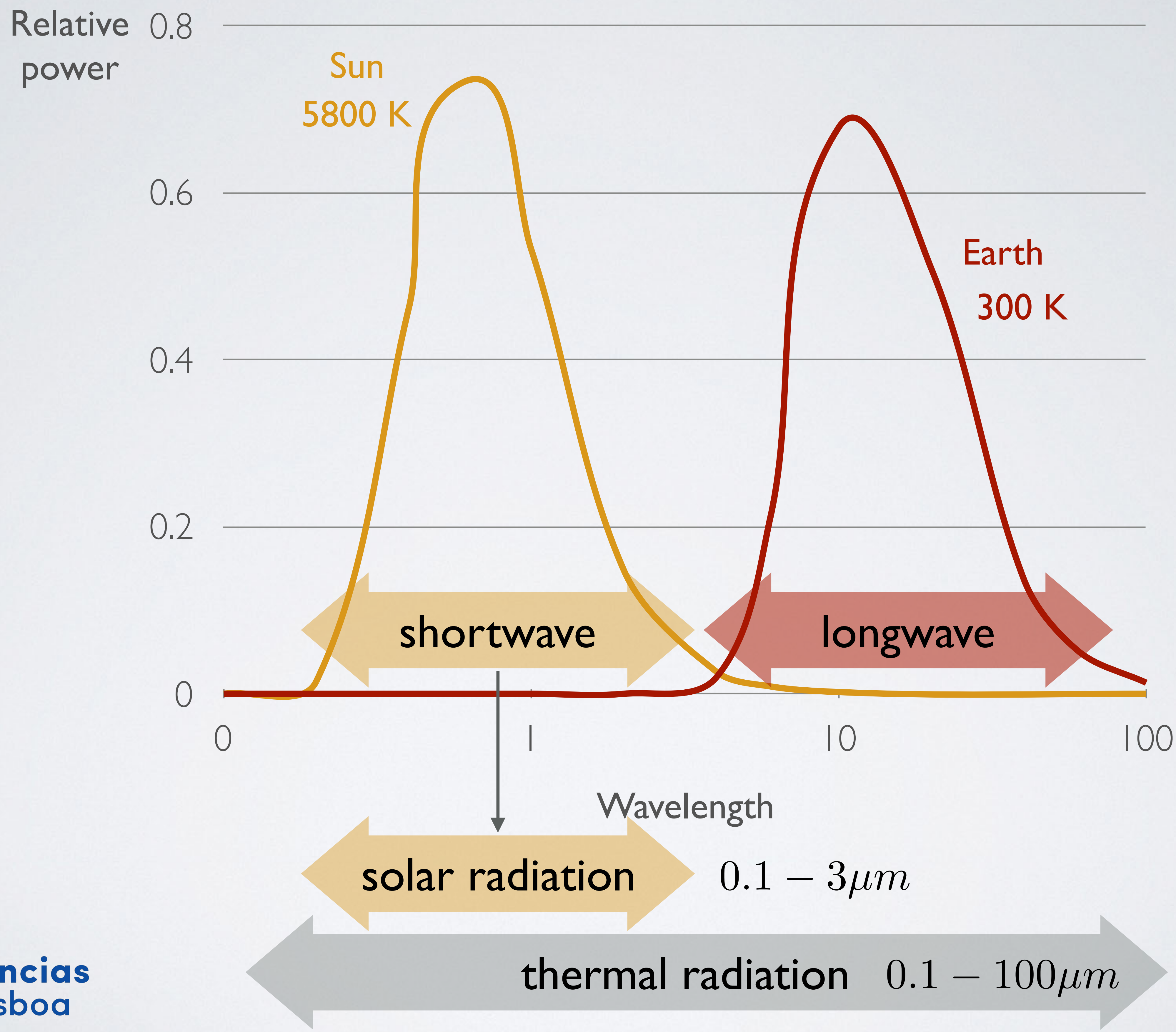
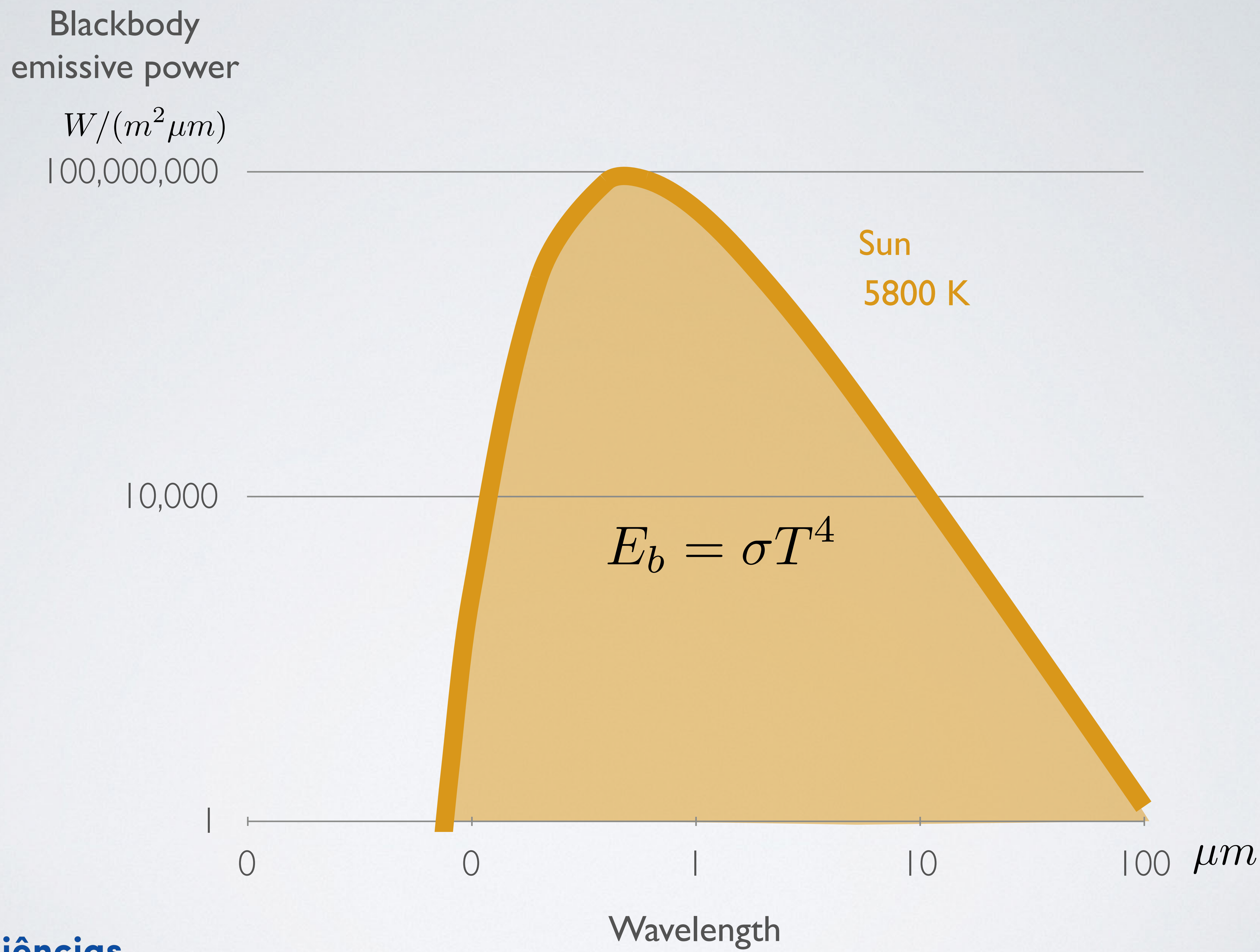
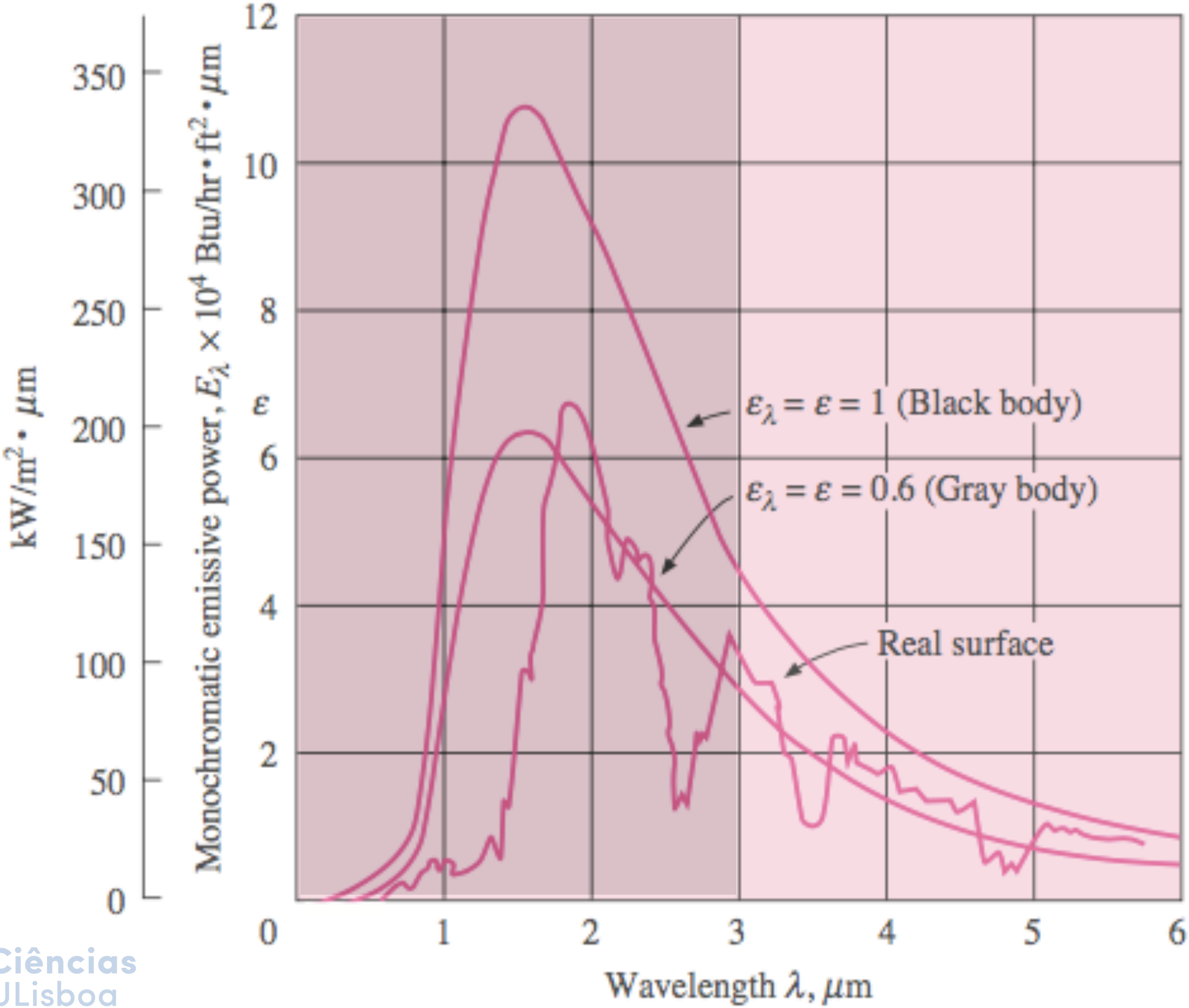
Thermal radiation

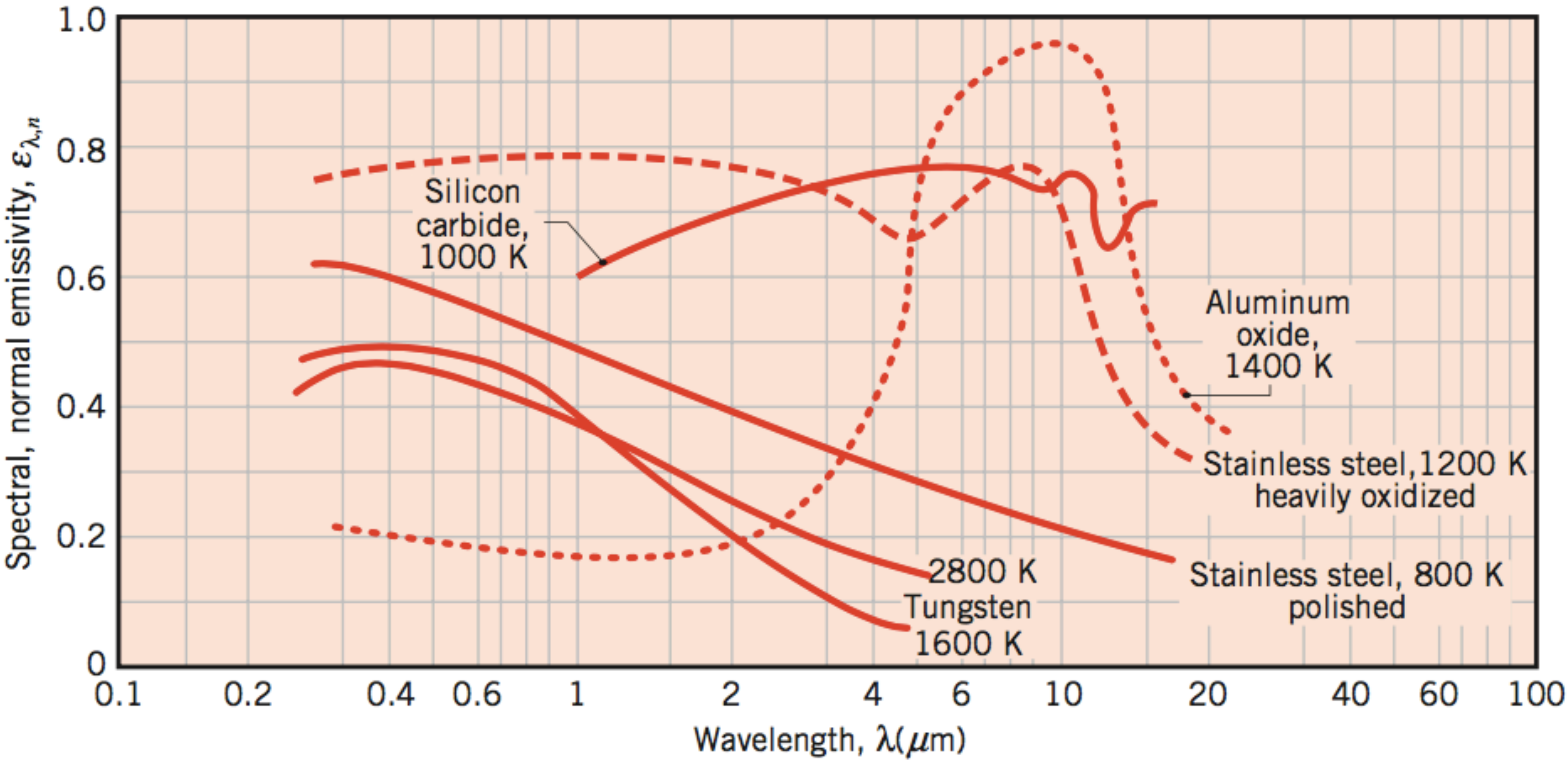


Ciências ULisboa

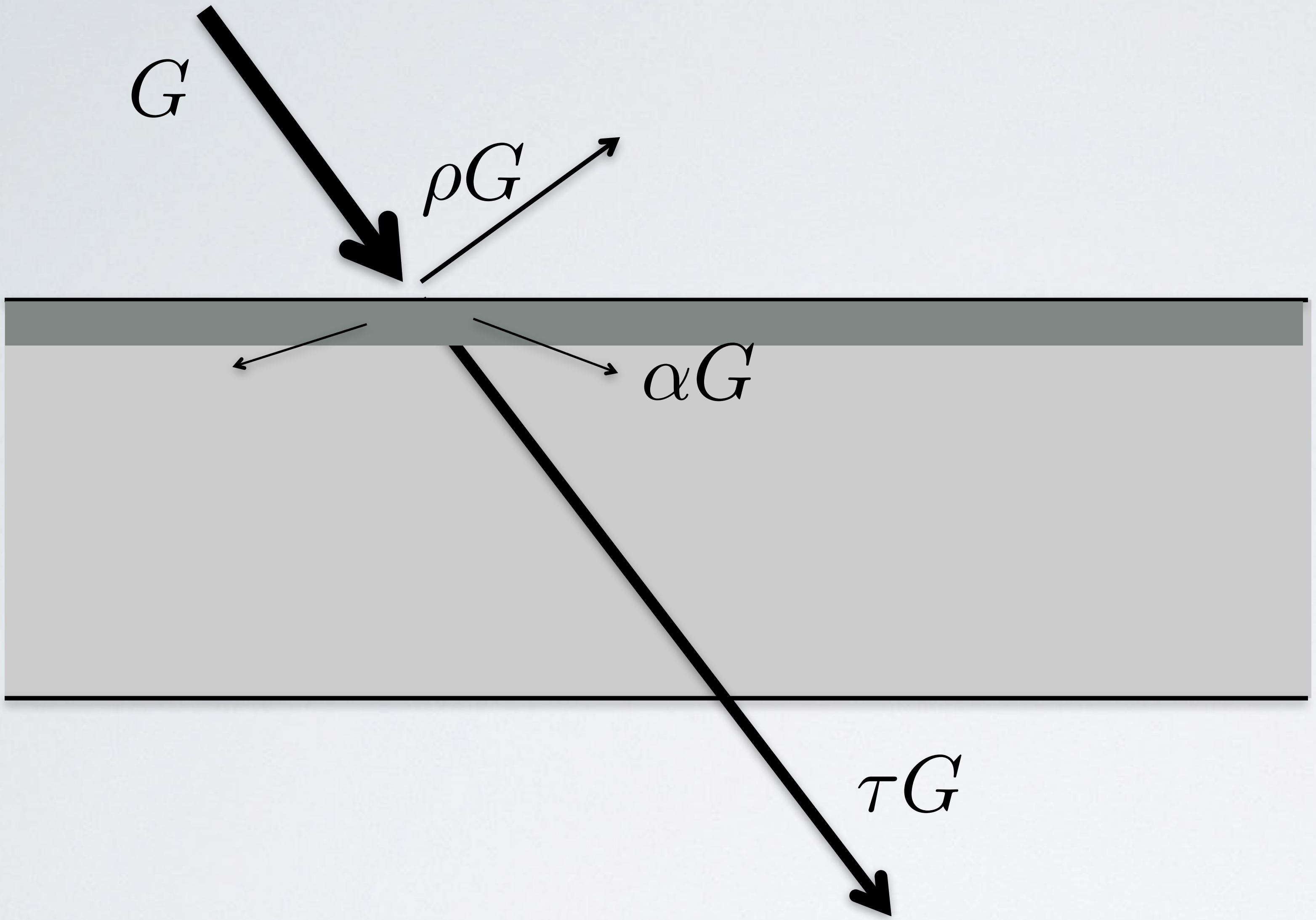

Blackbody
emissive power
W/(m²μm)
100,000,000
10,000
1
Sun
5800 K
0
0
1
10
100
μm
Wavelength

$$E_b = \sigma T^4$$


kW/m^2 • μm
0
50
100
150
200
250
300
350
Monochromatic emissive power, $E_\lambda \times 10^4$ Btu/hr • ft^2 • μm
0
2
4
6
8
10
12
$\varepsilon_\lambda = \varepsilon = 1$ (Black body)
$\varepsilon_\lambda = \varepsilon = 0.6$ (Gray body)
Real surface
1
2
3
4
5
6
Wavelength λ, μm


1.0
0.8
0.6
0.4
0.2
0
Spectral, normal emissivity, $\varepsilon_{\lambda,n}$
0.1
0.2
0.4
0.6
1
2
4
6
10
20
40
60
100
Wavelength, λ(μm)
Silicon carbide, 1000 K
Aluminum oxide, 1400 K
Stainless steel, 1200 K heavily oxidized
Stainless steel, 800 K polished
2800 K
Tungsten
1600 K

Materials	Solar absorptivity	Solar reflectivity	Longwave emissivity
Clay	0.65-0.80		0.85-0.95
Asphalt	0.85-0.98		0.90-0.98
Brick	0.65-0.80		0.85-0.95
Concrete	0.65-0.80		0.85-0.95
Dark stone	0.65-0.80		0.95
Marble		0.56	0.93
Clear glass	0.05	0.08	0.90-0.95
White paint	0.12-0.18		0.89-0.97
Red paint	0.74		0.96
Black paint	0.97		0.96
Whitewash	0.20-0.50		0.85-0.95



$$\rho + \alpha + \tau = 1$$

Reflectivity, $\rho(\lambda)$

Absorptivity, $\alpha(\lambda)$

Transmissivity, $\tau(\lambda)$

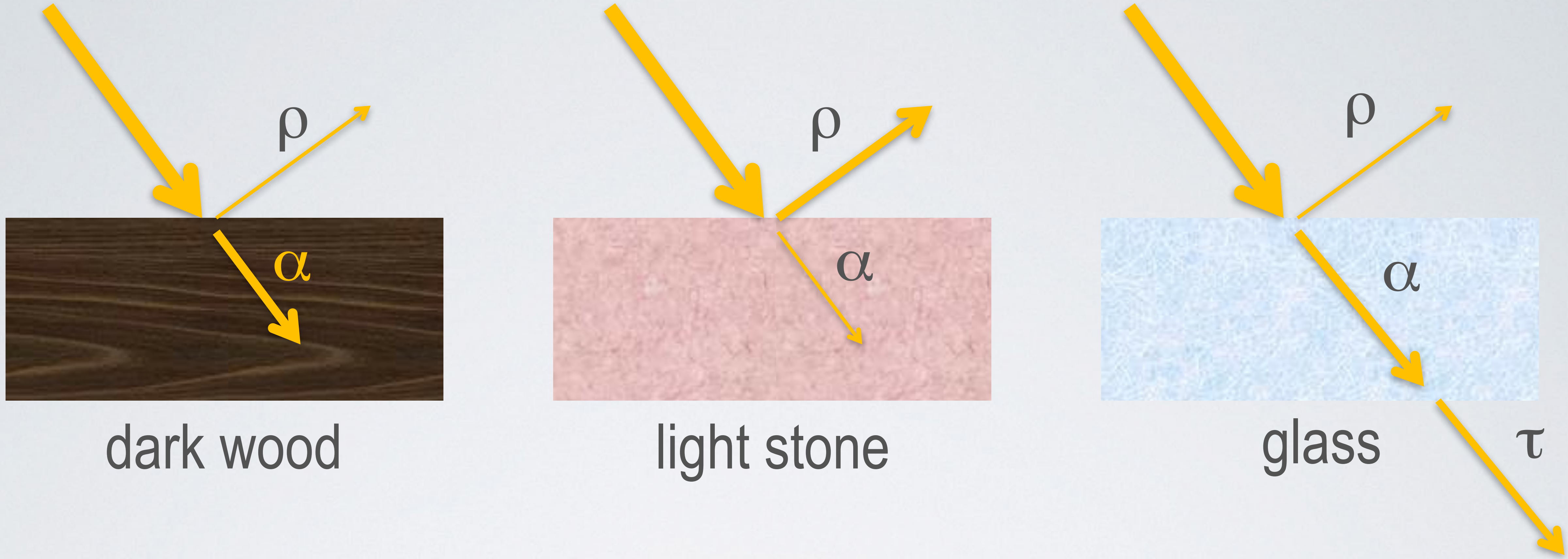
Opaque materials

$$\tau(\lambda) = 0$$

Translucent materials

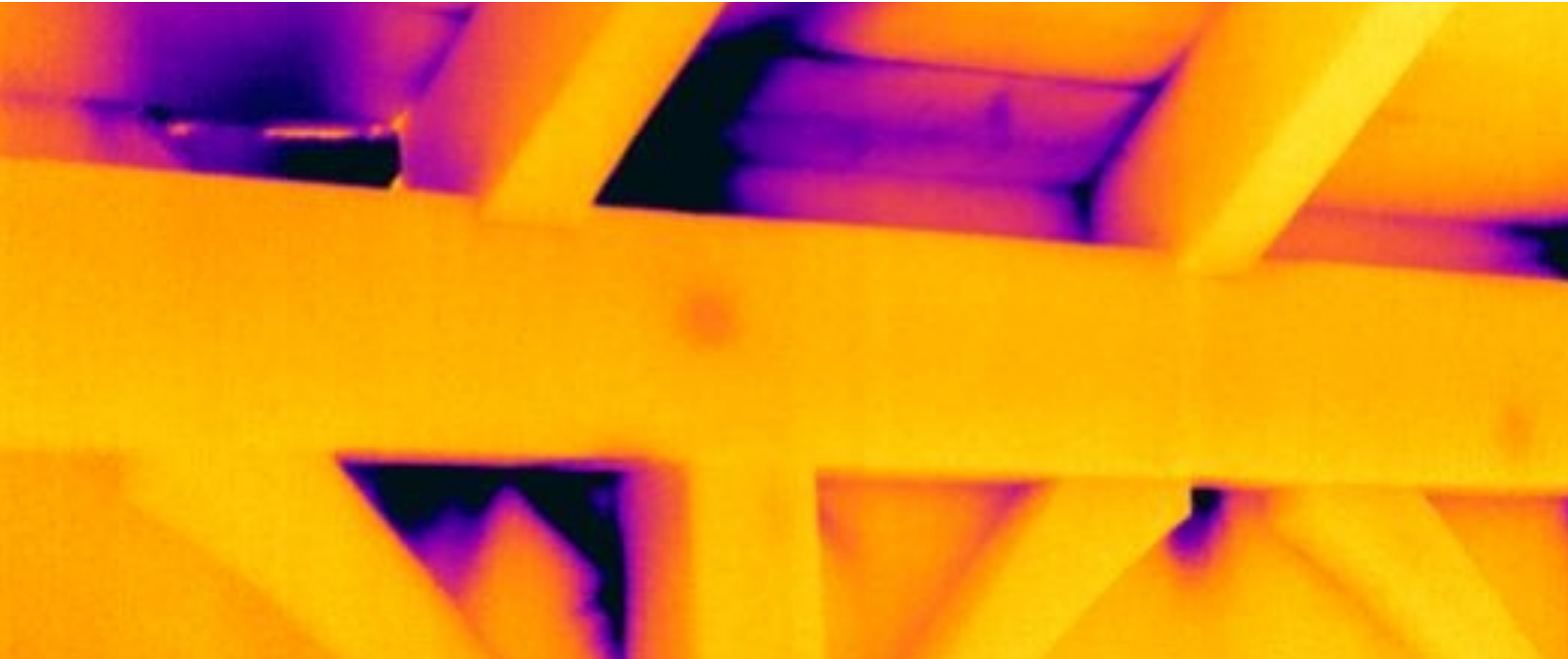
$$\tau(\lambda) \neq 0$$

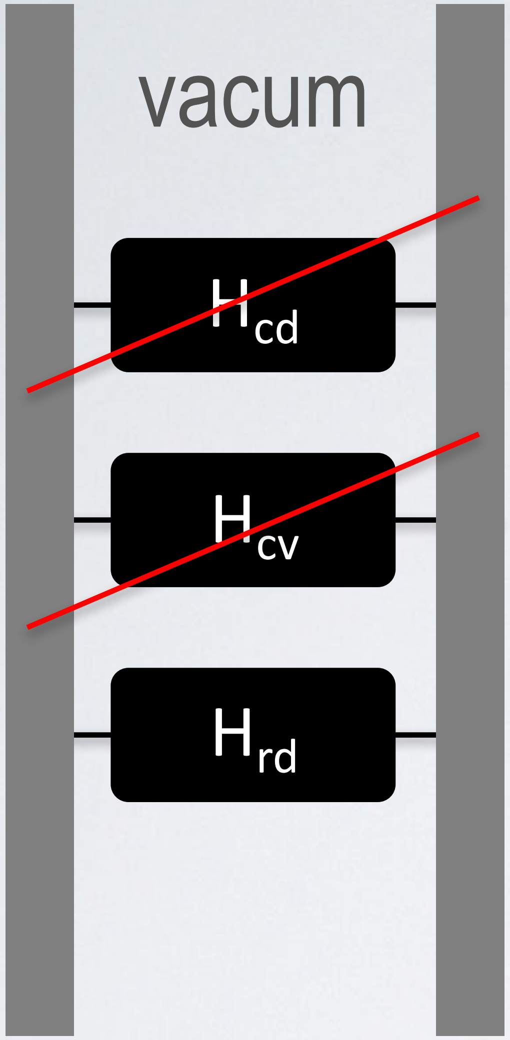
Ciências ULisboa



Almost all buildings materials are opaque to solar radiation.
Glass transmits solar radiation, but is opaque to longwave radiation.

