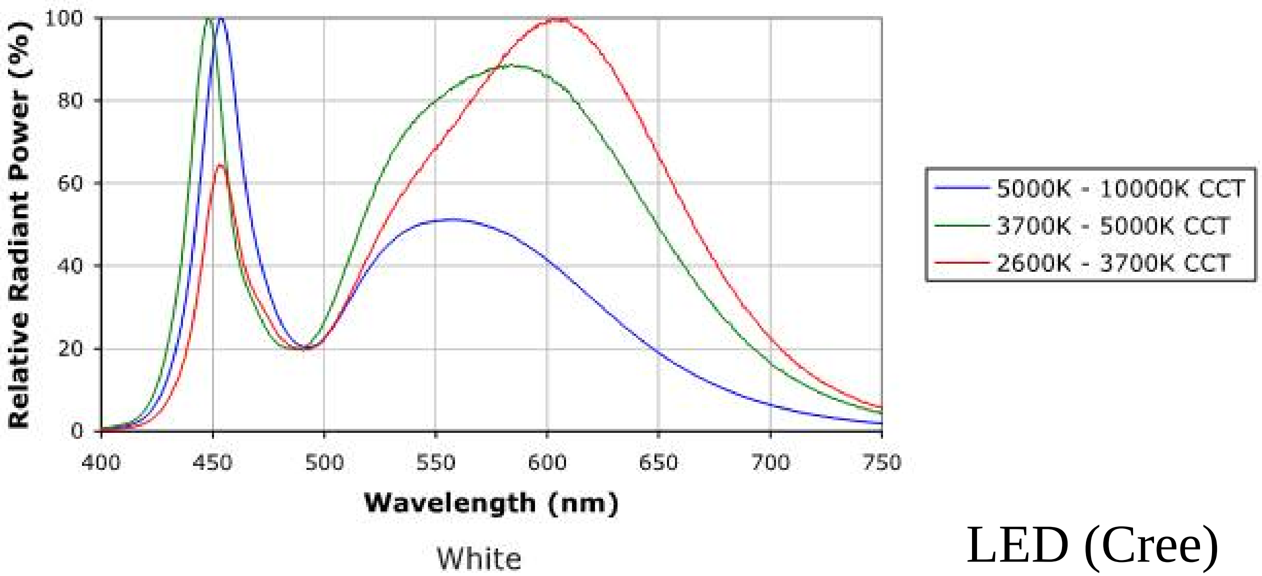
- Change of light output over the life of the lamp
- T5s have excellent lumen maintenance of 95% until end of useful life, then it drops off rapidly
- LM-80 test for LEDs: Extrapolation from test after at least 6,000 hrs
- LED life time is defined as L70 (70% of initial lamp flux)





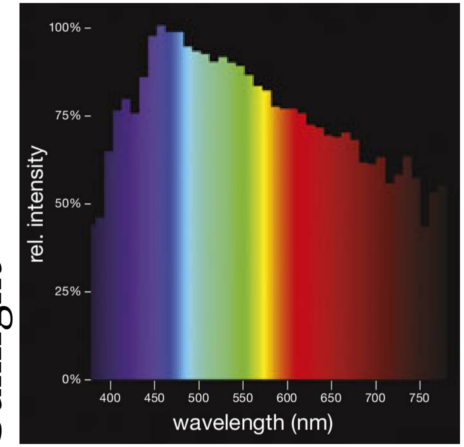
Spectral Power Distribution

- Emitted spectrum depends on lamp type
- Peaky or smooth
- Affects CCT and CRI

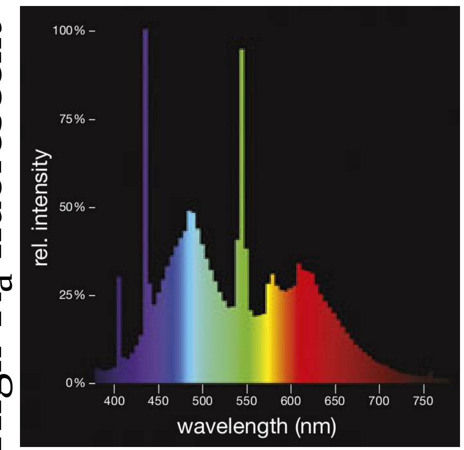


LED (Cree)

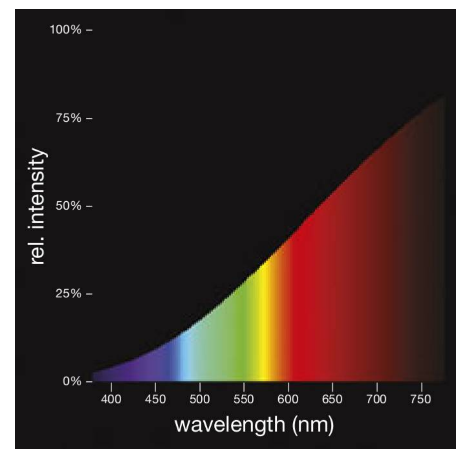
Sunlight



High-R_a fluorescent



Incandescent

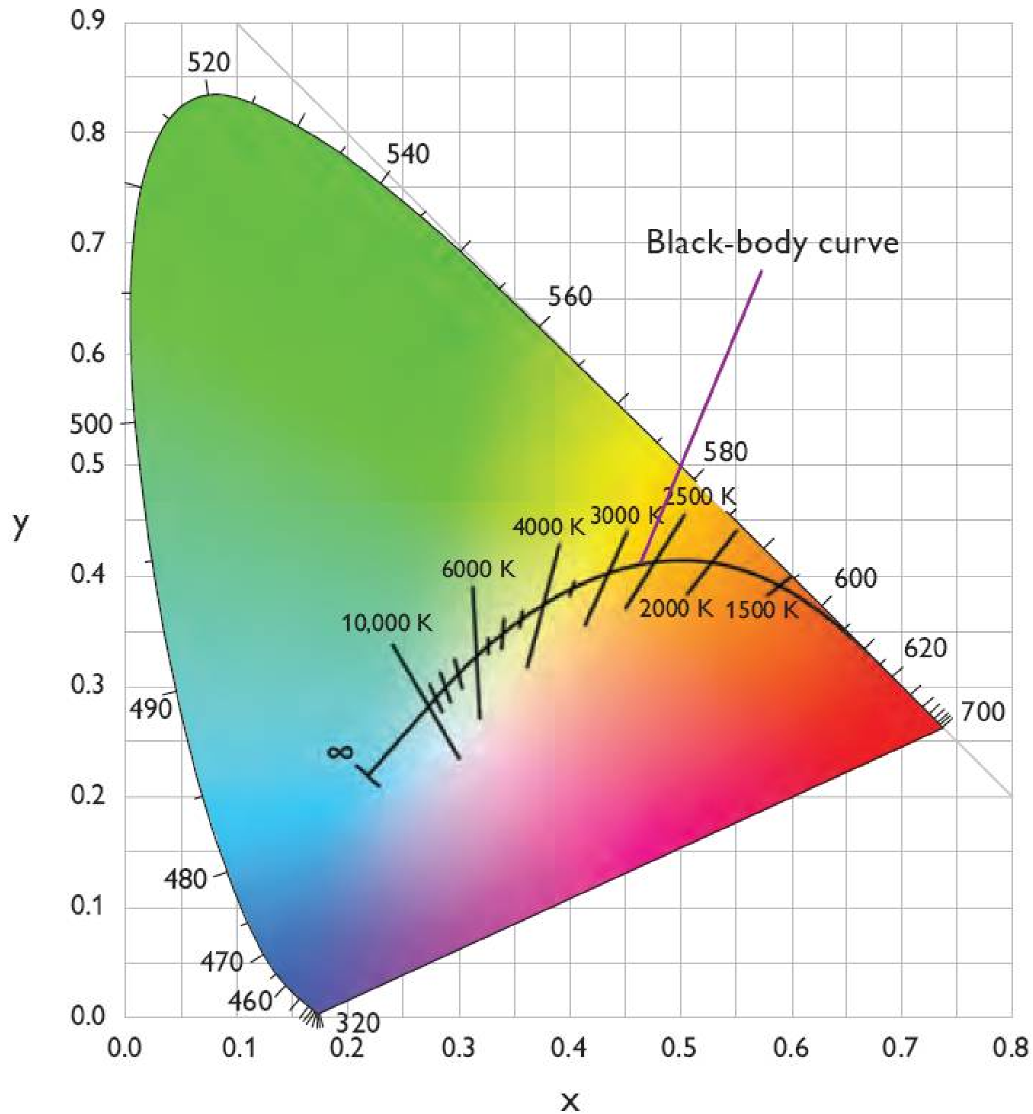


Correlated Colour Temperature

- Only defined for white(-ish) light
- Nearest colour along isotherm on Planckian locus

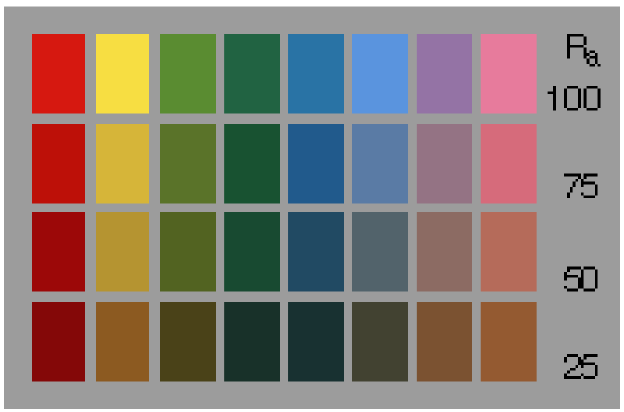
CCT	CCT class
below 3,300K	warm
3,300...5,300K	intermediate
above 5,300K	cold

Classes of correlated colour temperature



Colour Rendering Index

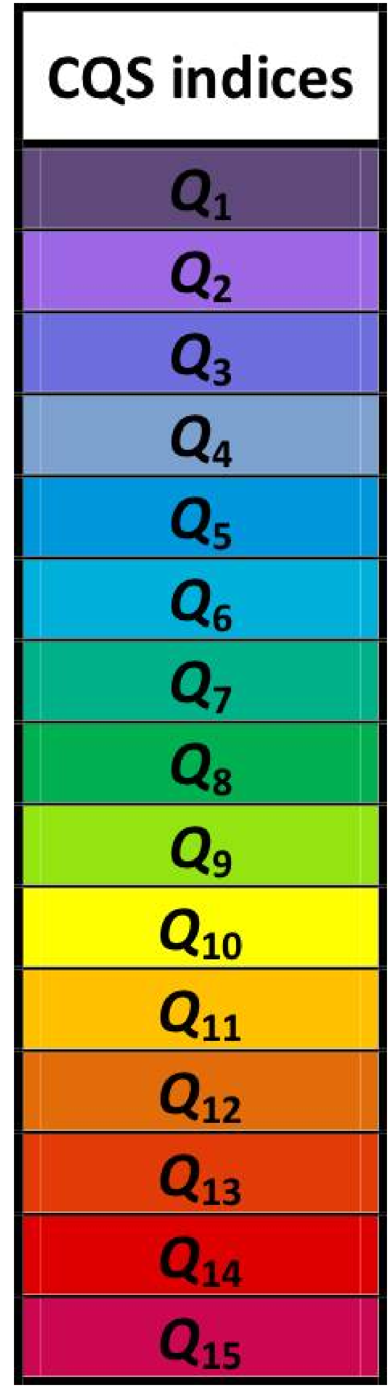
- Attempts to describe how well the light source reproduces object colours
- Reference light source is black body (CCT <5,000K) or daylight (CCT >5,000K)
- Ra (general CRI) uses 8 pastel test swatches
- Ra14 adds six saturated colours



