EPFL

CIVIL - 450: THERMODYNAMICS of COMFORT in BUILDINGS

Dolaana Khovalyg

Lecture 06:

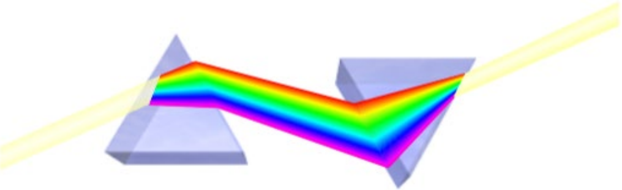
Performance of Windows

9 May 2025

Course Information - Schedule

Classroom GC D0 386 is on the Lausanne campus

WEEK	Date	Content	Location
1	21.02.2025	Intro to thermal comfort and human thermoregulation	GC D0 386
2	28.02.2025	Human body energy balance	GC D0 386
3	07.03.2025	Exergy analysis in the built environment (*guest lecture*)	GC D0 386
4	14.03.2025	Lab #1 in Fribourg (climatic chamber). Measurements and instrumentation.	EPFL-Fribourg
5	21.03.2025	Group work on Lab #1	GC D0 386
6	28.03.2025	Group work on Lab #1	GC D0 386
7	04.04.2025	Invisible radiant heat: transparent & translucent building elements and their effect on comfort (*guest lecture*)	GC D0 386
8	11.04.2025	Lab #1 presentations, reports submission	GC D0 386
9	18.04.2025	Good Friday (holiday)	No class
10	25.04.2025	Easter break	No class
11	02.05.2025	Lab #2 in Fribourg (building prototype)	EPFL-Fribourg
12	09.05.2025	Building-environment interaction and energy balance Group work on Lab #2	GC D0 386
13	16.05.2025	Group work on Lab #2	GC D0 386
14	23.05.2025	Group work on Lab #2	GC D0 386
15	30.05.2025	Lab #2 presentations, reports submission. Course summary and course evaluation.	GC D0 386



CONTENT:

- Introduction:
  - Electromagnetic waves and spectra
  - Radiant and luminous fluxes, solar irradiance/irradiation, illuminance
- Performance of windows and shades:
  - Transmittance / Reflectance / Absorbtion
  - g and g_{tot} values, their typical ranges
- Overview of measuring instruments

Energy travelling as Electromagnetic Waves

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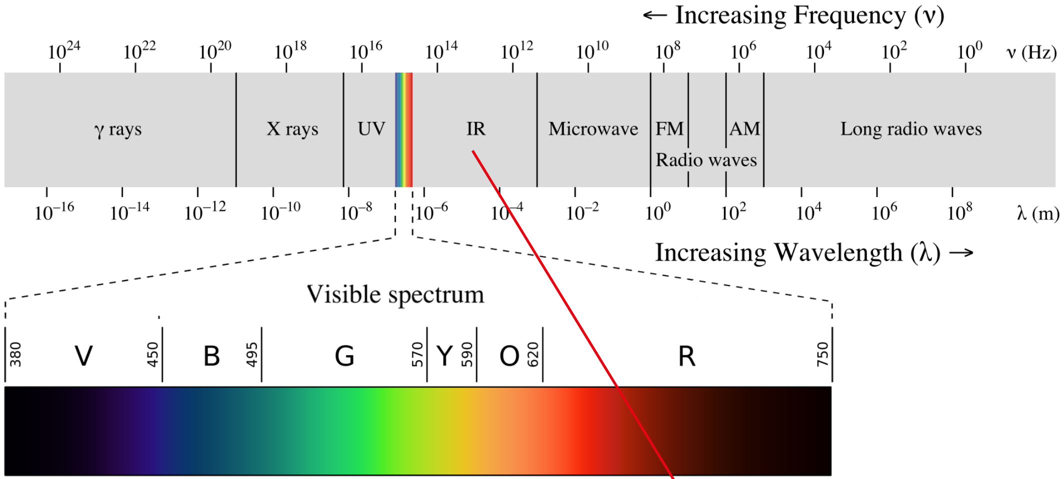
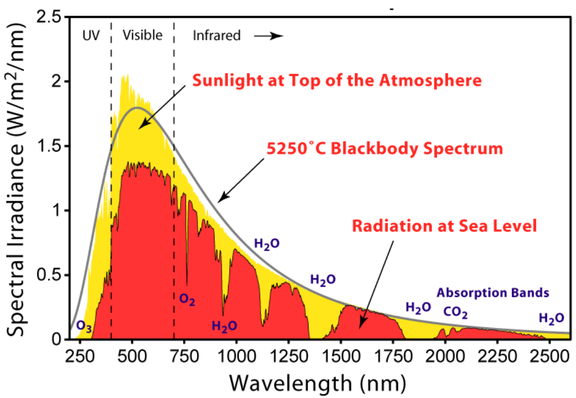
- Any **electromagnetic wave (EM)** can be characterized by its frequency **ν** or its wavelength **λ**:

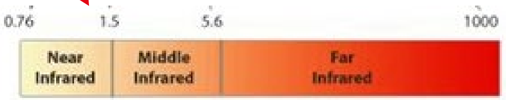
$$\mathbf{c = \nu \cdot \lambda} \qquad (6\text{-}1)$$

c - wave velocity in [m/s]

- For EM waves, various «bands» are defined according to the physical phenomena they can trigger or undergo
- For humans, **visible wavelengths** are from 380 to 780 nm
- The **infrared band** is subdivided into three (near, middle, and far)





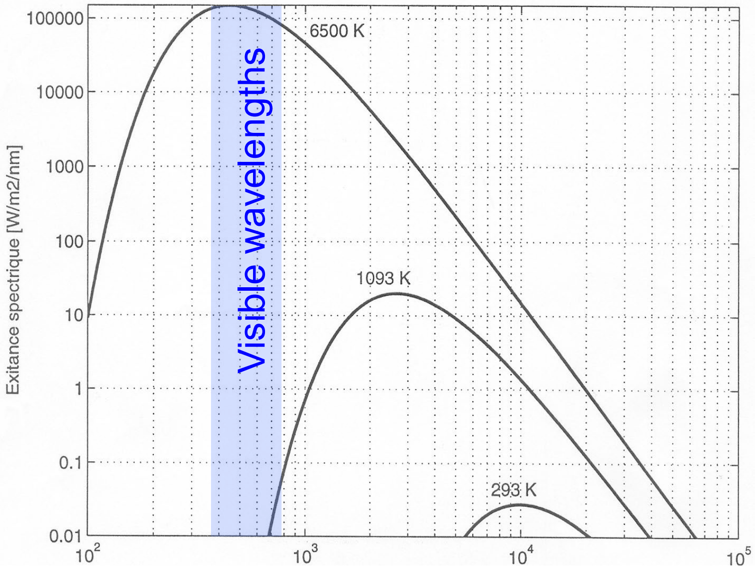


At sea level, solar energy is distributed as follows:
3% **UV**, 55% **Visible**, 42% **Infrared**

