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Session ID: **ENG445DK**

ENG-445

Building Energetics

Building Envelope

Assist. Professor
Dolaana KHOVALYG

7 November 2024



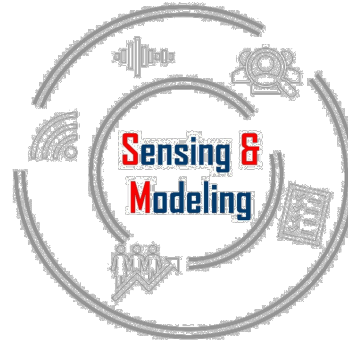


Advancing human comfort studies and the design and control of occupant-centered thermal systems

PURPOSE:

- Promote the well-being and thermal comfort of building occupants
- Reduce operational energy for thermal conditioning in buildings

RESEARCH TOPICS:

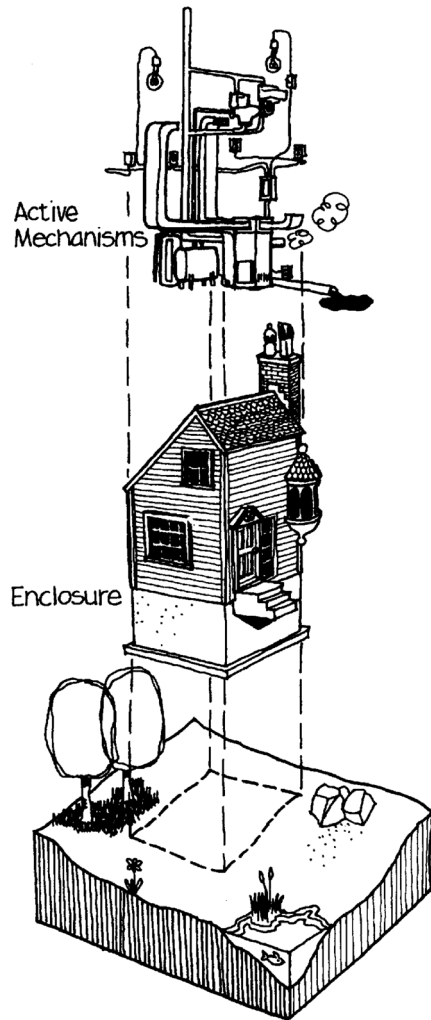


More details on the ICE activities online: <https://www.epfl.ch/labs/ice/>



Week	Date	Topic	Timing	Teacher	Project (AS, MF)
9	07/11	Building envelope, thermal performance of building elements	45' x 2	DK	Tutorial building envelope
		Exercises	45'		
10	14/11	Heating and cooling demand in buildings	45' x 2	DK	Free work
		Exercises	45'		
11	21/11	Thermal systems for heating and their effect of human comfort	45' x 2	JY	Free work
		Exercises	45'		
12	28/11	Thermal systems for cooling and their effect of human comfort	45' x 2	DK	Tutorial heating systems (emission systems)
		Exercises	45'		

JY – Jaafar Younes, a postdoc from the ICE lab



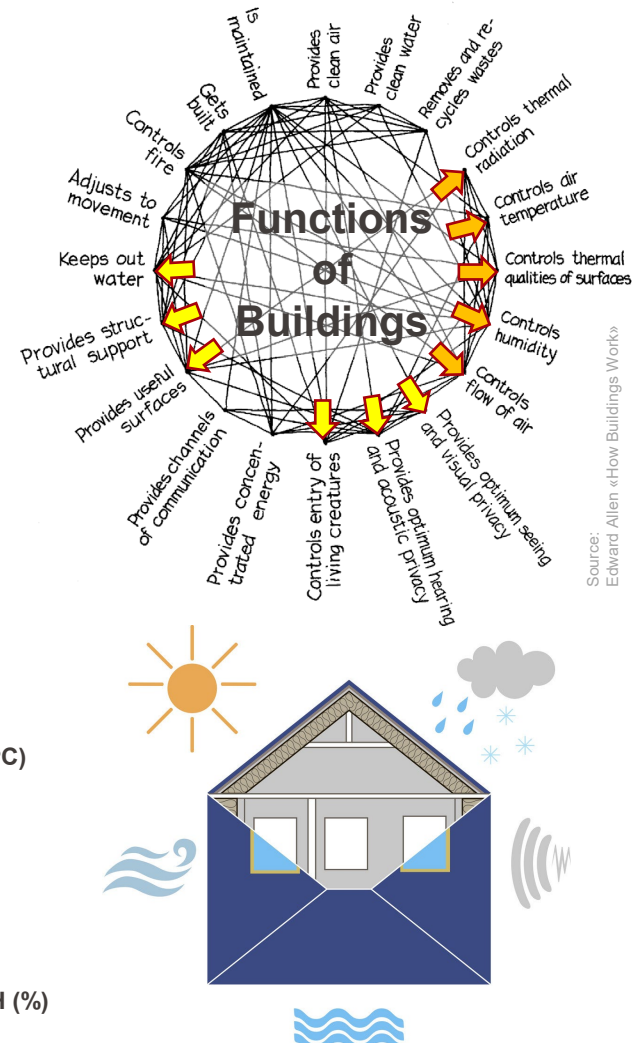
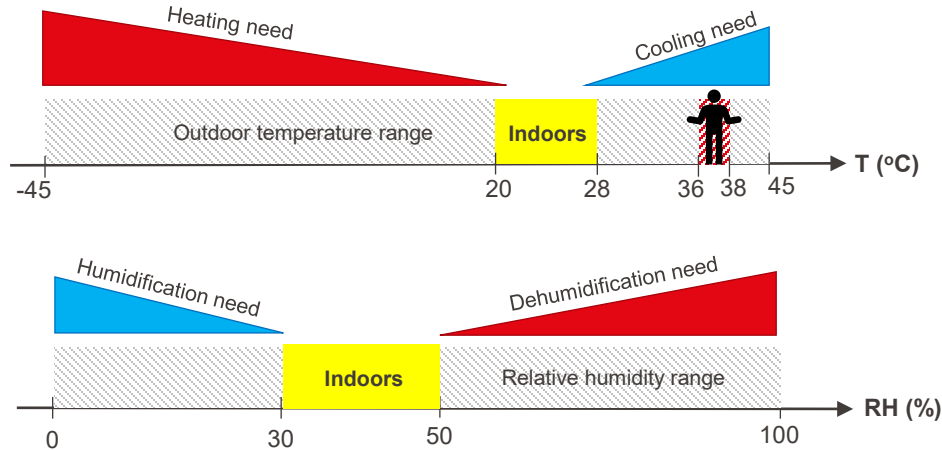
Source: Edward Allen «How Buildings Work» (2005)