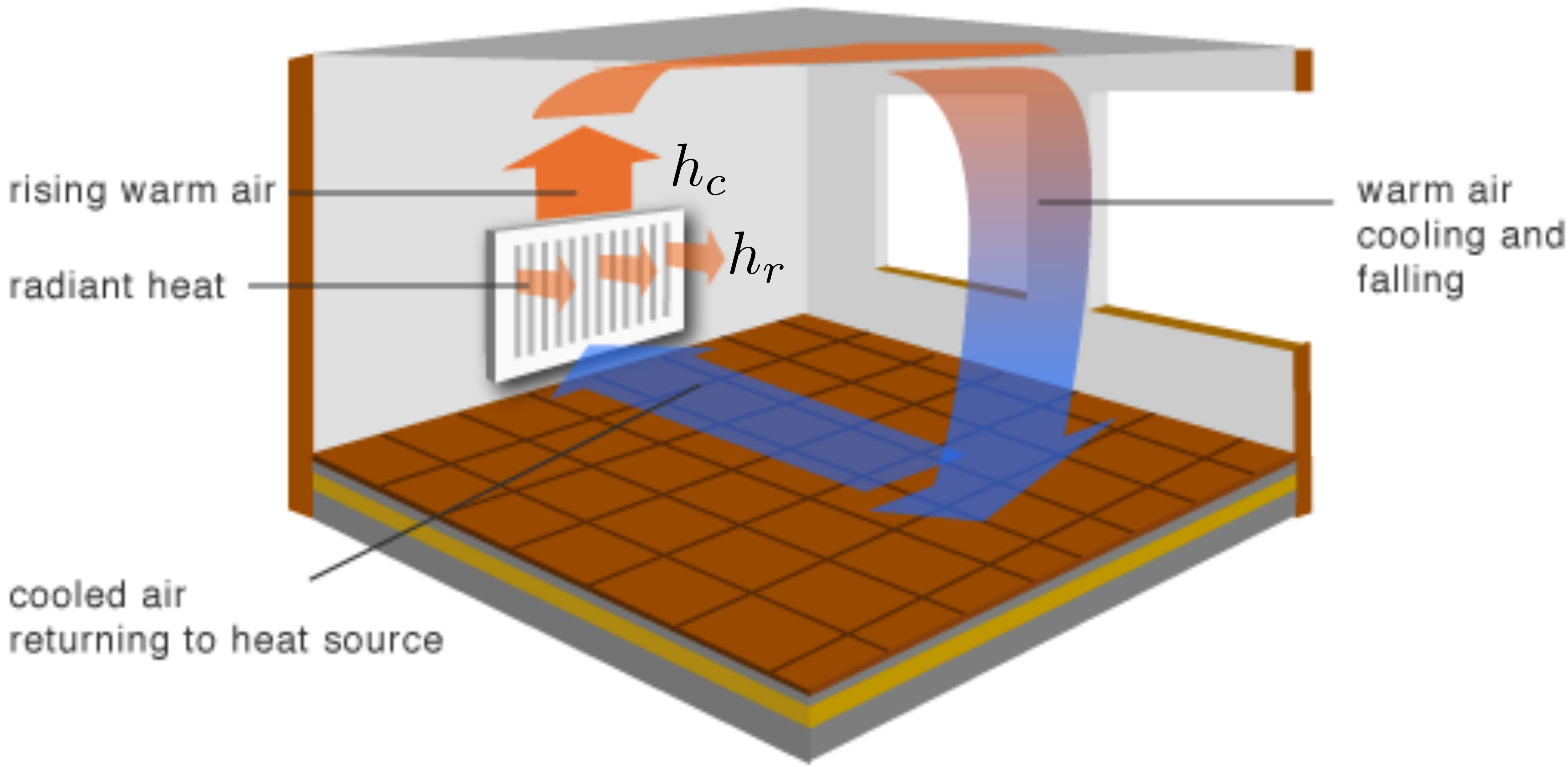
Radiative heat transfer

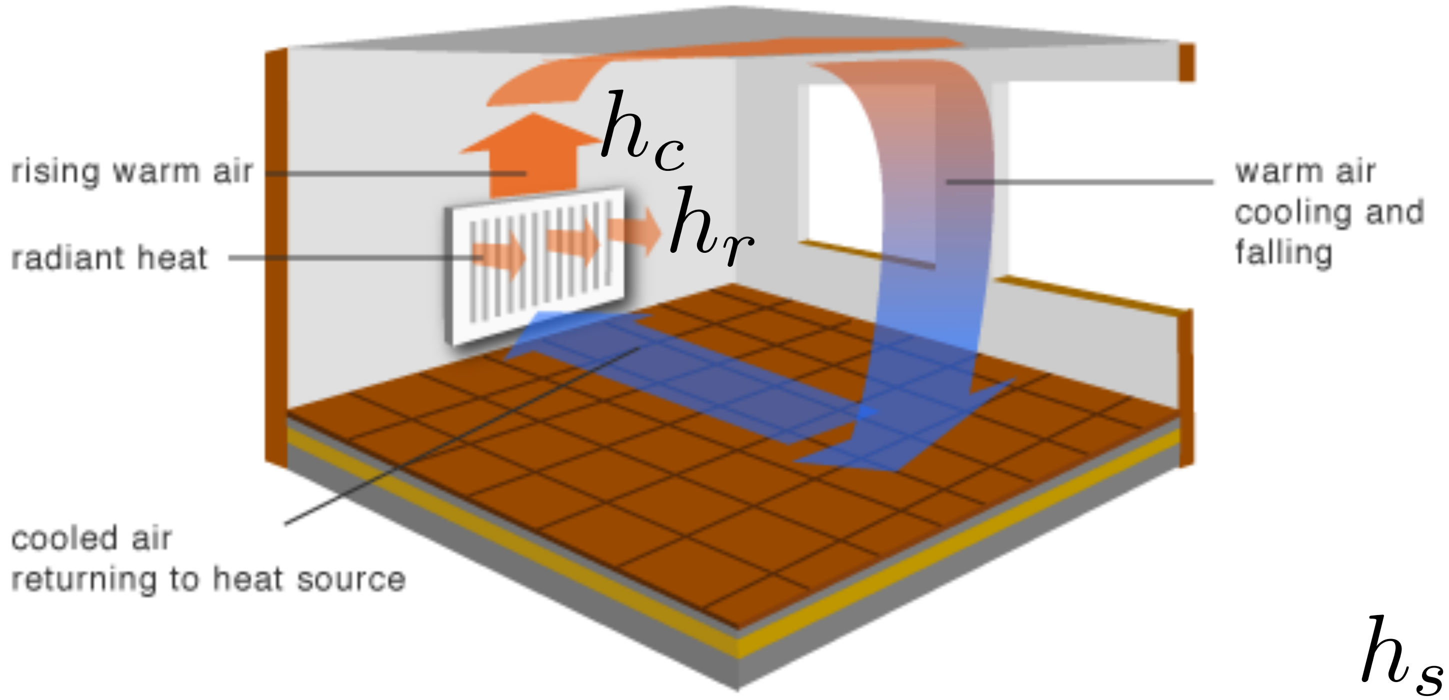




- Heat transfer by thermal radiation requires no matter.

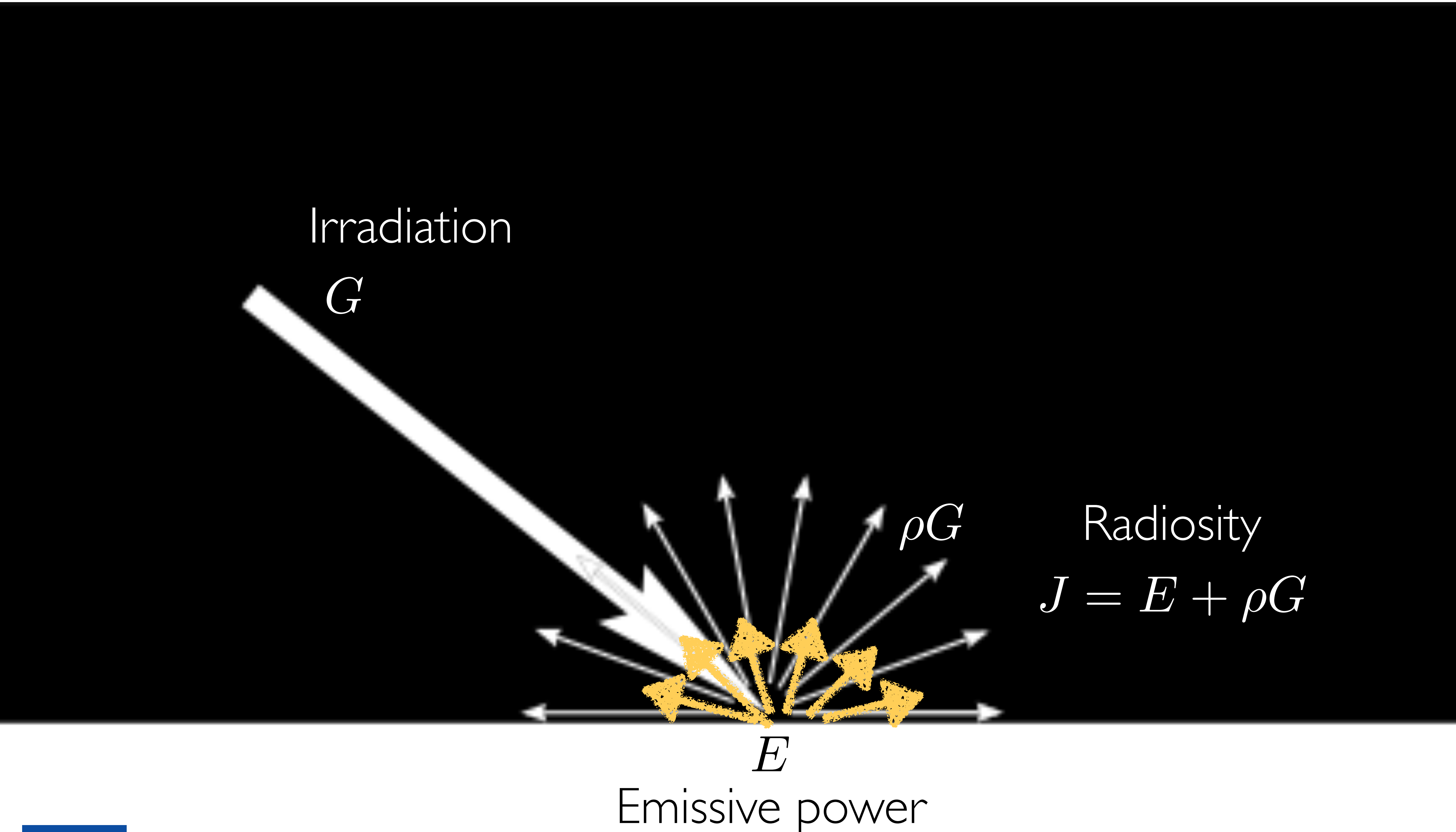
- Buildings assumptions:
  - The air between buildings do not interact in the heat transfer process, it is fully transparent;
  - Buildings components are opaque and diffuse for long-wave radiation (including windows).


rising warm air
h_c
radiant heat
h_r
warm air
cooling and
falling
cooled air
returning to heat source