Some physical characteristics of a radiant flux

- An electromagnetic flux is generally composed of *a huge number of waves* each having its own wavelength, a spectrum shows how the radiant power is distributed over wavelengths
- Any surface at T > 0 K spontaneously emits electromagnetic waves. Although it is called *thermal* radiation, this is not heat
- The spectrum of this radiation (called black-body spectrum) varies with the temperature.

For common ambient temperatures ~293K, the emitted spectrum is located around 10 µm (i.e. in far infrared)



- **Radiant flux per unit wavelength $\Phi_{e,\lambda}$** - spectral flux usually in [W/nm]
- **Radiant power *emitted*, *reflected*, *transmitted* or *received* Φ_e** - radiant flux in [W]

  Φ_e is computed by integrating $\Phi_{e,\lambda}$ (i.e. the spectrum) over the wavelengths

- **Radiant flux *received by a surface* per unit area I - irradiance** or **flux density** in [W/m^2]

  When dealing with irradiance, the orientation of the receiving plane must be specified!z

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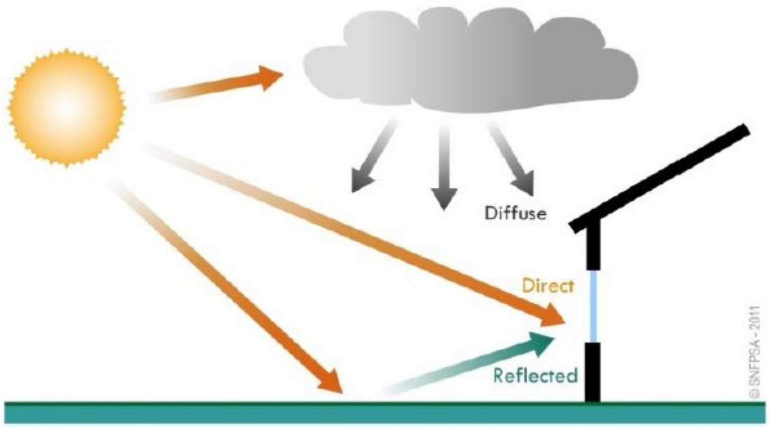
Irradiance and irradiation incident on a surface

- **Global solar irradiance I_g** in [W/m^2] incident on a surface can be divided into 3 components according to its source:

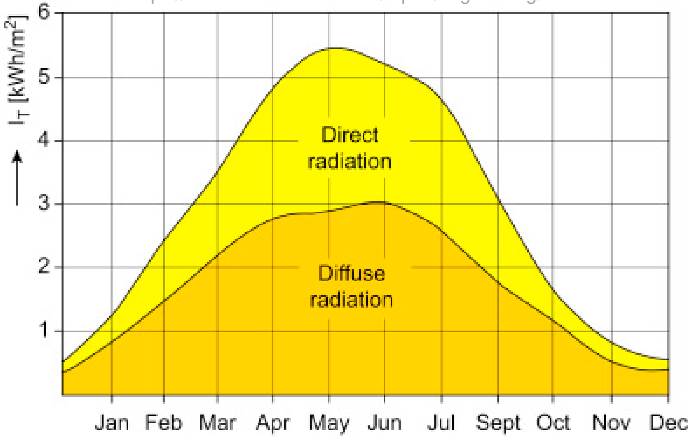
  - **direct (or beam) irradiance I_b**: for the beam coming from the sun
  - **diffuse irradiance I_d**: for the part coming from the rest of the visible sky vault
  - **reflected irradiance I_r:** from reflections over the ground and surrounding obstructions located in front of the surface

$$I_g = I_b + I_d + I_r \quad \text{in [W/m}^2\text{]} \quad (6\text{-}2)$$

- It is common that I_d+I_r are not separately distinguished and are called **diffuse component**
- When irradiance is *integrated over a period of time*, the result is called **irradiation** measured in [kWh/m^2]



https://www.sciencedirect.com/topics/engineering/direct-radiation



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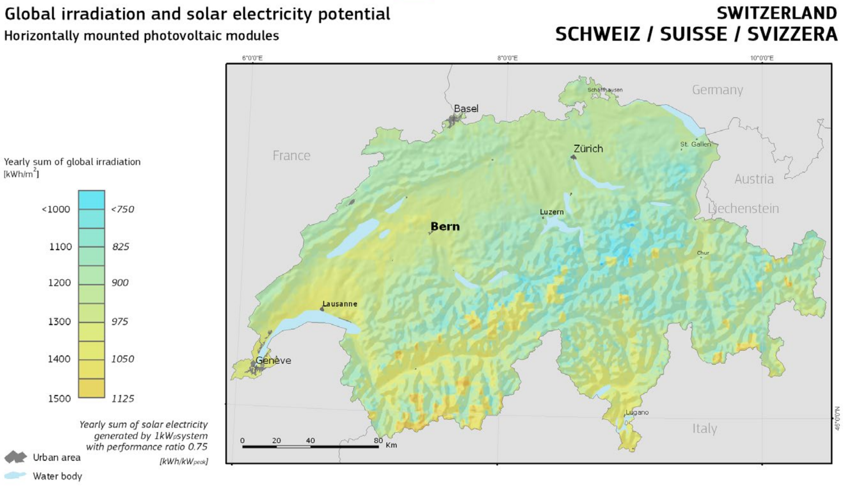
Sources of irradiance/irradiation data