CONTENT:

- Introduction to the Building Envelope
- Modes of Heat Transfer and their Properties
- Thermal Properties of the Building Elements:
 - Opaque Elements (walls, roofs)
 - Thermal Bridges (linear and point)
 - Transparent Elements (windows)

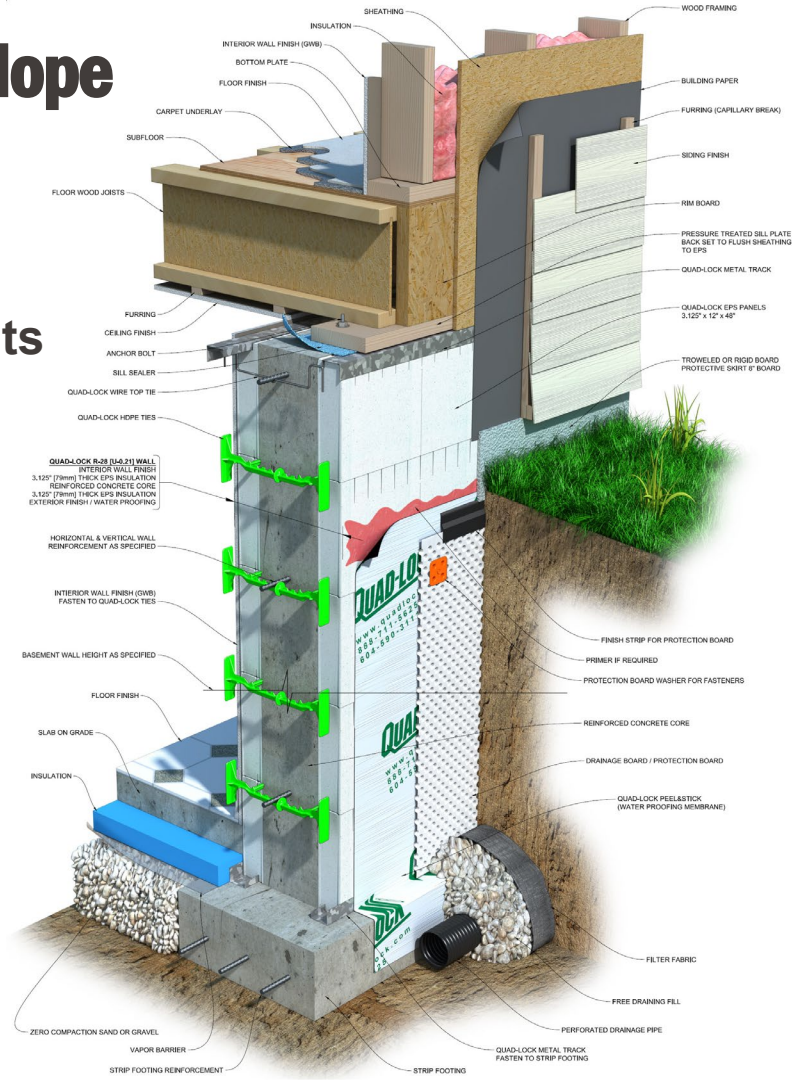
Building Envelope

- A physical **barrier** between the **interior** and the **exterior**
- The place where **energy flow is interrupted** (protects the house against energy loss and air and water infiltration)
- An enclosure that maintains **stable temperature** and **humidity** inside for comfort of occupants



Elements of the Building Envelope

- **Structural elements**
steel, concrete, timber, masonry, *etc.*
- **Insulating (thermal control) elements**
glass wool, stone wool, EPS, PU/PIR, *etc.*
- **Transparent elements**
windows, skylights
- **Water, air, vapor control elements**
wraps, membranes, *etc.*
- **Finishing**
interior finishing, external façade
- **Connections**
joints, ties, battens, *etc.*



Opaque

(traditional façade)

without air gap or with air gap
(vented, ventilated, enclosed)