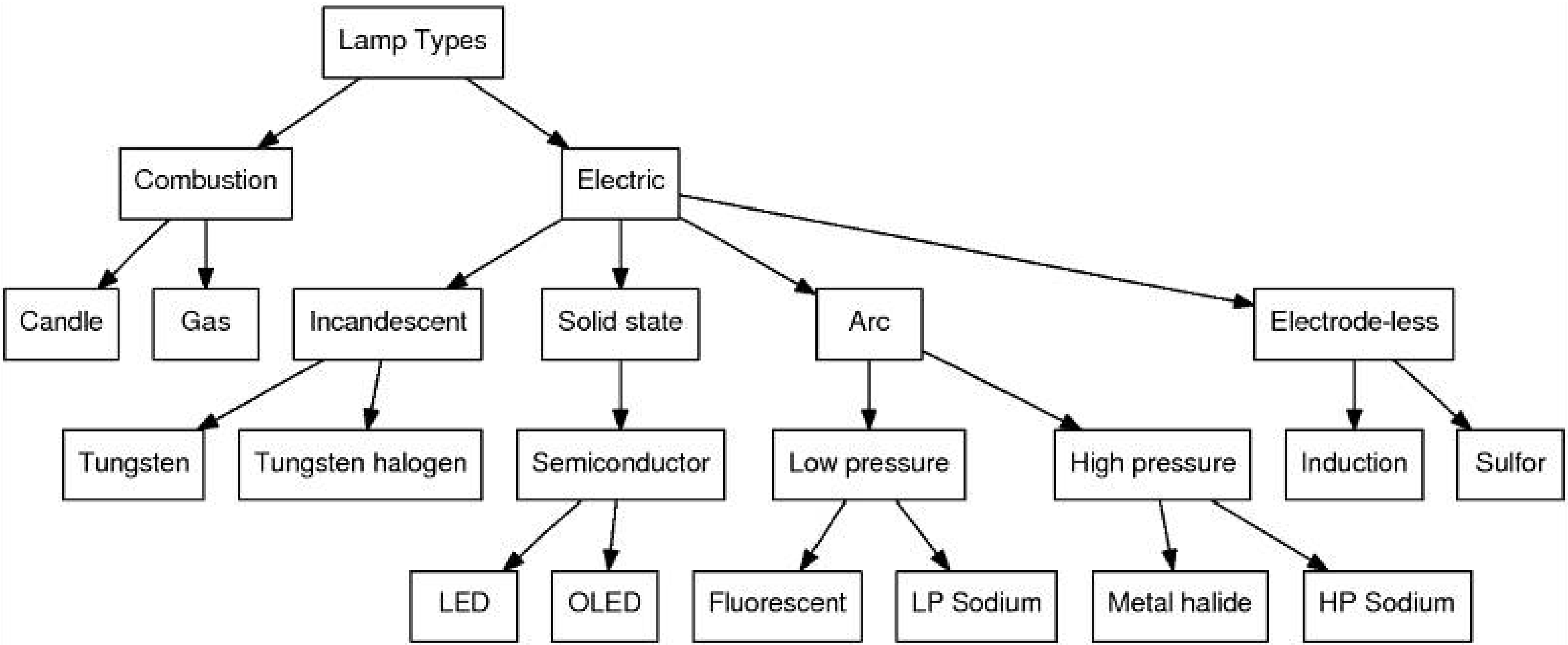
Name	Appr. Munsell	Appearance under daylight	Swatch
TCS01	7,5 R 6/4	Light greyish red	
TCS02	5 Y 6/4	Dark greyish yellow	
TCS03	5 GY 6/8	Strong yellow green	
TCS04	2,5 G 6/6	Moderate yellowish green	
TCS05	10 BG 6/4	Light bluish green	
TCS06	5 PB 6/8	Light blue	
TCS07	2,5 P 6/8	Light violet	
TCS08	10 P 6/8	Light reddish purple	
TCS09	4,5 R 4/13	Strong red	
TCS10	5 Y 8/10	Strong yellow	
TCS11	4,5 G 5/8	Strong green	
TCS12	3 PB 3/11	Strong blue	
TCS13	5 YR 8/4	Light yellowish pink	
TCS14	5 GY 4/4	Moderate olive green (leaf)	

Colour Quality Scale

- Tries to address shortcomings of CRI
- Developed by US NIST
- No standard yet
- Triggered by CRI's failure to predict the perceived colour rendering of LED lamps
- 15 saturated samples
- Chroma is allowed to increase without penalty



Lamp Types


Lamp Types
Combustion
Electric
Candle
Gas
Incandescent
Solid state
Arc
Electrode-less
Tungsten
Tungsten halogen
Semiconductor
Low pressure
High pressure
Induction
Sulfor
LED
OLED
Fluorescent
LP Sodium
Metal halide
HP Sodium

Tungsten

Light goes out for incandescent bulbs

Phased ban on the sale of incandescent lightbulbs is completed following EU directive to reduce energy use of lighting

Leo Hickman
guardian.co.uk, Friday 31 August 2012 12.13 BST

Incandescent lightbulbs have been phased out in Europe from September 2009 and September 2012. Photograph: Ina Fassbender/Reuters

"After more than an a century lighting up the world, the switch will be flicked off across the EU for the final time on incandescent bulbs on Saturday as the phased ban on their sale is completed.

"From 1 September, an EU directive aimed at reducing the energy use of lighting means that retailers will no longer be allowed to sell 40W and 25W incandescent bulbs. Similar bans came into effect for 60W and 100W incandescent bulbs over the past three years. The restrictions are predicted to save 39 terawatt-hours of electricity across the EU annually by 2020.

"Earlier this year, the UK government said the ban would bring an "average annual net benefit" of £108m to the UK between 2010 and 2020 in energy savings. But the phase-out of incandescents has been met with resistance by some users who say replacement technologies, such as CFLs, halogens and LEDs, do not perform as well. Despite the substantial long-term financial savings promised, the higher upfront price of replacement bulbs has also been criticised by those opposing the ban."

Fluorescent

- The work horse for office lighting
- High efficacy
- Dimmable
- Life time of 20,000 to 30,000 hrs
- Old magnetic ballast:
  100 Hz flicker, inefficient
- HF electronic ballasts:
  No flicker, up to 98% efficient
- Beware: T5, T8 (1/8”) but
  T16, T26 (mm)

Fluorescent

The international colour designation code for lamps consists of three numerals. The first indicates colour rendering (R_a range), the second and third CCT (in Kelvin).

Numeral 1st numeral	R_a range	Light colour 2nd + 3rd numeral	Colour temperature in Kelvin
9	90 – 100	27	2,700 K
8	80 – 89	30	3,000 K
7	70 – 79	40	4,000 K
6	60 – 69	50	5,000 K
5	50 – 59	60	6,000 K
4	40 – 49	65	6,500 K

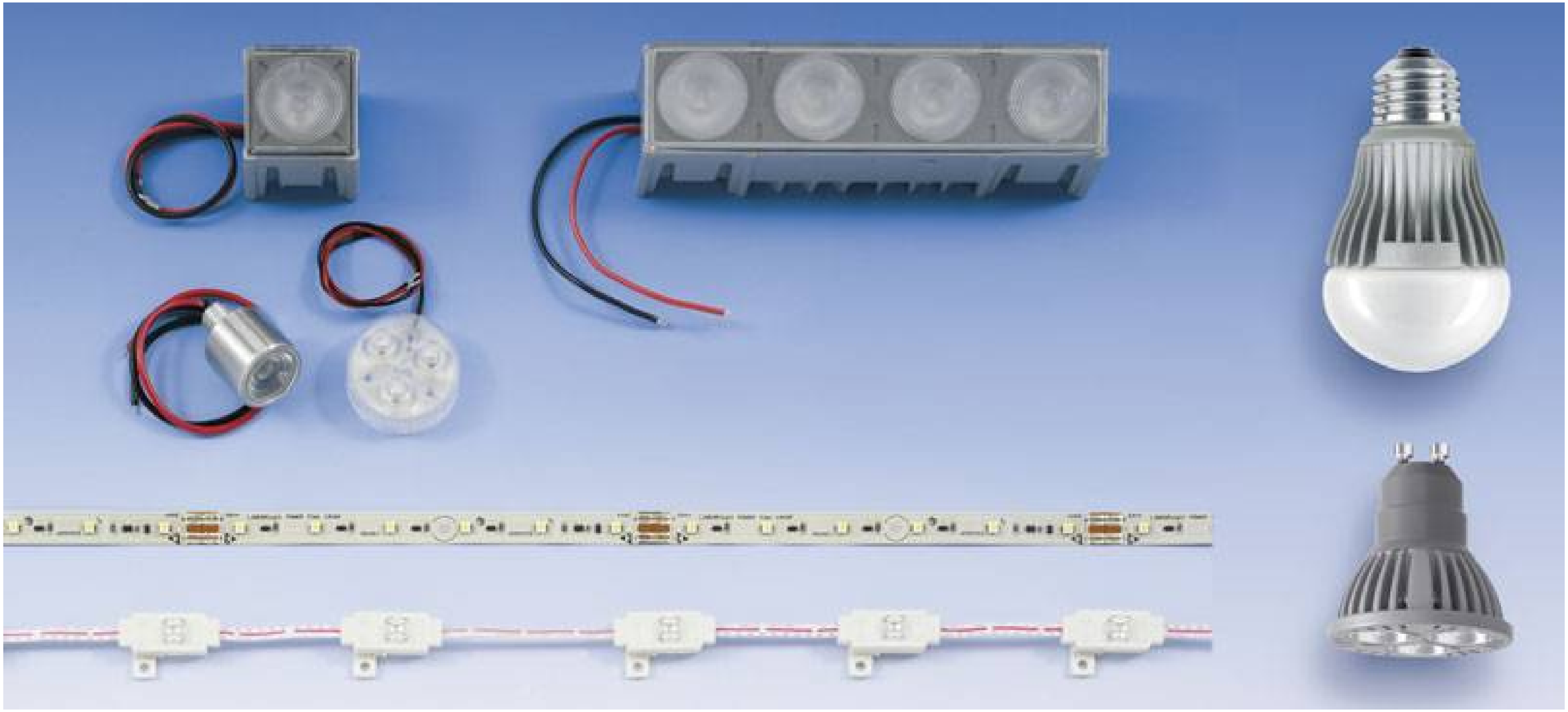
Compact Fluorescent

- Many poor-quality lamps still available; but newer products are much improved
- Warm-up times used to be long
- Not normally dimmable
- Relatively low lumen package
- Can be a direct replacement for tungsten if ballast is integrated
- Lower efficacy than linear fluorescents

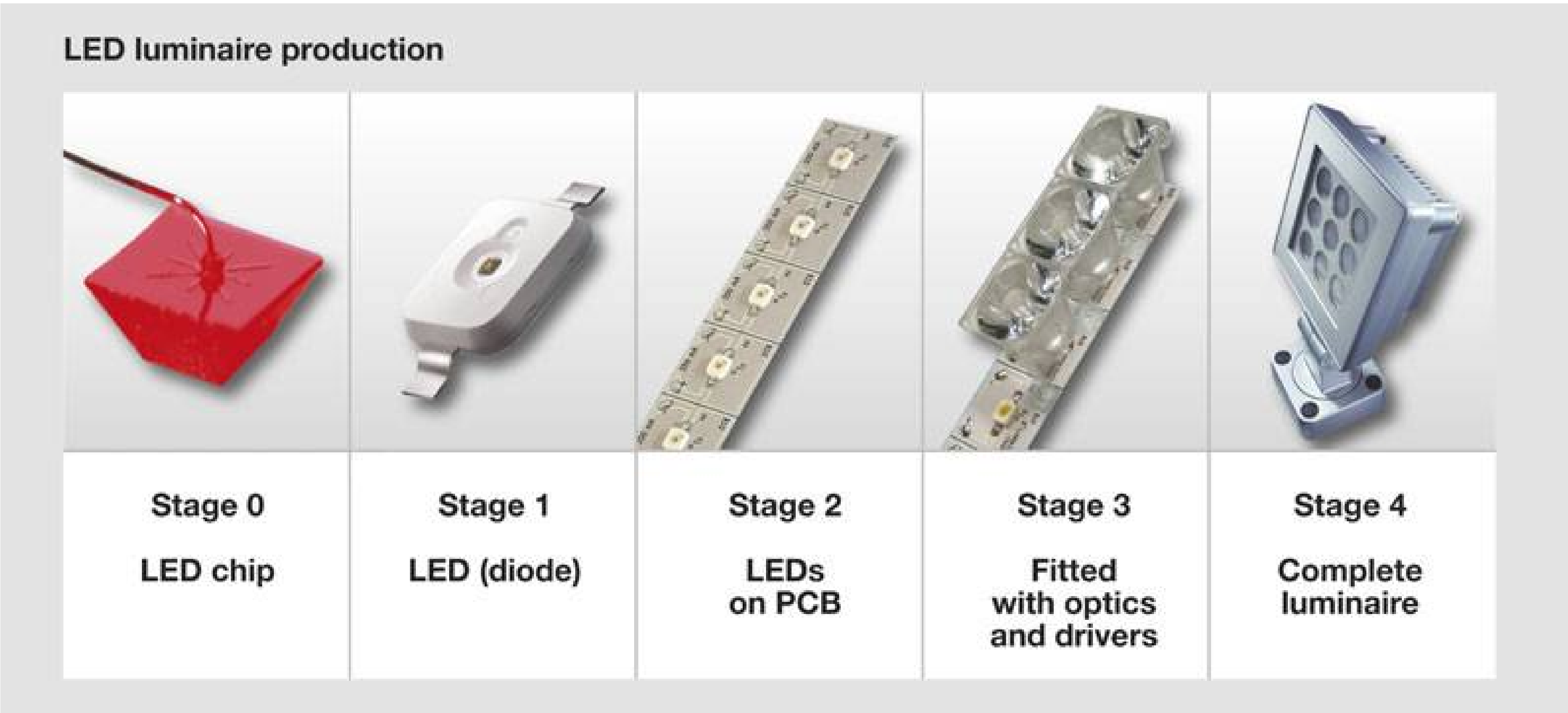
Metal Halide

- High output
- Good colour rendering
- High efficacy and high output: are replacing Sodium lamps for street lighting
- Not dimmable
- Limited switching
- Long warm-up time
- Restrike time