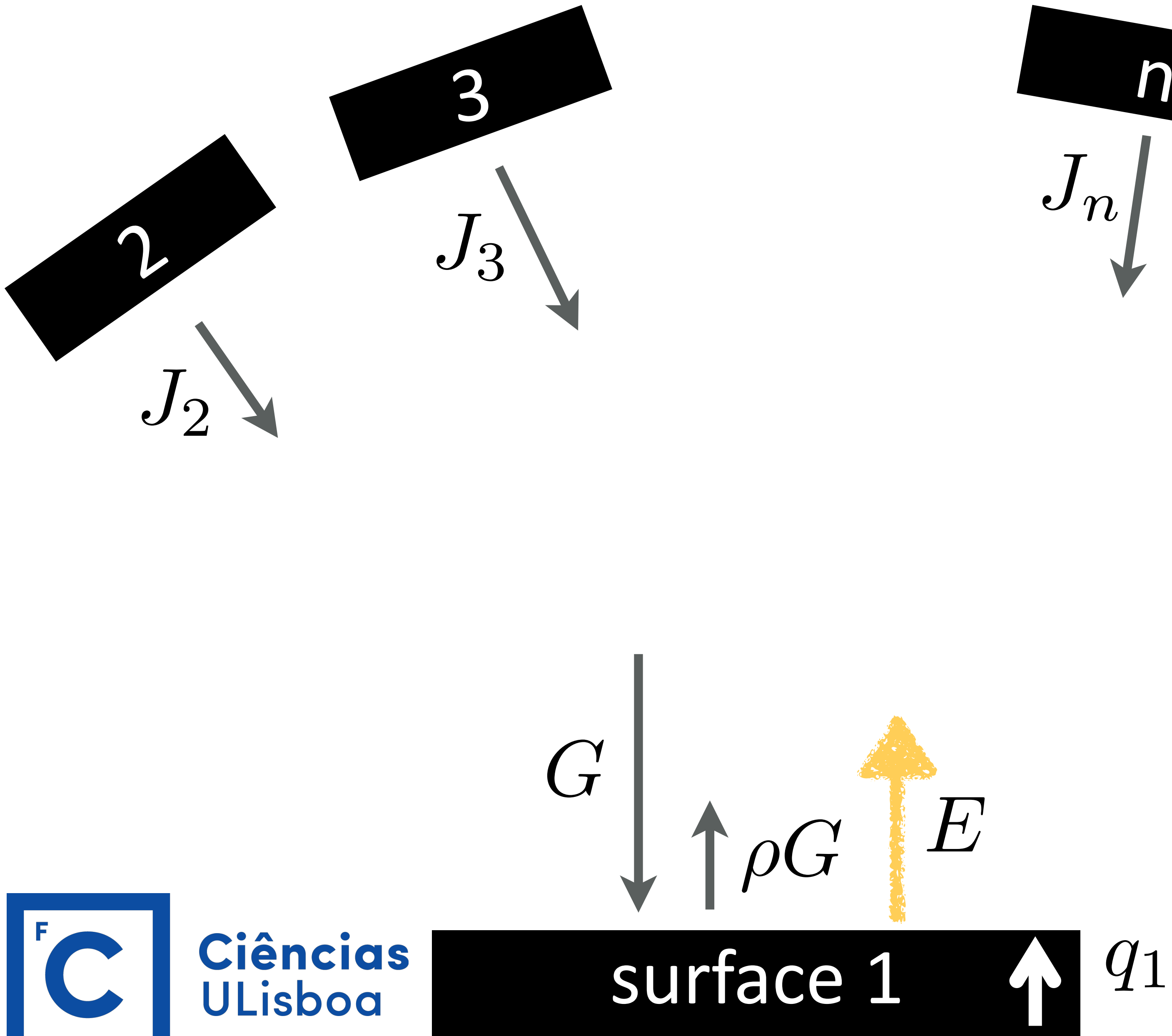


$$h_s = h_c + h_r$$

$$R_s = 1/h_s$$

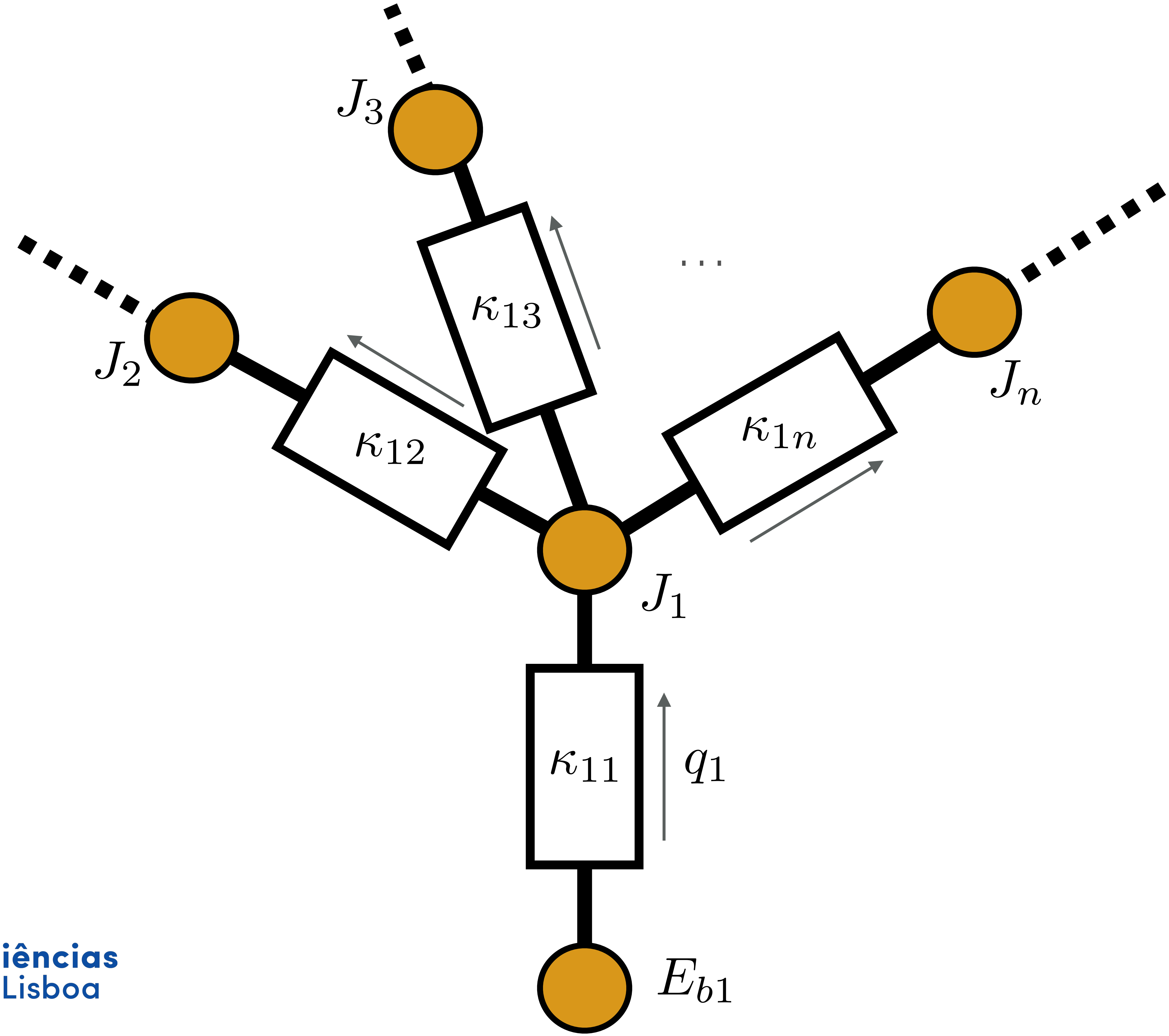


Ciências ULisboa



$$q_1 = \frac{A_1 \varepsilon_1}{1 - \varepsilon_1}(E_{b1} - J_1)$$

$$q_1 = \sum_j A_1 F_{1j}(J_1 - J_j)$$



Ciências ULisboa

E_b
J $[W/m^2]$

κ
$[m^2]$

geometrical conductance

$$\kappa_{ii} = \frac{A_i \varepsilon_i}{1 - \varepsilon_i}$$

$$\kappa_{ij} = A_i F_{ij} = A_j F_{ji}$$

T $[K]$

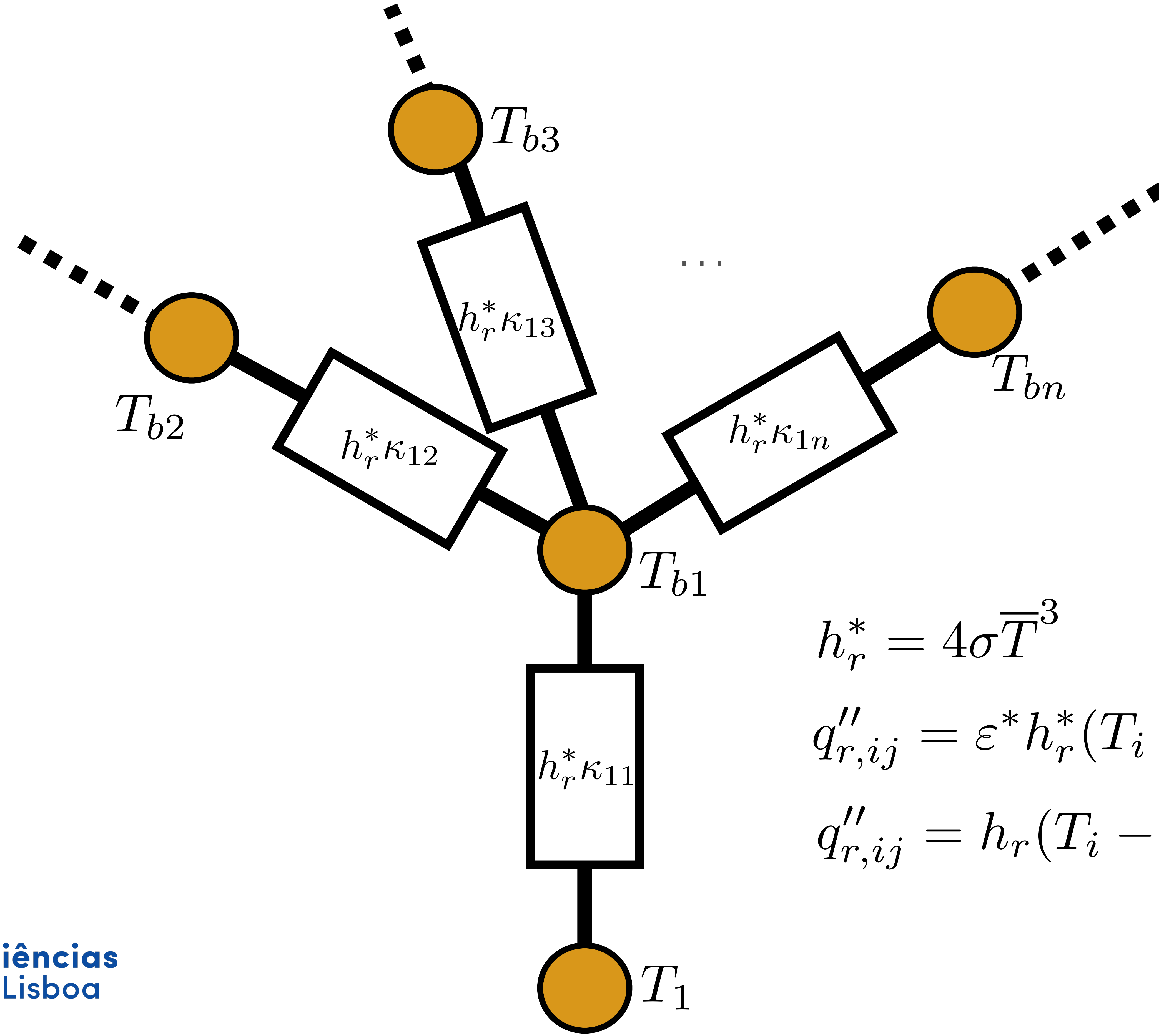
H
$[W/K]$

thermal conductance

$$J = \sigma T_b^4$$

blackbody
equivalent
temperature

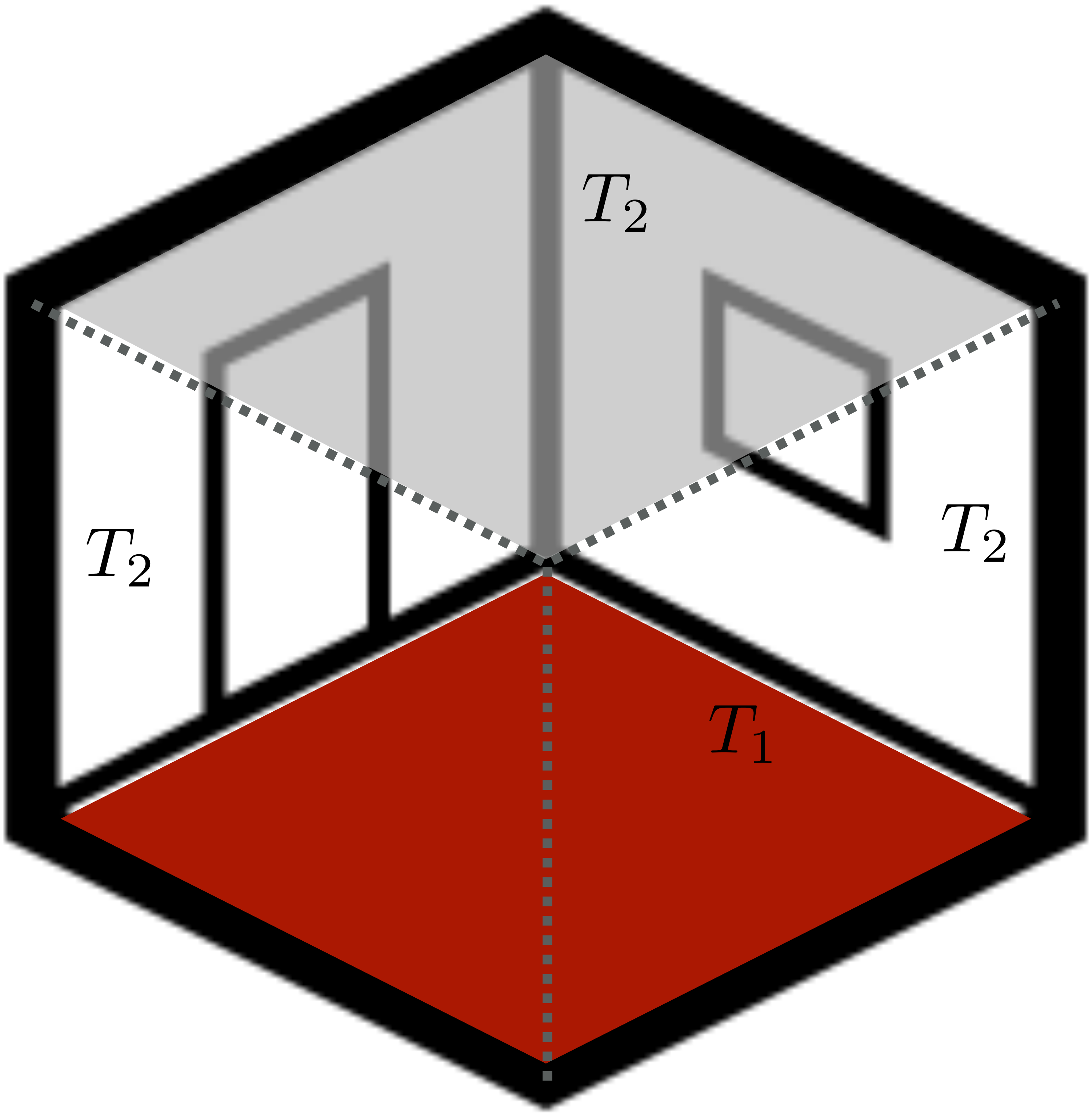
Ciências
ULisboa

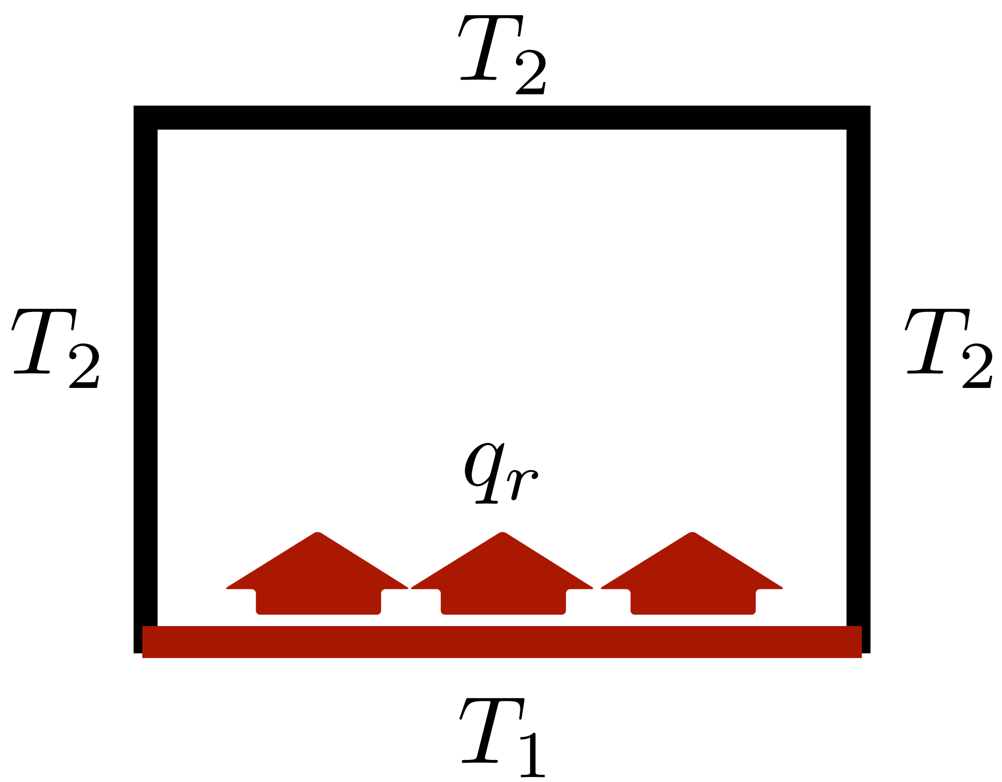


$$h_r^* = 4\sigma\overline{T}^3$$

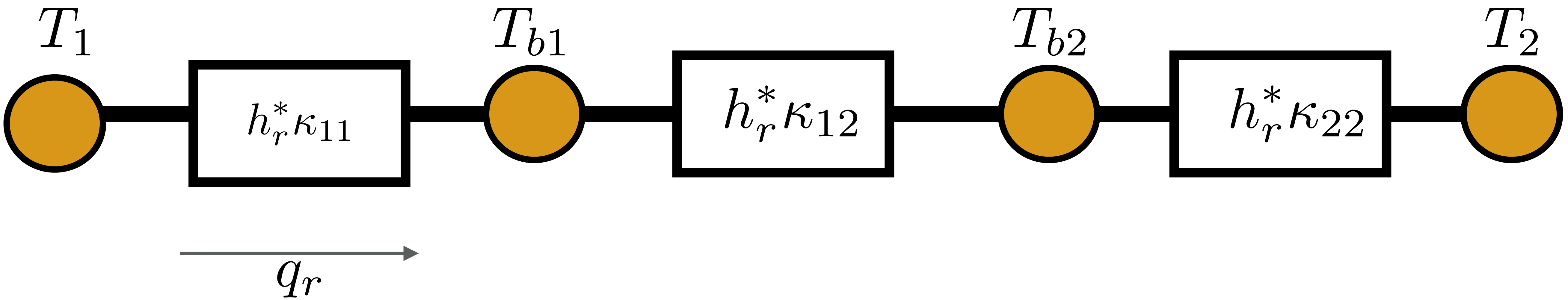
$$q''_{r,ij} = \varepsilon^* h_r^*(T_i - T_j)$$

$$q''_{r,ij} = h_r(T_i - T_j)$$





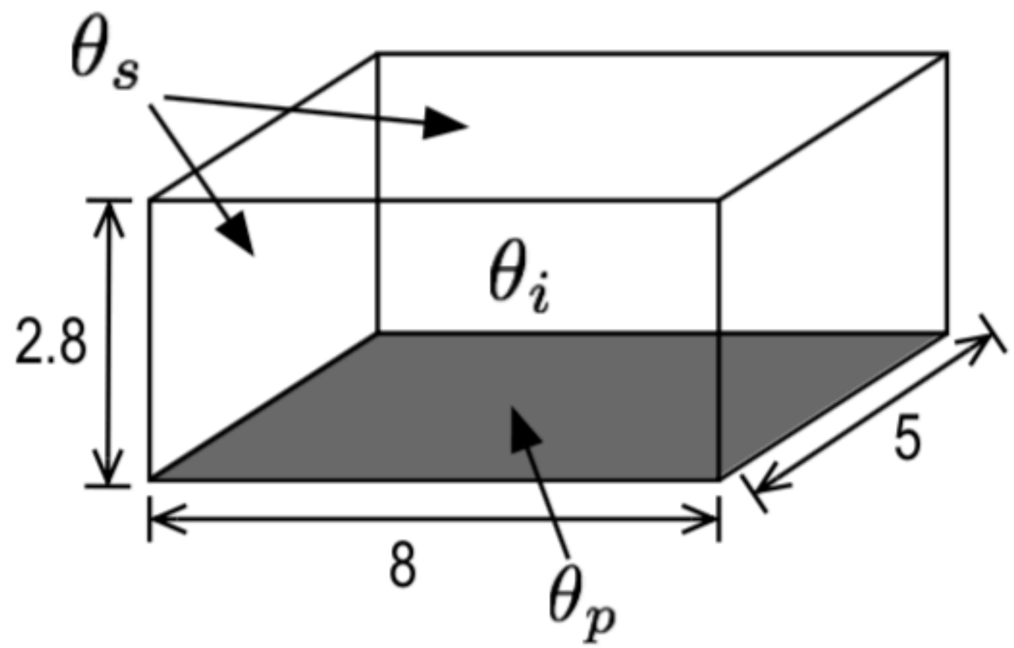
Ciências ULisboa



$$q_r = A_1 \varepsilon^* h_r^* (T_1 - T_2)$$

$$\varepsilon^* = \left(\frac{1 - \varepsilon_1}{\varepsilon_1} + \frac{1}{F_{12}} + \frac{1 - \varepsilon_2}{\varepsilon_2} \frac{A_1}{A_2} \right)^{-1}$$

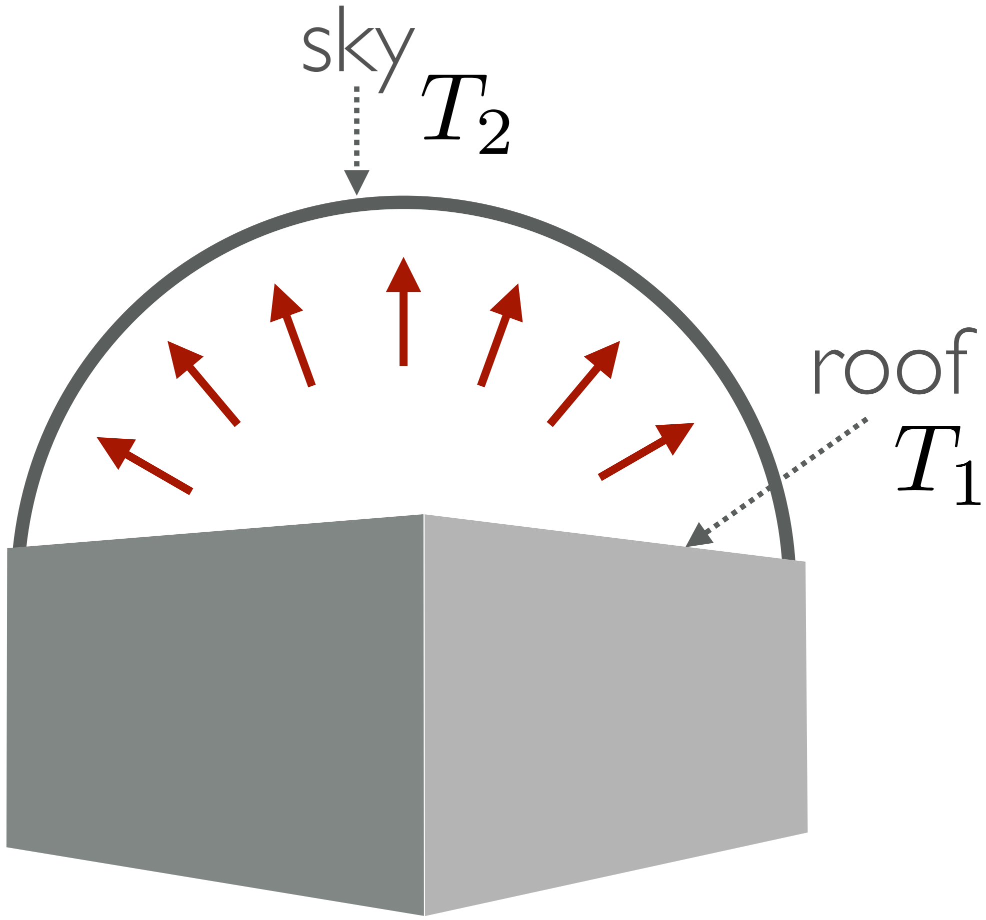
Exercício 3.1.1 **calcular os coeficientes de transmissão de calor** por convecção e radiação sem recorrer a valores tabelados, para a transferência de calor entre uma superfície aquecida (pavimento, $\theta_p = 35°C$) e o ar ($\theta_i = 20°C$), no caso da convecção, e as restantes superfícies ($\theta_s = 20°C$), no caso da radiação. Considerar que todas as superfícies possuem uma emissividade espectral no infravermelho de 0.9.



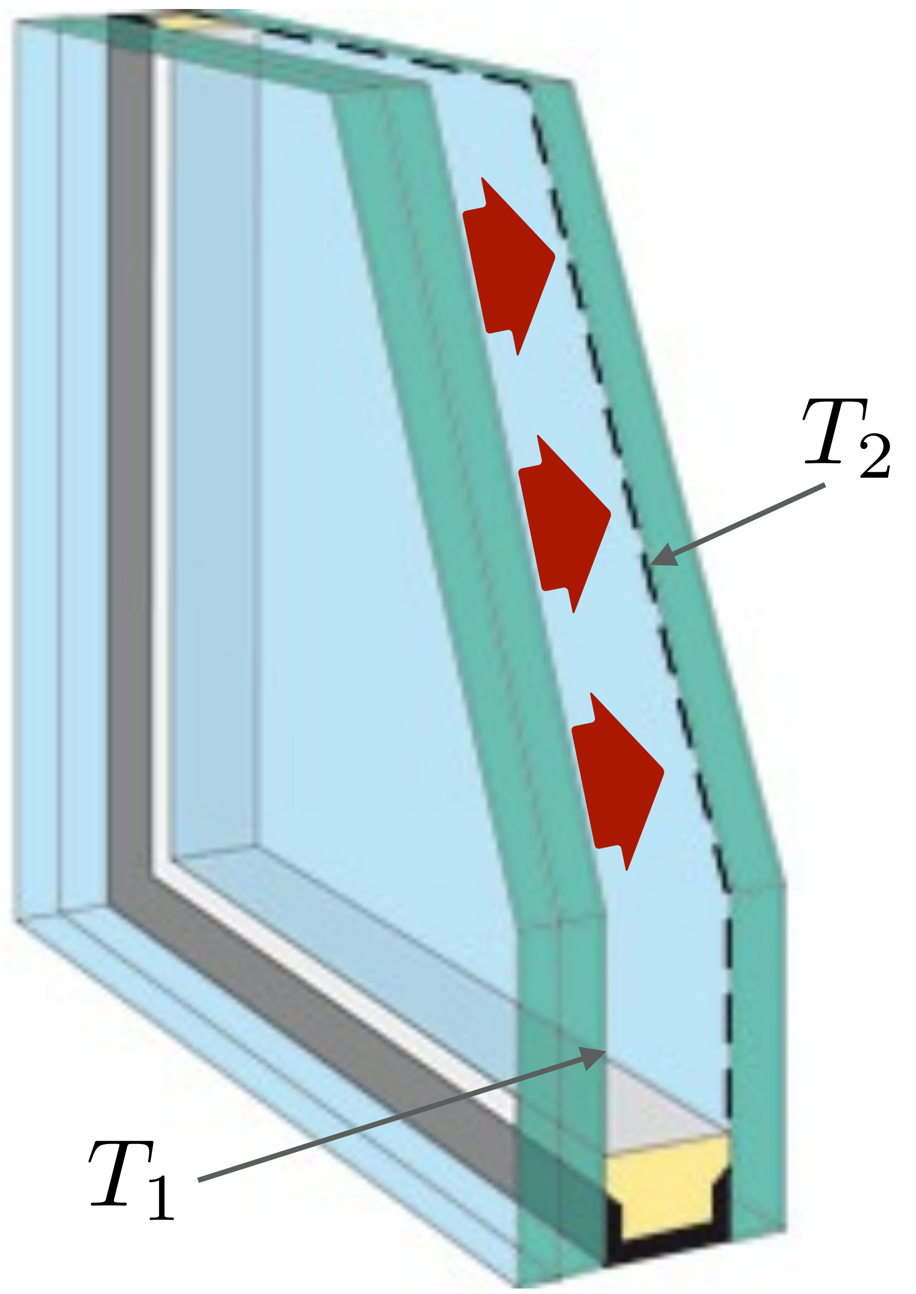
$$A_1 \ll A_2$$

$$q_r = A_1 \varepsilon^* h_r^* (T_1 - T_2)$$

$$\varepsilon^* = \varepsilon_1$$



Ciências
ULisboa



$$q_r = A_1 \varepsilon^* h_r^* (T_1 - T_2)$$

$$\varepsilon^* = \left(\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1 \right)^{-1}$$

Ciências ULisboa

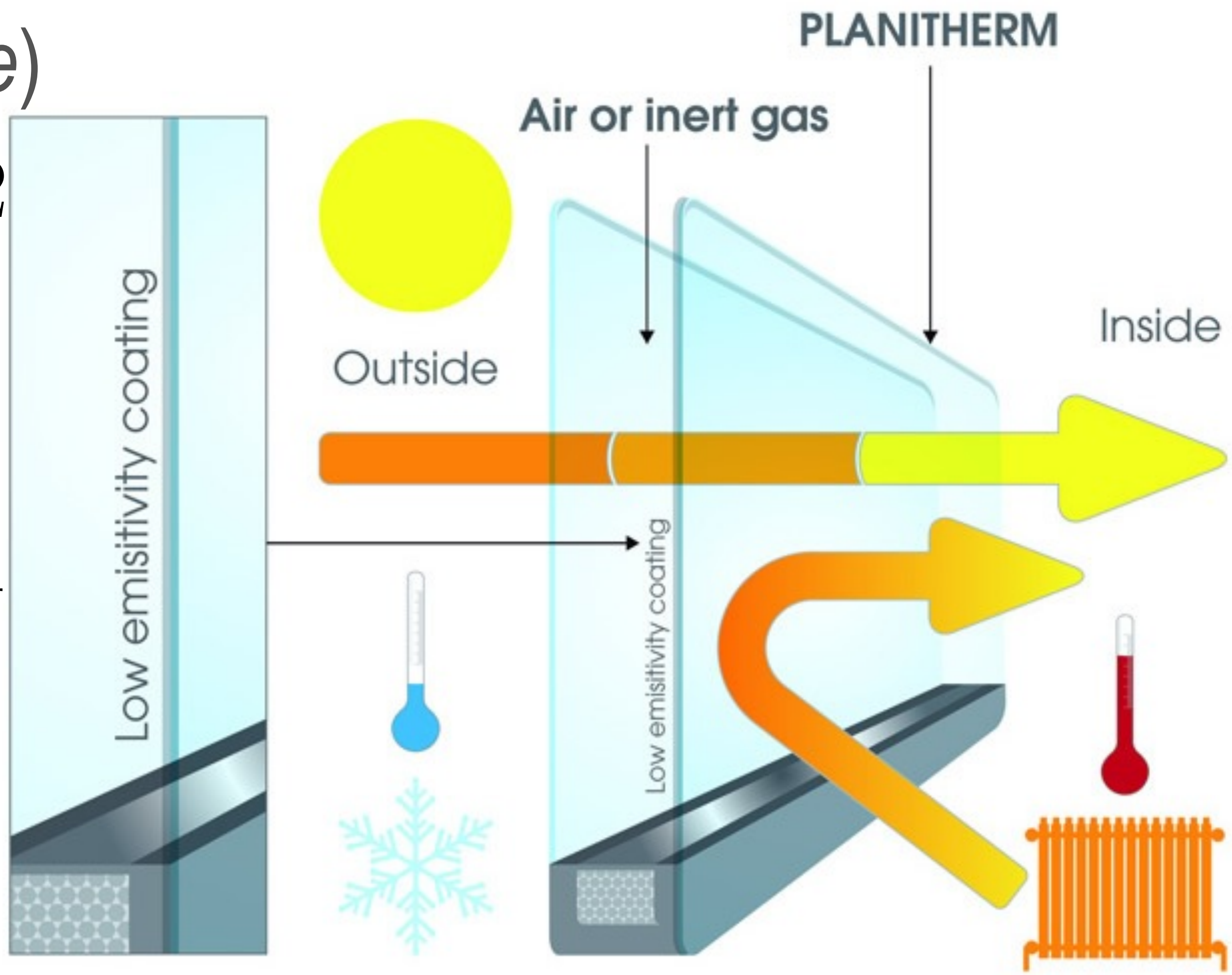
current glass (*both emissive*)

$$\varepsilon_1 = \varepsilon_2 = 0.9 \rightarrow \varepsilon^* = 0.8$$

low emissivity coating (*one reflexive*)

$$\varepsilon_1 = 0.9, \varepsilon_2 = 0.2 \rightarrow \varepsilon^* = 0.2$$

$$\varepsilon_1 = 0.2, \varepsilon_2 = 0.2 \rightarrow \varepsilon^* = 0.1$$



standard overall thermal resistance* [m²K/W]

Surfaces	Heat flow	Gap width [mm]						
		5	10	15	25	50	100	300
Vertical		0.11	0.15	0.17	0.18	0.18	0.18	0.18
Horizontal	upwards	0.11	0.15	0.16	0.16	0.16	0.16	0.16
Horizontal	downwards	0.11	0.15	0.17	0.19	0.21	0.22	0.23

*only for air gaps, not valid for other gases and assuming *hr=4.33 W/m²K (Both emissive)*

Non ventilated air gaps

Radiation

standard overall thermal resistance* [m^{2}K/W]

Surfaces	Heat flow	Gap width [mm]						
		5	10	15	25	50	100	300
Vertical		0.18	0.33	0.45	0.56	0.56	0.56	0.56
Horizontal	upwards	0.18	0.33	0.40	0.40	0.40	0.40	0.40
Horizontal	downwards	0.18	0.33	0.45	0.65			1.34

*only for air gaps, not valid for other gases and
assuming *hr=0.54 W/m^{2}K (one emissive and one reflexive)*

Ciências
ULisboa

Exercício 3.1.4 Para um vidro duplo vertical com duas lâminas de vidro separadas por uma lâmina de ar:

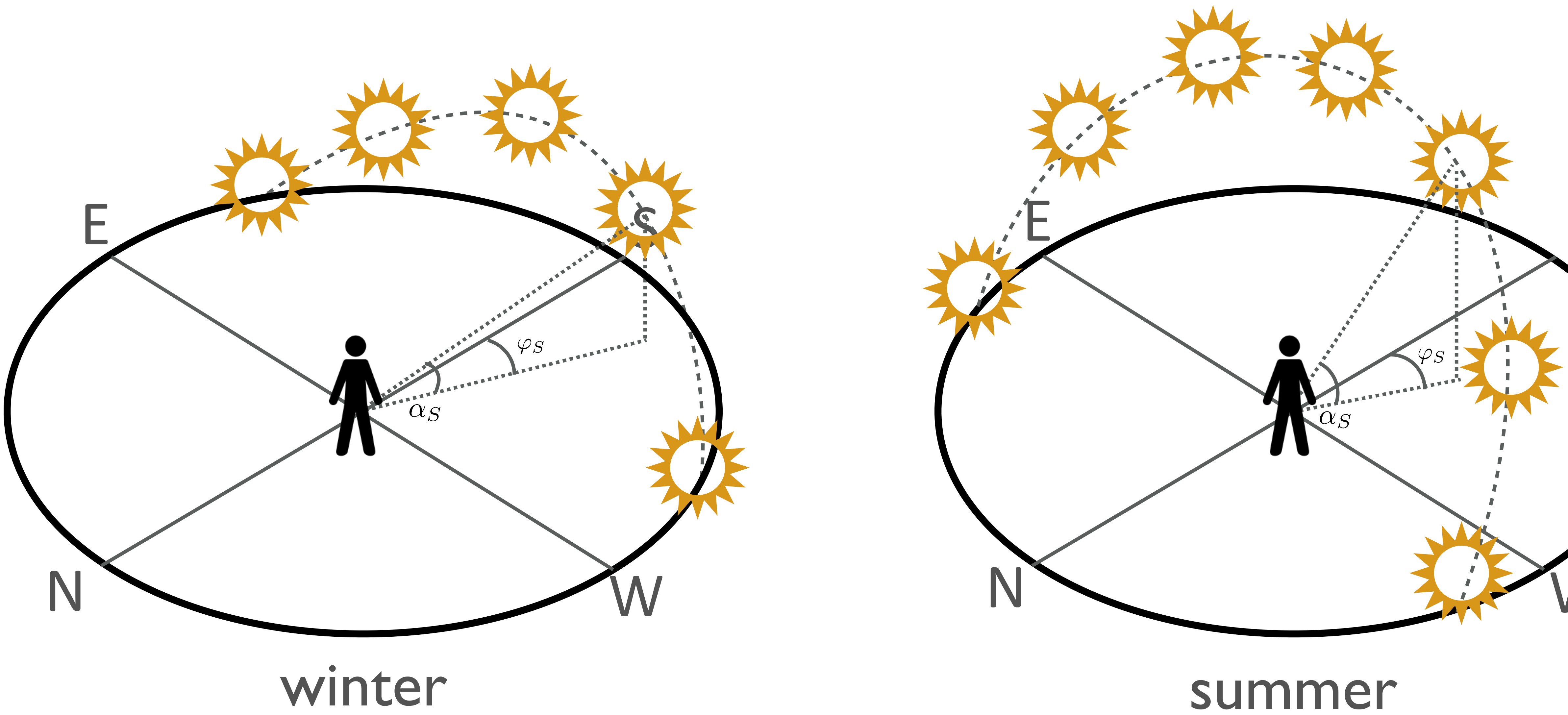
a) Calcular o coeficiente de transmissão de calor por radiação entre as duas lâminas de vidro a cerca de 30°C e com emissividade espectral ao infravermelho de 0.9;

b) Calcular o coeficiente de transmissão global entre as duas lâminas, considerando que o coeficiente de transmissão de calor por convecção é 2 $W/(m^2K)$;

c) Calcular o coeficiente de transmissão térmica (U) do vidro duplo, desprezando a transferência de calor por condução através dos vidros;

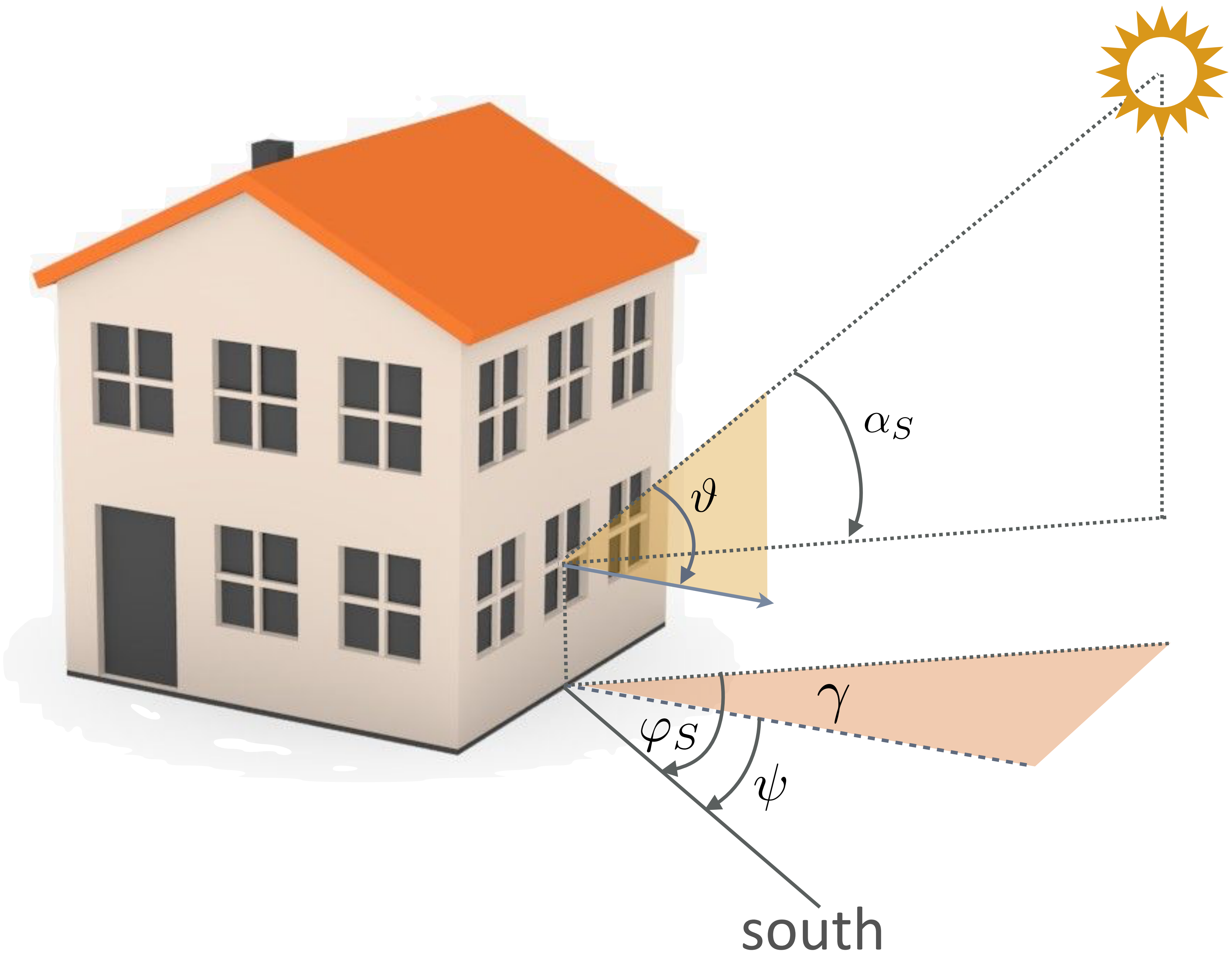
d) Considerando que um dos panos de vidro possui um revestimento selectivo com espessura desprezável e com emissividade espectral ao infravermelho de 0.2, repetir as alíneas anteriores.