Source: www.swisspor.ch

Curtain Wall

(double-skin façade)

reduced DSF, closed cavity
façade, internal sunshield

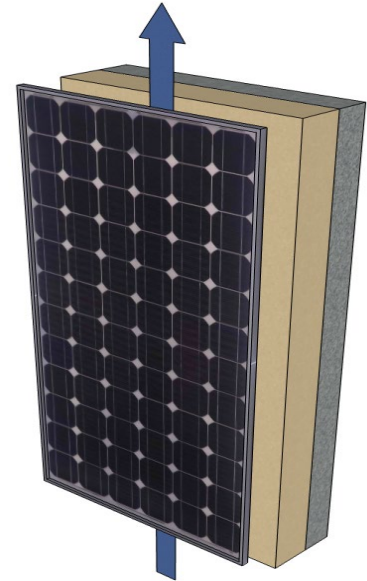


Source: R. Miller, pinterest

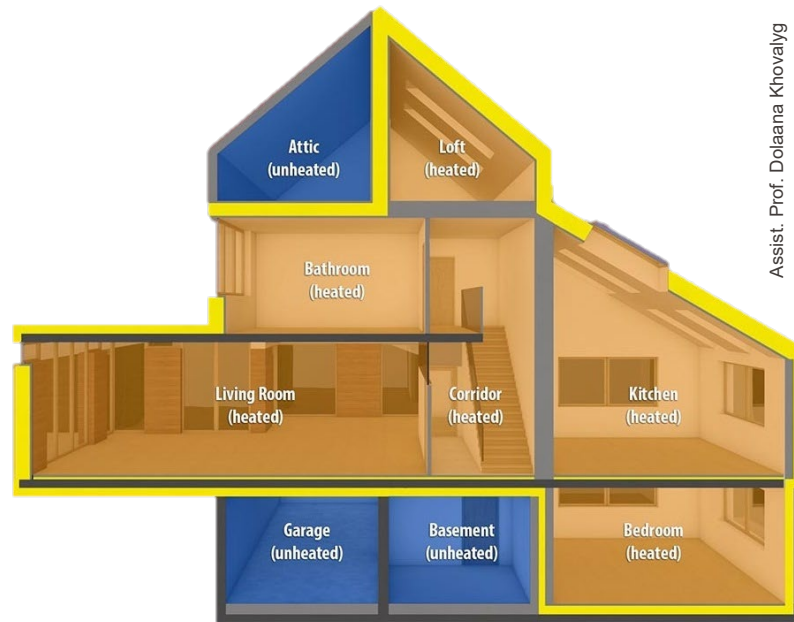
BIPV

(active façade)

opaque, translucent,
transparent

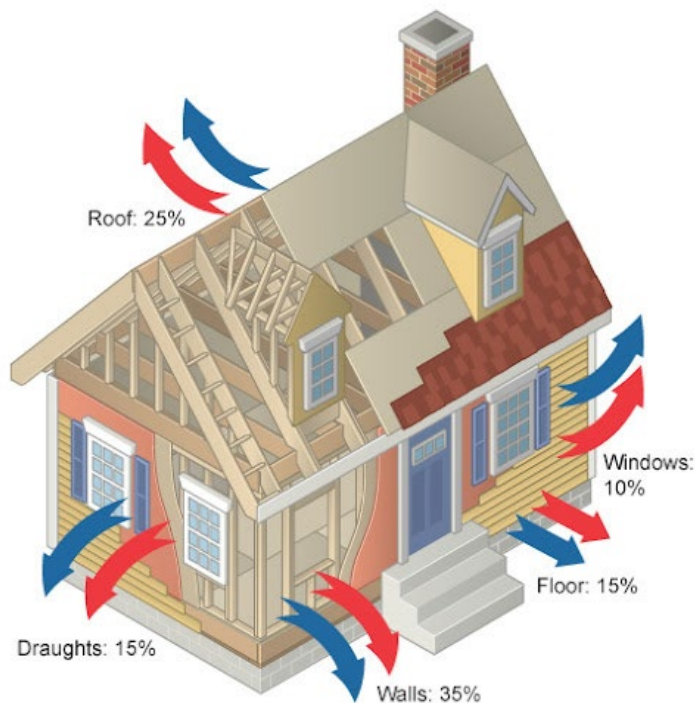


- A boundary where **heat losses** and **heat gains** are *accounted* and *effectively controlled*
- It *fully wraps* the **indoor conditioned space**, it often located *over the building outer envelope*.
- A well-thought design of the thermal boundary is *a crucial factor* for *enhanced building performance* in terms of **comfort** and **energy use**



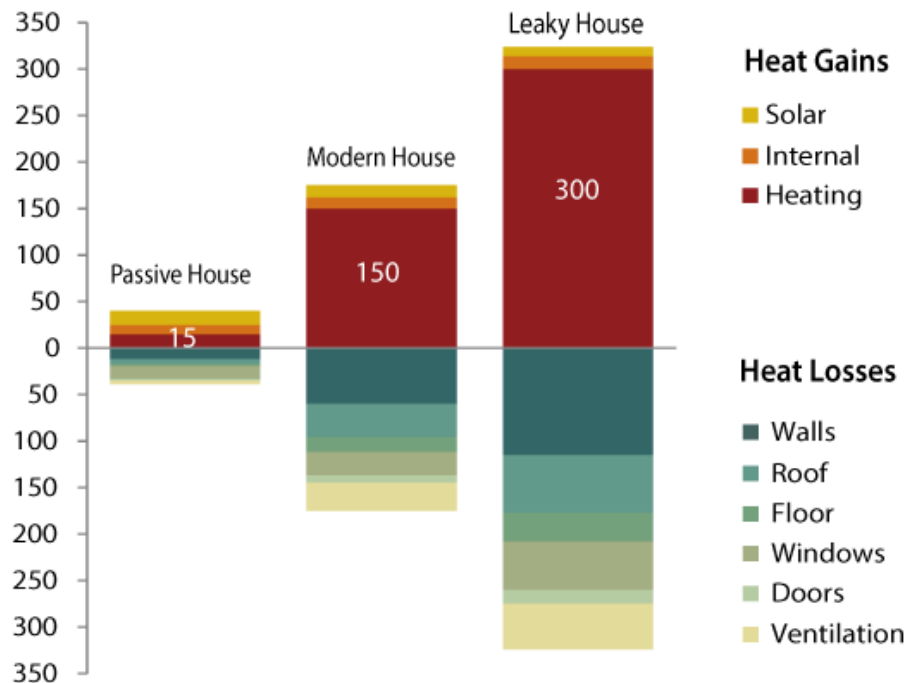
Where to Insulate?