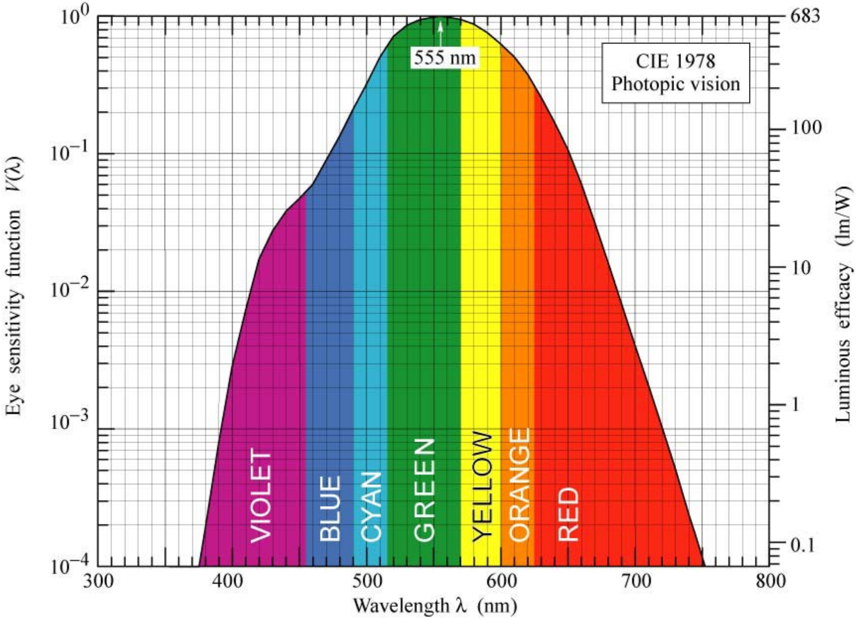
- **Solar irradiance/irradiation data for specific locations are important climatic information for the analysis of buildings**
- There are multiple reliable sources:
  - METEONORM software: www.meteonorm.com
  - Online web databases:
    - PVGIS: re.jrc.ec.europa.eu/pvgis/
    - SODA-IS: www.soda-is.com
    - SATEL-LIGHT: www.satel-light.com
  - Current values at Swiss meteorological stations: www.meteoswiss.admin.ch/home/measurement-values.html?param=messwerte-globalstrahlung-10min&chart=hour
- Swiss standard SIA 2028 «Données climatiques pour la physique du bâtiment, l'énergie et les installations du bâtiment»

A global yearly irradiation map for horizontal surfaces available from PVGIS:
(click here to enlarge)



Characterizing the visible component of a radiant flux

- The human eye's sensitivity strongly varies over the range of visible wavelengths modelled by a function called **V(λ)**
- Therefore, to quantify the «visible» (or «luminous») content of a radiant flux, its spectral flux $\Phi_{e,\lambda}$ must first be weighted by **V(λ)**
- The resulting «photometric» characteristics are measured using a SI unit called «**lumen**» [lm]
- Φ_v **luminous flux** in [lm]: luminous power emitted, reflected, transmitted or received
- E_v **illuminance** in [lm/m²] or [lx]: luminous flux *received by a surface* per unit area



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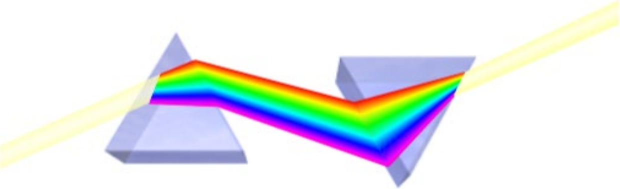

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Characterizing radiant flux interactions with materials

- What happens to a radiant flux Φ_e incident on a pane of material?
  - Specular or diffuse reflection
  - Direct, diffuse or redirected transmission
  - Absorption (this part is converted to heat)
- Because of the energy conservation law:

$$\Phi_{reflected} + \Phi_{transmitted} + \Phi_{absorbed} = \Phi_e \quad (6\text{-}3)$$

After dividing the previous equation by Φ_e:

$$\Phi_{reflected}/\Phi_e + \Phi_{transmitted}/\Phi_e + \Phi_{absorbed}/\Phi_e = 1$$

- Rewriting this by defining factors:

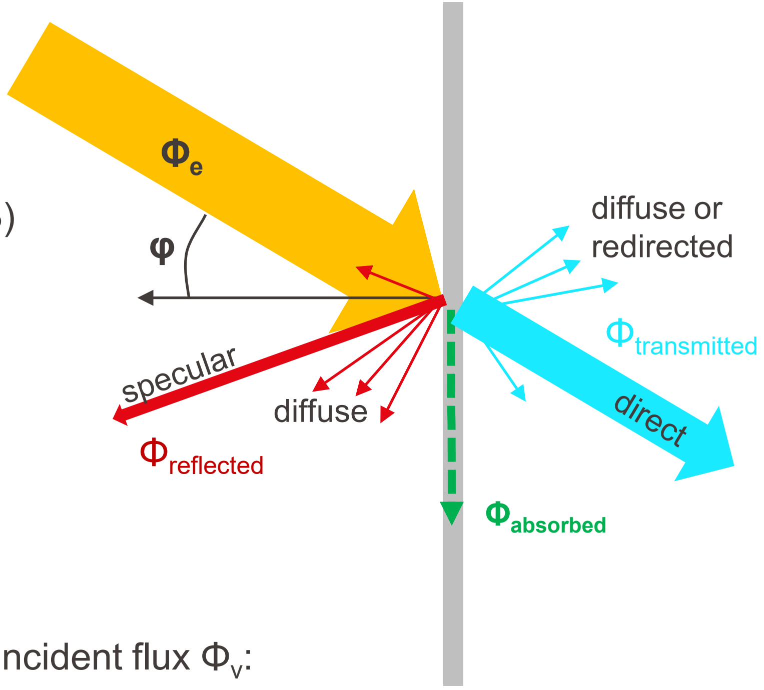
$$\rho + \tau + \alpha = 1 \quad (6\text{-}4)$$