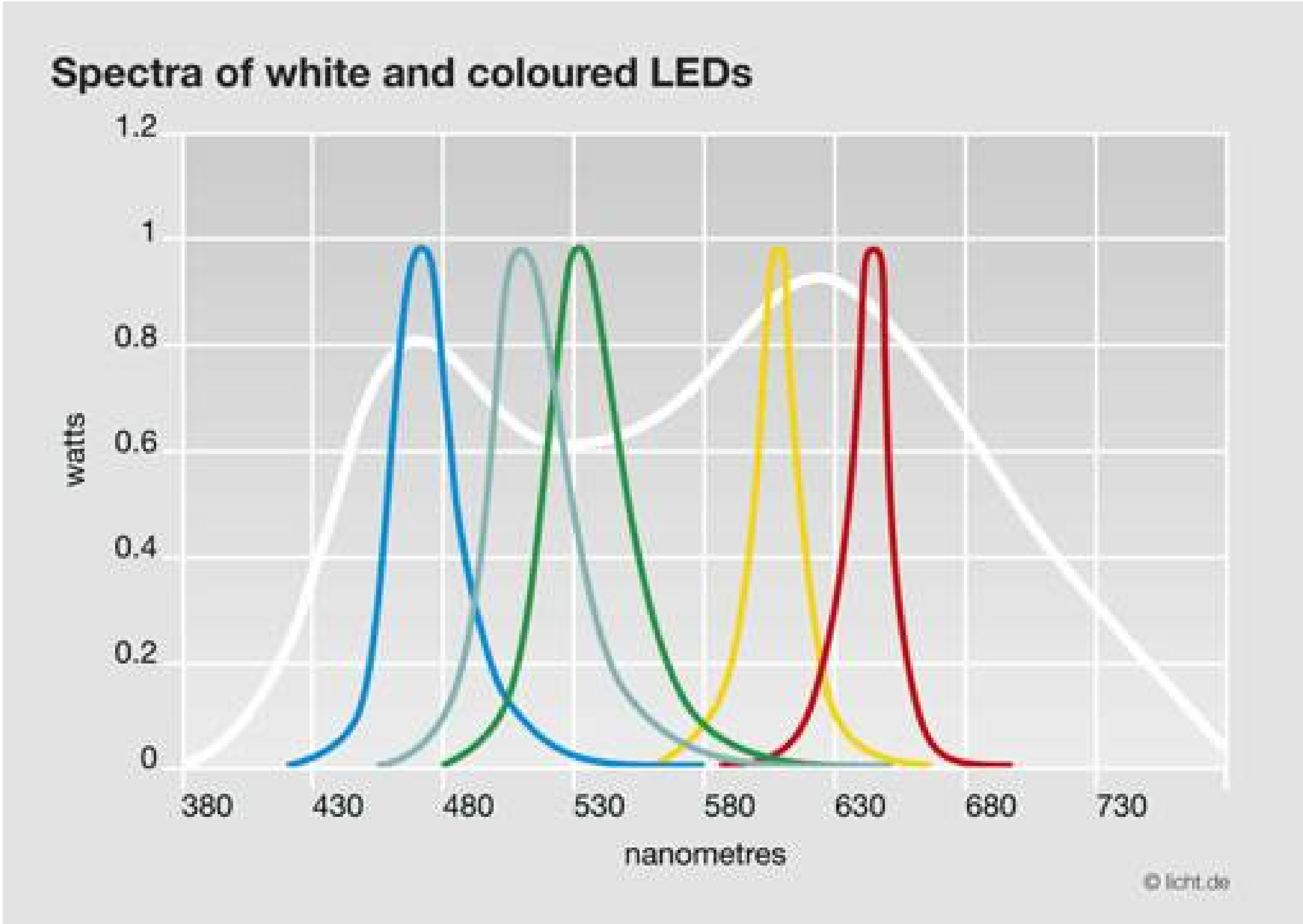
LED



LED


LED luminaire production
Stage 0
LED chip
Stage 1
LED (diode)
Stage 2
LEDs
on PCB
Stage 3
Fitted
with optics
and drivers
Stage 4
Complete
luminaire

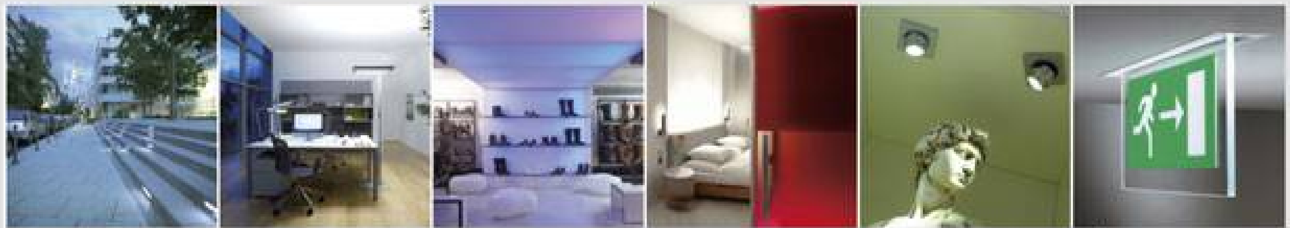
LED



White light can be achieved with R+G+B
or B+Phosphor (Fluorescent lamps are UV+Phosphor)

LED – Light Source of the Future?

LEDs in lighting today and in the future



	City/street	Office	Shop	Hotel/Home	Museum	Emergency Lighting
LEDs						
Today/2010	●●	●	●	●	●●	●●
In 3 years	●●●	●●●	●●●	●●●	●●●	●●●●
In 10 years	●●●●	●●●●	●●●●	●●●●	●●●●	●●●●
Fluorescent lamps						
Today/2010	●	●●●●	●●	●●	●●	●●
In 3 years	●	●●●	●●	●●	●●	●
In 10 years		●●	●●	●●	●●	
High-pressure sodium vapour lamps						
Today/2010	●●●●		●●			
In 3 years	●●		●●			
In 10 years	●		●			
High-intensity discharge lamps						
Today/2010	●●●		●●		●	●●
In 3 years	●		●●		●	
In 10 Jahren			●		●	
Halogen lamps						
Today/2010		●	●●	●●●●	●●●	
In 3 years			●	●●	●●	
In 10 years				●	●	

Nr.	Lamp type	Power rating (Watts)	Luminous flux (lumens)	Luminous flux (lumens/Watts)	Light colour	Colour rendering index
Linear three-band fluorescent lamps						
1	T5; 16 mm dia.[1]) high luminous efficacy	14 – 35	1,250 – 3,650[2])	89 – 104	ww,nw,dw	80 – 89
2	T5; 16 mm dia.[1]) high luminous flux	24 – 80	1,850 – 7,000[2])	77 – 88	ww,nw,dw	80 – 89
3	T8; 26 mm dia.	18 – 58	1,350 – 5,200	75 – 90[3])	ww,nw,dw	80 – 89
Compact fluorescent lamps						
4	2-, 4-, 6-tube lamp	5 – 120	250 – 9,000	50 – 75	ww,nw	80 – 89
5	2-tube lamp	18 – 80	1,200 – 6,000	67 – 75	ww,nw,dw	80 – 89
6	4-tube lamp	18 – 36	1,100 – 2,800	61 – 78	ww,nw	80 – 89
	2D-lamp	10 – 55	650 – 3,900	65 – 71	ww,nw,dw	80 – 89
Energy-saving lamps						
7	Incandescent shape	5 – 23	150 – 1,350	30 – 59	ww	80 – 89
8	Standard shape	5 – 23	240 – 1,500	48 – 65	ww	80 – 89
230 V halogen lamps						
9	with jacket	25 – 250	260 – 4,300	10 – 17	ww	≥ 90
10	miniature	25 – 75	260 – 1,100	10 – 15	ww	≥ 90
11	with reflector	40 – 100			ww	≥ 90
12	with base at both ends	60 – 2,000	840 – 44,000	14 – 22	ww	≥ 90
Low voltage 12 V halogen lamps						
13	with reflector	20 – 50			ww	≥ 90
14	pin-based lamps	5 – 100	60 – 2,300	12 – 23	ww	≥ 90
Metal-halide lamps						
15	with base at one end	35 – 150	3,300 – 14,000	85 – 95	ww,nw	80 – 89, ≥ 90
16	with base at both ends	70 – 400	6,500 – 36,000	77 – 92	ww,nw	80 – 89, ≥ 90
High-pressure sodium vapour lamps						
17	tubular	35 – 1,000	1,800 – 130,000	51 – 130	ww	20 – 39
Low-pressure sodium vapour lamps						
18	tubular	18 – 180	1,800 – 32,000	100 – 178	yellow	
Light emitting diodes						
19	LED	0.7 – 1.5	18 – 27	13 – 23		

II *Luminaires*

Parts

- Light source (lamp)
- Reflector
- Aperture, possibly with lens
- Housing for lamp alignment and protection
- Ballast or power supply, might be separated
- Power connection
- Lamp socket

Types

- Suspended: pendant, chandelier, highbay, lowbay
- Surface-mounted: Ceiling, wall, track
- Recessed
- Free-standing: pole, uplighter, bollard
- Specialised



Fittings





Criteria

- Efficiency: Light Output Ratio, LOR (conventional)
  Efficacy: Lumens per circuit Watt (conventional and LED)
- Distribution:
  luminous intensity distribution curve, LIDC
- Glare
- Protection: IP rating
- Mounting
- Design
- With LED fittings, we can no longer distinguish between 'the lamp' and 'the fitting'. They are one integrated unit now.
- Good thermal management is paramount for LED fittings. It determines the efficacy and life time.

LOR

- Relative total/upward/downward output: LOR, ULOR, DLOR
- Use Flux Fraction Ratio for absolute flux values: FFR = UFF / DFF = ULOR / DLOR
- Upward flux reaches working plane only after being reflected by the ceiling
- Avoid 'cave effect': Ceilings and walls should be lit, too.
- LOR should be as high as possible
- LOR meaningless with LED fittings. Use luminaire efficay (lm/W) instead.

Light output ratio	
LOR	86 %
ULOR	36 %
DLOR	50 %
FFR	0.72 (41:58)
BLF	1.00

Part L 2010 – LOR

- Part L-2010 defines min. luminaire lumens per circuit Watt:
  - Non-domestic: 55 lm/W
  - Domestic: 45 lm/W
  - Display lighting: 22 lm/W
- These are luminaire lumens, not lamp lumens!
- These are circuit Watts, not lamp Watts!
- (Next Part L will increase requirements, possibly to 75 lm/W)
- Measure of the efficiency of the luminaire, including ballast electrical losses and fitting light losses
- Pick fitting with high LOR/efficacy

Part L 2013 - LENI

- Lighting Energy Numeric Indicator
- BS EN 15193:2007 Energy performance of buildings — Energy requirements for lighting
- This is no longer about installed power:
  - Encourage use of high energy efficient luminaires and controls (P_n, P_{pc}, P_{em})
  - Encourage use of daylight-linked controls (F_D Daylight, F_O Absence, F_C Maintenance)
- Calculations are not very complicated, but a bit cumbersome