1. In **unfinished attic spaces**, insulate between and over the floor joists to seal off living spaces below
2. In **finished attic rooms** with or without dormer
3. All **exterior walls**
4. **Floors** above cold spaces, such as vented crawl spaces and unheated garages
5. **Band joists**
6. Replacement or storm **windows**, and caulk and seal **around** all the **windows** and **door**



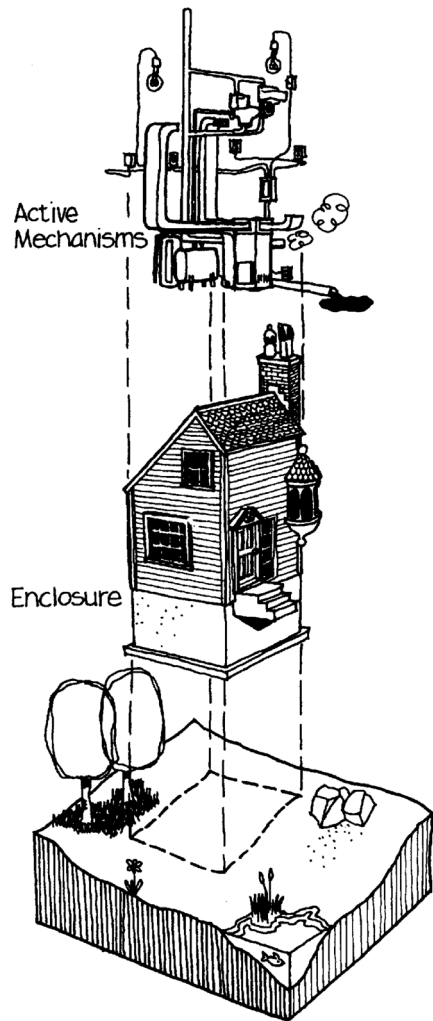
The Value of a Well Insulated Home

Average heating gains and losses by house type in kWh/m²a



Data: typical values for Northern European climates

shrinkthatfootprint.com



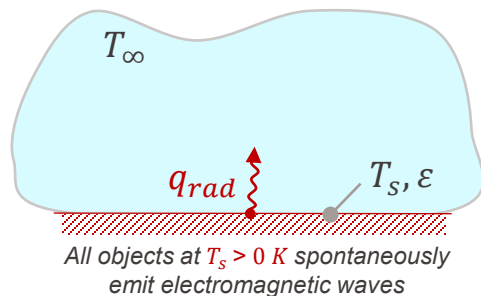
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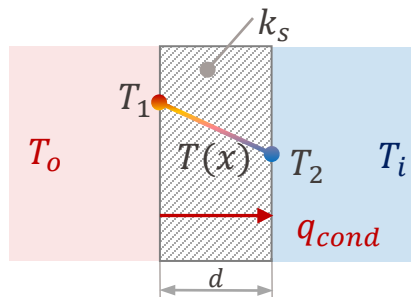
Radiation

energy transfer in the space by electro-magnetic waves (no need in a medium)



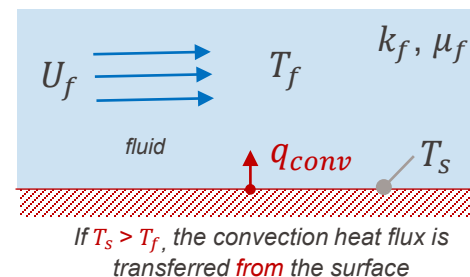
Conduction

energy transfer from molecule to molecule due to the temperature gradient (in solids)



Convection

transport of energy due to **diffusion** (random molecular motion) and by **bulk motion** of the fluid



Heat flux q (W/m^2)

Stefan – Boltzmann's Law:

$$q_{rad} = \varepsilon \cdot \sigma \cdot T_s^4$$

$$\Delta q_{rad} = h_{rad} \cdot (T_s - T_\infty)$$

Temperature gradient should be positive since heat flows **spontaneously** from the **hot** to the **cold** medium according to the 2nd law of thermodynamics