Solar geometry



$$\sin \alpha_S = \cos \lambda \cos \delta \cos \omega + \sin \lambda \sin \delta$$

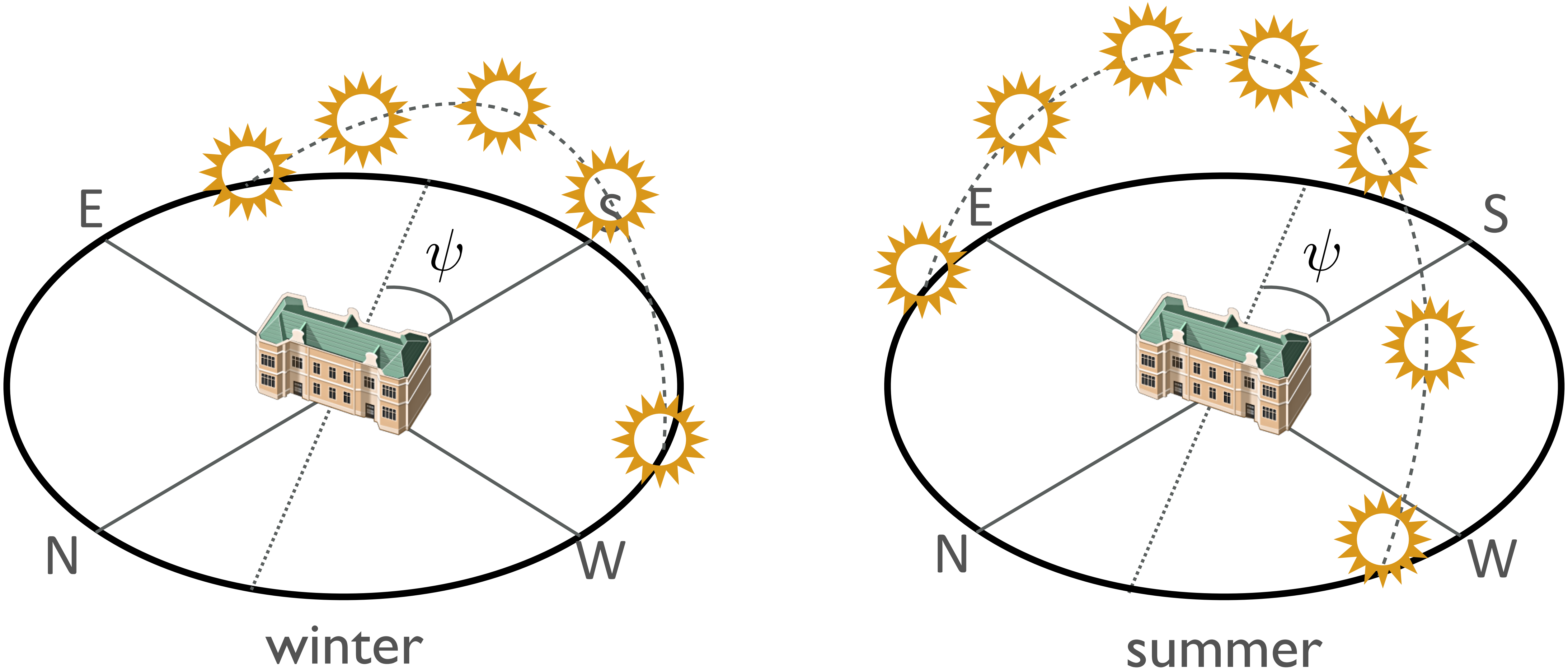
$$\cos \varphi_S = \frac{\sin \alpha_s \sin \lambda - \sin \delta}{\cos \alpha_S \cos \lambda}$$

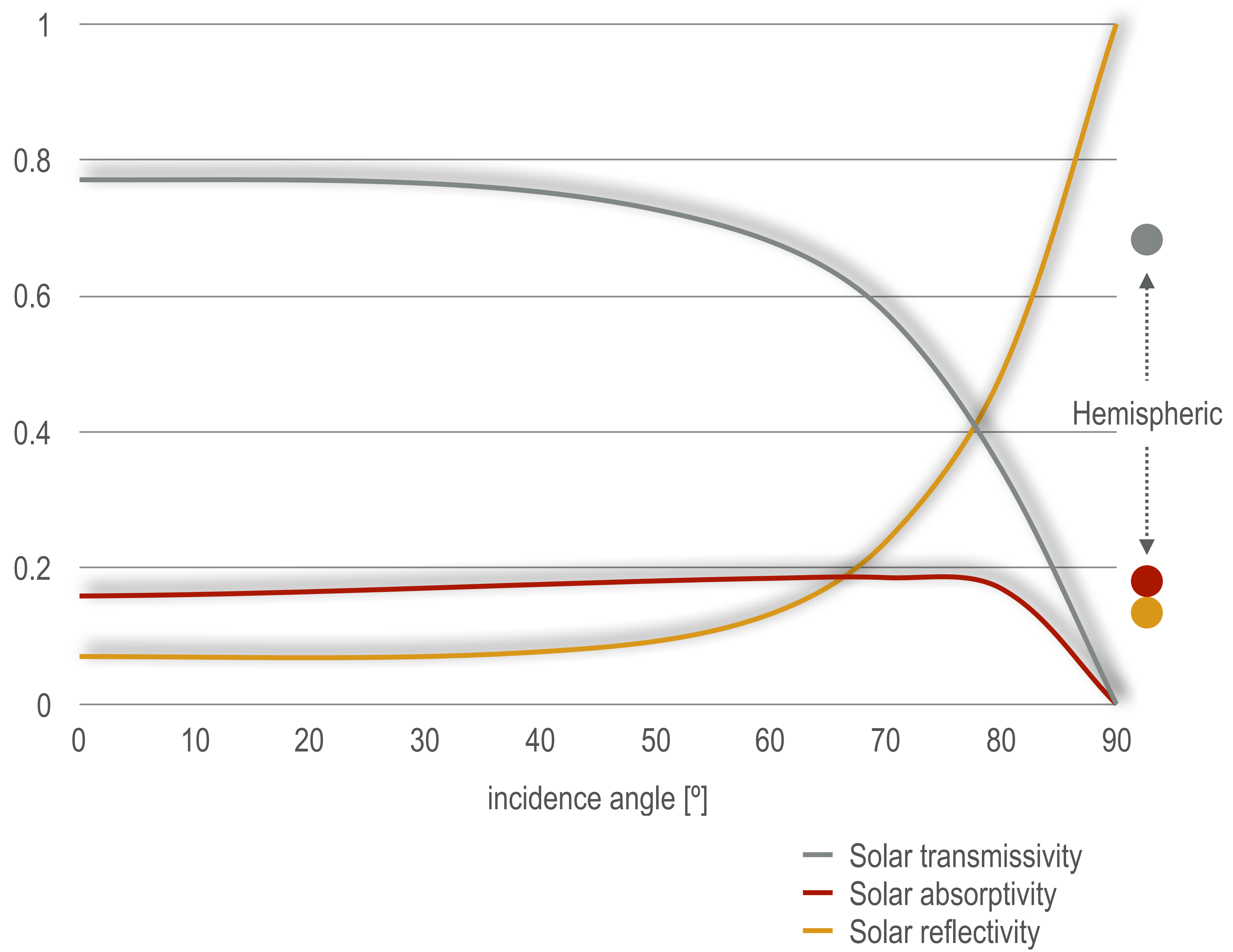


Any surface: $\cos\vartheta = \cos\alpha_s \cos\gamma \sin\beta + \sin\alpha_s \cos\beta$

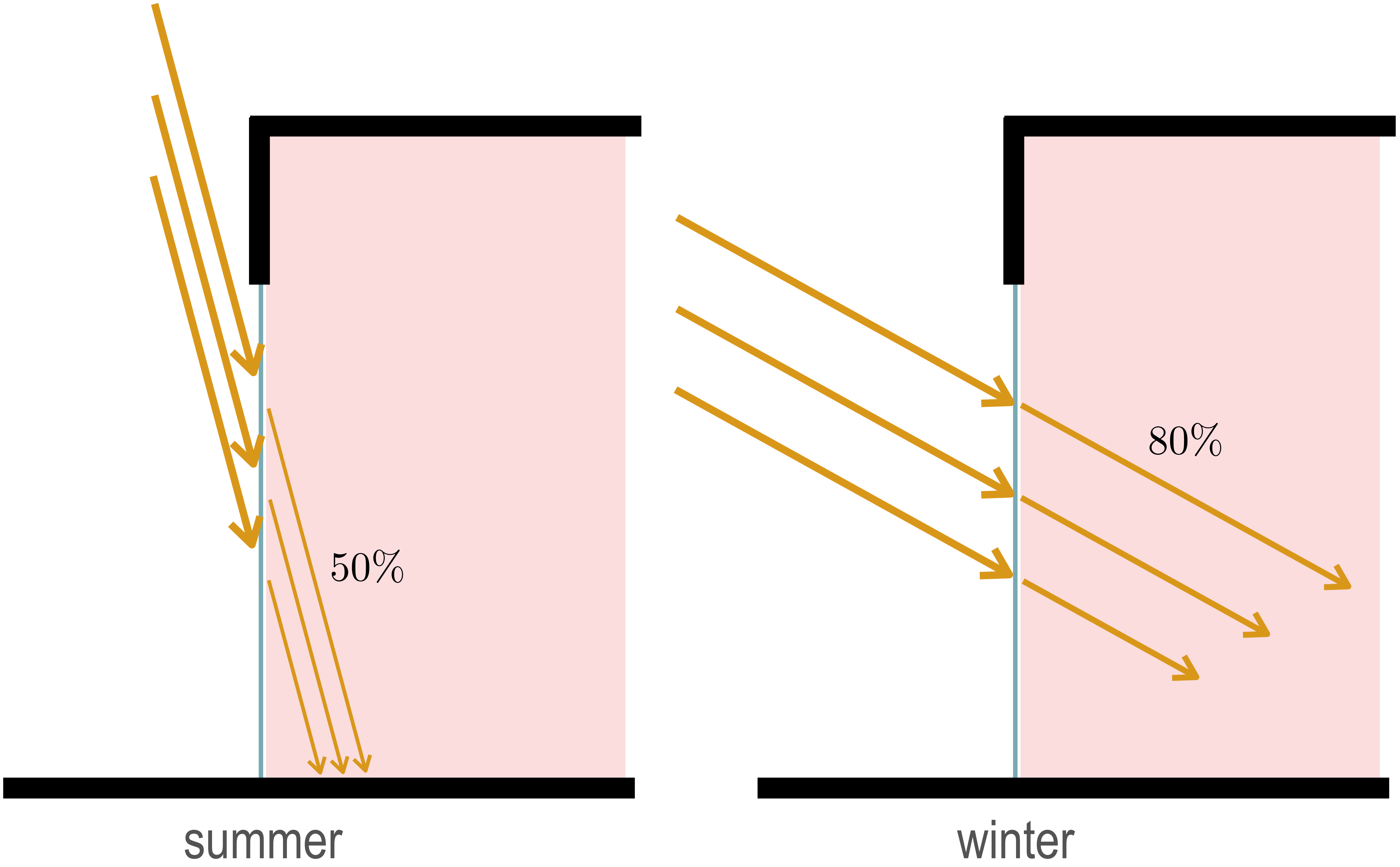
Vertical surface: $\cos\vartheta = \cos\alpha_s \cos\gamma$

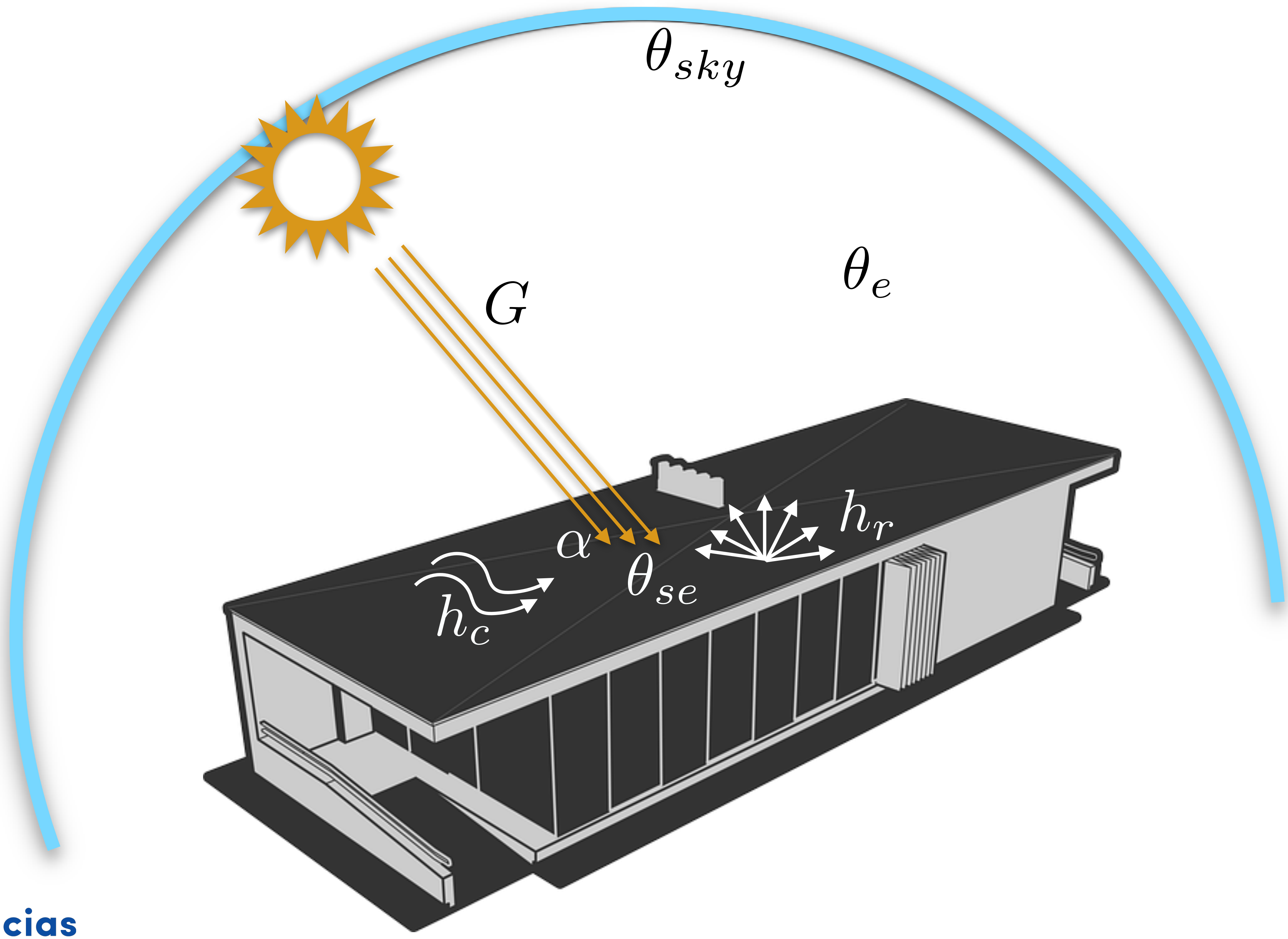
Ciências ULisboa


E
S
ψ
N
W
winter
E
S
ψ
N
W
summer



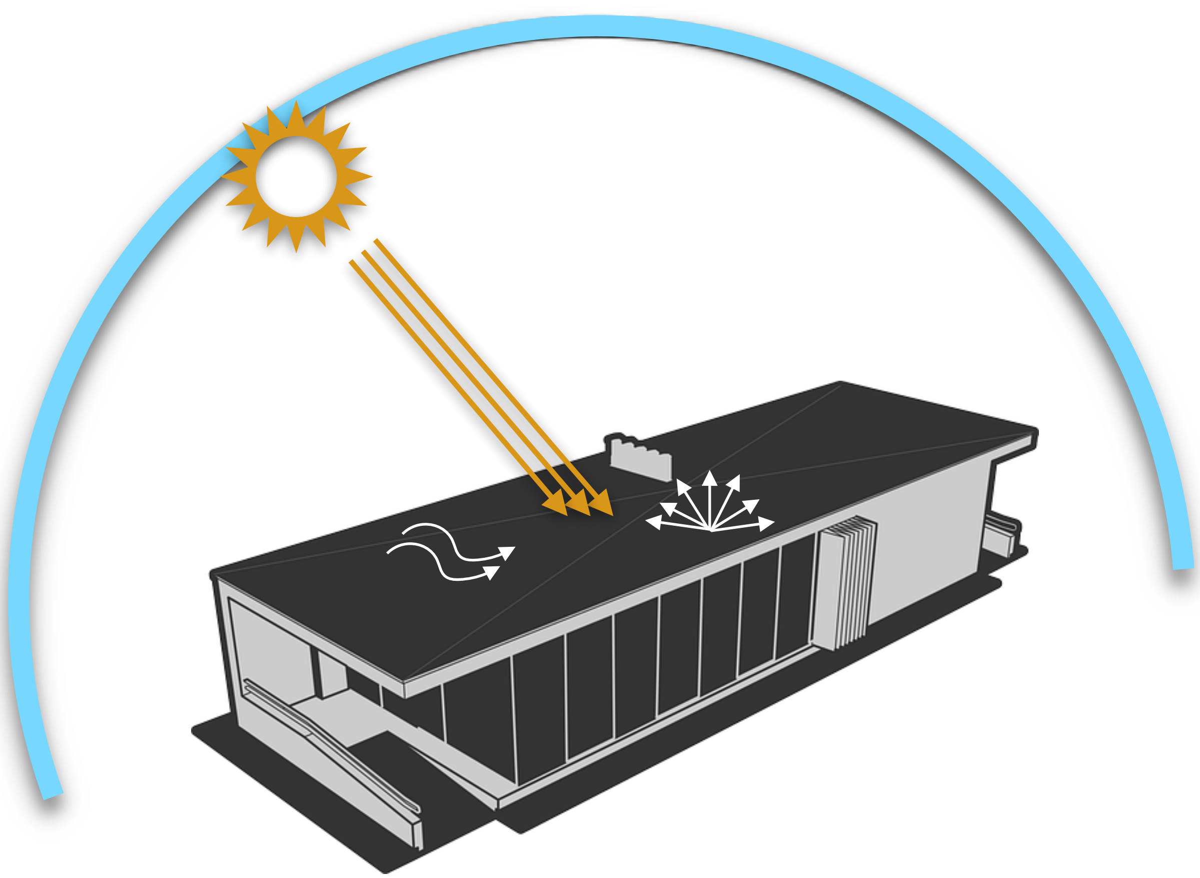
1
0.8
0.6
0.4
0.2
0
0
10
20
30
40
50
60
70
80
90
incidence angle [º]
Hemispheric
Solar transmissivity
Solar absorptivity
Solar reflectivity

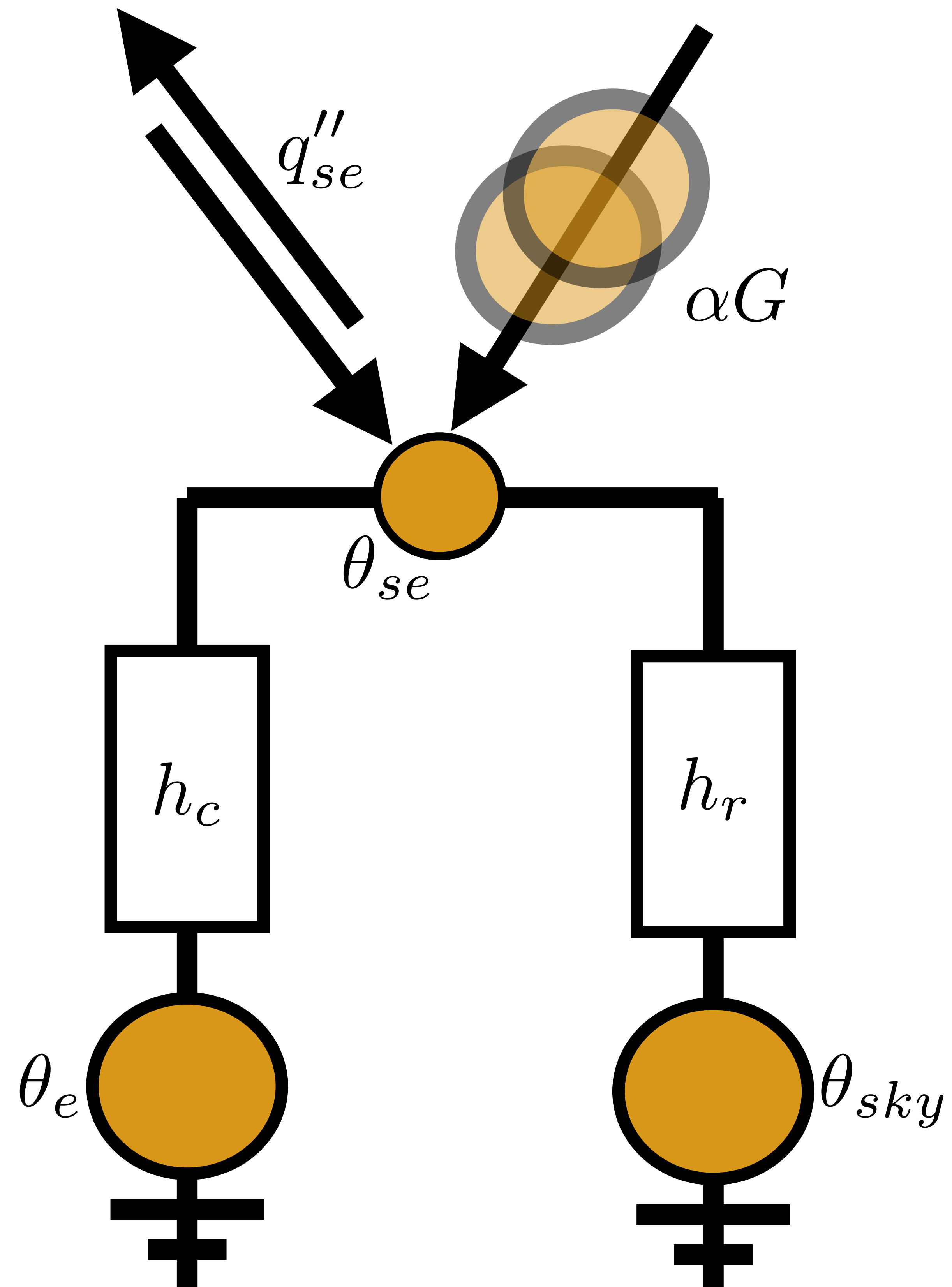

50%
80%
summer
winter



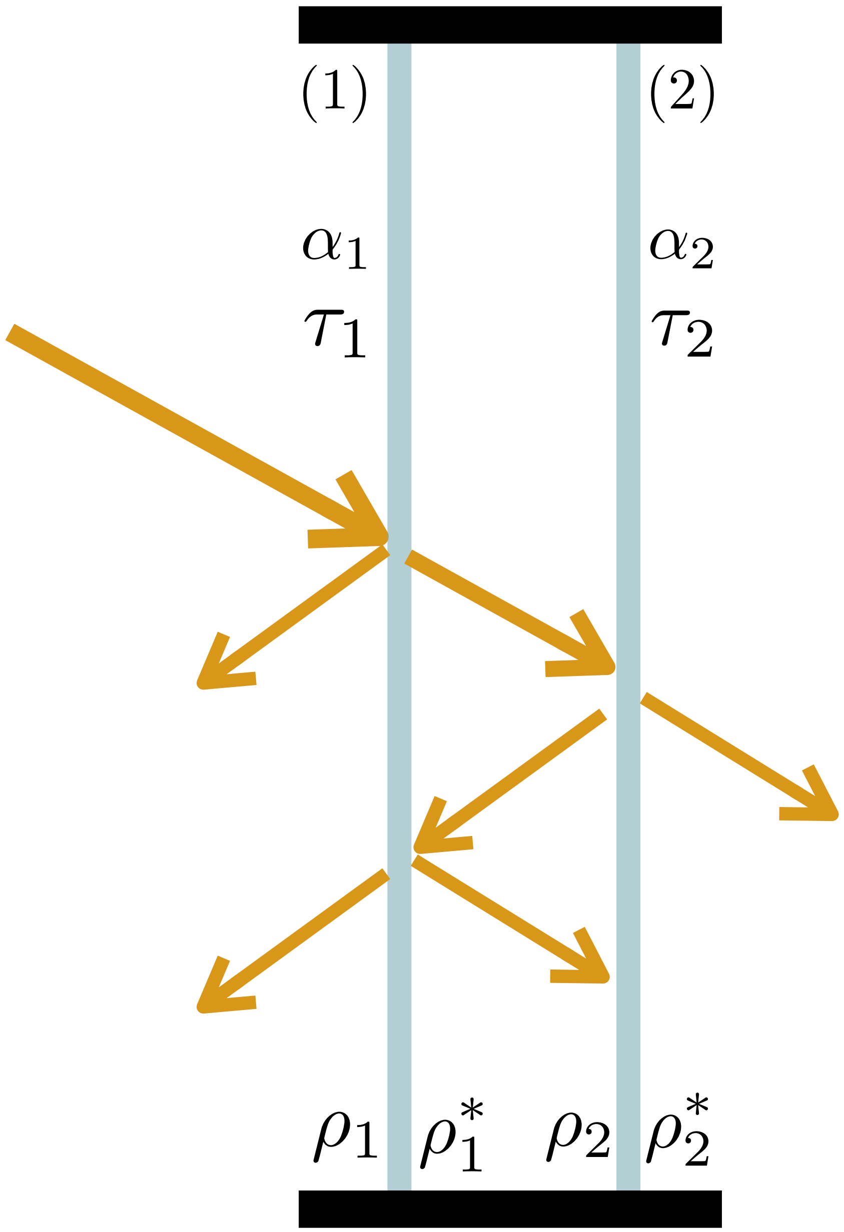
Ciências ULisboa

$$q''_{se} = \alpha G - h_c(\theta_{se} - \theta_e) - h_r(\theta_{se} - \theta_{sky})$$