LENI

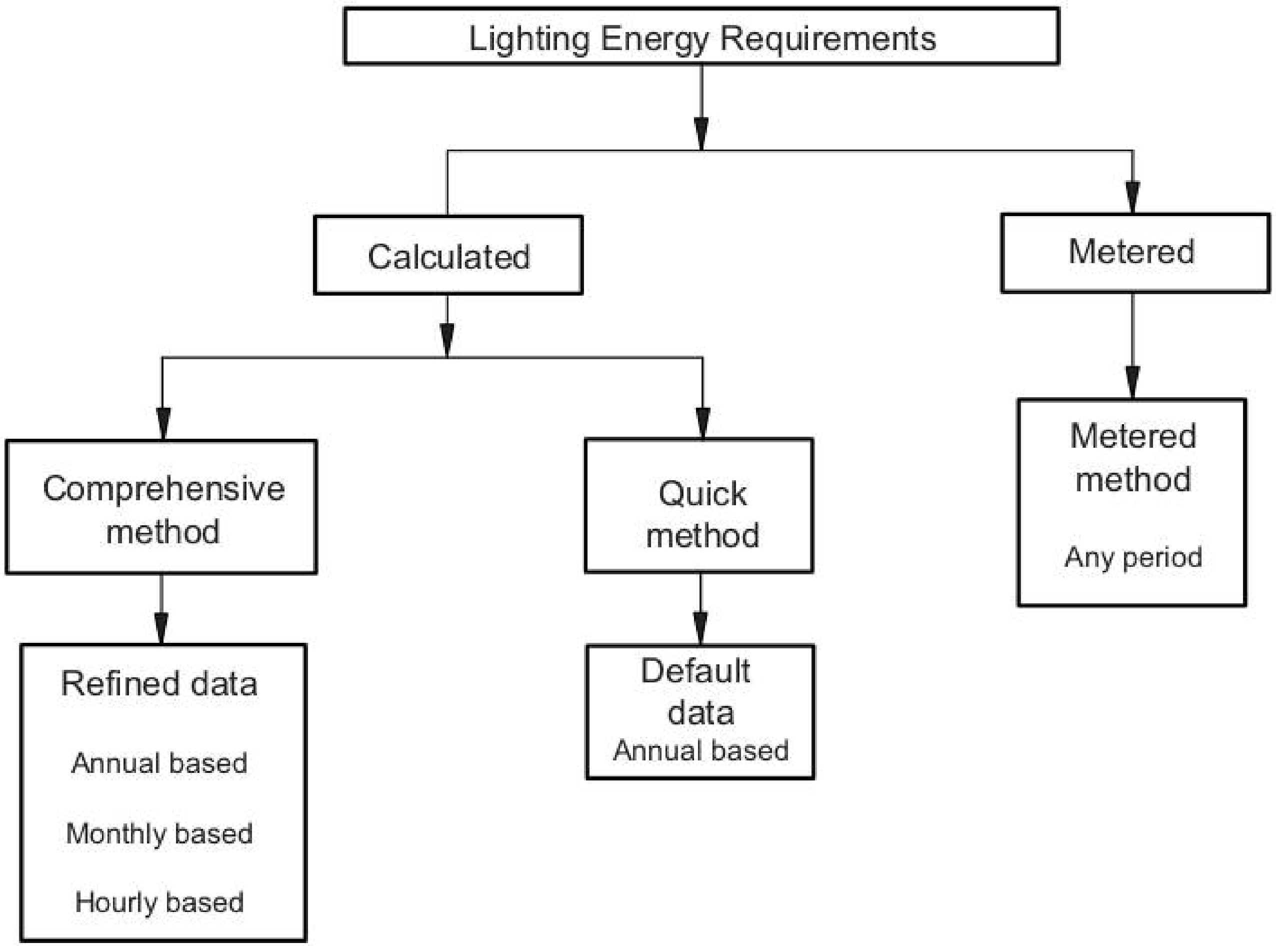


Figure 1 — Flow chart illustrating alternative routes to determine energy use

LENI (contd)

- Steps:
  - Calculate the installed electrical power for lighting and controls
  - Calculate F_C, F_D, F_O for lighting scheme (controls, daylight, occupancy)
  - Calculate LENI for the project in kWh/m^2/year
  - LENI = Energy for Lighting + Energy for standby
  - $LENI = \{F_C \times P_n/1000 \times [(t_D \times F_D \times F_O) + (t_N \times F_O)]\}/A + \{(P_{em} \times t_{em})/A + \{P_{pc} \times [t_y - (t_D + t_N)]/A\}\}/1000$

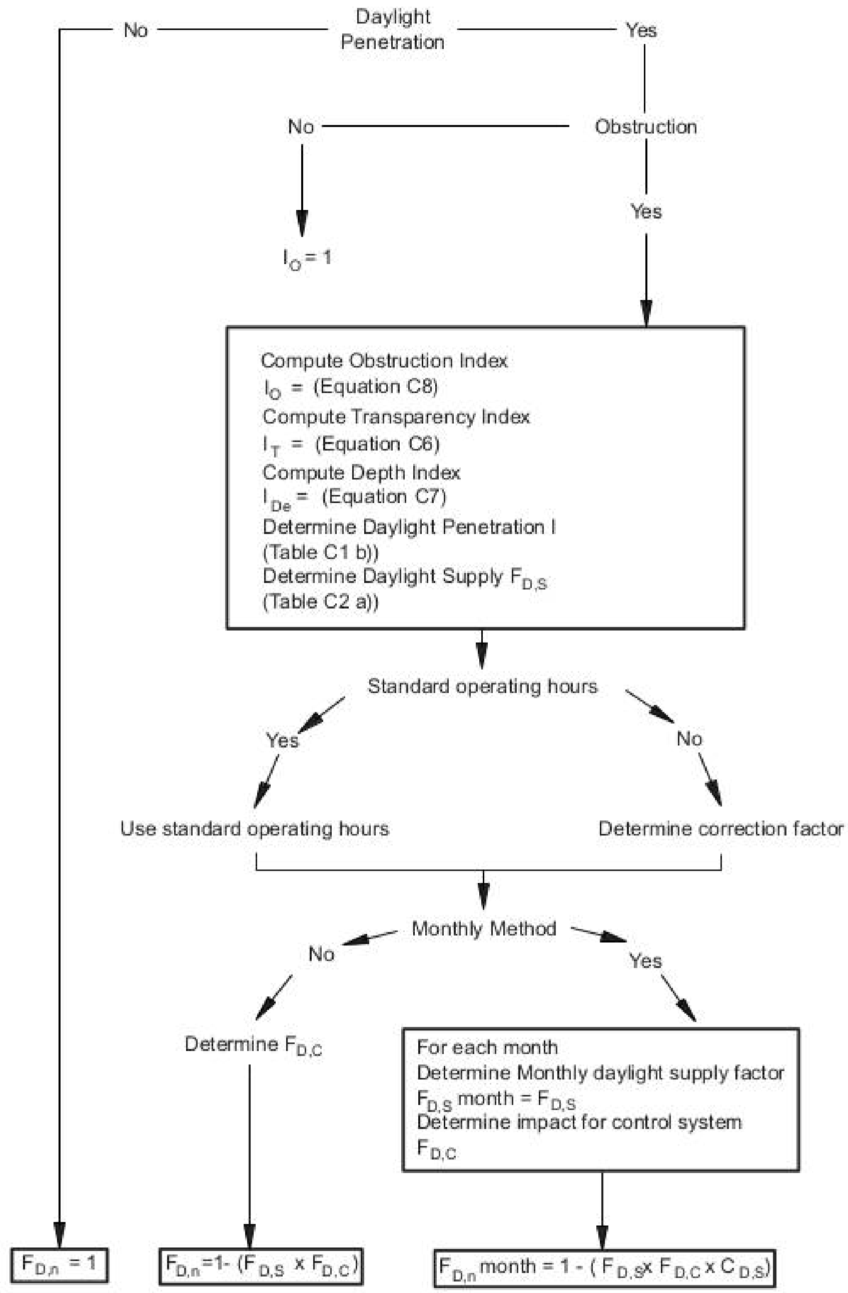
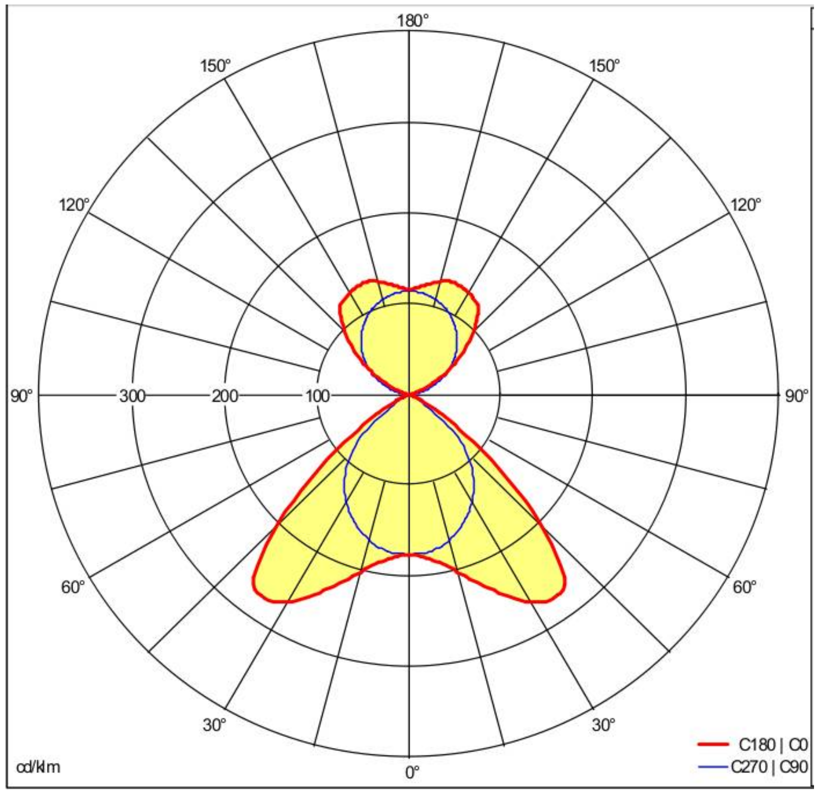


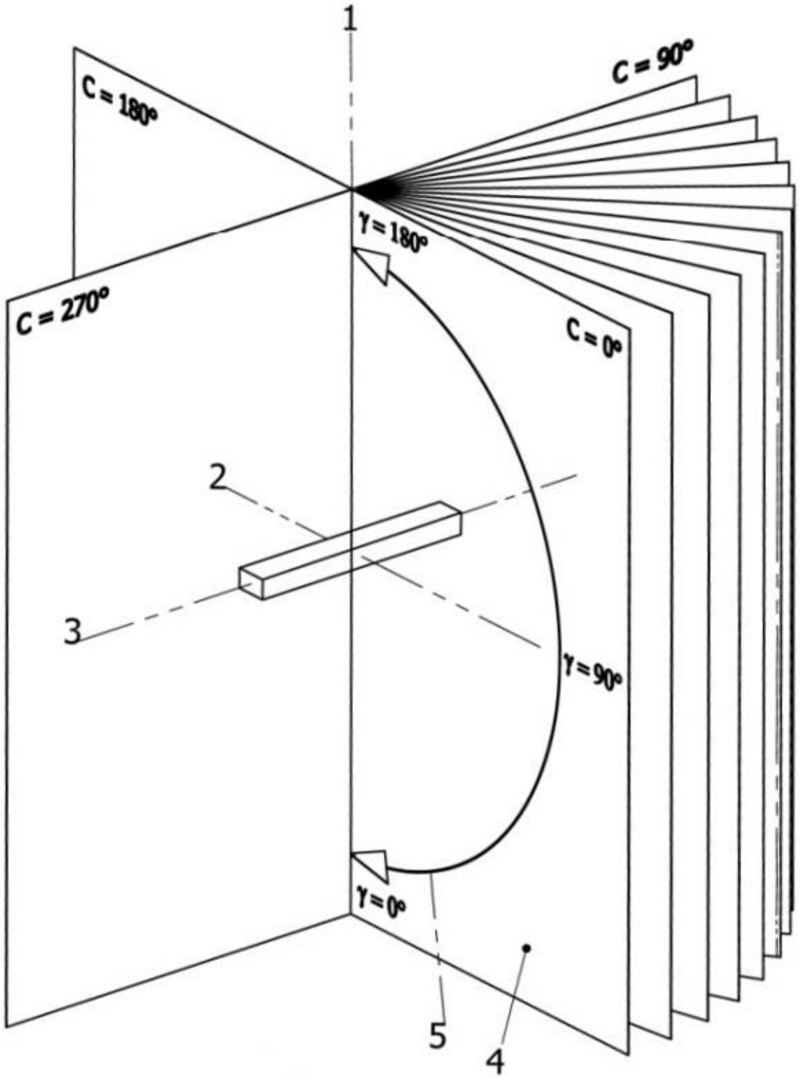
Figure 2 — Flow chart illustrating the determination of the daylight dependency factor $F_{D,n}$ in a zone

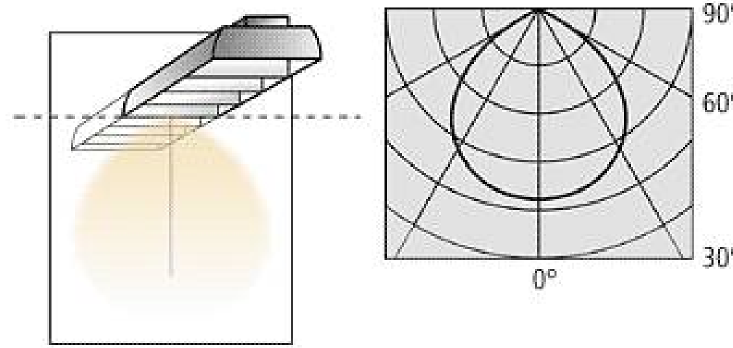
Intensity Distribution

- a.k.a. Light Distribution Curve, Luminous Intensity Distribution Curve
- Describes the photometric characteristics of a luminaire
- Relative photometry: Lamp and luminaire are measured separately; LDC is normalised to cd/1,000 lm. This allows it to be used with different lamps.
- Absolute photometry of LEDs: Light source is integral part of the fitting and can't be separated. LDC is not normalised