Fourier's Law:

$$q_{cond} = \frac{k_s}{d} \cdot (T_1 - T_2)$$

Newton's Law of Cooling:

$$q_{conv} = h_c \cdot (T_s - T_f)$$

Heat transfer coefficient h ($W/m^2 K$)

$$h_{rad} = \varepsilon \cdot \sigma \cdot (T_s^2 + T_\infty^2) \cdot (T_s + T_\infty)$$

$$h_{cond} = \frac{k_s}{d}$$

$$h_{cond} = f(\text{surface, fluid properties, velocity})$$

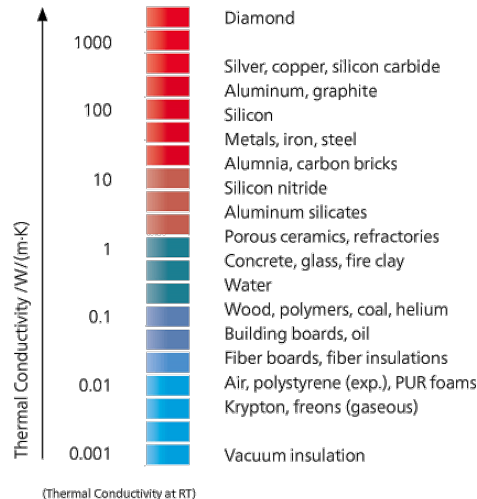
Radiation

Emissivity ε (-): effectiveness of the surface in emitting energy as *thermal radiation*, can have a value from 0 (shiny mirror) to 1 (blackbody). Per Kirchhoff's law, **emissivity (ε)** is equal to **absorptivity (α)** of the material.

Metal	Emissivity	Non-metal	Emissivity
Bare aluminum	0.02–0.4	Concrete (rough)	0.93–0.96
Gold	0.02–0.37	Glass	0.76–0.94
Copper	0.02–0.74	Wood	0.8–0.95
Lead	0.06–0.63	Carbon	0.96
Brass	0.03–0.61	Human skin	0.98
Nickel	0.05–0.46	Paper	0.7–0.95
Steel	0.07–0.85	Plastic	0.8–0.95
Tin	0.04–0.08	Rubber	0.86–0.94
Silver	0.01–0.07	Water	0.67–0.96
Zinc	0.02–0.28	Sand	0.76–0.9

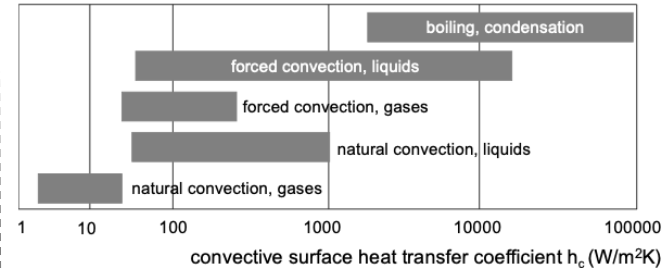
Conduction

Thermal Conductivity k or λ ($\text{W/m}^2\text{K}$): amount of heat than can be conducted during 1 second through 1 m^2 of a *homogeneous layer* of material subjected to a temperature gradient 1 K/m .

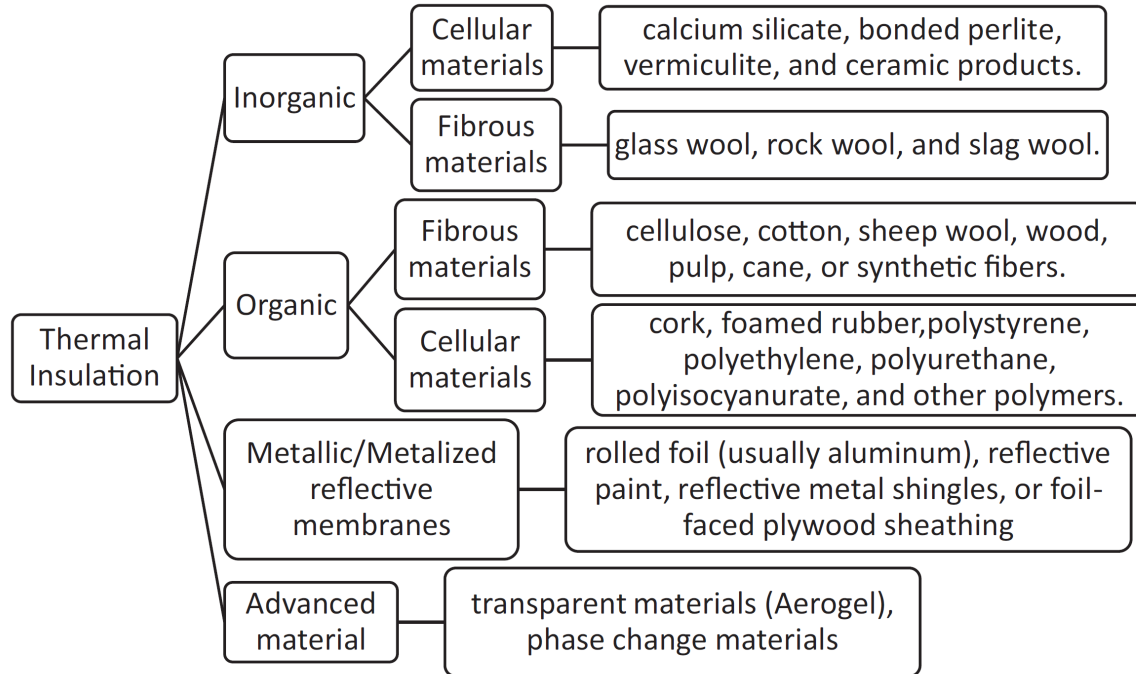


Convection

Convective heat transfer coefficient h_{conv} ($\text{W/m}^2\text{K}$): quantitative characteristic of convective heat transfer between a fluid medium and the surface (wall) flowed over by the fluid. Varies for *free* and *forced* convection, *internal* or *external* flow, and *laminar* or *turbulent* flow.