ρ – reflectance, **τ** –transmittance, **α** - absorption

- Similar equation can be specified for a luminous incident flux Φ_v:

$$\rho_v + \tau_v + \alpha_v = 1 \quad (6\text{-}5)$$

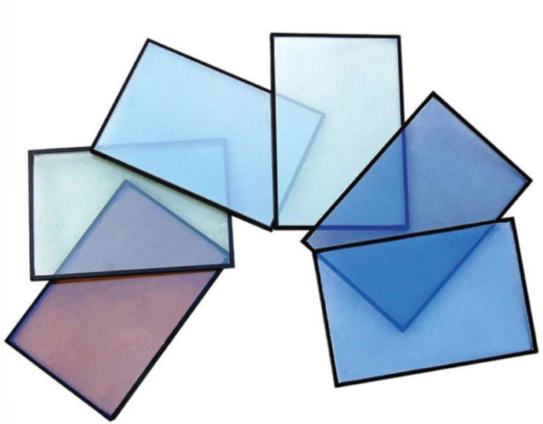
- These characteristics depend on the incidence angle **φ**



Estimations from specific words & visual clues

- **Opaque material**: $\tau_v = 0$
- **Mirror:** high ρ_v , reflection is mainly specular
- **Opaque white surface**: high ρ_v , reflection is mainly diffuse
- **Transparent material**: high τ_v
- **Clear glass**: high τ_v , transmission is mainly direct, reflection is mainly specular
- **Extra-clear glass** (also called «**white glass**»): particularly high τ_v
- **Translucent material**: relatively high τ_v, transmission and reflection are mainly diffuse
- **Reflecting glass**: high ρ_v
- **Absorbing glass**: high α_v
- **Tinted glass**: the spectra of the *reflected* and *transmitted* fluxes are altered either by a special coating or chemical additives in the glass

Clear glass vs. white glass



Special coatings affecting the colour appearance of the glazing

Transmittance of a clear glass pane

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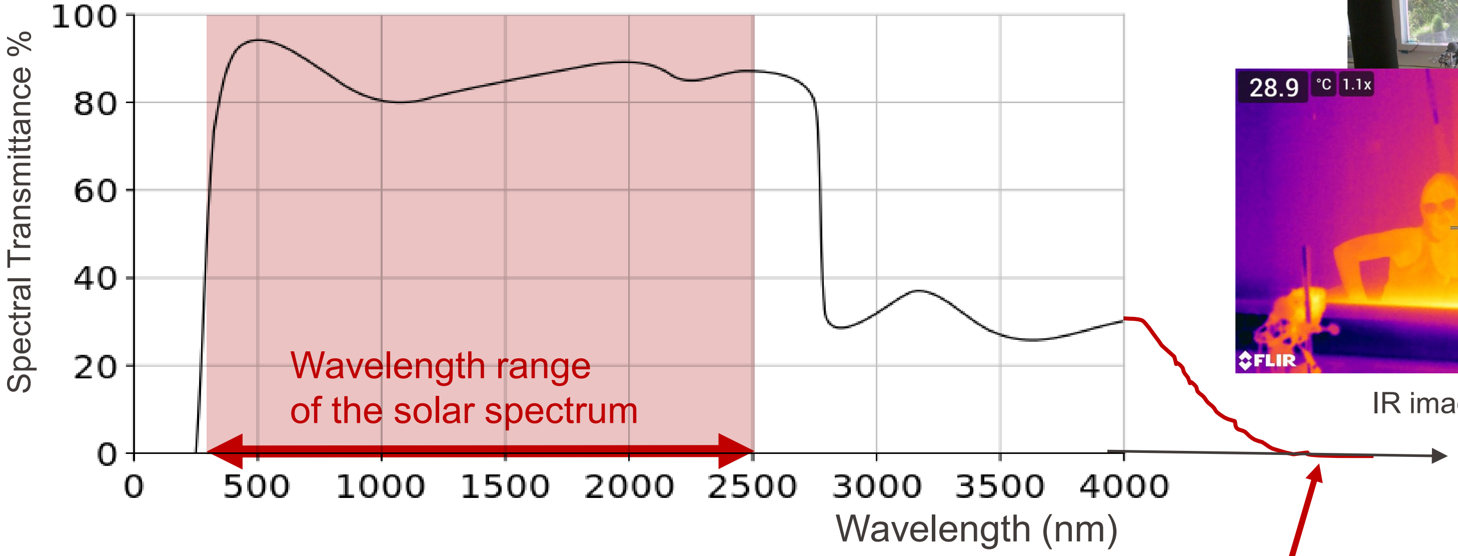
- Glass is a **selective** material since its *spectral transmittance* differs largely between **solar wavelength range** (high transmittance, $\tau_{v,0.3\text{-}3\ nm} > 0$) and **thermal radiation wavelengths** range at common ambient temperatures ~293 K (no transmittance, $\tau_{v,\ 4\text{-}100\ nm} \sim 0$)
- This explains the strong greenhouse effect caused by glass



IR image from LAB 2

glass transmittance rapidly decreases to ~0 for wavelengths > 4000 nm

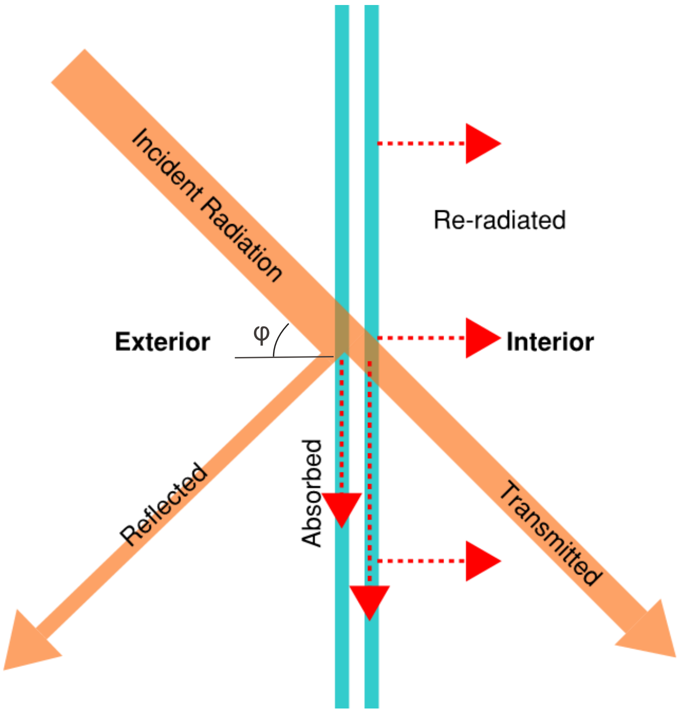
g-value (also called Solar Factor or Total Solar Energy Transmittance)