Ciências ULisboa



Group properties

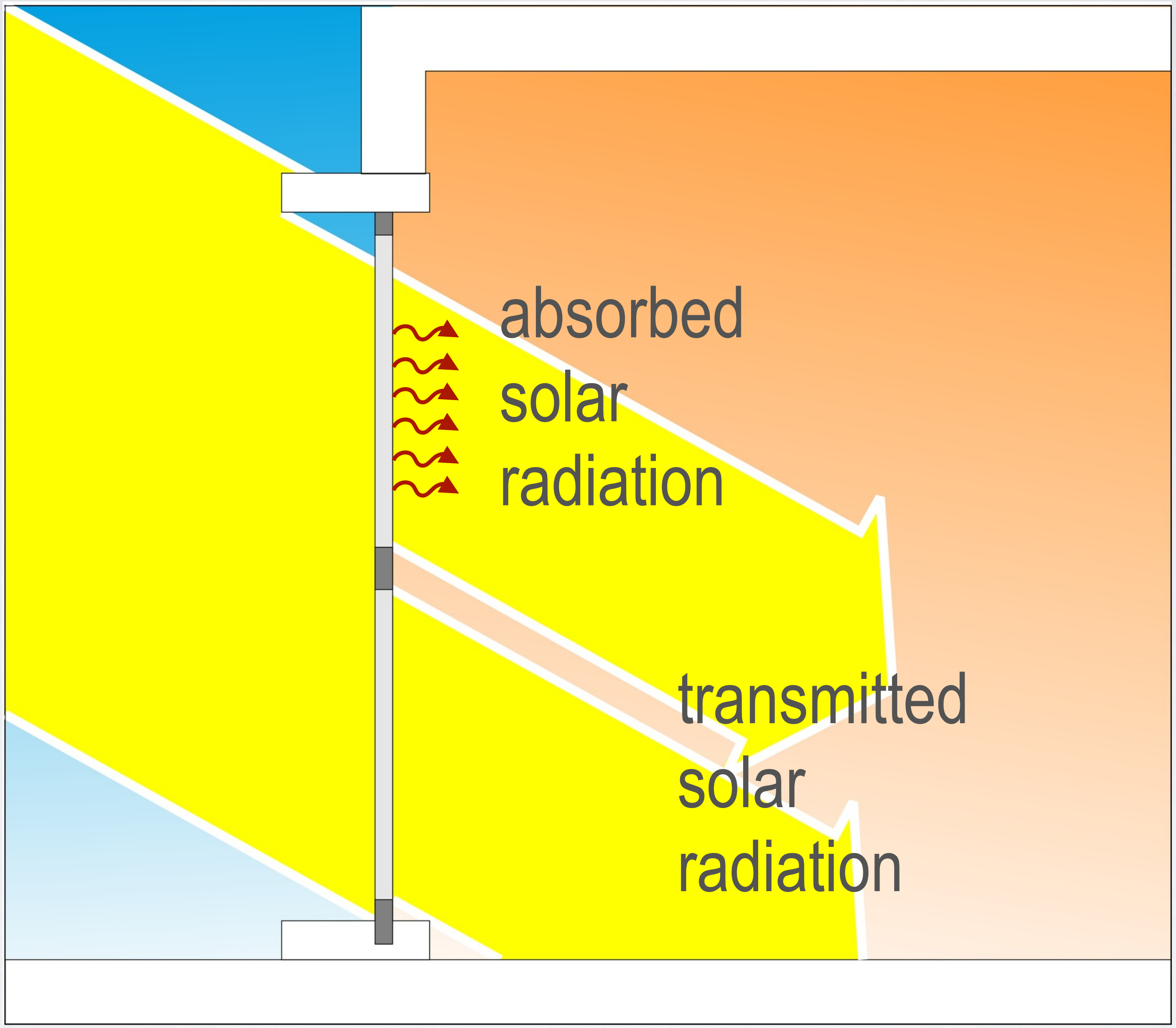
$$\rho_{12} = \rho_1 + \frac{\rho_2 \tau_1^2}{1 - \rho_1^* \rho_2}$$

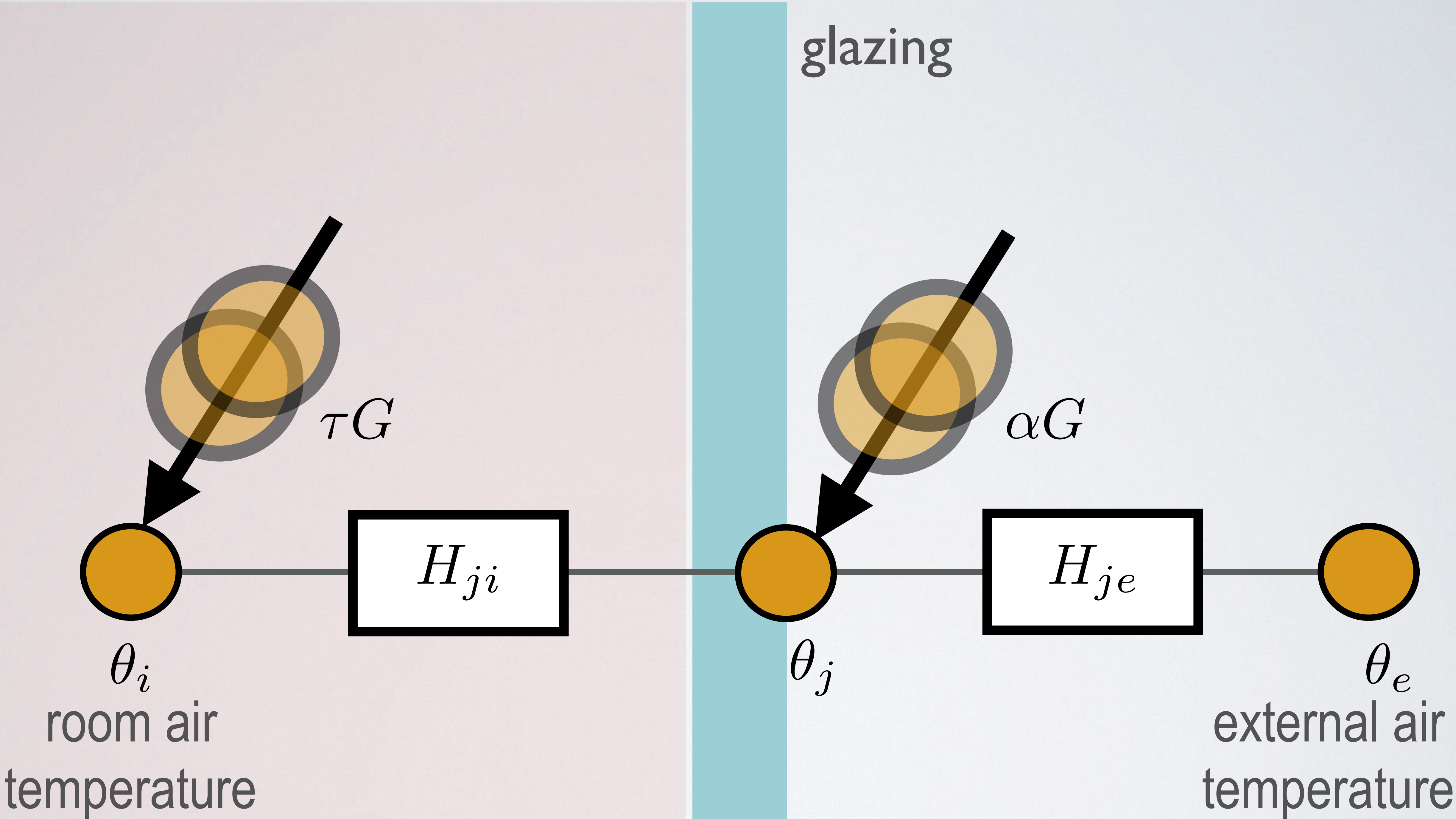
$$\tau_{12} = \frac{\tau_1 \tau_2}{1 - \rho_1^* \rho_2}$$

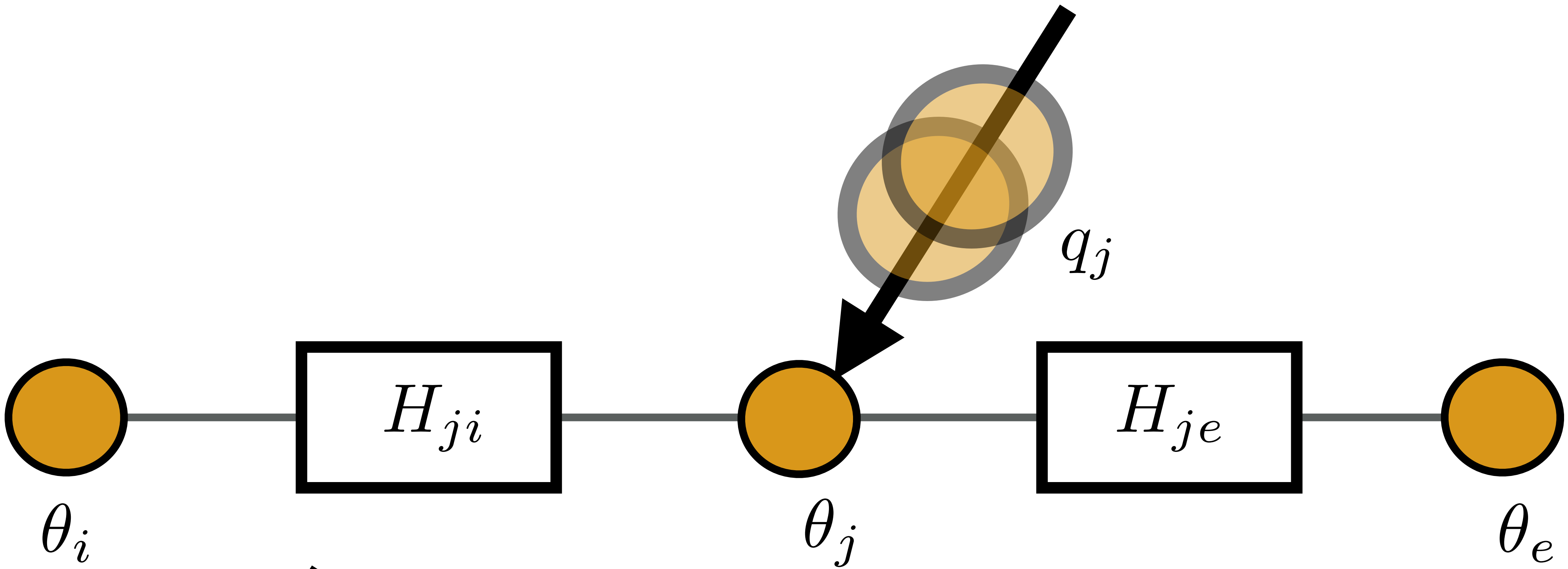
Individual properties

$$\alpha_{1 \Rightarrow 12} = \alpha_1 + \frac{\alpha_1 \rho_2 \tau_1}{1 - \rho_1^* \rho_2}$$

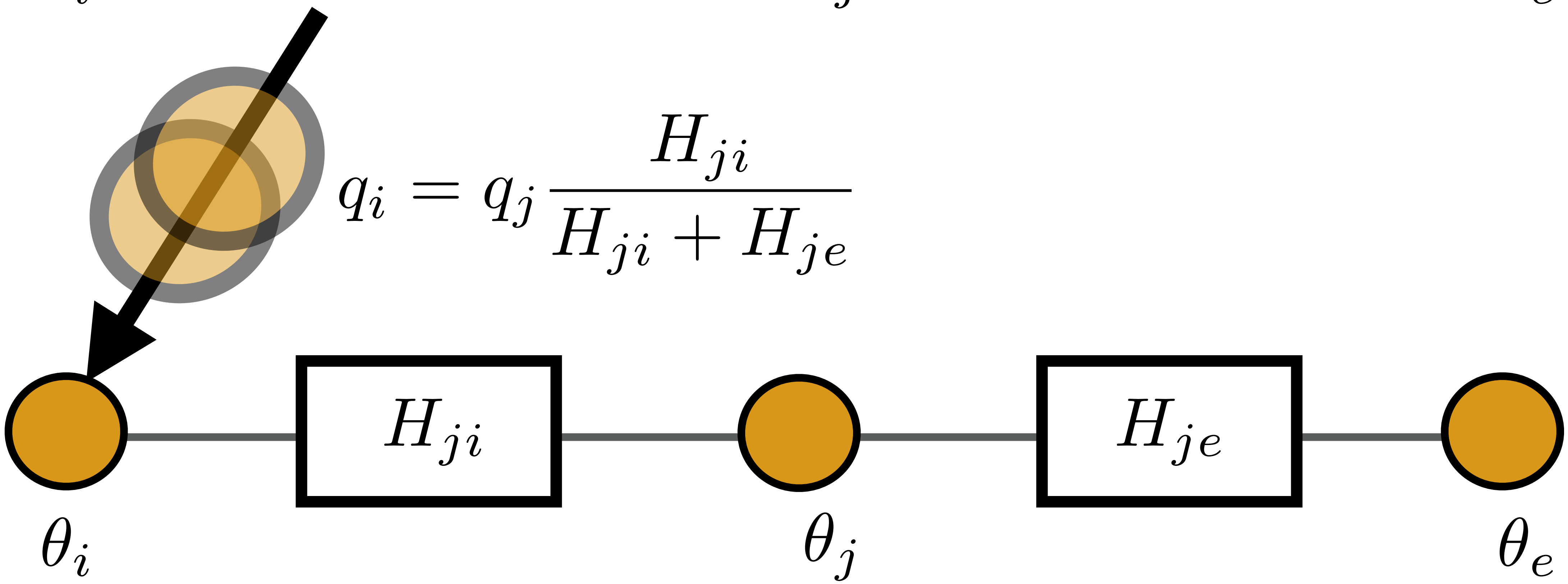
$$\alpha_{2 \Rightarrow 12} = \frac{\alpha_2 \tau_1}{1 - \rho_1^* \rho_2}$$

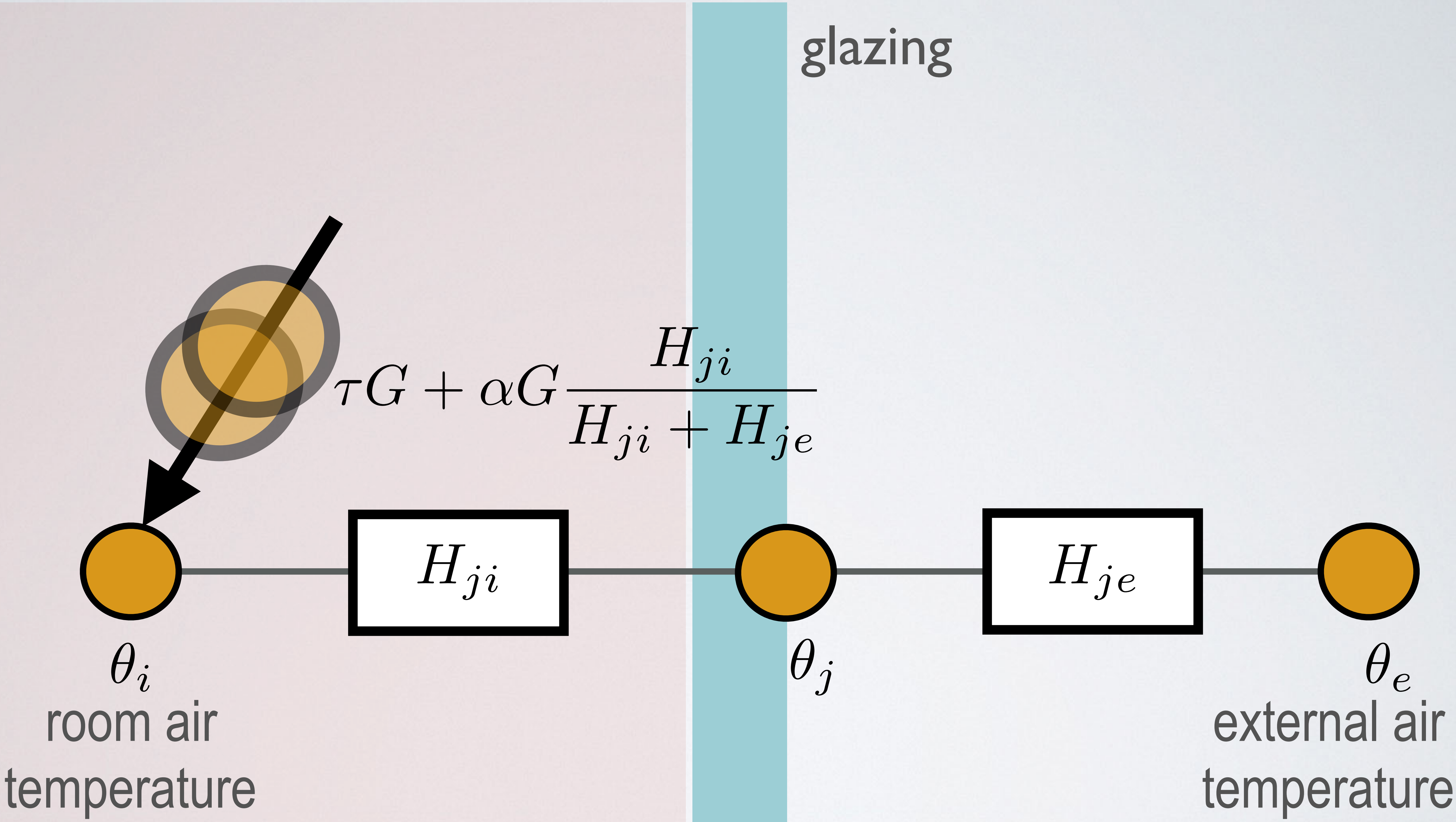

absorbed
solar
radiation
transmitted
solar
radiation


glazing
τG
αG
H_{ji}
H_{je}
θ_i
room air temperature
θ_j
θ_e
external air temperature