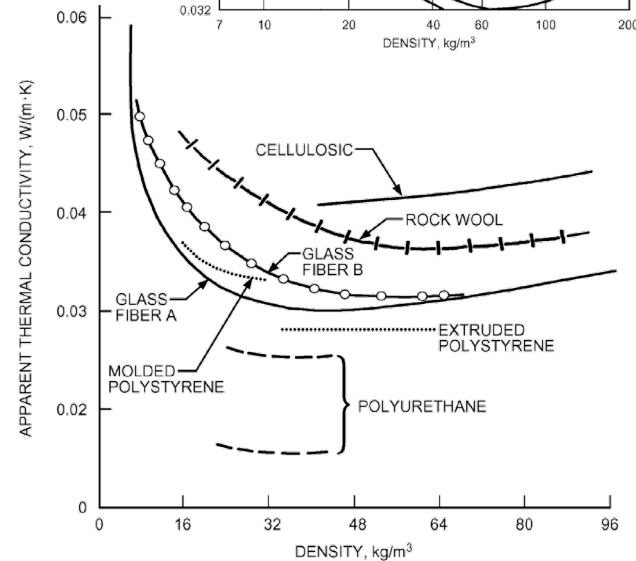
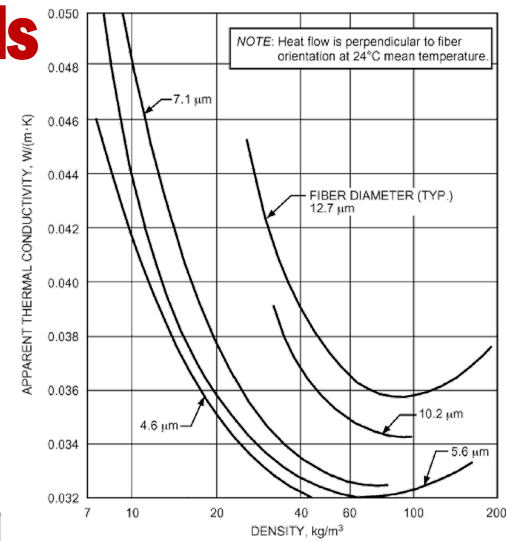


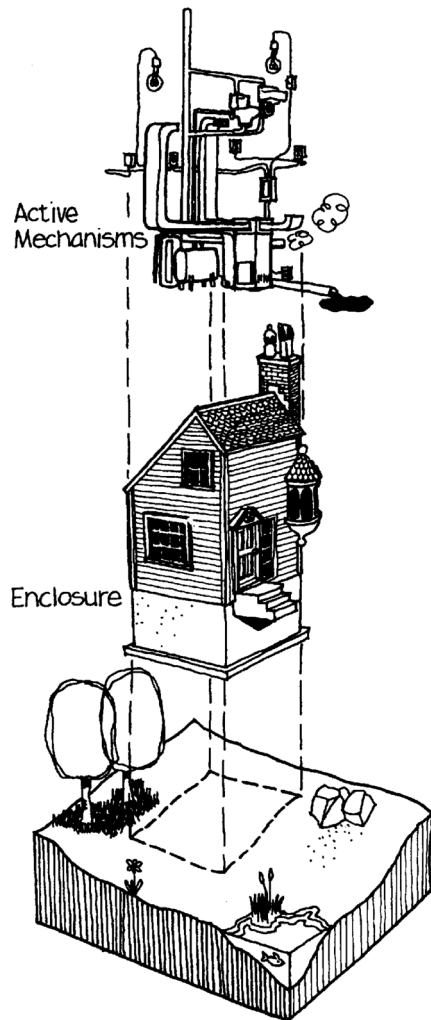
- Insulation materials restrict the flow of heat
(which in turn **reduces** ability of **building assemblies to dry out** when **wet**)



EPFL Conductive Properties: Insulation Materials

- **Apparent Thermal Conductivity** ($\text{W/m}^2\text{K}$) – amount of heat than can be conducted during 1 second through 1 m^2 of a porous layer of material subjected to a gradient in temperature of 1 K/m .
 - captures the effect of **convection** and **radiation** in *pores*
 - affected by **structural parameters** such as *density*, *matrix type* (fibrous or cellular), and *thickness*





Source: Edward Allen «How Buildings Work» (2005)

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- Rate of heat transfer per *unit area* driven by the *temperature gradient*, [W/m²]:

$$q = U \cdot (T_{hot} - T_{cold})$$

Thermal transmittance,
Overall heat transfer coefficient, [W/m²K]

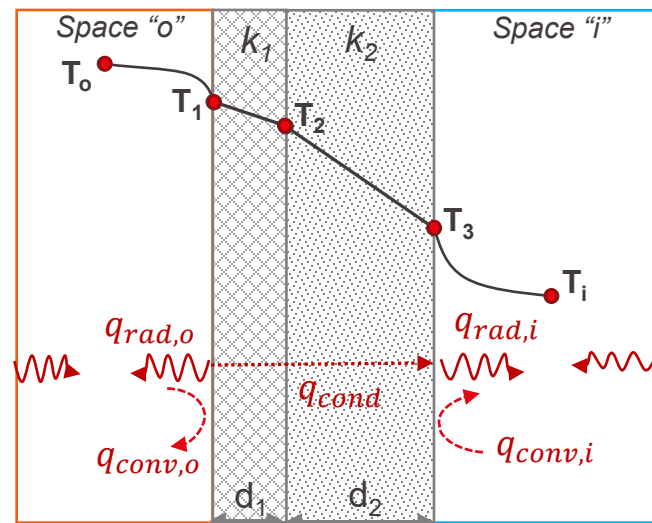
Temperature gradient, [K]