- **Solar gains through a glazing include**:
  - radiation *transmitted* directly through the glass
  - energy absorbed by the glass and then released as heat towards the interior (via radiation and convection)

$$g = \frac{total\ solar\ gains\ transmitted}{incident\ irradiation\ (on\ the\ window\ pane)} = \tau_e + q_i \quad (6\text{-}6)$$

τ_e - **solar global transmittance**, ratio between the irradiance on the inner surface of the window and the irradiance incident on the outer surface of the window

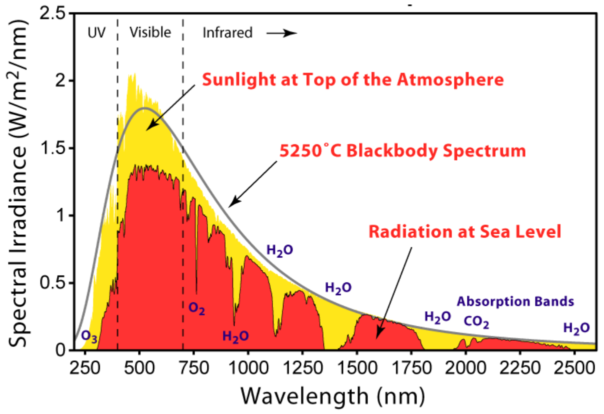
q_i - **secondary internal heat transfer factor,** ratio of the *total heat transferred indoors* and the *global irradiance* incident on the outer surface of the window

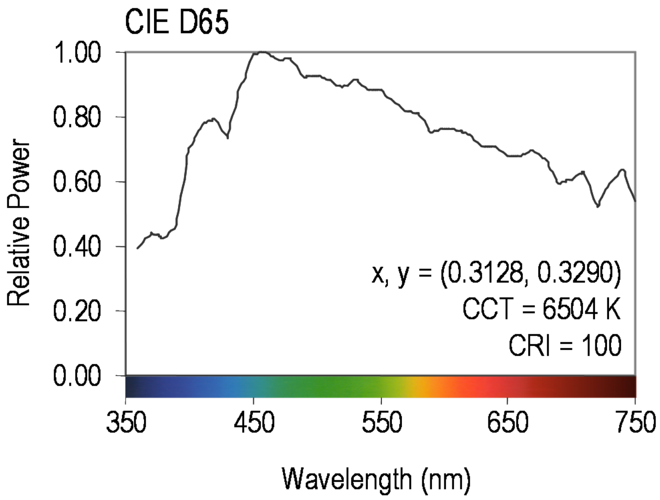


- g-values are usually specified for a radiation beam at *normal incidence* relatively to the glass plane! (angle of incidence φ=0°)

Standard glazing information

- The most useful glazing's characteristics that are provided by their manufacturers are rarely spectral but defined for 2 standard spectra:
  - **Solar direct transmittance** $\tau(solar, n, h)$ (directional-hemispherical) for normal incidence, thus abbreviated (n-h), with the standard solar spectrum at sea level
  - **Secondary internal heat transfer factor** q_i (same conditions as above)
- **g value,** calculated from equation (6-6)
- **Light transmission** $\tau_v(D65, n, h)$ (normal-hemispherical) (n-h) with the standard CIE D65 illuminant spectrum





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Computing g-values of glazing

- **Some glass manufacturers offer online tools to compute g-values and several other characteristics of their products**

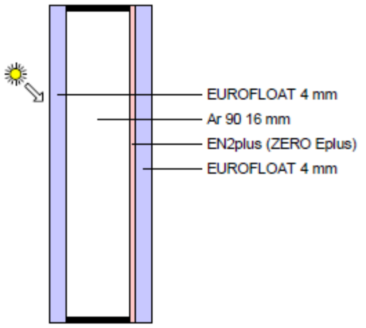
  Usually they require to register before being allowed to use them for free

  - www.euroglas.com/en/service-portal/calculation-programmes/glace.html
  - glassanalytics.guardian.com/
    (particularly interesting: the visual appearance of various glazing can be compared)
  - A software called WINDOW 7 based on a large collection of optical data for glazing products

- Even if a particular glazing composition can be evaluated by these tools it may not be manufacturable or simply unrealistic

Glazing:

Window tilt angle: 90 °



Comments:

Calculated glazing characteristics:

Thermal transmittance Ug:	1.12 W/m²K	EN 673:2011
Total solar energy transmittance (solar factor g):	64.3 %	EN 410:2011
Light transmittance:	81.6 %	
Light reflectance (outside):	11.9 %	
Light reflectance (inside):	11.5 %	
Light absorptance:	6.5 %	
Solar direct transmittance:	56.2 %	
Solar direct reflectance (outside):	25.7 %	
Solar direct absorptance:	18.1 %	
Secondary internal heat transfer factor:	8.1 %	
UV-Transmittance:	30.0 %	
UV-Reflectance:	17.5 %	
UV-Absorptance:	52.6 %	
General colour rendering index (transmission):	97.7	
Selectivity (light transmittance / solar factor g):	1.27	
Shading coefficient (solar factor g / 0.87):	73.9 %	
Shading coefficient (solar factor g / 0.8):	80.4 %	

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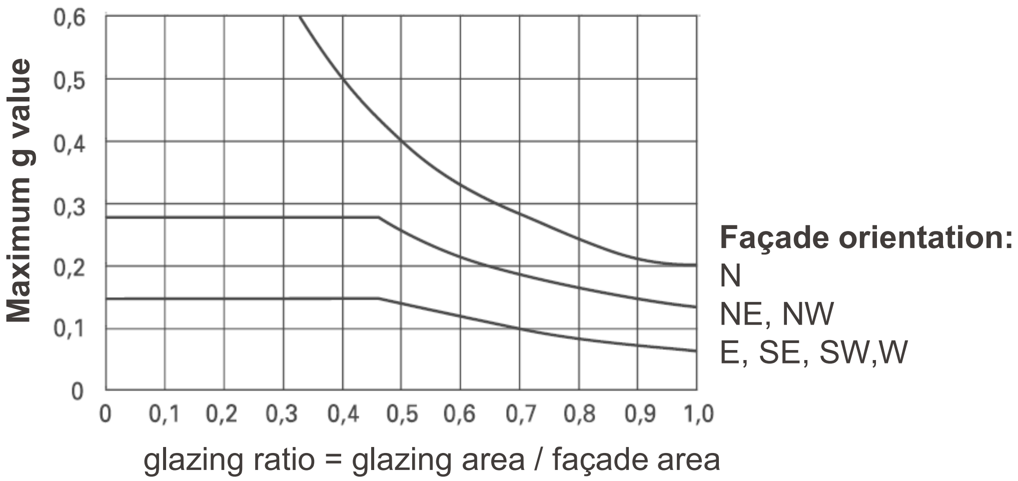
What is an efficient solar protection?