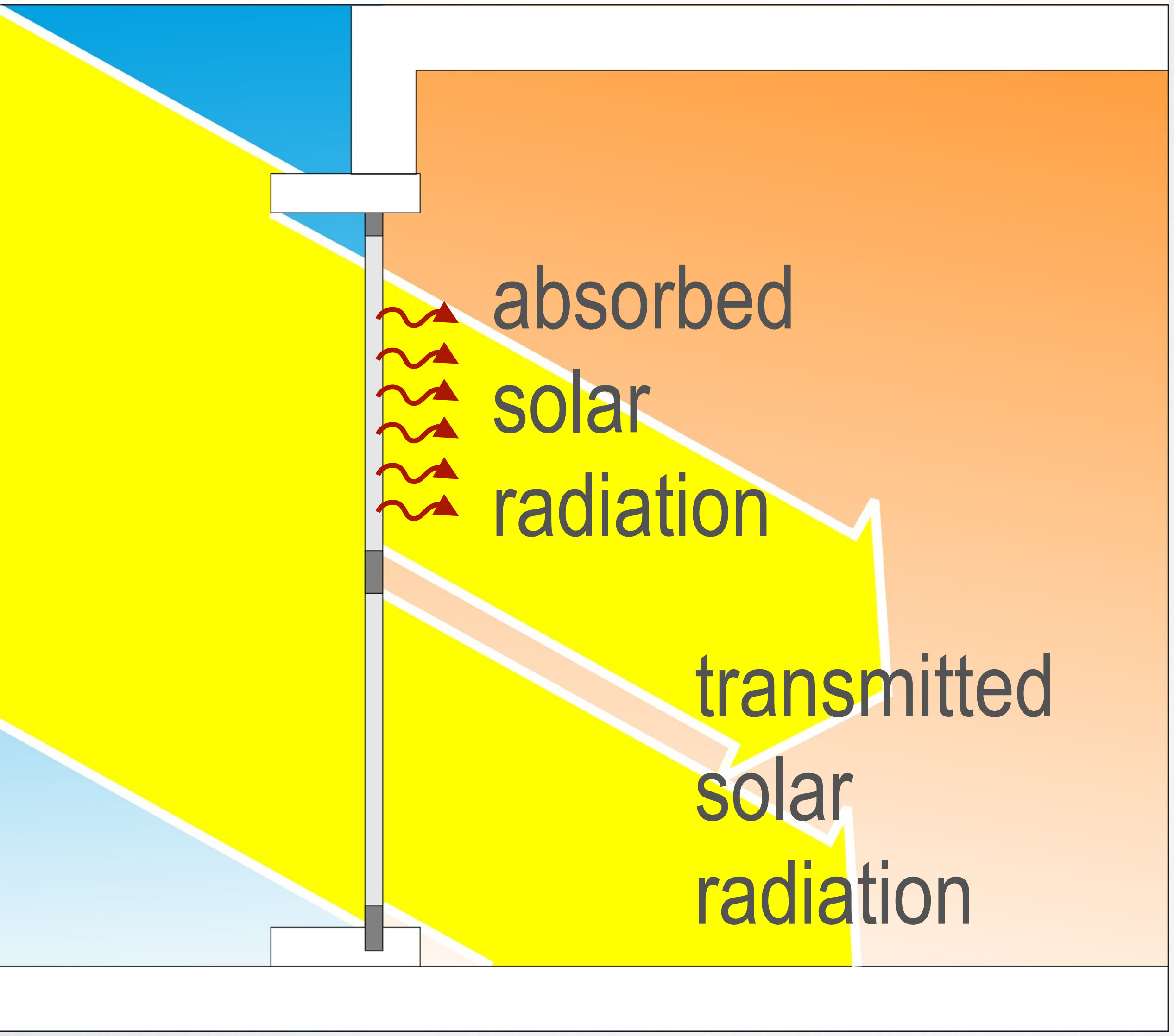


$$q_i = q_j \frac{H_{ji}}{H_{ji} + H_{je}}$$





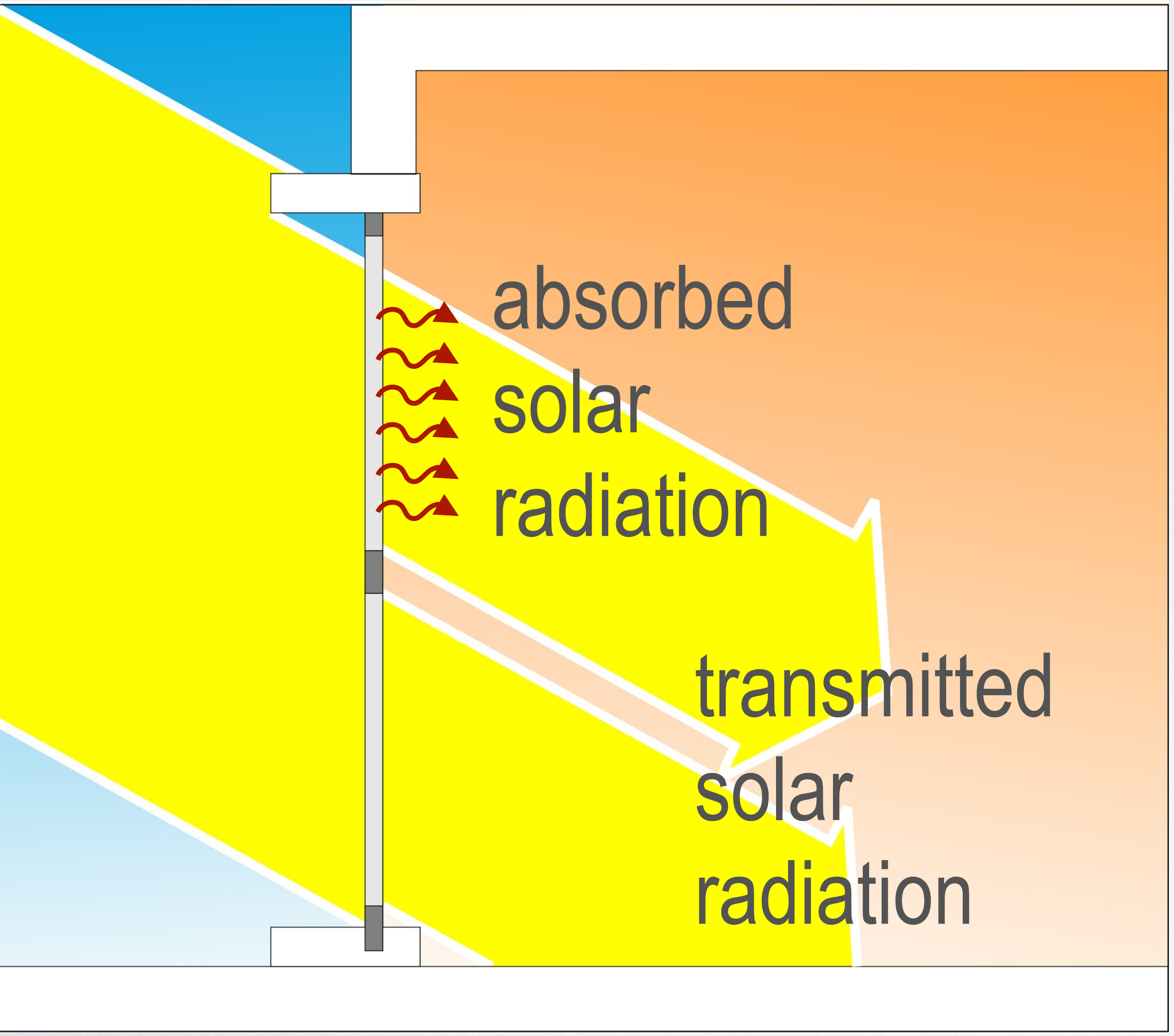
Ciências ULisboa



$$g = \tau + \alpha \frac{H_{ji}}{H_{ji} + H_{je}}$$

transmitted solar radiation + absorbed solar radiation

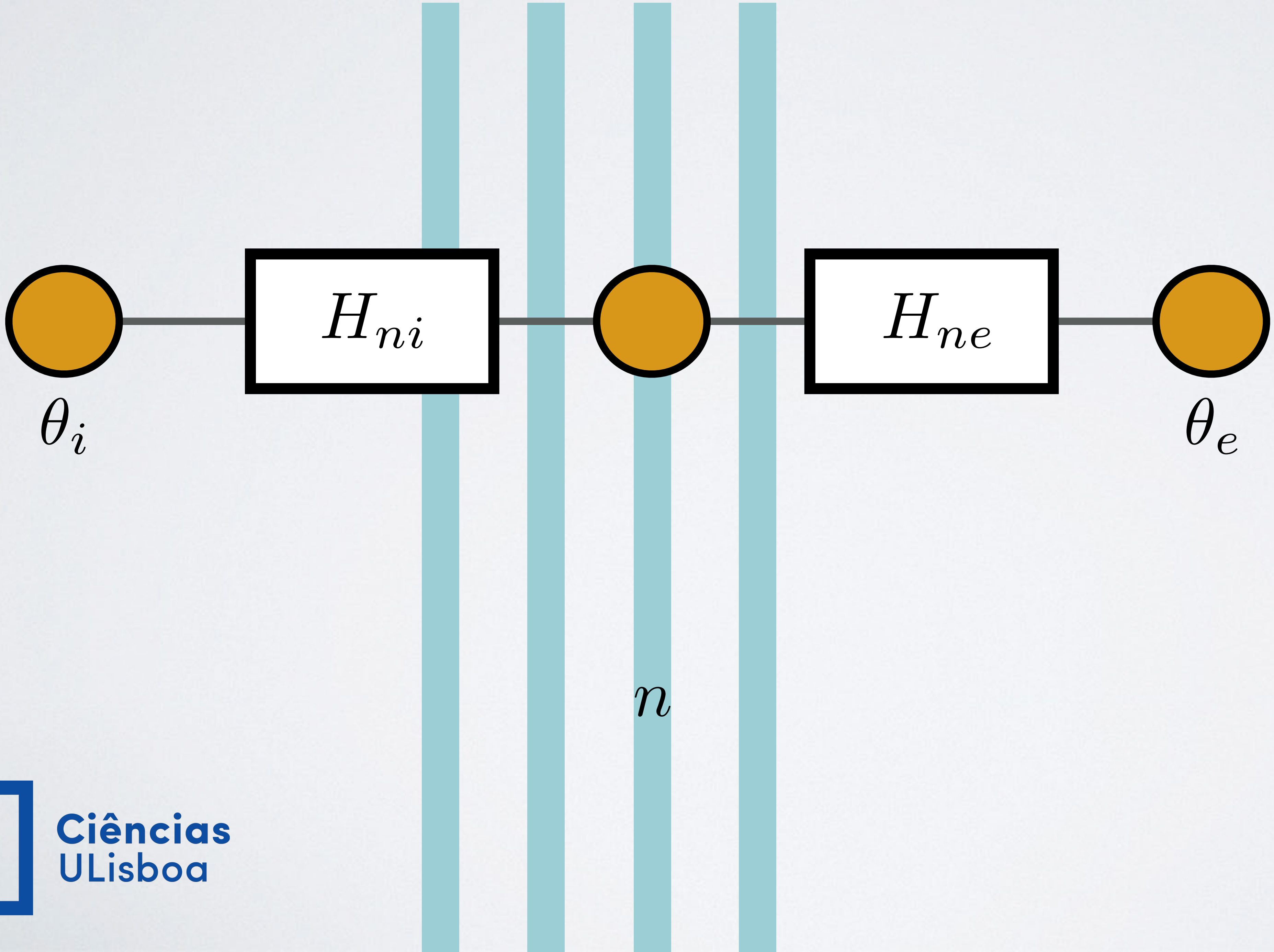
$$g(\vartheta) = \tau(\vartheta) + \sum_n \left(\alpha_n(\vartheta) \frac{H_{ni}}{H_{ni} + H_{ne}} \right)$$



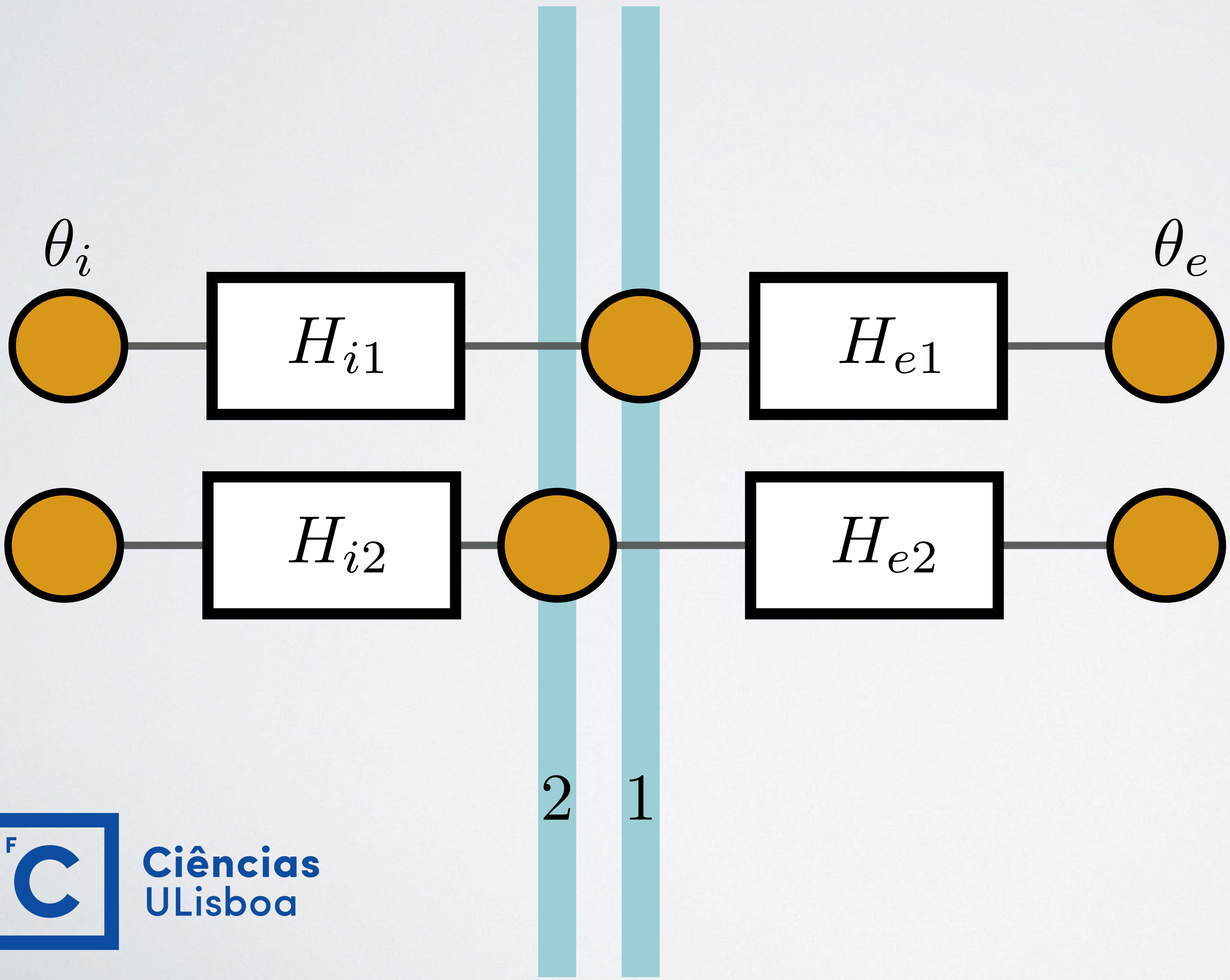
transmitted solar radiation + absorbed solar radiation

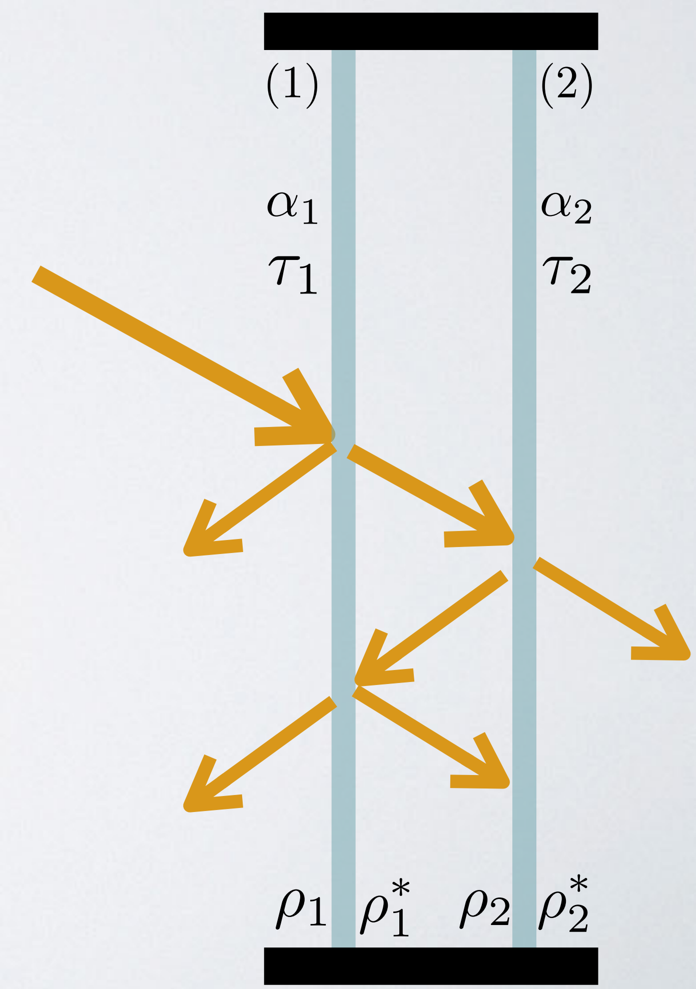
Ciências ULisboa

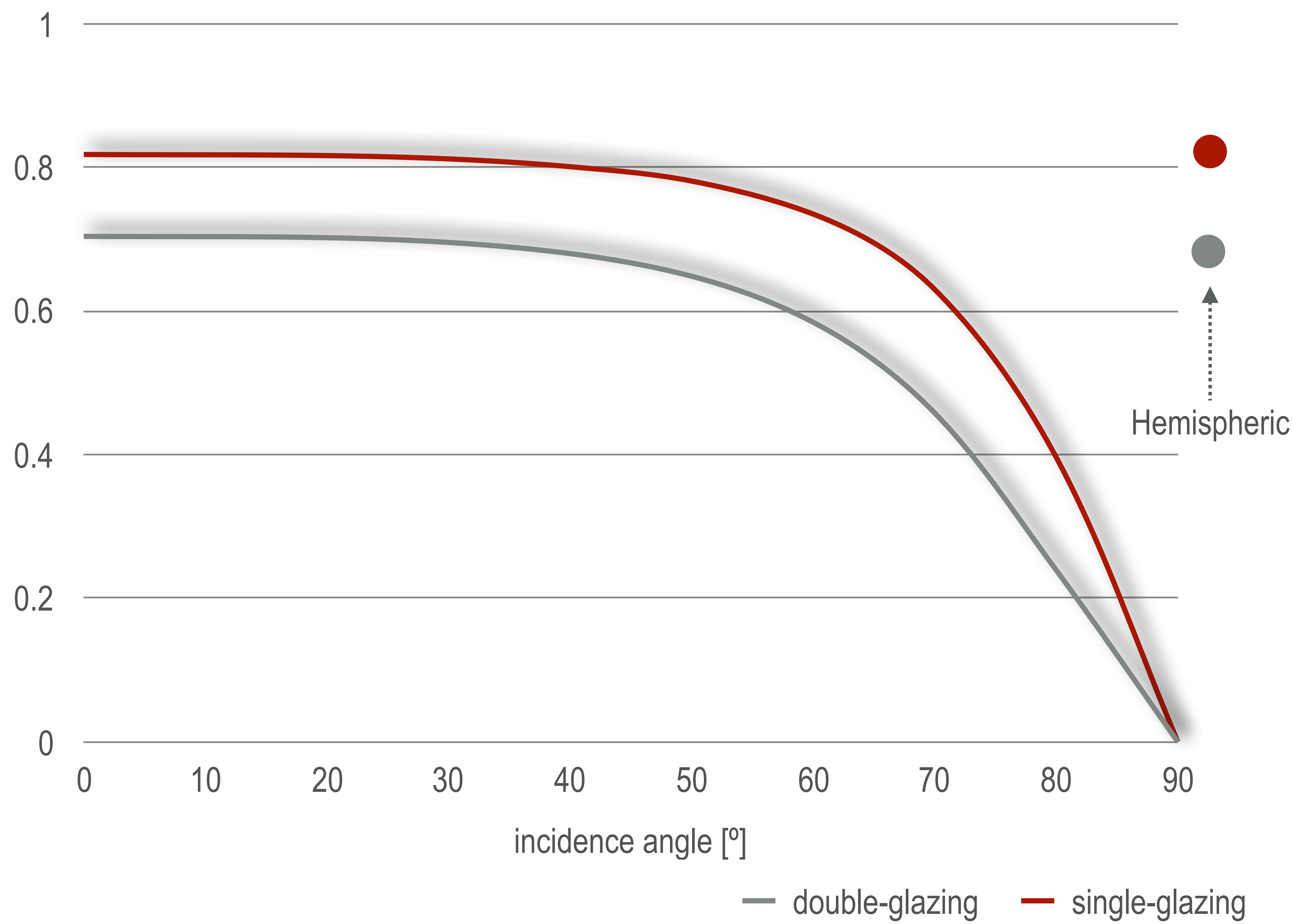
$$g(\vartheta) = \tau(\vartheta) + \sum_n \left(\alpha_n(\vartheta) \frac{H_{ni}}{H_{ni} + H_{ne}} \right)$$



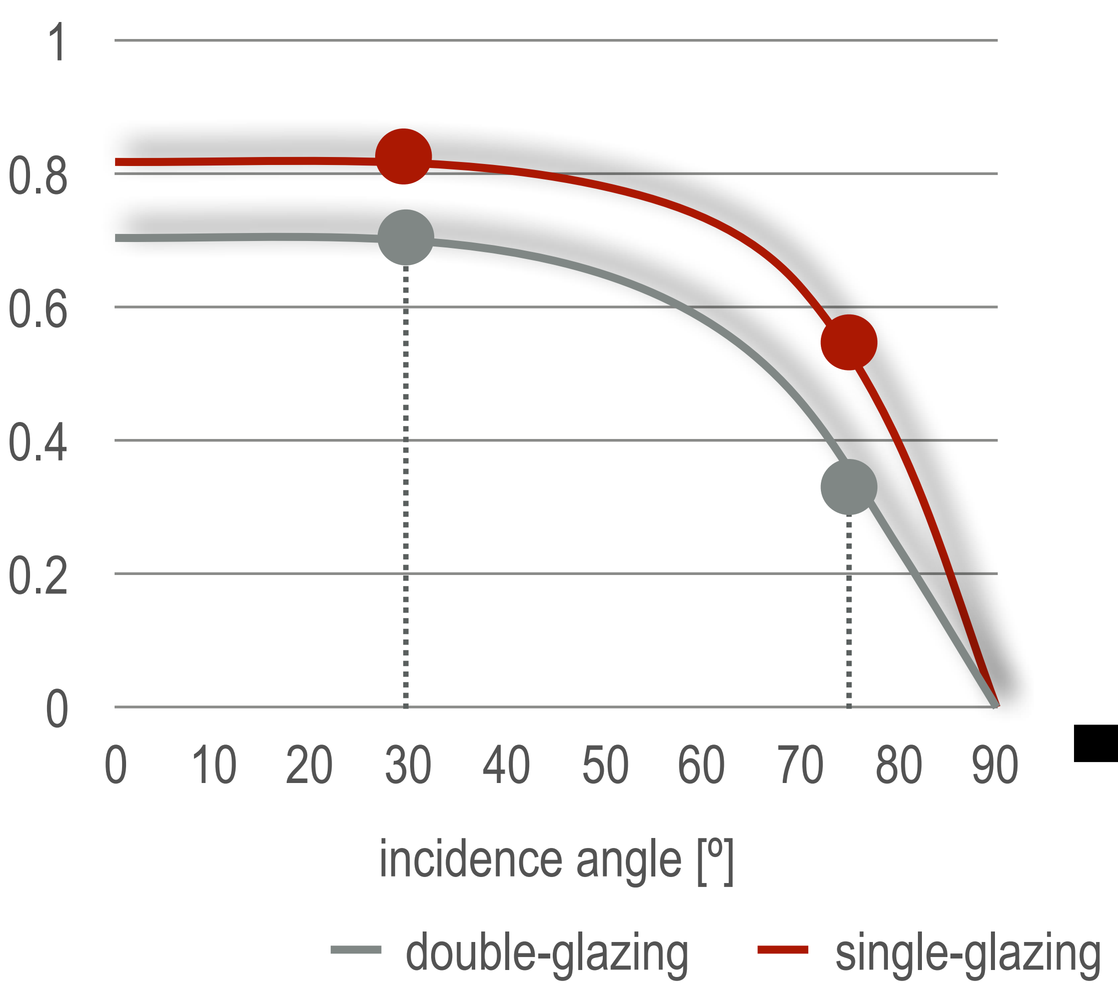
$$g = \tau_{12} + \alpha_{1\Rightarrow 12}\frac{H_{i1}}{H_{i1}+H_{e1}} + \alpha_{2\Rightarrow 12}\frac{H_{i2}}{H_{i2}+H_{e2}}$$