- Thermal Transmittance (U-value**, W/m²K) – heat transfer coefficient, an **indicator of the efficiency** to **promote** heat conduction by the material
- Thermal Resistance (R-value**, m²K/W) – the capacity of a material to **resist** heat flow

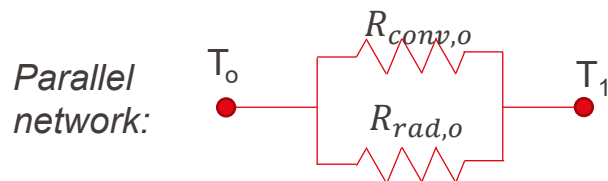
$$U = \frac{1}{R_{tot}}$$

- Conduction:** $q_{cond} = \frac{k}{d} \cdot (T_1 - T_2) \Rightarrow R_{cond,i} = \frac{d_i}{k_i}$
- Convection:** $q_{conv} = h_{conv} (T_s - T_{\infty}) \Rightarrow R_{conv} = \frac{1}{h_{conv}}$
- Radiation:** $q_{rad} = h_{rad} (T_s - T_{\infty}) \Rightarrow R_{rad} = \frac{1}{h_{rad}}$

- Using *the electrical circuit analogy*, **heat transfer problems** can be analyzed using **network of thermal resistances** forming a **thermal circuit**
- Example for a simple **composite wall**:



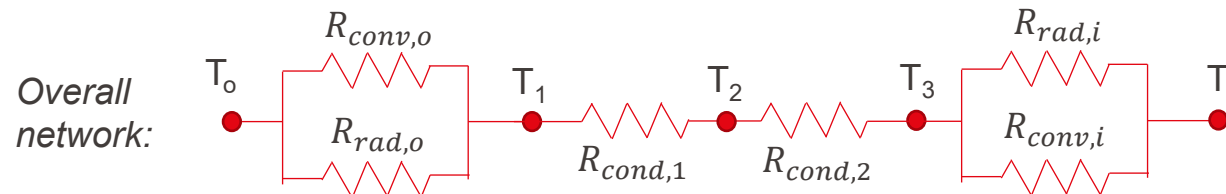
$$R_{1-3} = \frac{d_1}{k_1} + \frac{d_2}{k_2}$$



$$R_{o-1} = \frac{1}{(h_{conv,o} + h_{rad,o})}$$

and

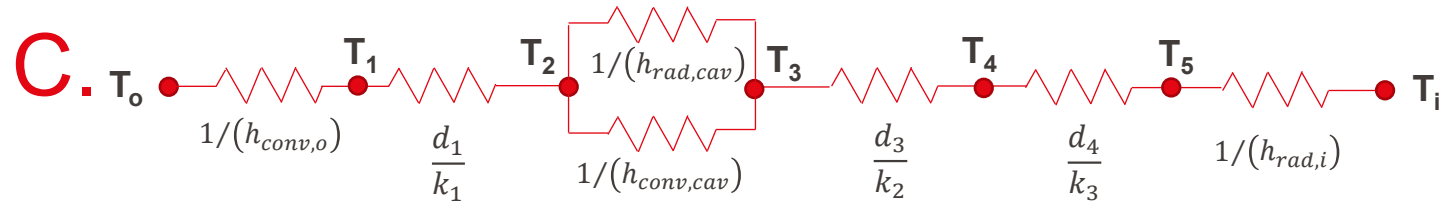
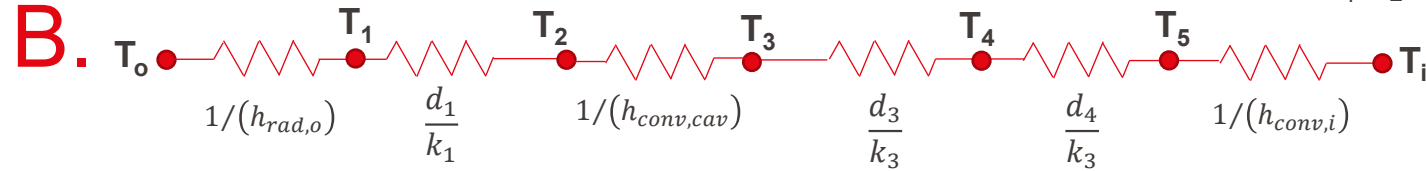
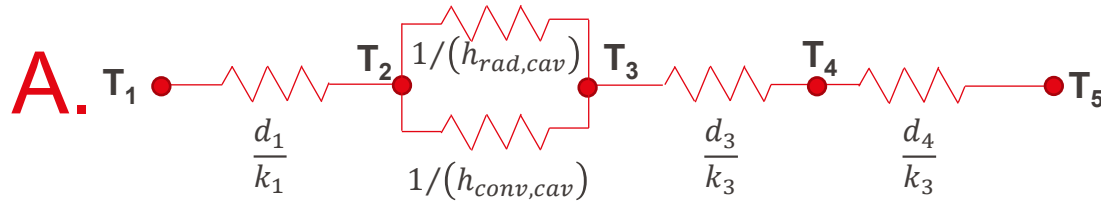
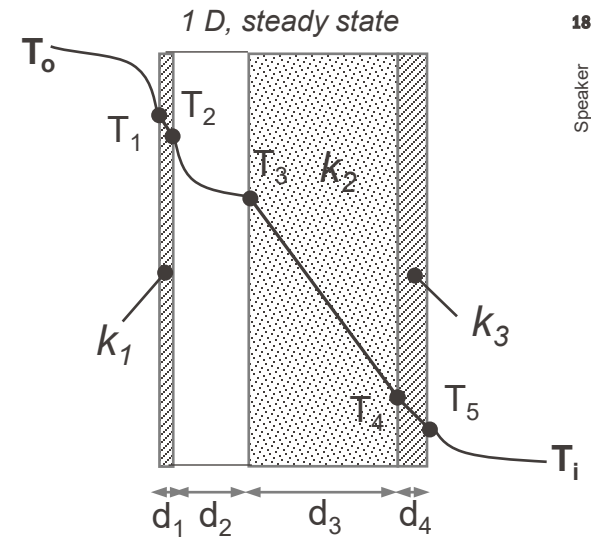
$$R_{3-i} = \frac{1}{(h_{conv,i} + h_{rad,i})}$$