- To prevent buildings to overheat in summer and to avoid the need of an artificial cooling installation (or to reduce its power), **solar gains must be limited!**
- Swiss standard SIA180:2014 specifies 3 methods to ensure, at the design stage, that the risk of overheating will remain limited.

  - A first requirement is to check the **maximum g value allowed** for glazing combined with their solar protection devices
  - Unfortunately, there are very few glazing reaching so low g values *without* any additional solar protection device such as blinds



Light transmittance τ_v versus g-value of glazing

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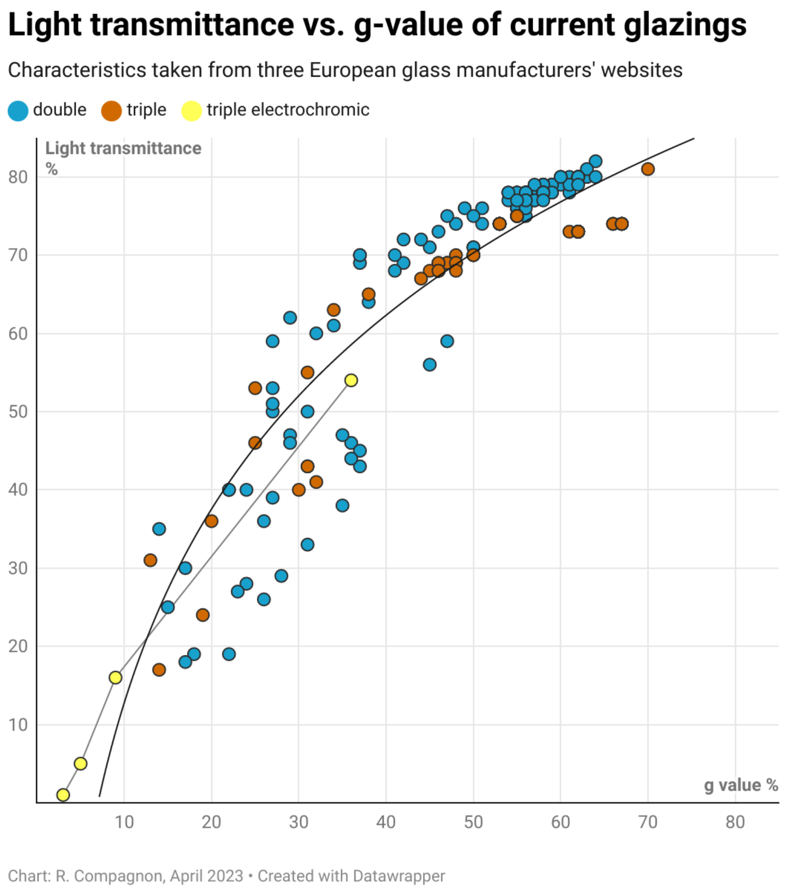
- These 2 characteristics are rather correlated
- Important conclusion: unfortunately "*solar control glazing*" (i.e. with low g-values) always significantly decrease the provision of daylight (low light transmission)
- glassdbase.epfl.ch provides such data + many more characteristics (even spectral) for several glazing



g_{tot} : g values of glazing + shading system

- The total energy transmittance of a combination of a glazing + a solar protection system can also be defined, this value is often noted g_{tot}
- Standard EN 14501 defines performance classes according to g_{tot}

Class	g_{tot}	Evaluation
4	$g_{tot} < 0.10$	Very good effect
3	$0.10 \leq g_{tot} < 0.15$	Good effect
2	$0.15 \leq g_{tot} < 0.35$	Moderate effect
1	$0.35 \leq g_{tot} < 0.50$	Little effect
0	$g_{tot} \geq 0.50$	Very little effect