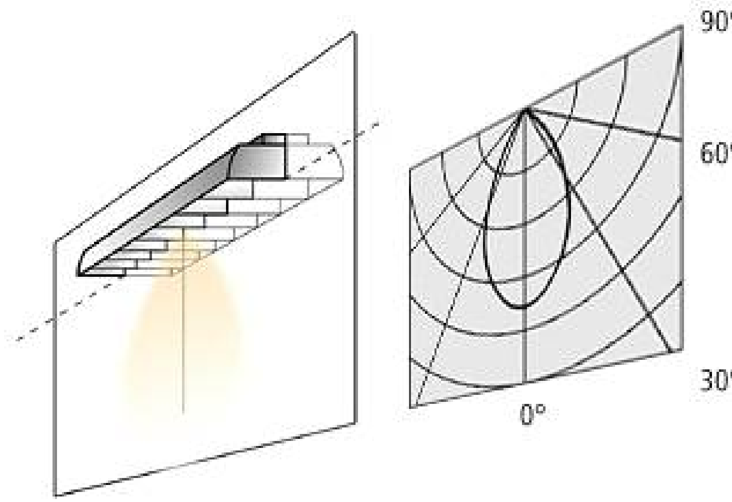


Intensity Distribution – C-Planes



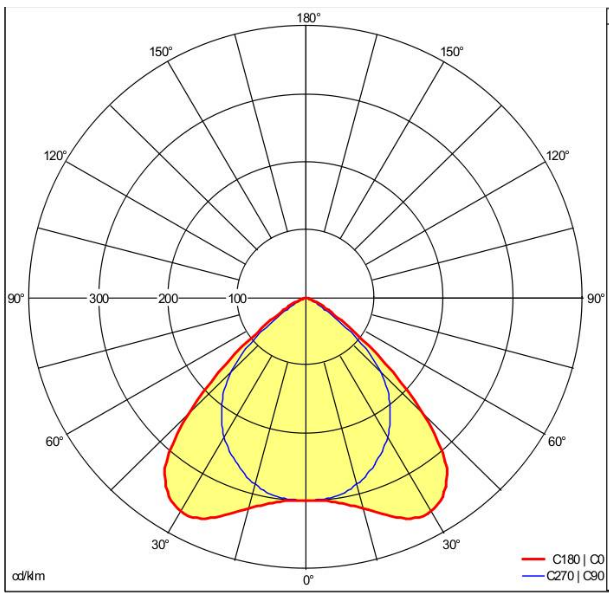


C0 – C180: at right angles to the lamp
C90 – C270: parallel to the lamp

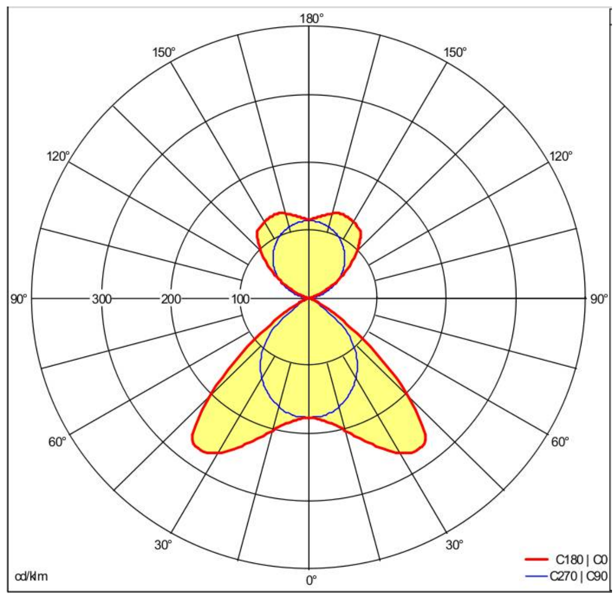


Intensity Distribution

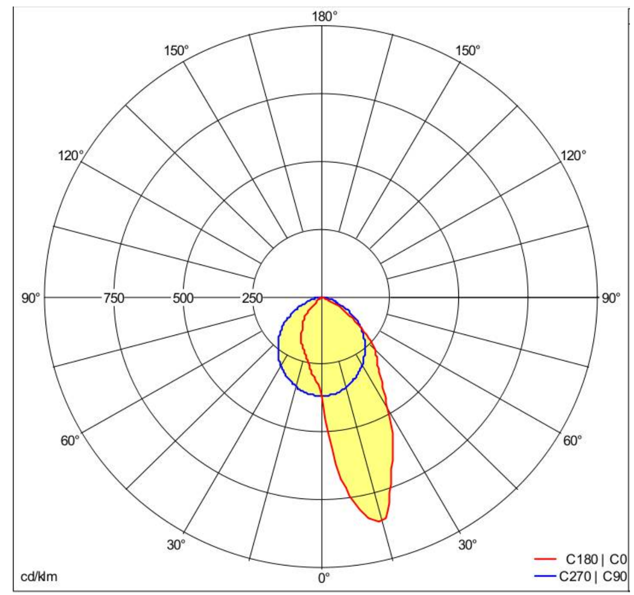
Thorn
Optus IV



Direct
(ceiling-mounted)



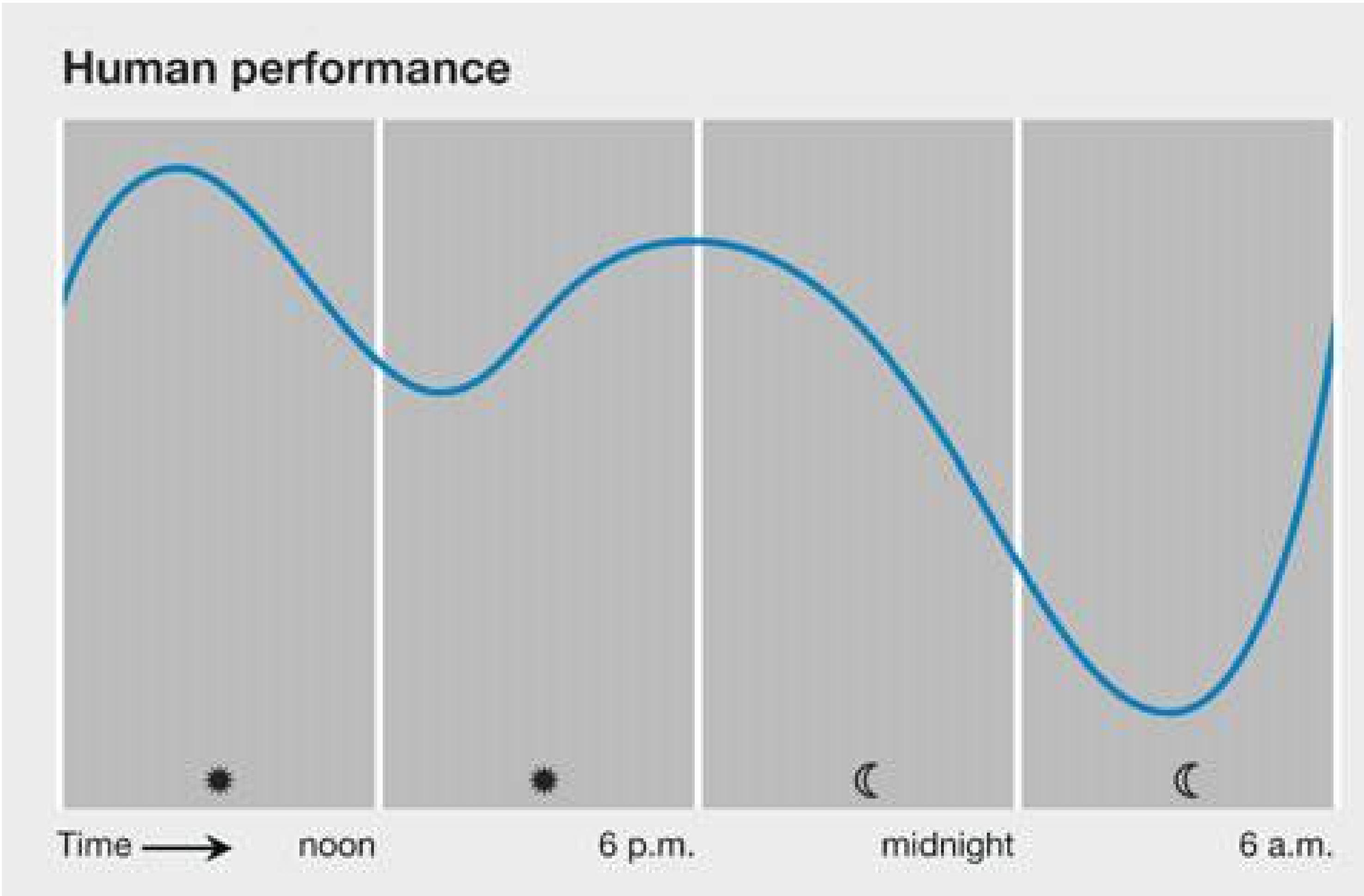
Direct-indirect
(pendant)



Asymmetric
(for whiteboard)

III *Light & Health*

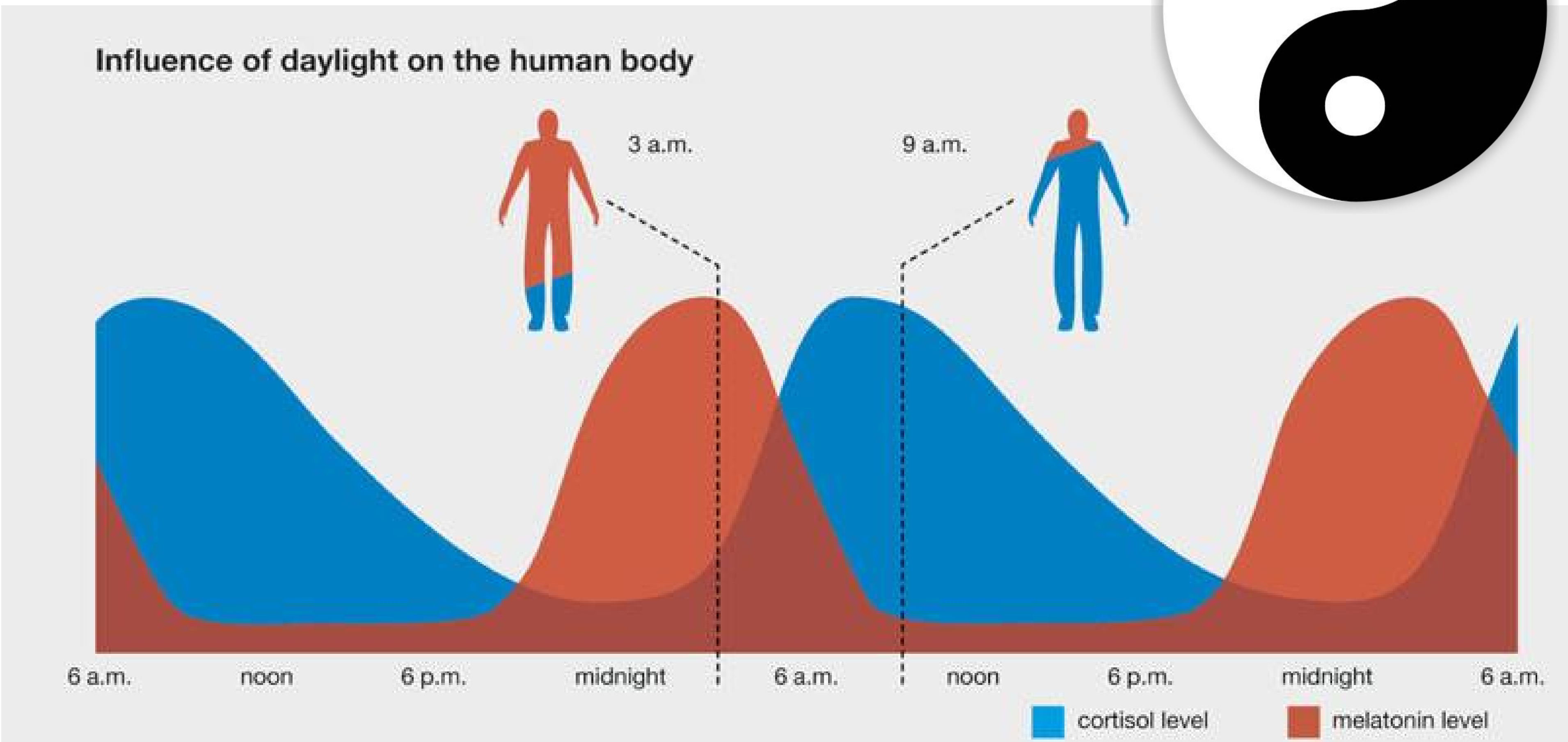
Human Alert Curve



Bodily Clock

Our body's clock is synchronised with the natural environment through natural light.