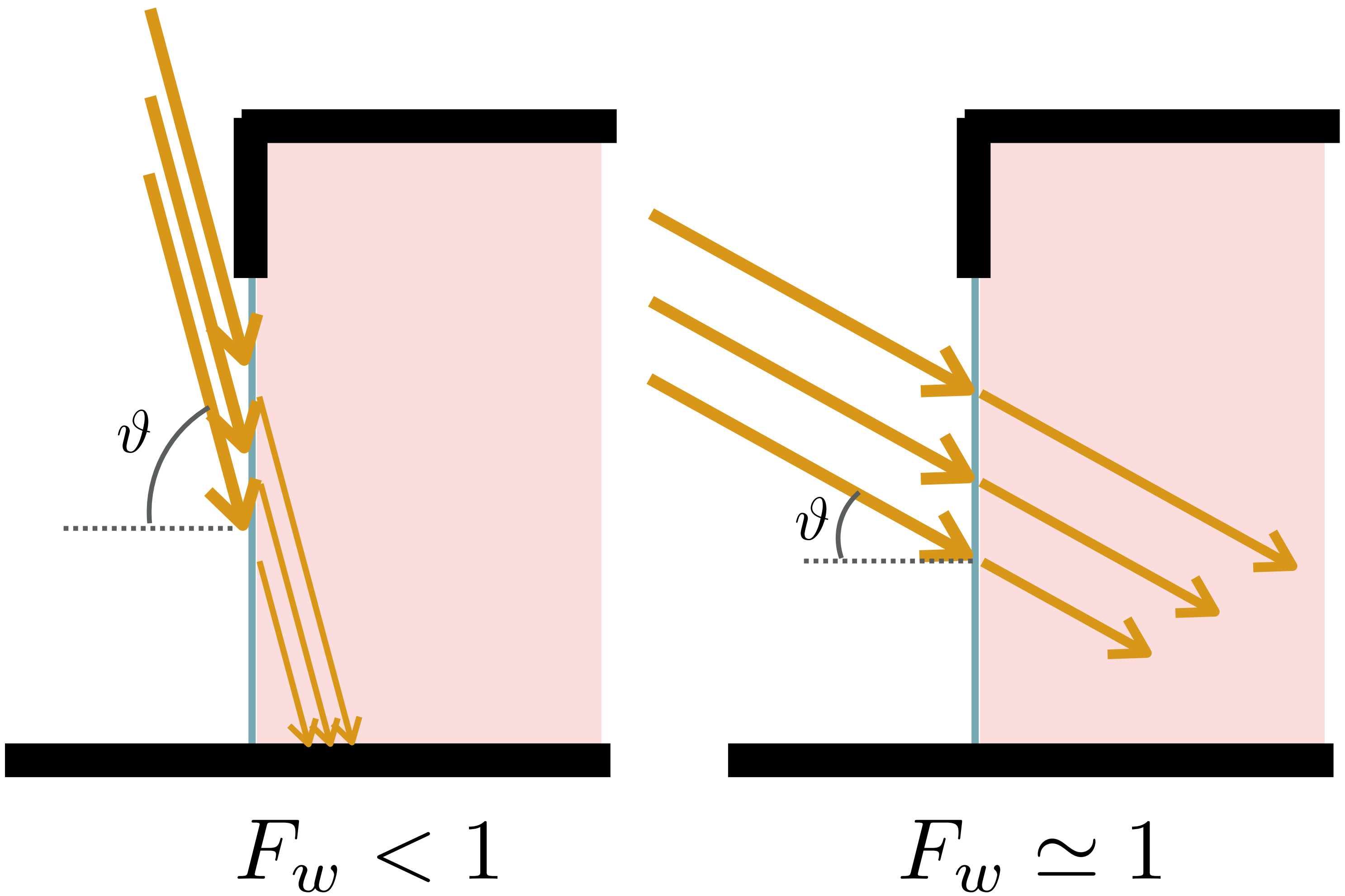






Ciências ULisboa

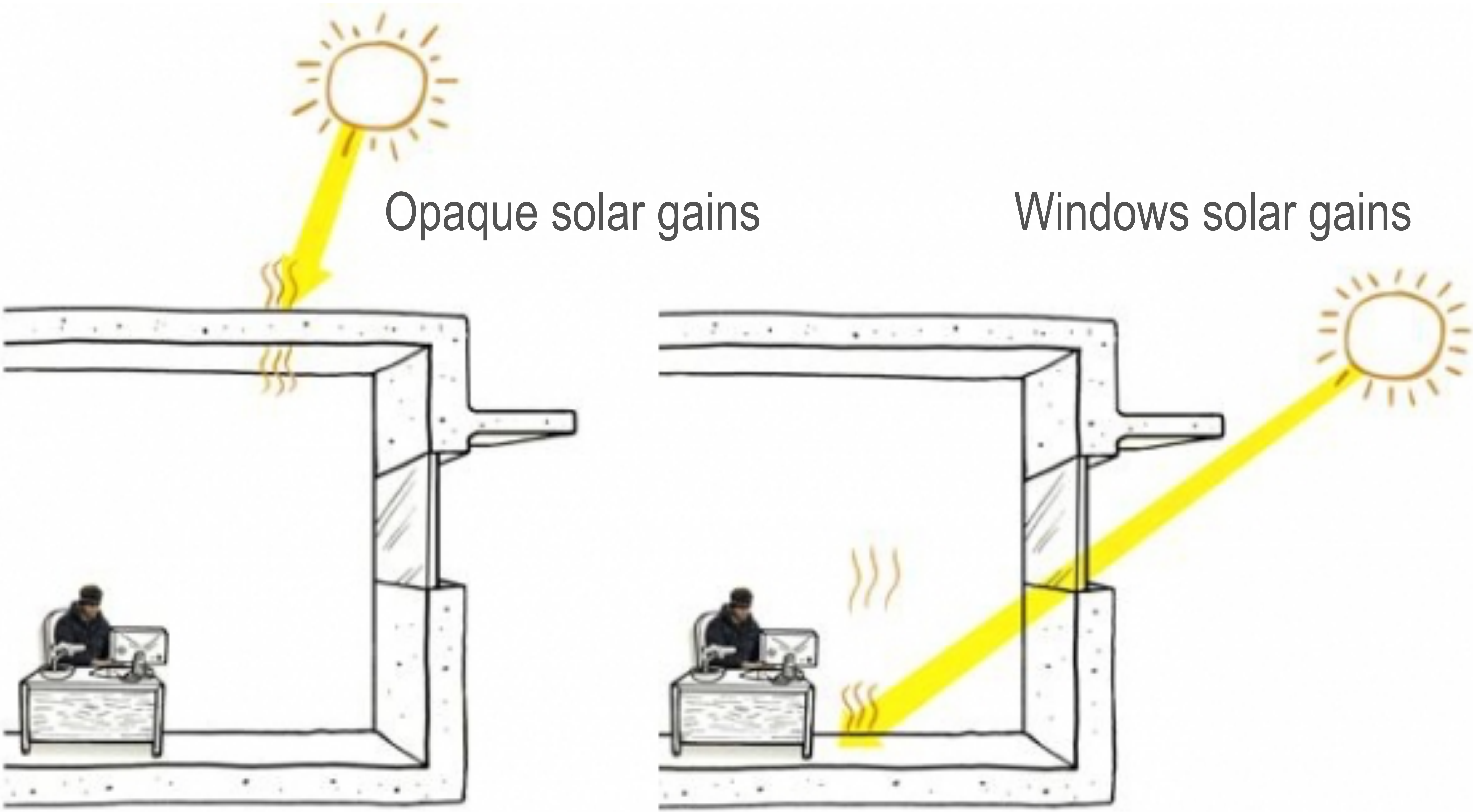


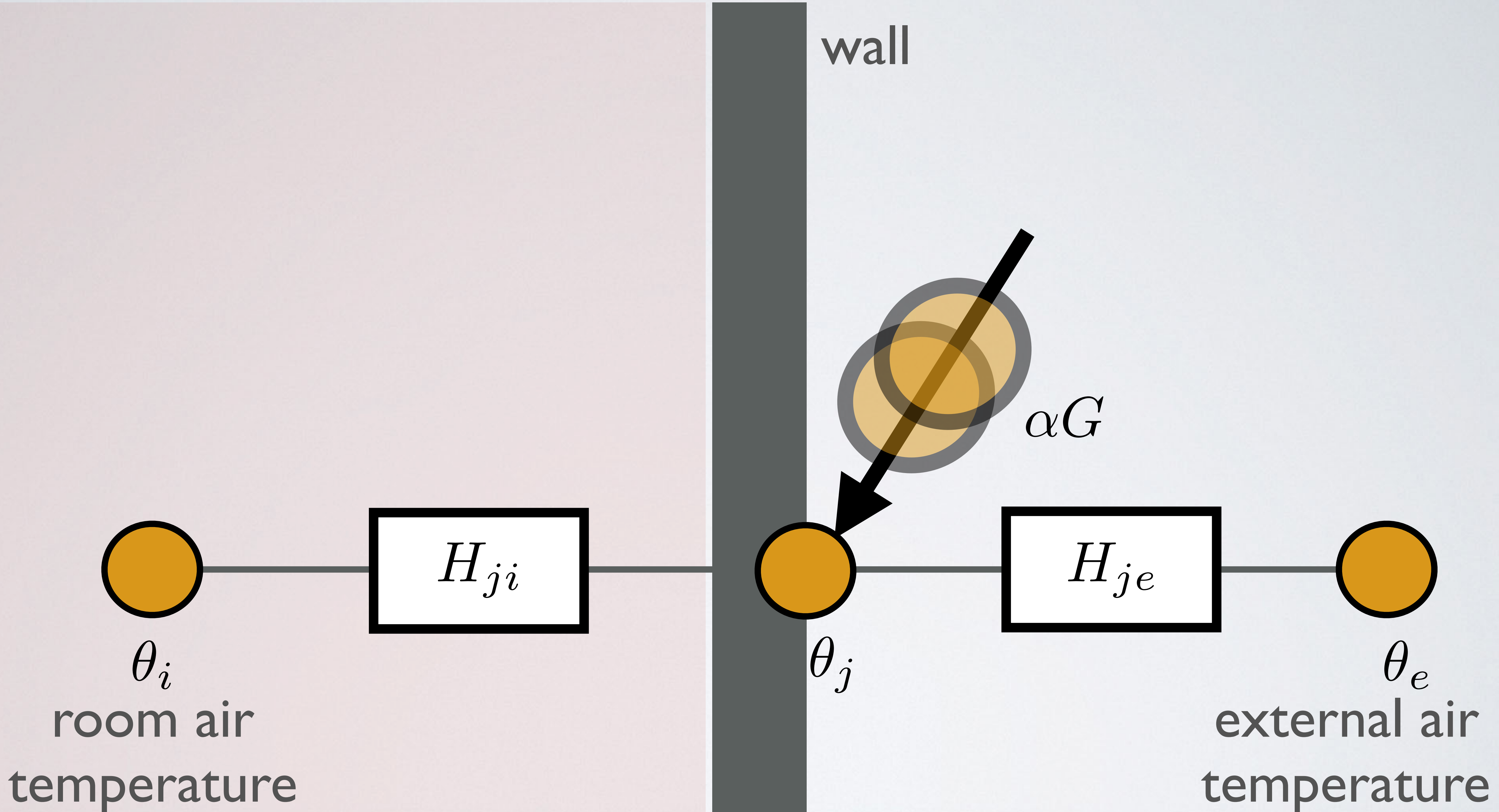


$$g(\vartheta) = g_{\perp} F_w$$

Ciências
ULisboa

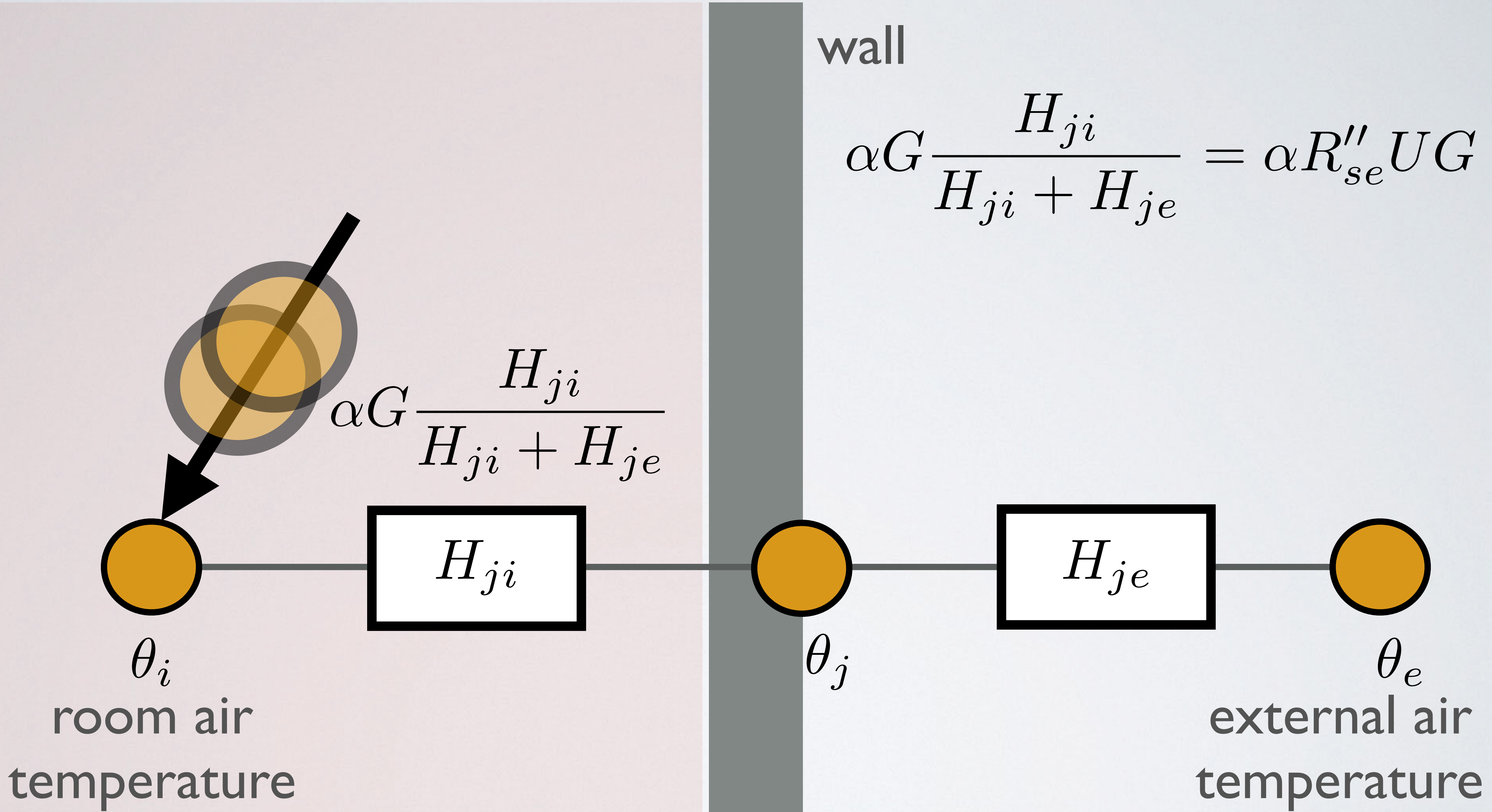
Opaque solar gains

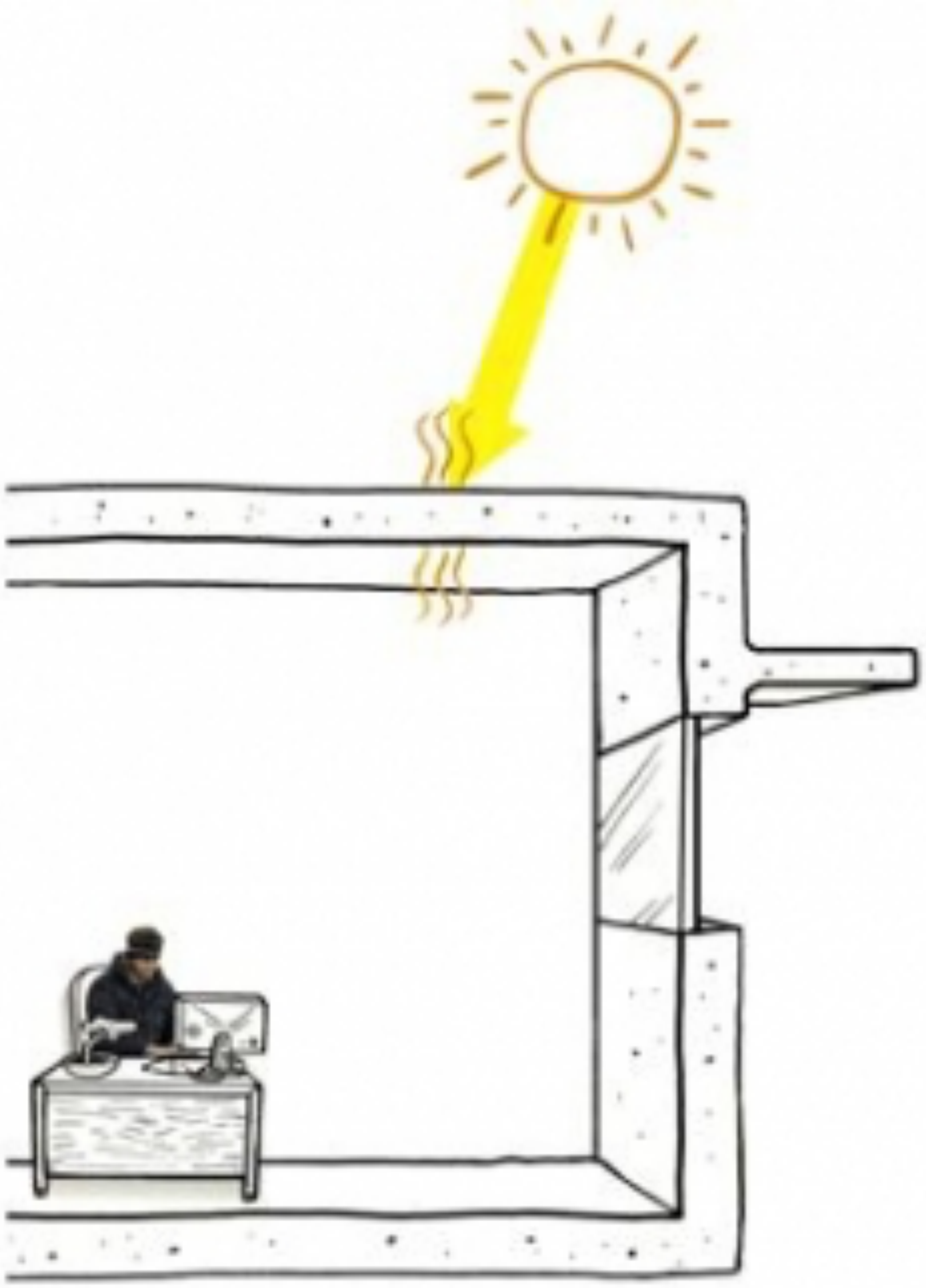




Ciências ULisboa

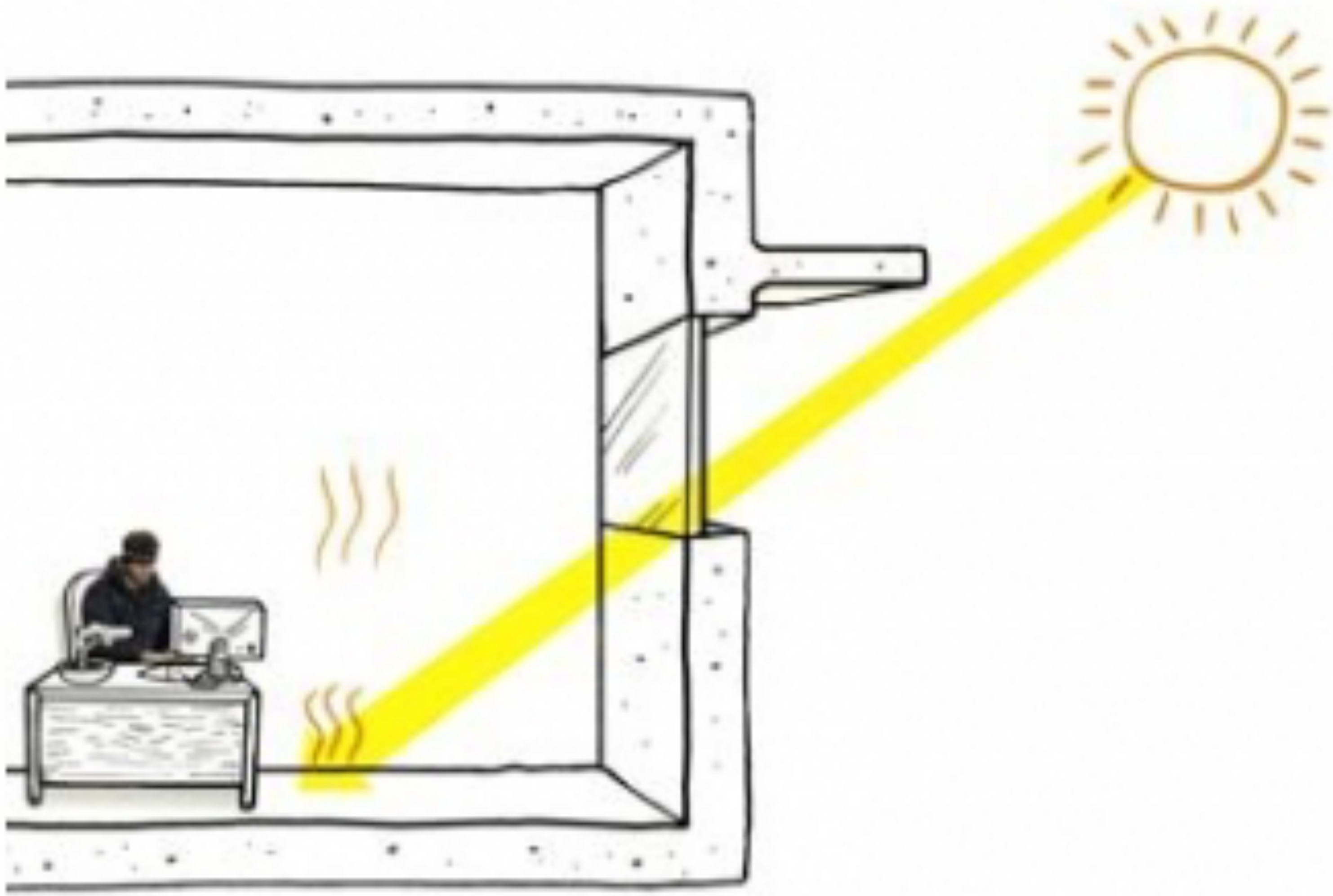
$$\alpha G \frac{H_{ji}}{H_{ji} + H_{je}} = \alpha R''_{se} U G$$





Opaque solar gains:

- solar radiation
- collecting area
- opaque U-value
- solar absorptivity

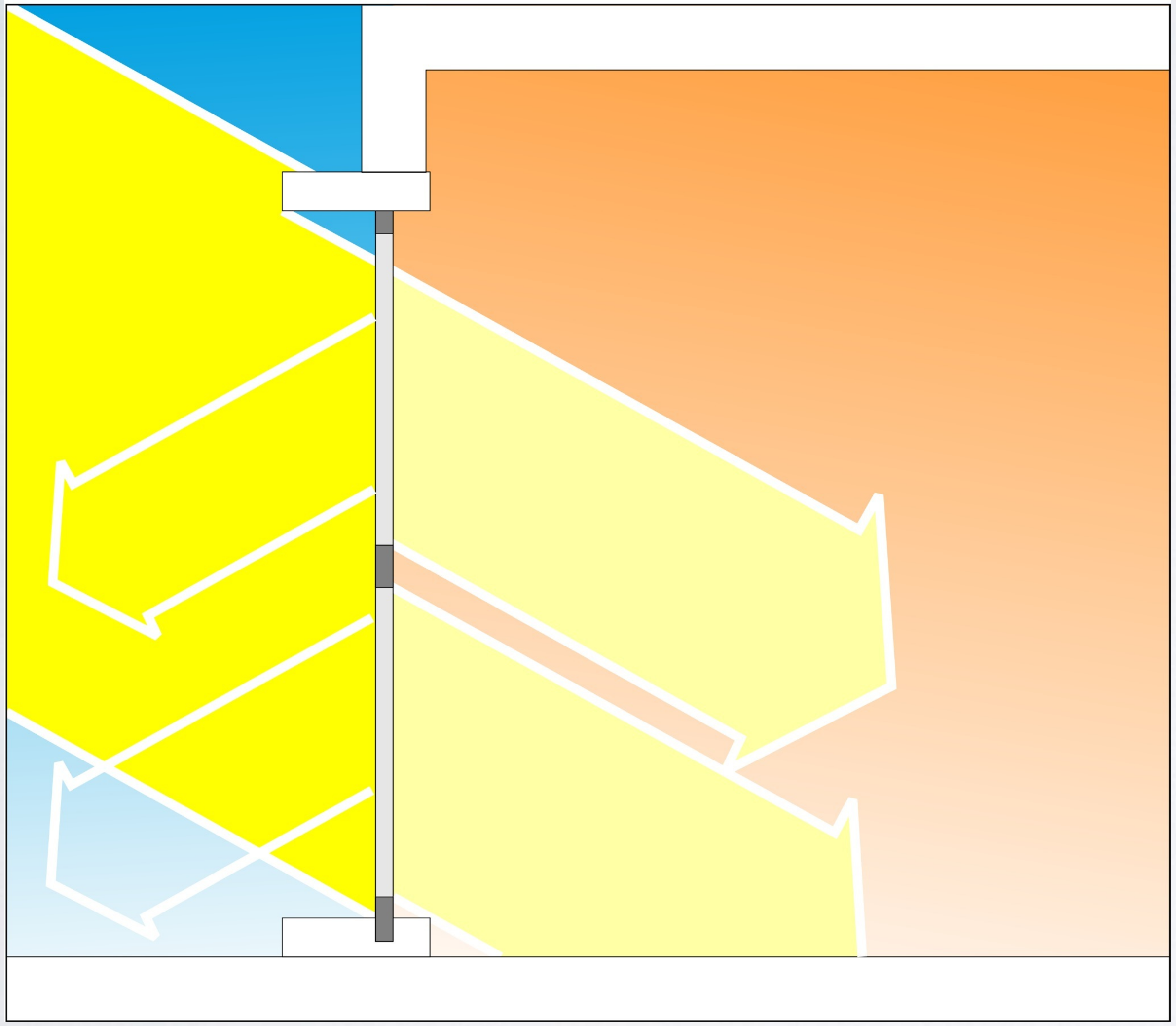


Window solar gains:

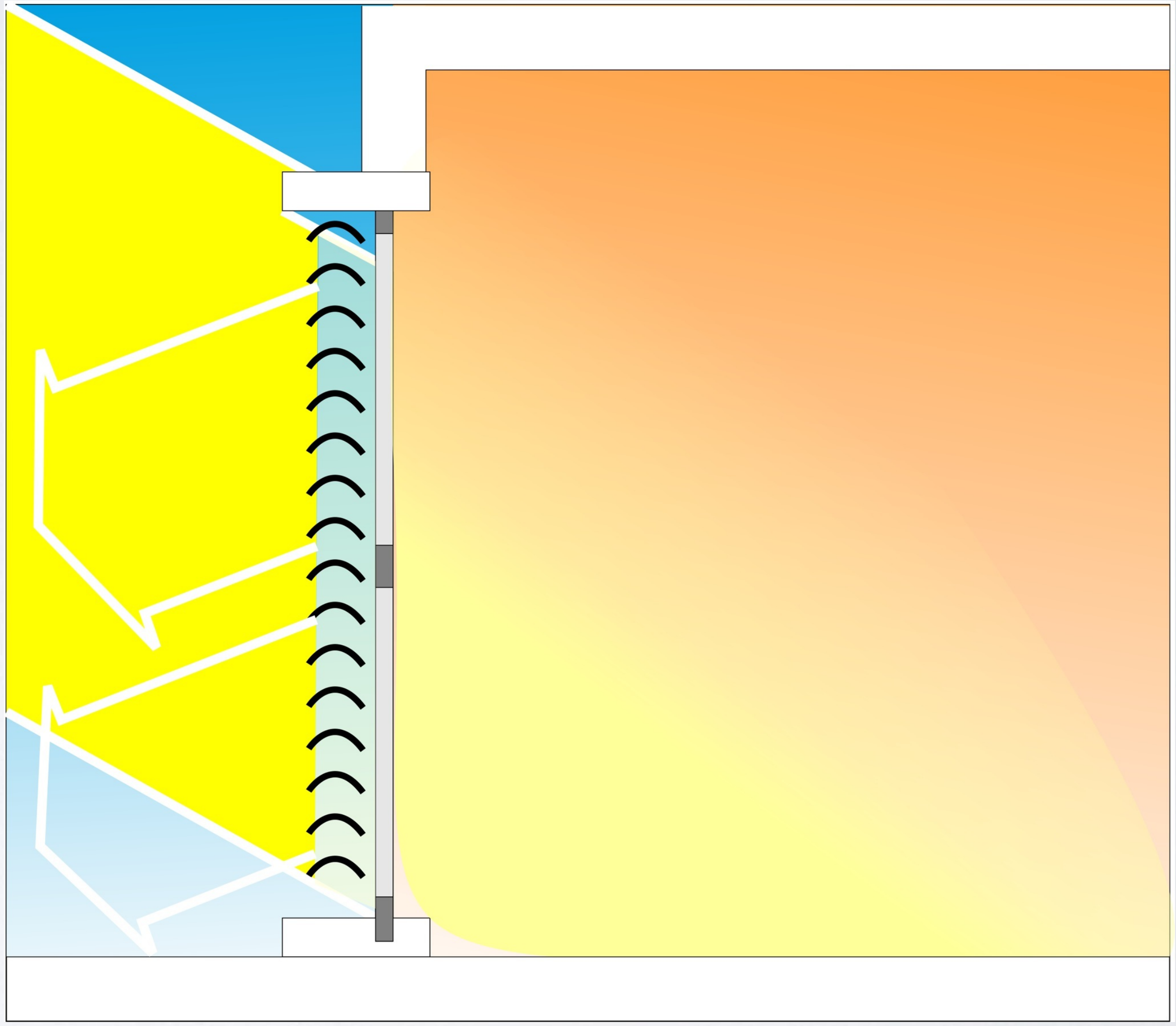
- solar radiation
- collecting area
- shading
- incidence angle
- glazing g-value

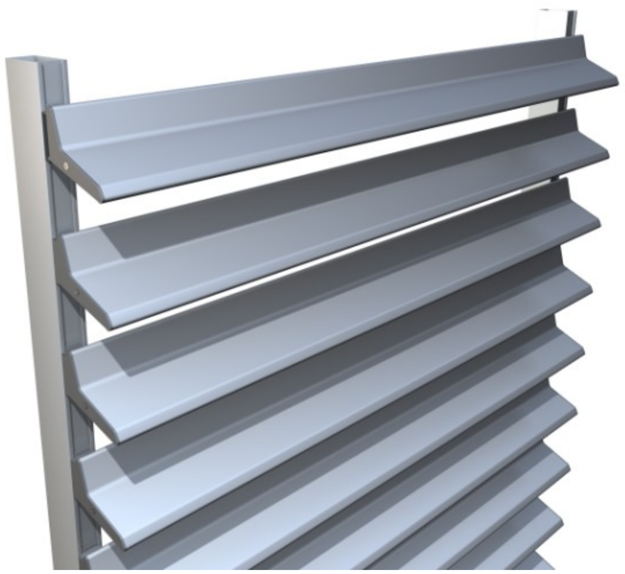
Exercício 3.2.7 A radiação solar absorvida por uma parede dupla de alvenaria de tijolo é $500\,W/m^2$. Os panos de alvenaria são iguais e têm uma espessura de 12.5 cm. Entre esses existe 15 cm de isolamento térmico. **Estimar a temperatura** entre o pano de alvenaria exterior e o isolamento térmico, para condições de regime permanente, quando o ar exterior e o ar interior se encontram à mesma temperatura de 20°C. Considerar que o céu se encontra à mesma temperatura do ar exterior. Propriedades termofísicas da alvenaria de tijolo: $R'' = 0.45\,m^2K/W$ e do isolamento térmico: $\lambda = 0.04\,W/(mK)$.