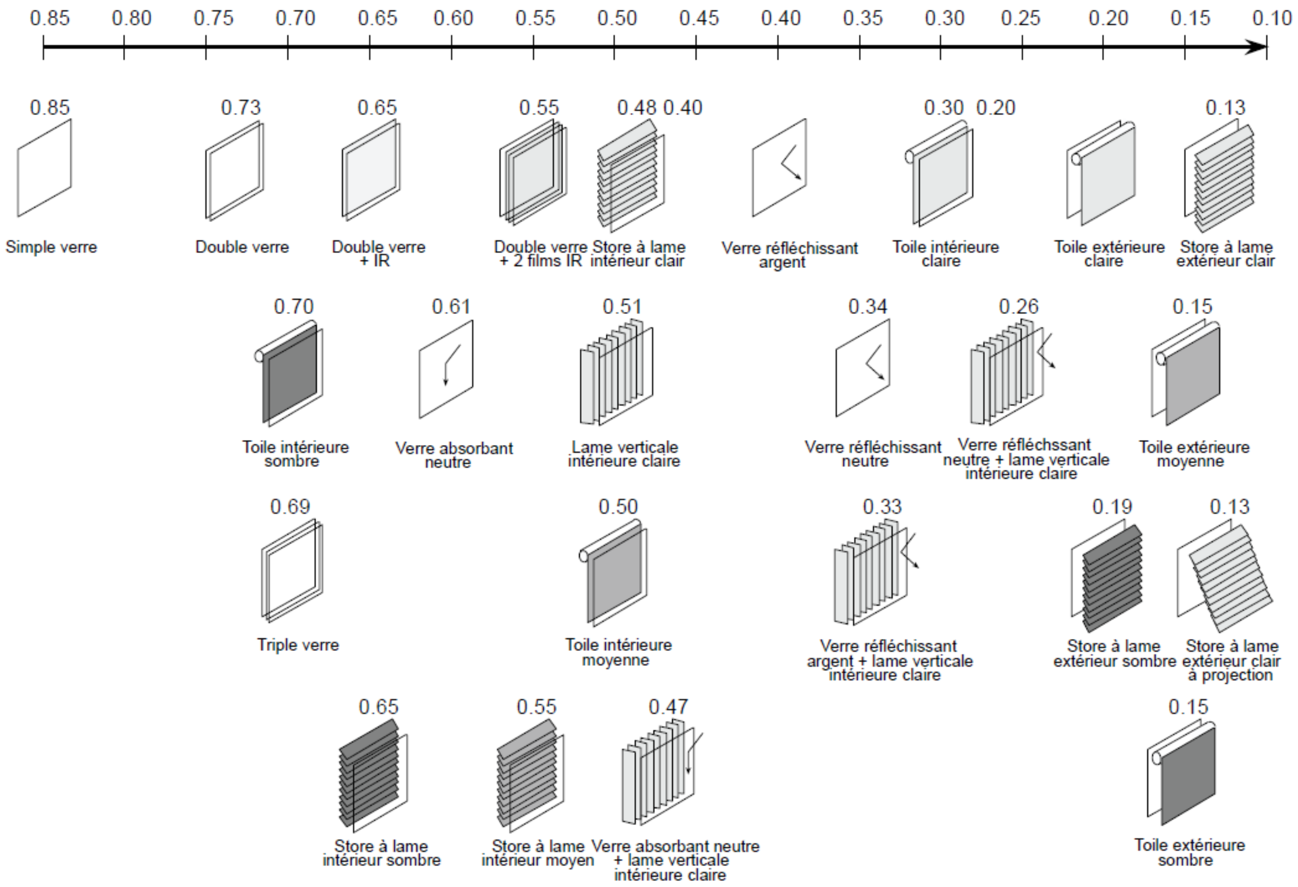
  - Since g_{tot} also depends of the glazing type, it is often specified for a series of "reference glazing types". By default or if not specified, type C glazing is assumed.

Glazing	U^2	g^3
A : clear single glazing	5.8	0.85
B : clear double glazing	2.9	0.76
C : low emission double glazing	1.2	0.59
D : reflective double glazing with a low emission layer	1.1	0.32

[2] Thermal transmittance of the glazing alone (W/m^2K)
[3] Solar factor of the glazing alone

  - Quite frequently, g_{tot} values are not provided by manufacturers or remain "hidden" somewhere in their products technical documentations.
  - See also: European solar shading organisation website: es-so.com

Examples of g and g_{tot} values



Source: Architecture climatique équilibrée, PACER (1996)

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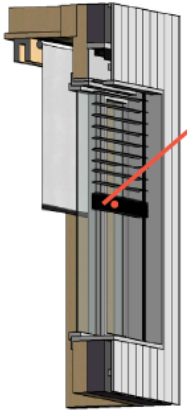
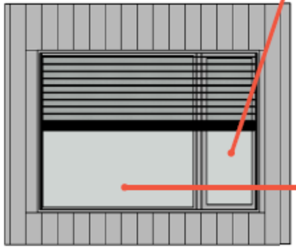
Example: CELLS window system





External blinds

Venetian blinds
Motorized and KNX controlled
Cut-off angle variable
Slat colour grey (int.) ecru white (ext.)
Slat size 80mm

Tilt opening window (Ug = 1.0 W/m²K)

Wooden frame, white mat RAL 9010
Motorized and KNX controlled
Double glazing
Solar Heat Gain Coefficient 65%
Light transmittance 75%
Joint decompression

Fixed glazing (Ug = 1.0 W/m²K)

Wooden frame, white mat RAL 9010
No opening
Double glazing
Solar Heat Gain Coefficient 65%
Light transmittance 75%

Characteristics of a textile internal blind

- Of course g_{tot} value is affected by textile's colour!

SCREEN NATURE

Screen Nature

Samples tested using a spectrometer Lambda 950 Perkin in September-16
Samples tested according to EN 14500 standard defining the measurements and calculation methods as specified in standards "solar protection devices combined with glazing - calculation of solar and light transmittance - part 1: EN 13363-1 simplified method" or part 2: EN 13363-2 detailed method" and EN 410 "Glass in building - Determination of luminous and solar characteristics of glazing".

Echantillons testés avec un spectromètre Lambda 950 Perkin en septembre-16
Echantillons testés selon la norme EN 14500 fixant les méthodes de mesure et de calcul en référence aux normes "dispositifs de protection solaire combinés à un vitrage - calcul du facteur de transmission solaire et lumineuse - partie 1 : EN 13363-1 méthode simplifiée ou partie 2 : EN 13363-2 méthode détaillée" et la norme EN 410 "verre dans la construction détermination des caractéristiques lumineuses et solaires des vitrages".

Openness factor (OF) / Coefficient d'ouverture (Co): 4%	Thermal factors / Valeurs thermiques: Fabric / Tissu			Fabric + Glazing / Tissu + Vitrage — gtot internal blind / gtot intérieur: EN 13363-1								EN 13363-2				Optical factors / Valeurs optiques									
Colours / Coloris	Ts	Rs	As	A		B		C		D		C		D		Tv	Rv	Tvndif	Tvdifh	Tuv	Daylight utilisation / Utilisation lumière naturelle	Glare control / Contrôle de l'éblouissement EN 14501-2021	Glare control / Contrôle de l'éblouissement EN 14501-2005	Night privacy / Intimité de nuit	Visual contact with the outside / Vision vers extérieur
B119 White / Blanc	33	58	9	0.42	1	0.42	1	0.39	1	0.26	2	0.36	1	0.18	2	0.33	0.63	0.29	0.29	0.08	3	0	1	2	0
0319 Linen / Lin	30	56	14	0.43	1	0.43	1	0.39	1	0.26	2	0.36	1	0.19	2	0.30	0.59	0.27	0.26	0.07	3	0	1	2	0
0348 Silver / Argent	29	51	20	0.46	1	0.45	1	0.41	1	0.27	2	0.39	1	0.2	2	0.27	0.51	0.23	0.24	0.09	2	0	1	2	0
0410 Sable / Sable	25	46	29	0.48	1	0.48	1	0.42	1	0.27	2	0.4	1	0.22	2	0.22	0.46	0.18	0.19	0.07	2	0	1	2	0
0349 Pearl / Perle	18	34	48	0.54	0	0.53	0	0.46	1	0.28	2	0.46	1	0.25	2	0.13	0.29	0.09	0.11	0.07	2	0	1	2	1
0441 Grey / Gris	8	14	78	0.64	0	0.63	0	0.52	0	0.3	2	0.53	0	0.29	2	0.07	0.12	0.03	0.05	0.05	1	1	2	2	2
1134 Bronze	7	11	82	0.66	0	0.64	0	0.53	0	0.3	2	0.54	0	0.3	2	0.06	0.10	0.01	0.05	0.05	1	1	3	2	2
0440 Charcoal / Charcoal	5	6	89	0.68	0	0.66	0	0.55	0	0.3	2	0.55	0	0.31	2	0.05	0.06	0.00	0.04	0.05	1	1	3	2	2