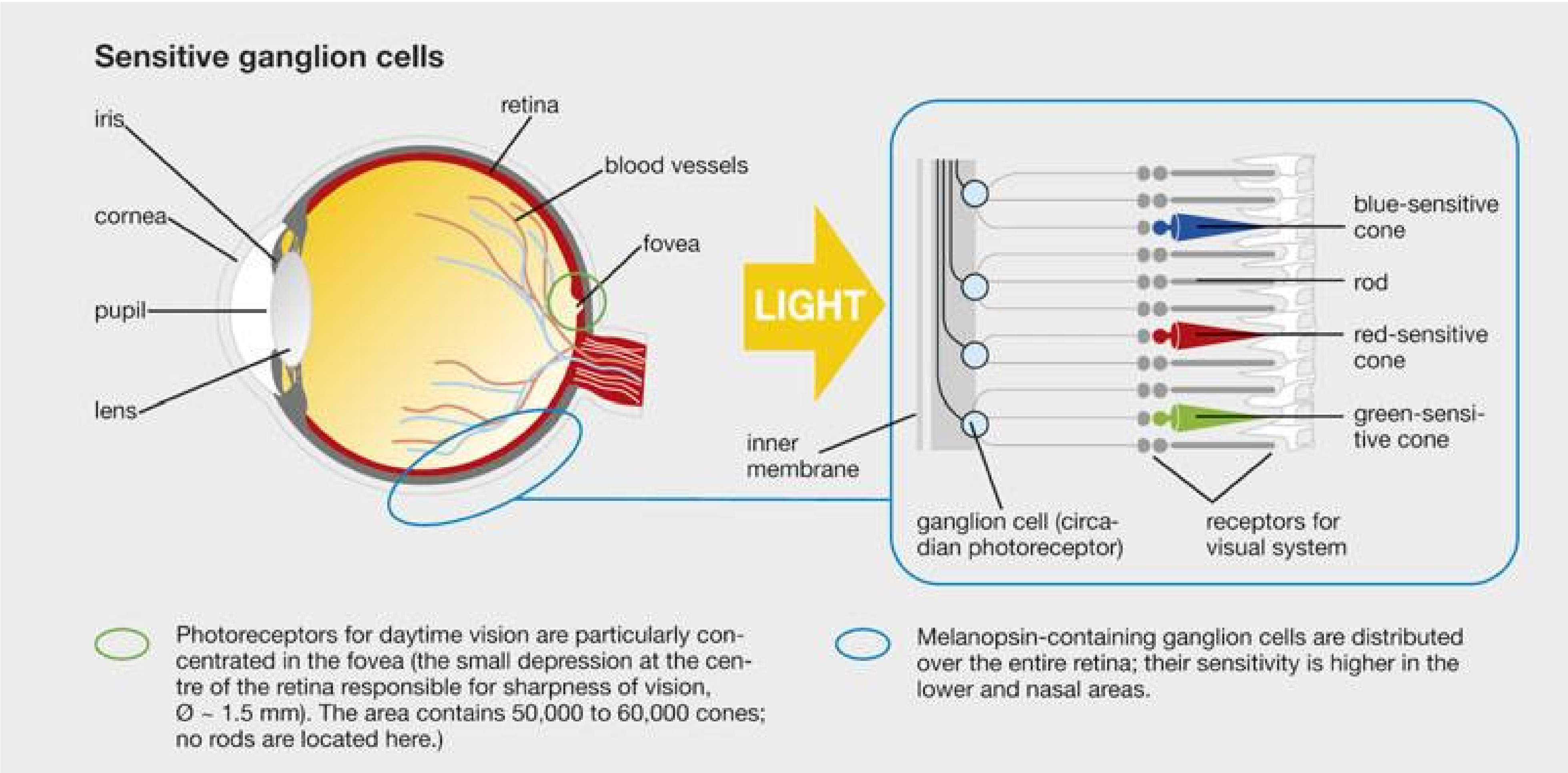
Cortisol v Melatonin



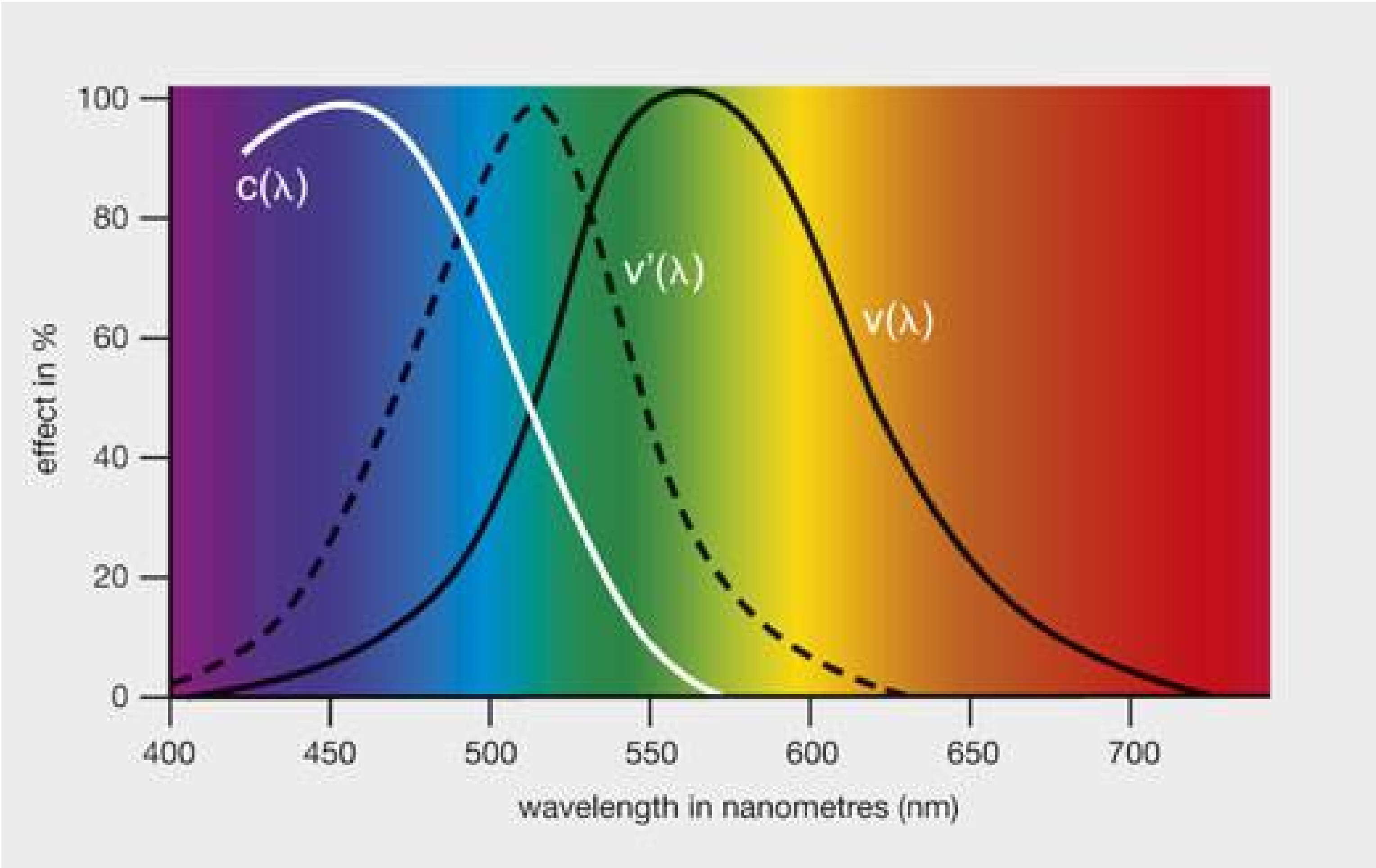
Stress hormone

"Hormone of darkness"