Glazing with low g-value



Shading devices



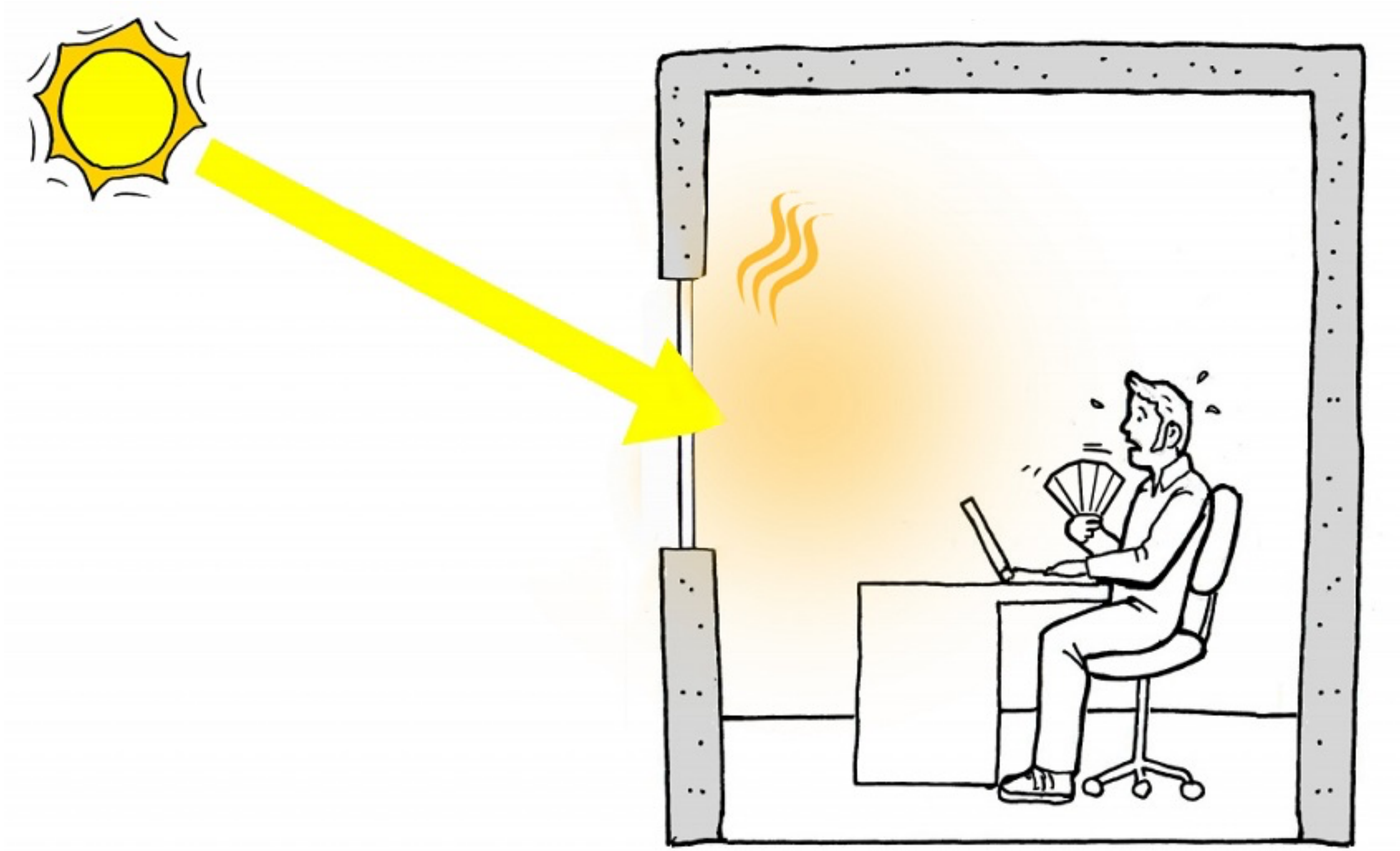


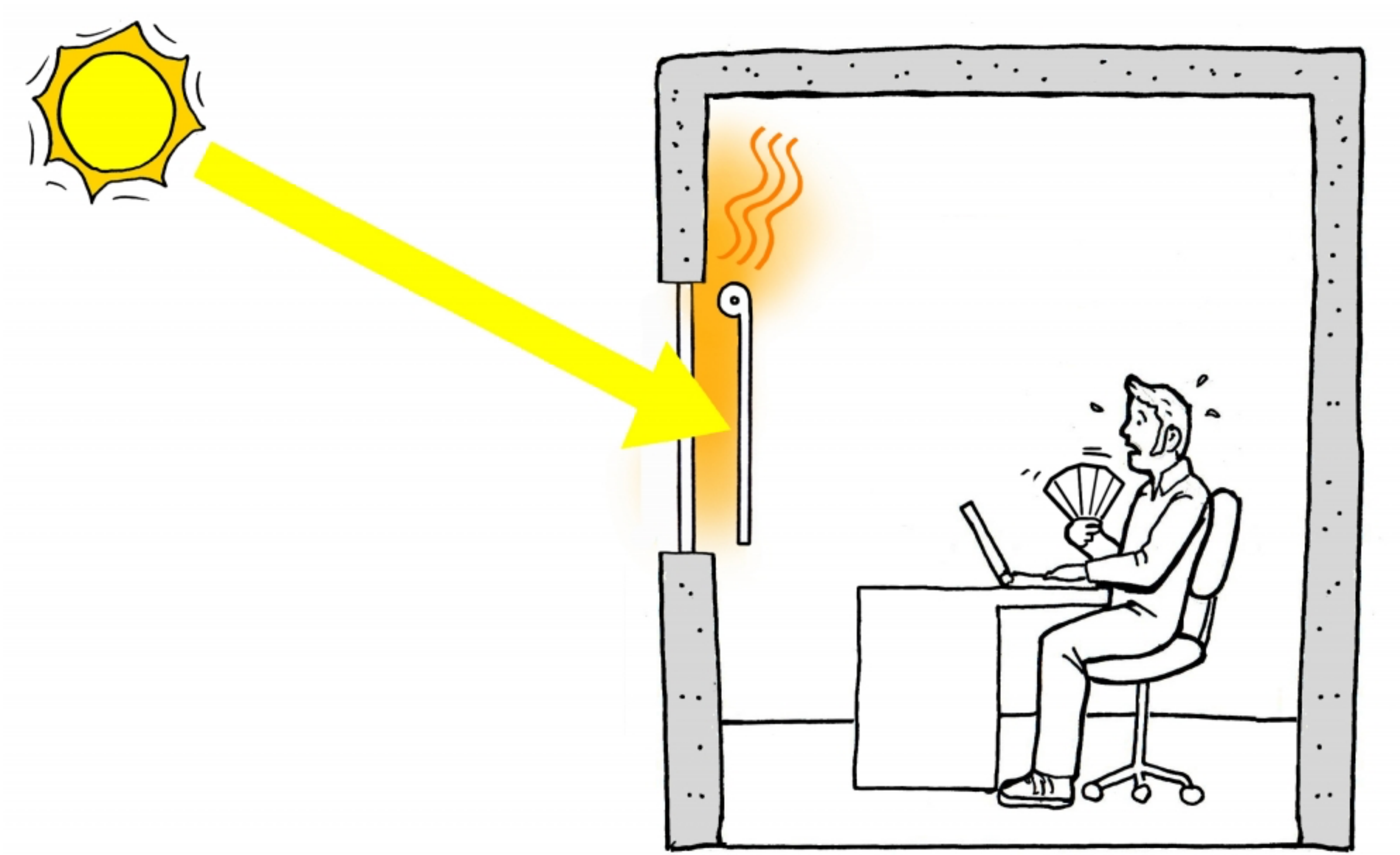
external

internal

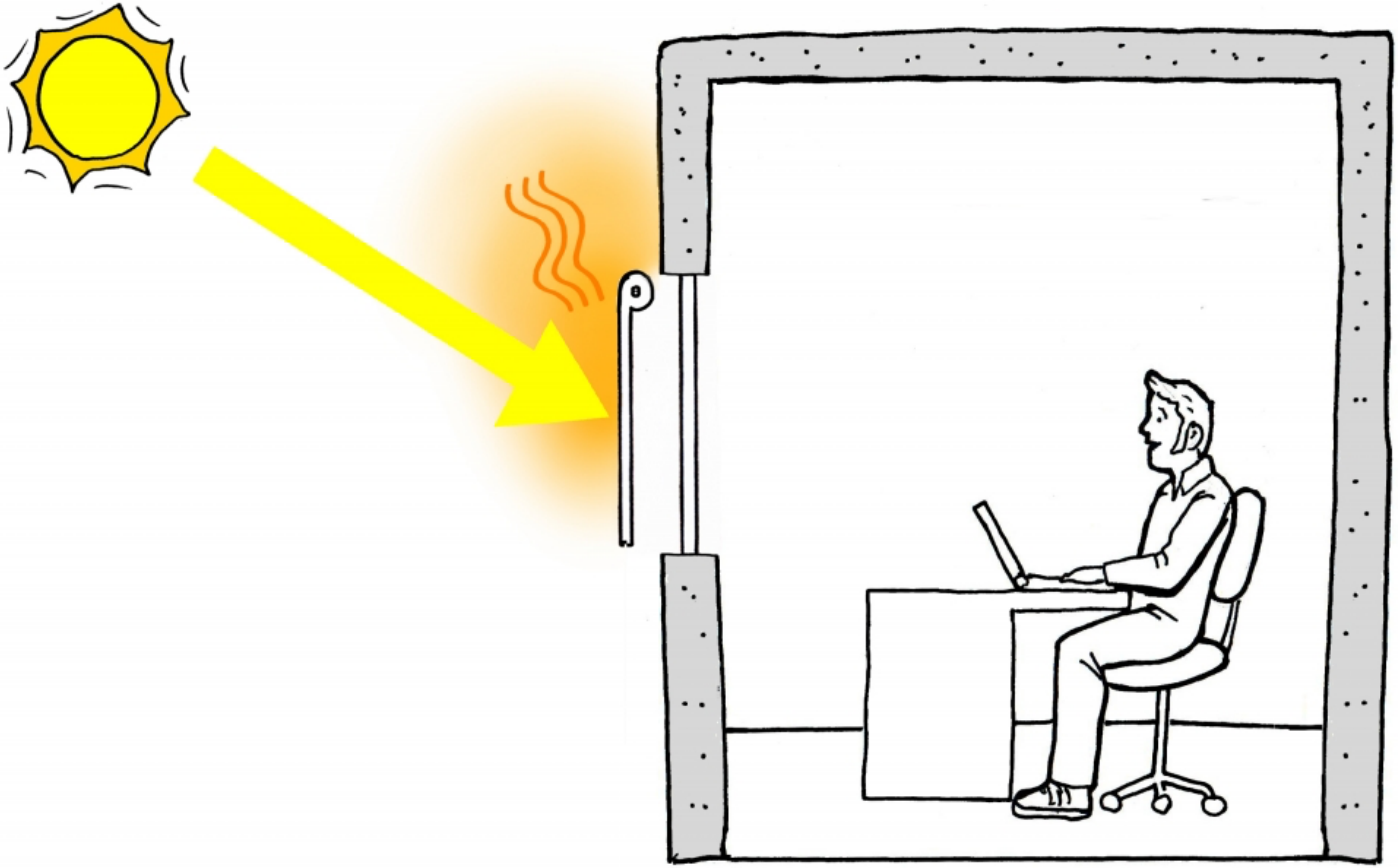
mid-pane

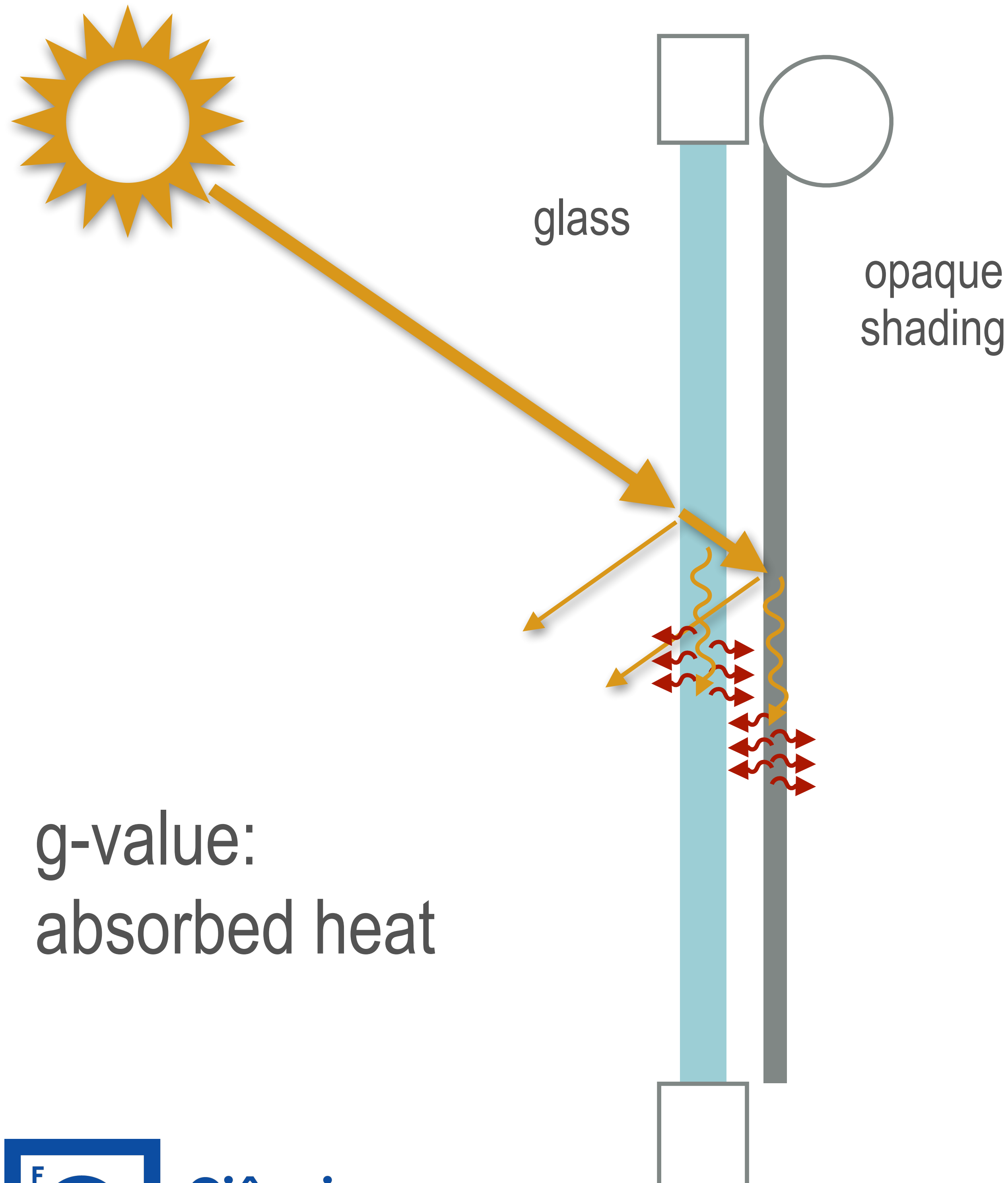
Ciências ULisboa



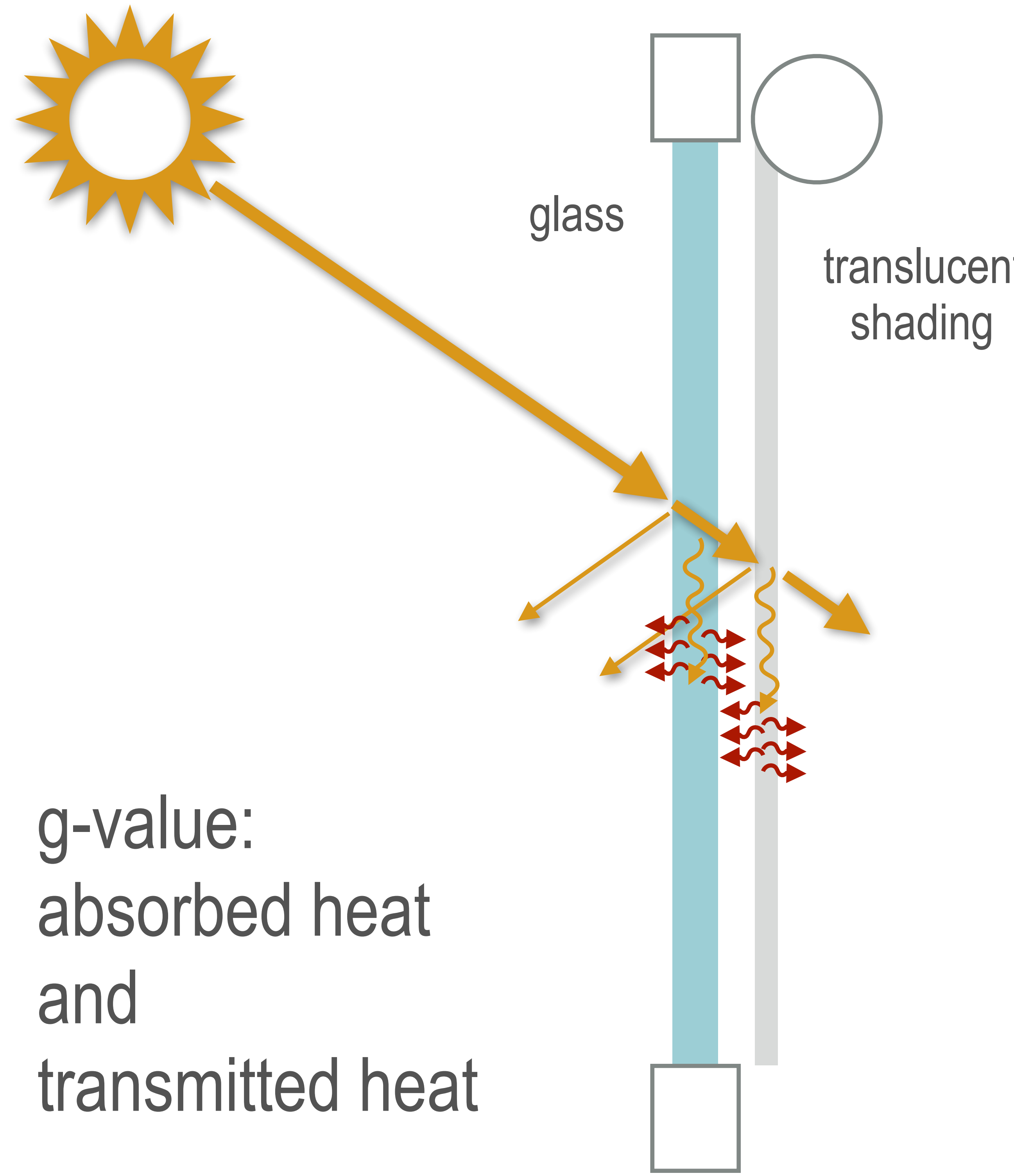


Ciências
ULisboa





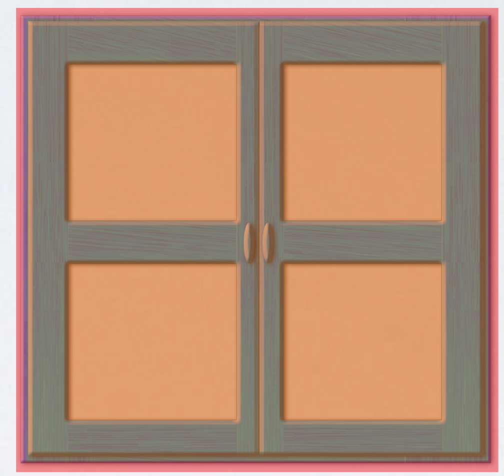
g-value:
absorbed heat



g-value:
absorbed heat
and
transmitted heat

window frame decreases collecting area

$$F_g = \frac{A_g}{A_w}$$



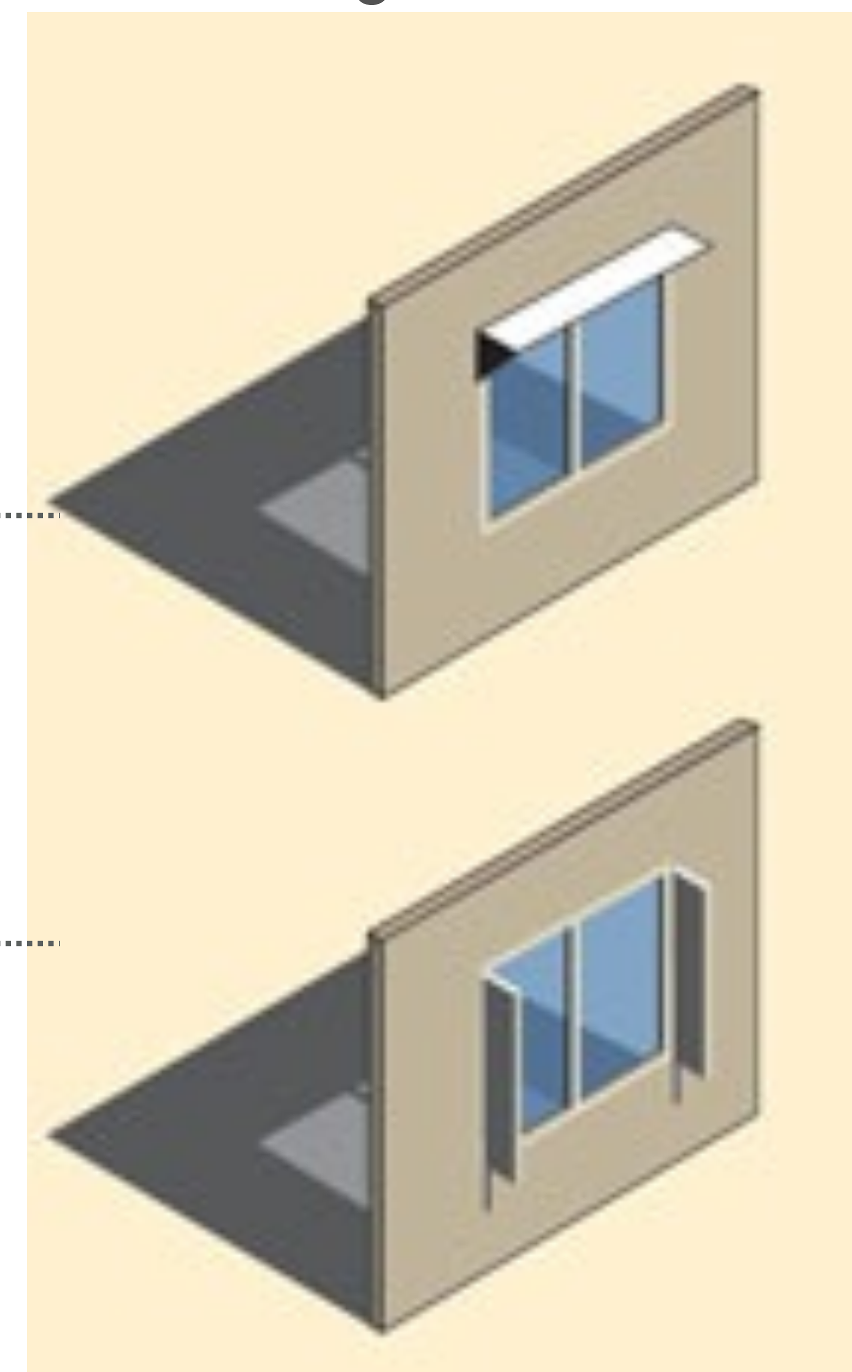
window area

A_w

glazing area

A_g

Overhang

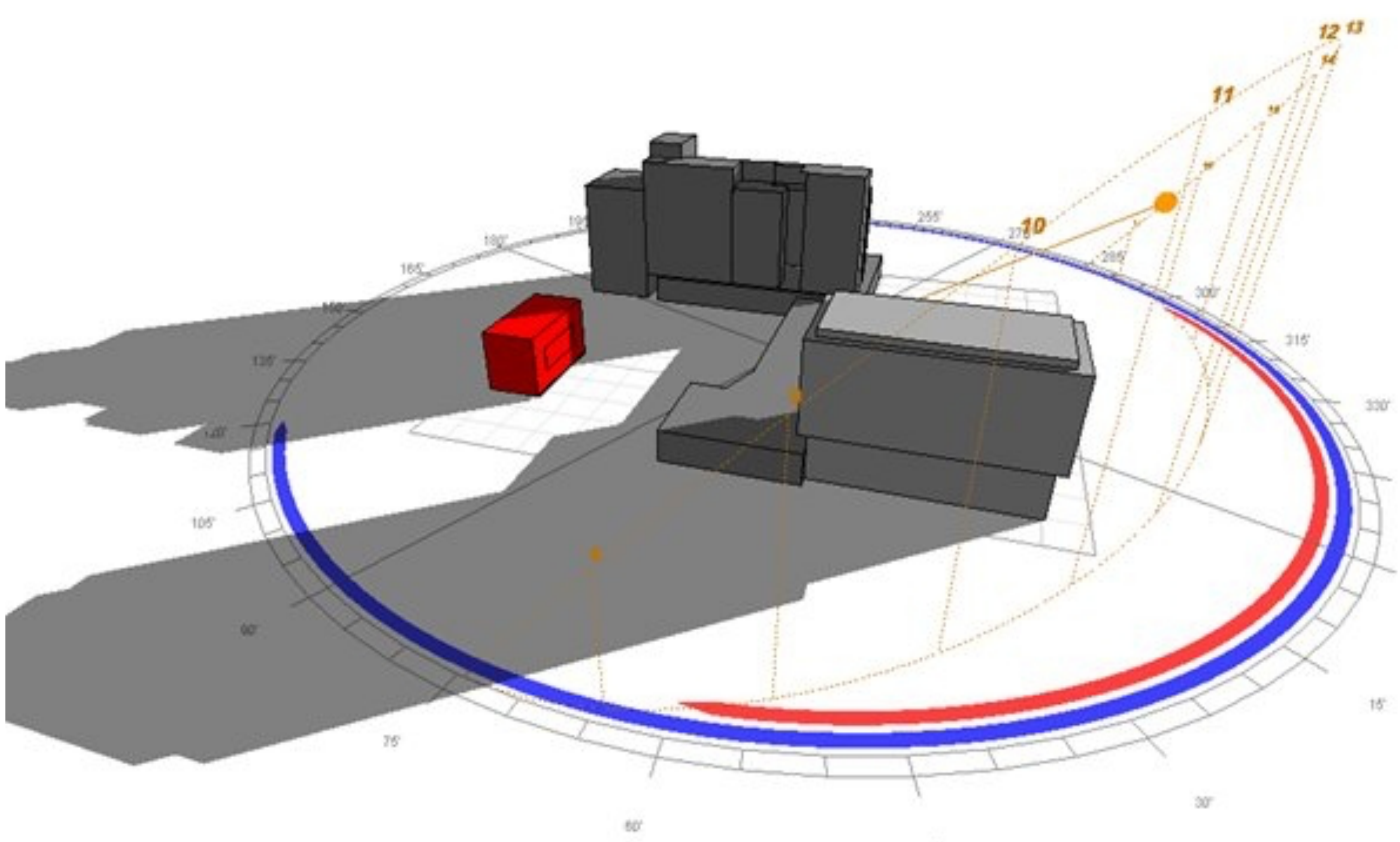


Correction factors

F_o

F_h

F_f



Horizon obstructions

Side fins

Ciências ULisboa

$$\Theta = (\theta_i - \theta_e)\left[1 + c_1 \frac{A_w}{A}\left(1 - c_3 - \frac{c_2 G}{\theta_i - \theta_e}\right)\right]$$

A Façade area

A_w Windows area

Low solar radiation

$$\Theta \simeq (\theta_i - \theta_e)\left(1 + c_1 \frac{A_w}{A}\right) \dashrightarrow \frac{A_w}{A} \downarrow$$

High solar radiation

$$\Theta \simeq (\theta_i - \theta_e)\left(1 - c_1 c_2 \frac{G}{\theta_i - \theta_e}\frac{A_w}{A}\right) \dashrightarrow \frac{A_w}{A} \uparrow$$