Source: https://www.sunscreen-mermet.fr/gammes/screen-nature.html

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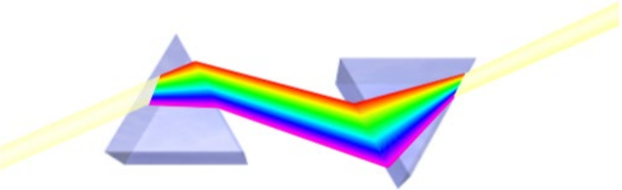
EPFL



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Thermographic cameras

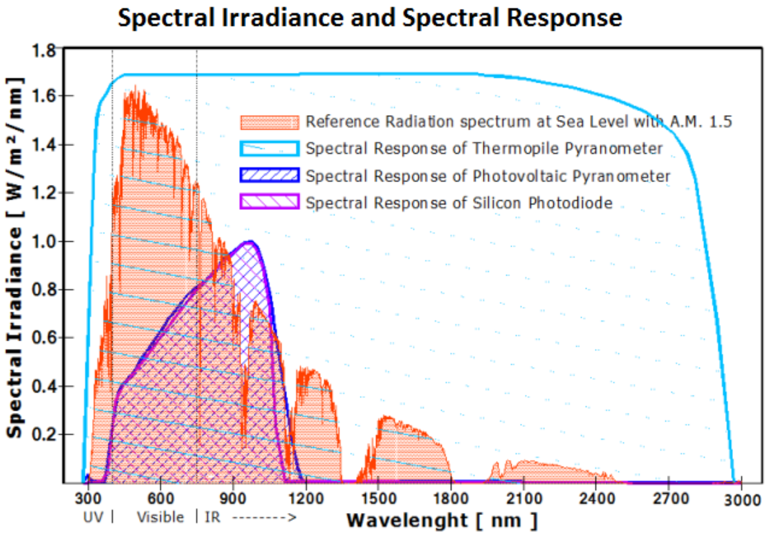
- **Thermographic cameras** are able to make images from the radiant flux received in the infrared wavelength region, typically **2 ≤ λ ≤ 5.5** [μm] or **7 ≤ λ ≤ 13 to 19** [μm]
  - Images are produced in a false colour scale indicating the "*apparent*" temperature of the visible surface from the radiant
  - "*Apparent*" temperature is close to true temperature only if the emissivity of the surface is close to 1 (which is the case for dielectric materials)
- **Beware the possible reflections on specular surfaces (typically glass)**
- **Various camera types differ:**
  - According their picture resolutions from 80x60 to 640x480 pixels
  - their prices: from ~350 CHF to ~100 kCHF

IR image

RGB image

Pyranometer

- Sunlight irradiance I_g is measured by a device called "**pyranometer**" accounting for radiation incoming for the whole sky hemisphere at all wavelengths from 300 to 2500 nm
(which is not the case for all sensor types!)
- When dealing with irradiance, the orientation of the receiving plane must be specified. If not specified, one can assume horizontal plane.
- Sometimes solar irradiance data are provided for a plane maintained perpendicular to the direction of the sun. This is called **direct normal irradiance**
- Some advanced devices can measure the **direct** and **diffuse** components separately (for example, SPN1 by Hukseflux)

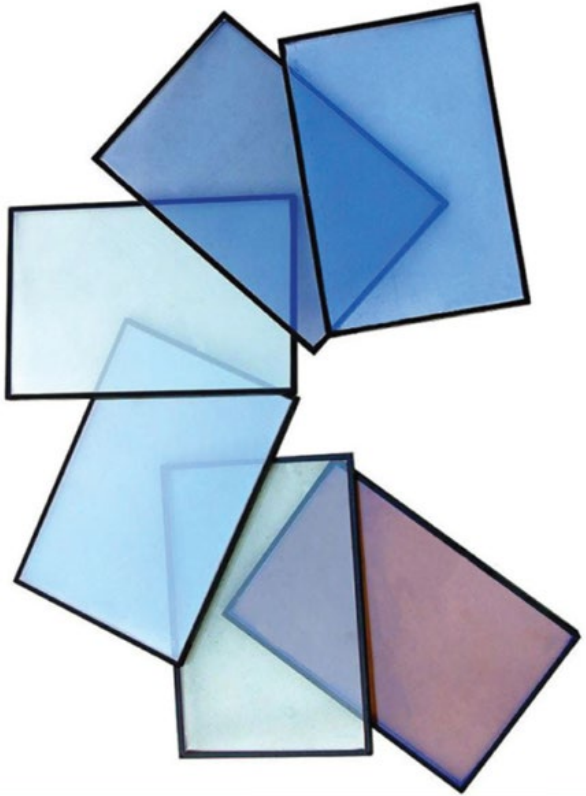


The SPN1 pyranometer

Assist. Prof. Dolaana Khovalyg

Luxmeter

- Illuminance E_v is measured by a device called "**luxmeter**" accounting for radiation incoming from the whole hemisphere above the sensor
- When dealing with illuminance, the orientation of the receiving plane must be specified! If not specified, one can assume horizontal plane.
- Some devices can also measure some color characteristics of the incoming light flux (e.g. x,y color coordinates, color temperature)



Thank you for your attention

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