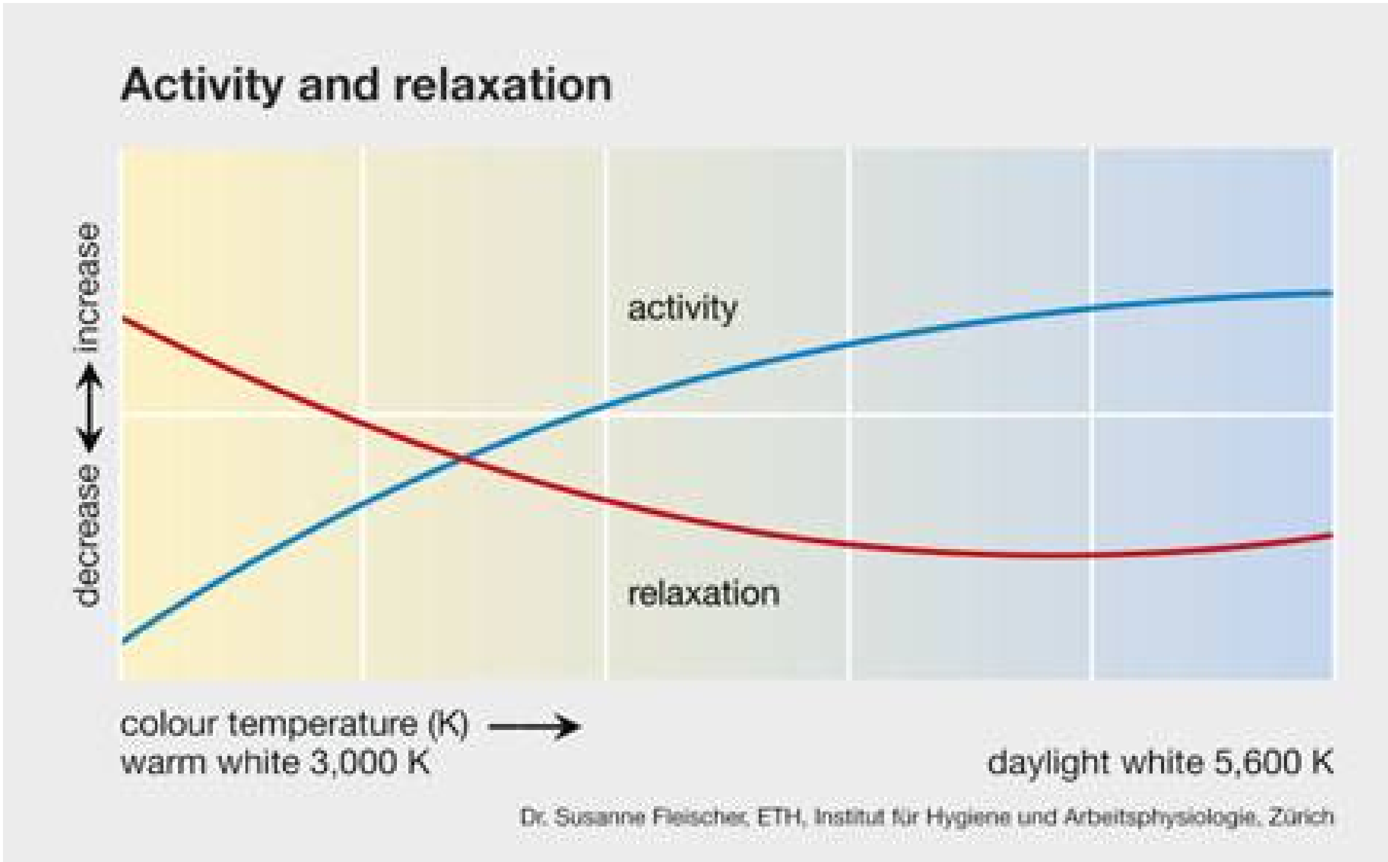
Photo Receptors



Circadian Response Function



CCT v Hormone Levels

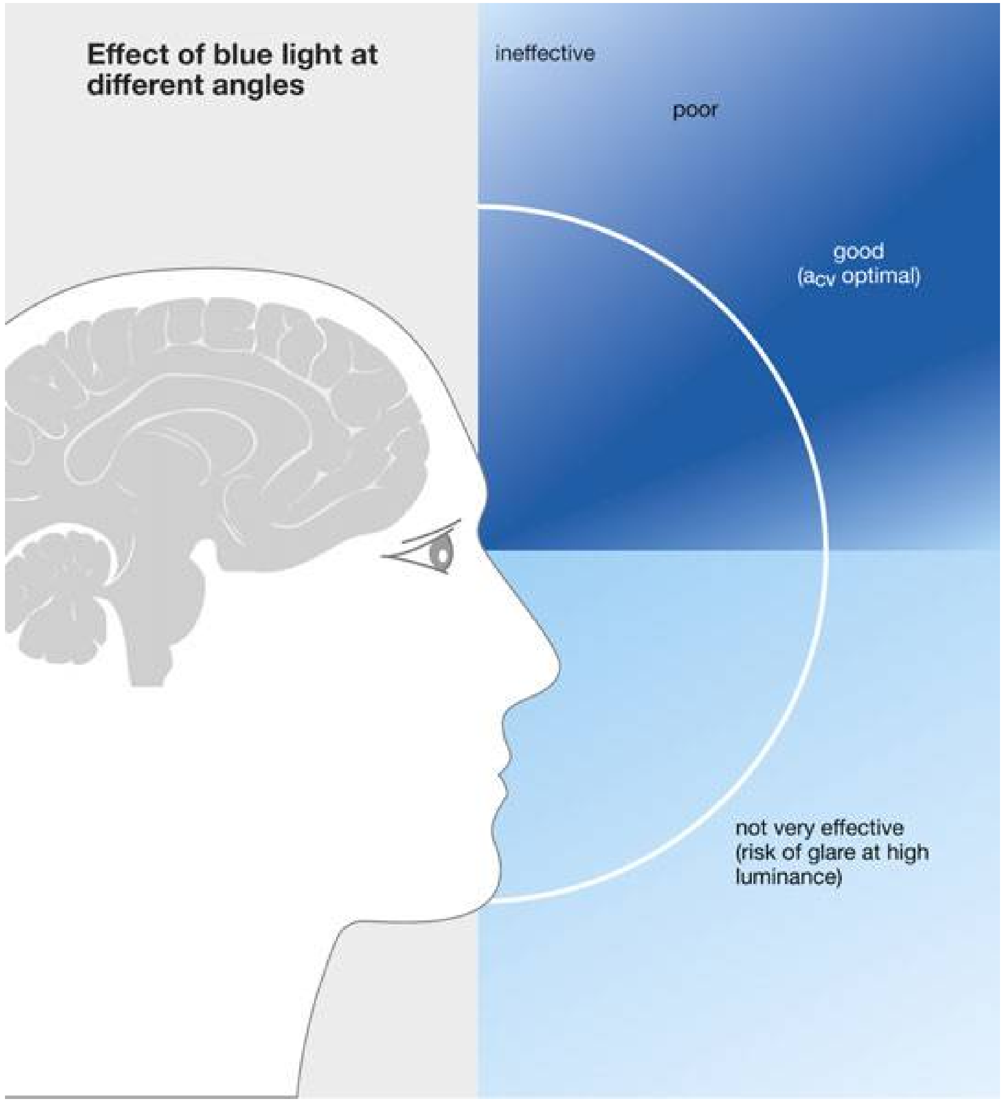


To be effective, light levels need to be higher than normal with artificial light

SAD Lamp

2,000 – 10,000 lx
are needed for any
biological effect
to occur

Natural Light = Light from Above

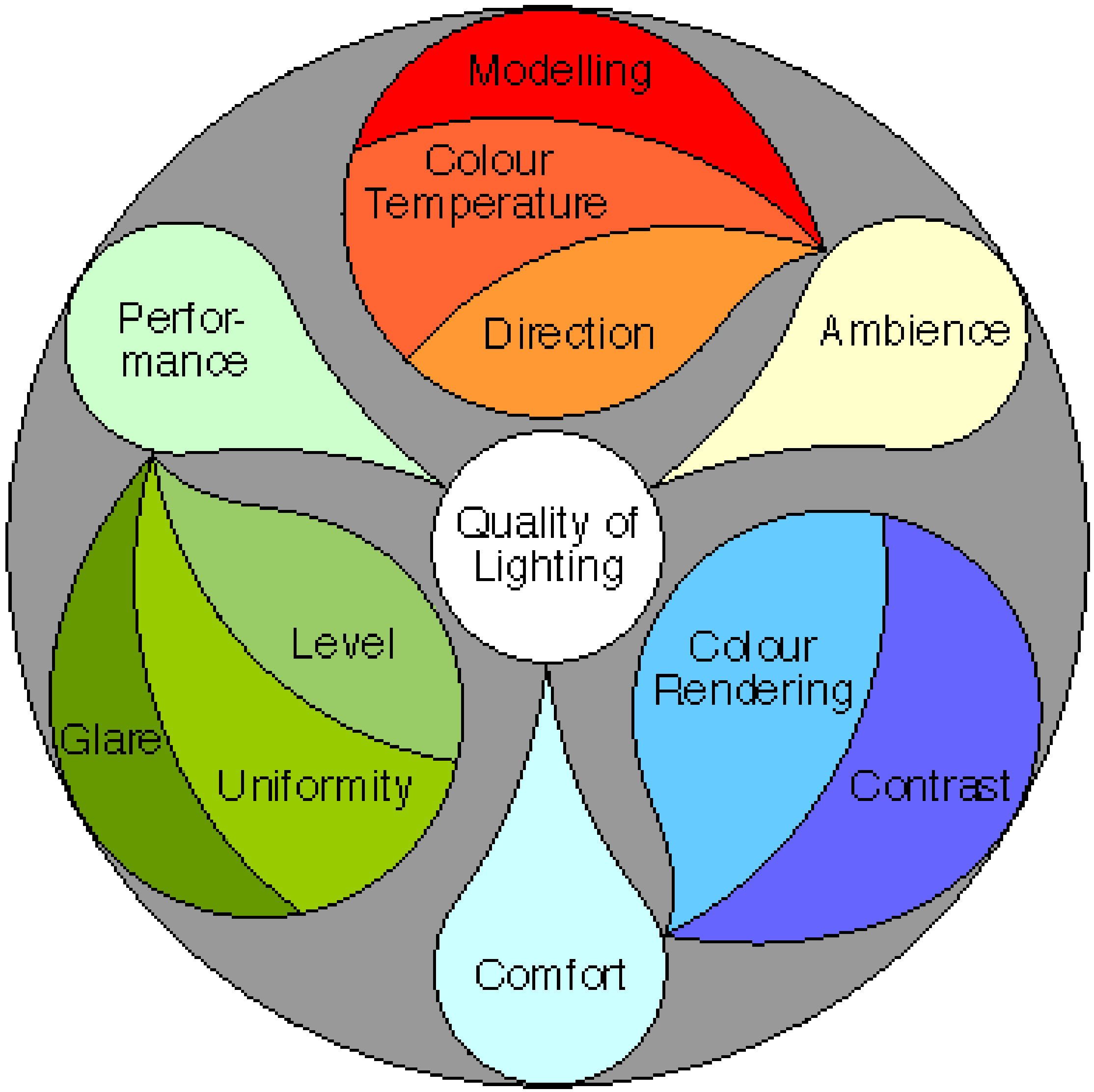


Flicker

- Flicker used to be a problem with fluorescent lighting on magnetic ballasts. This is a health risk!
- HF electronic ballasts got rid of this problem
- LED lighting (specifically, the drivers) has put the issue back on the agenda
- You must assume that an LED light source flickers unless the manufacturer proves otherwise.
- LED flicker can be much worse than magnetic fluorescent flicker
- See separate flicker presentation...

VI *Lighting Design*

Objectives


Modelling
Colour Temperature
Direction
Ambience
Perfor-
mance
Quality of Lighting
Level
Glare
Uniformity
Colour Rendering
Contrast
Comfort

Performance – Illuminance Level

“The illuminance and its distribution on the task area and the surrounding area have a great impact on how quickly, safely and comfortably a person perceives and carries out the visual task.

“All values of illuminances specified in this standard are maintained illuminances and will provide for visual comfort and performance needs.” [BS EN 12464-1]

The recommended scale of illuminance (in lx) is:

20 - 30 - 50 - 75 - 100 - 150 - 200 - 300 - 500 - 750 - 1000 - 1500 - 2000 - 3000 - 5000

Performance – Illuminance Level

The required maintained illuminance should be increased, when:

- visual work is critical,
- errors are costly to rectify,
- accuracy or higher productivity is of great importance,
- the visual capacity of the worker is below normal,
- task details are of unusually small size or low contrast,
- the task is undertaken for an unusually long time.

The required maintained illuminance may be decreased when:

- task details are of an unusually large size or high contrast,
- the task is undertaken for an unusually short time.

Performance – Uniformity

Uniformity: E_{min} / E_{avrg}

Task area: ≥0.7

Immediate surrounding area: ≥0.5 (0.5 m strip)

Performance – Glare

- Is caused by a large difference between the object or background luminance and a very bright light source
- Light source may be the sun, an artificial source, or even reflected light
- Leads to reduced visibility and/or discomfort

We will talk about glare in one of the next DEEAL lectures.

Example from BS EN 12464-1

3	Offices				
Ref. no.	**Type of interior, task or activity**	**$\bar{E}_m$** lx	**UGR_L** -	**R_a** -	**Remarks**
3.1	Filing, copying, etc.	300	19	80	
3.2	Writing, typing, reading, data processing	500	19	80	DSE-work: see 4.11.
3.3	Technical drawing	750	16	80	
3.4	CAD work stations	500	19	80	DSE-work: see 4.11.
3.5	Conference and meeting rooms	500	19	80	Lighting should be controllable.
3.6	Reception desk	300	22	80	
3.7	Archives	200	25	80	

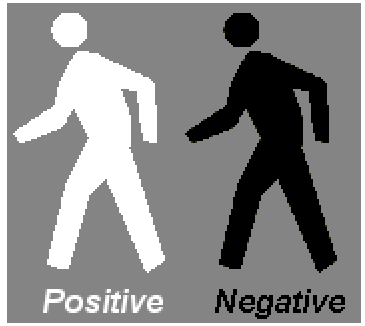
Comfort – Colour Rendering

Group	R_a	Importance	Typical application
1A	90...100	accurate colour matching	Galleries, medical examinations, colour mixing
1B	80...90	accurate colour judgement	Home, hotels, offices, schools
2	60...80	moderate colour rendering	Industry, offices, schools
3	40...60	accurate colour rendering is of little importance	Industry, sports halls
4	20...40	accurate colour rendering is of no importance	Traffic lighting

The CIE colour rendering groups

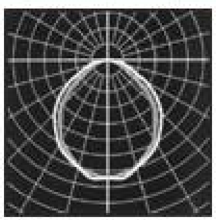
Comfort – Contrast

$$C = \frac{L_{object} - L_{background}}{L_{background}}$$

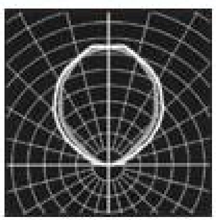


- Ensure objects are clearly visible against background, but avoid high contrast
- Positive contrast: Object lighter than background
- Negative contrast: Object darker than background

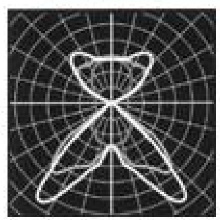
Ambience – Directionality & Modelling



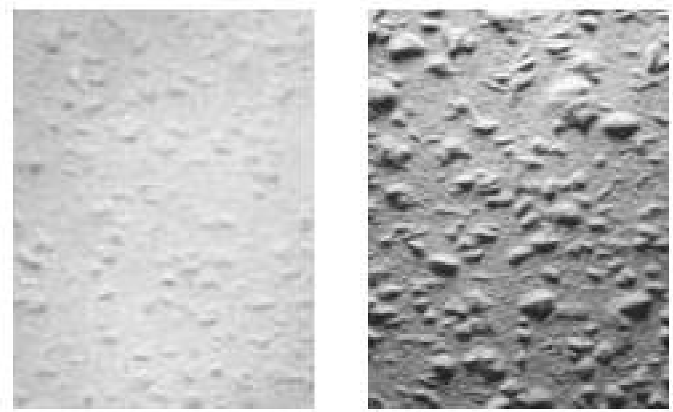
direct



indirect



direct-indirect



Diffusely and directly lit wall

Ambience – Colour Temperature

Illuminance [lux]	Colour of light sources		
	warm	neutral	cold
	Emotional response		
below 500	*pleasant*	neutral	cold
500...1,000			
1,000...2,000	stimulating	*pleasant*	neutral
2,000...3,000			
above 3,000	un-natural	stimulating	*pleasant*

The emotional reponse depends on the ambient illuminance level

- A CCT of 3,000 to 4,000K is typical for offices

V *Lumen Method*

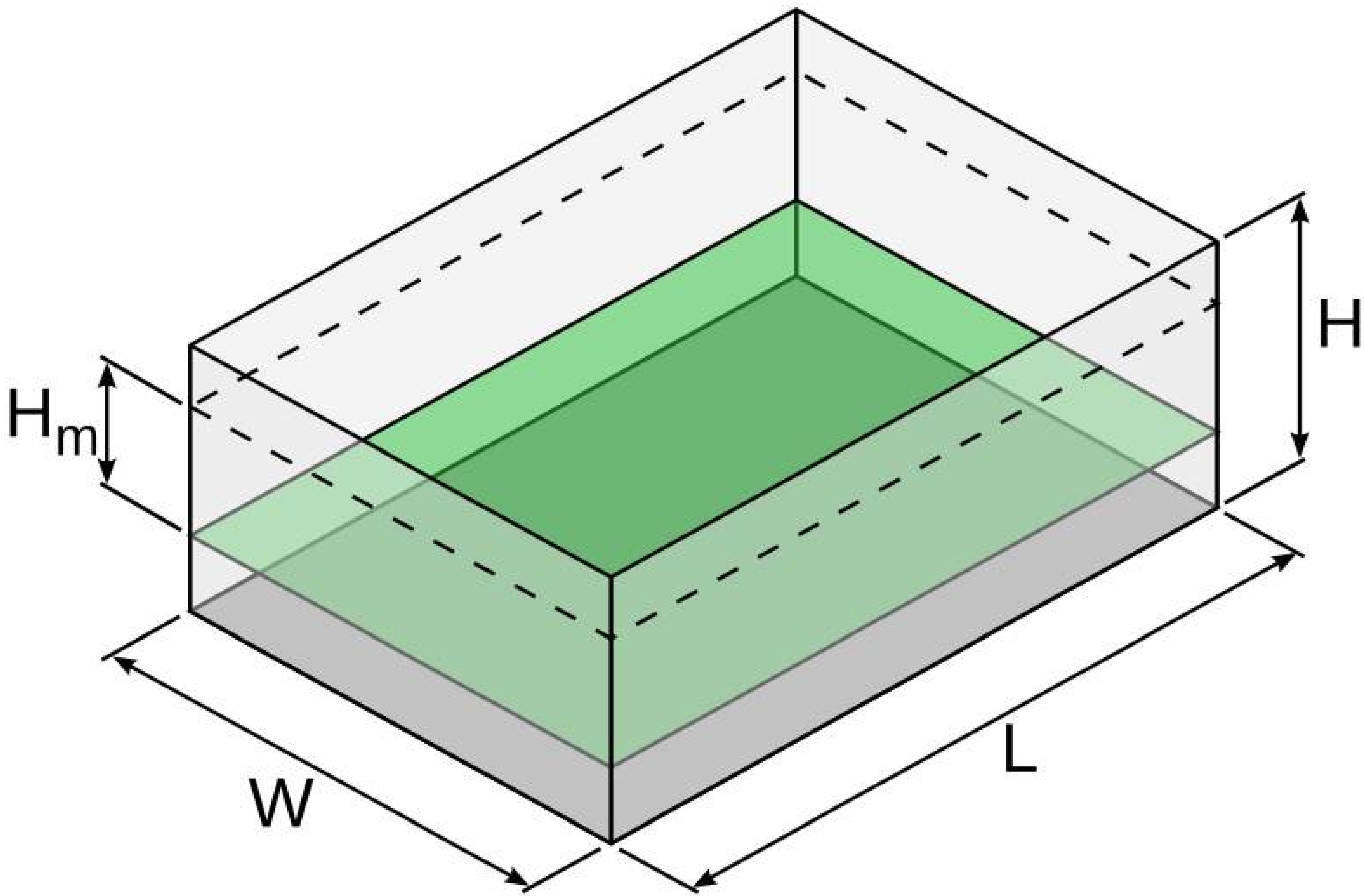
Lumen Method

- a.k.a. Flux method
- Simplified method to calculate illuminance levels in a room
- Based on a target illuminance E and a type of luminaire, calculate how many fittings are needed
- Intermediate steps:
  Room index RI, Maintenance Factor MF,
  Utilisation Factor UF, Spacing-to-Height ratio SHR

Lumen Method - Steps

1. Determine required illuminance E
2. Pick luminaire
3. Calculate the room index RI
4. Calculate the effective reflectances, C, W, F
5. Determine UF from table
6. Determine LLF from lamp data and maintenance tables
7. Calculate the number of luminaires
8. Decide on a luminaire layout
9. Check the maximum SHR is not exceeded
10. Calculate the actually achieved illuminance levels

Lumen Method - RI



Lumen Method - RI

Room index

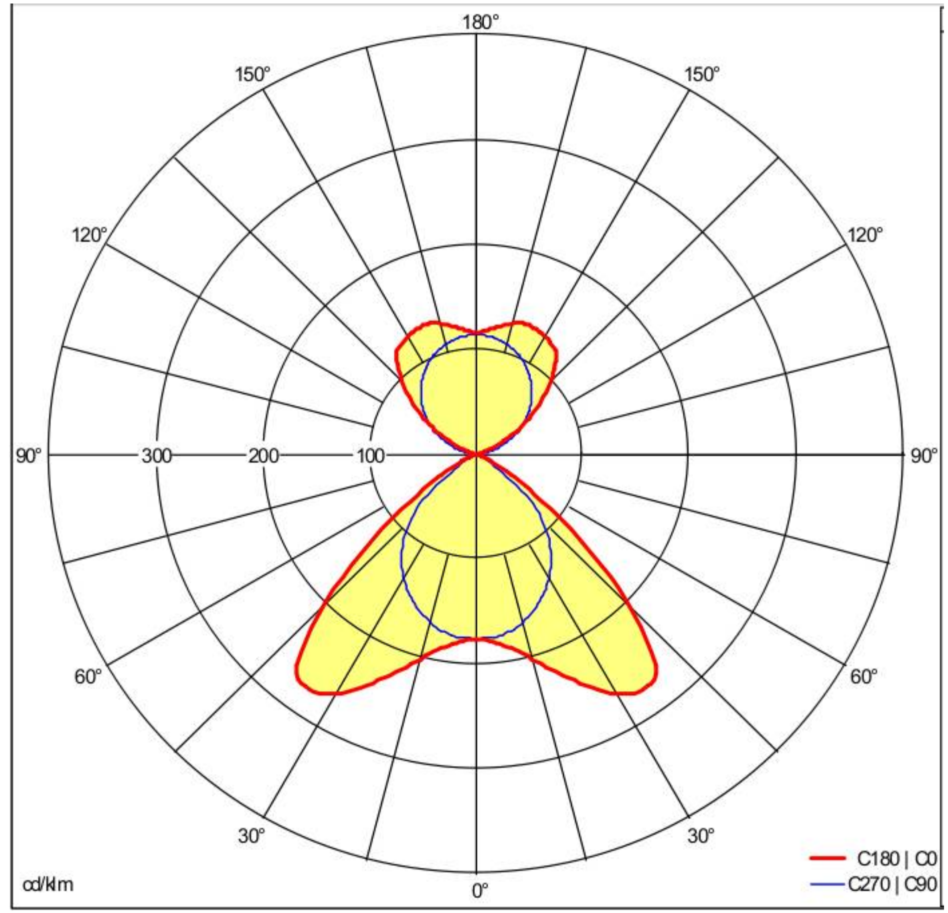
$$RI = \frac{L \cdot W}{H_m (L + W)}$$

L Length of room

W Width of room

H_m Mounting height of luminaires above working plane

Lumen Method - UF



Thorn Optus IV pendant direct-indirect luminaire

Lumen Method - UF

The Utilisation Factor is the proportion of the lamp lumens incident on the working plane, both directly and by inter-reflection. It depends on

- Luminaire's Light Output Ratio (LOR)
- Luminaire's light distribution
- Room index
- Reflectance of walls, ceiling, floor

Obtain UF from manufacturer's specifications.

UF – Example (Thorn Optus IV d-i)

Utilization Factors									
Room Reflectance Ceiling/Walls/Floor	Room Index								
	0.75	1.00	1.25	1.50	2.00	2.50	3.00	4.00	5.00
70 / 50 / 20	NA	60	64	67	71	74	76	78	80
70 / 30 / 20	NA	55	59	63	67	71	73	76	78
70 / 10 / 20	NA	52	56	60	65	68	70	74	76
50 / 50 / 20	NA	54	57	60	63	65	67	69	70
50 / 30 / 20	NA	51	54	57	61	63	65	67	68
50 / 10 / 20	NA	48	52	54	58	61	63	66	67
30 / 50 / 20	NA	49	51	53	56	57	59	60	61
30 / 30 / 20	NA	47	49	51	54	56	57	59	60
30 / 10 / 20	NA	45	47	50	53	55	56	58	59
0 / 0 / 0	NA	39	41	42	44	45	46	47	47

According to CIBSE Technical Memorandum No. 5 1980

SHR Nom =	2.00
SHR Max =	2.02
SHR Max TR=	2.29

Lumen Method - MF

Maintenance Factor

$MF = LLMF \cdot LSF \cdot LMF \cdot RSMF$

LLMF	Lamp Lumen maintenance Factor - the reduction in lumen output after specific burning hours
LSF	Lamp Survival Factor - the percentage of lamp failures after specific burning hours
LMF	Luminaire Maintenance Factor - the reduction in light output due to dirt deposited on or in the luminaire
RSMF	Room Surface Maintenance Factor - the reduction in reflectance due to dirt deposition

Assume MF = 0.7 if details are unknown.

LMF
Luminaire Maintenance Factor

Cleaning frequency (a)	1				2				3			
Environmental conditions	P	C	N	D	P	C	N	D	P	C	N	D
A Open luminaires	0.96	0.93	0.89	0.83	0.93	0.89	0.84	0.78	0.91	0.85	0.79	0.73
B Open-top reflectors	0.96	0.90	0.86	0.83	0.89	0.84	0.80	0.75	0.84	0.79	0.74	0.68
C Closed-top reflectors	0.94	0.89	0.81	0.72	0.88	0.80	0.69	0.59	0.84	0.74	0.61	0.52
D Closed reflectors	0.94	0.88	0.82	0.77	0.89	0.83	0.77	0.71	0.85	0.79	0.73	0.65
E Dustproof luminaires	0.98	0.94	0.90	0.86	0.95	0.91	0.86	0.81	0.94	0.90	0.84	0.79
F Luminaires with indirect emission	0.91	0.86	0.81	0.74	0.86	0.77	0.66	0.57	0.80	0.70	0.55	0.45

RSMF
Room Surface Maintenance Factor

Cleaning frequency (a)	1				2				3			
Environmental conditions	P	C	N	D	P	C	N	D	P	C	N	D
Direct emission	0.99	0.98	0.96	0.95	0.97	0.96	0.95	0.94	0.97	0.96	0.95	0.94
Direct/indirect emission	0.96	0.92	0.88	0.85	0.93	0.89	0.85	0.81	0.90	0.86	0.82	0.78
Indirect emission	0.94	0.88	0.82	0.77	0.91	0.84	0.77	0.70	0.84	0.78	0.72	0.64

Classification of Environmental Conditions

P (very clean room) pure
C (clean room) clean
N (average conditions) normal
D (dirty room) dirty

LLMF
Lamp Lumen Maintenance Factor

Hours of operation (h)	2000	4000	6000	8000	10000	12000	14000	16000	18000	20000
Tungsten halogen lamps/ low-voltage	0.95	--	--	--	--	--	--	--	--	--
Metal halide lamps	0.86	0.82	0.75	0.69	0.66	--	--	--	--	--
High-pressure sodium vapour lamps	0.99	0.98	0.98	0.97	0.97	0.96	0.96	0.95	0.95	0.94
Compact fluorescent lamps	0.92	0.88	0.85	0.83	0.83	--	--	--	--	--
Fluorescent lamps	0.96	0.95	0.94	0.93	0.92	0.91	0.90	0.89	0.88	0.88

LSF
Lamp Survival Factor

If defective lamps are replaced immediately, the lamp survival factor applied is LSF = 1.

Lumen Method – E

Average illuminance

$$E = \frac{F \cdot n \cdot N \cdot MF \cdot UF}{A}$$

F Initial lamp lumens
N Number of luminaires
n Lamps per luminaire
MF Maintenance factor
UF Utilisation factor
A Area

Lumen Method – SHR

Spacing-to-Height ratio

Even if average illuminance meets the target, ensure that the distribution of illuminance at the working plane is sufficiently uniform.

As a rule of thumb, the spacing S between the luminaries to should be no larger than 1.5 times the mounting height H_m, but consult the spec sheet.

$$\frac{S}{H_m} < 1.5$$

References

- Erco Light Scout
- licht.de
- SynthLight handbook
- CLEAR
- Solid-State Lighting Technology Fact Sheets
- Lou Bedocs: Why LENI?