$$R_{tot} = \frac{1}{U} = R_{o-1} + R_{1-3} + R_{3-i}$$

EPFL Network of Thermal Resistances

Which of the following thermal circuits corresponds to the **overall thermal resistance** through a **composite wall with a sealed air cavity**?



NAME EVENT / NAME PRESENTATION

D. NONE ABOVE

Does **the thermal transmittance of a building structure decrease linearly with thermal insulation thickness?**

- A. Yes
- B. No
- C. Not sure

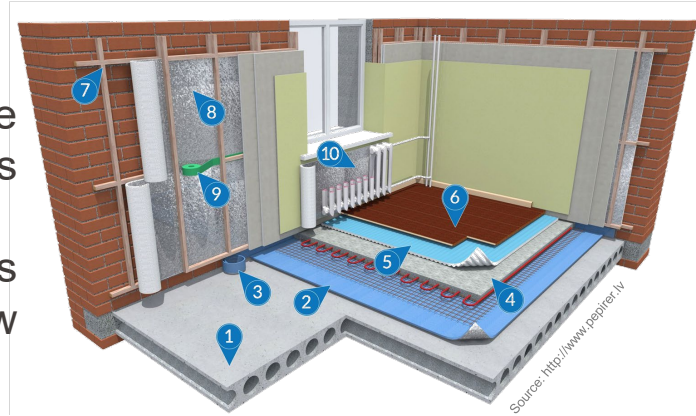
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Reflective Insulation

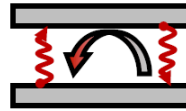
- Usually **aluminum foil**, which is applied to *one* or *both* sides of a number of substrate materials (kraft paper, plastic films, cardboard, etc.)
- Reduces **radiant heat transfer** using surfaces having **high reflectance** (low emissivity = low absorptivity) for *long wave radiation*



Horizontal gap (e.g., roof)

Vertical gap (e.g., wall)

Air gap thickness



	NO reflective insulation	WITH reflective insulation	NO reflective insulation	WITH reflective insulation
0.5" (1.27 cm)	0.14	0.44	0.14	0.43
0.75" (1.905 cm)	0.15	0.63	0.15	0.62
1.5" (3.81 cm)	0.17	1.07	0.15	0.70
3.5" (8.89 cm)	0.18	1.77	0.15	0.65

Source: ASHRAE Handbook 2017. Fundamentals

Standard	Title
ISO 6946	Building components and building elements – Thermal resistance and thermal transmittance – Calculation methods
ISO 7345	Thermal Insulation – Physical quantities and definitions
ISO 10211	Thermal bridges in building construction – Heat flows and surface temperatures – Detailed calculations
ISO 10456	Building materials and products – Hygrothermal properties – Tabulated design values and procedures for determining declared and designed thermal values
ISO 14683	Thermal bridges in building construction - Linear thermal transmittance - Simplified methods and default values
SIA 2024	Données d'utilisation des locaux pour l'énergie et les installations du bâtiment
SIA 180	Protection thermique, protection contre l'humidité et climat intérieur dans les bâtiments
SIA 380/1	Besoins de chaleur pour le chauffage

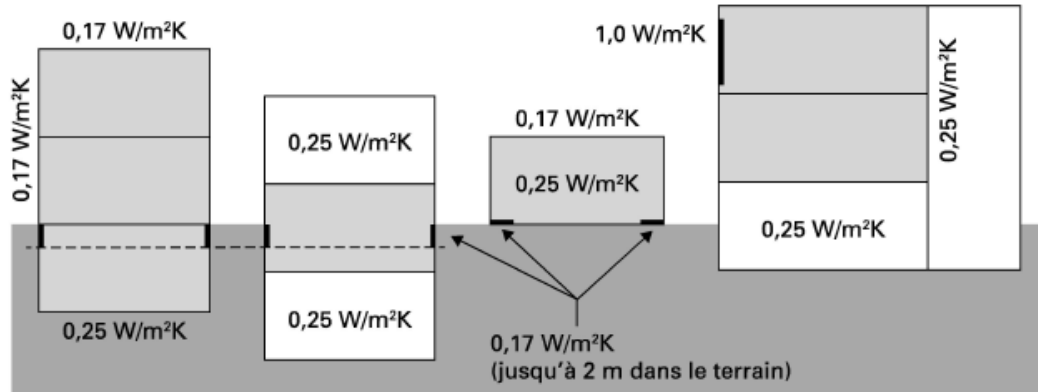
- Maximum permitted **U-values** (SIA 180)
- Limiting values of **U-value** for **renovated** and **new** buildings (indoor temperature 20°C) (SIA 380)

Building element	Envelope adjacent to exterior [W/m ² K]	Envelope element adjacent to unheated premises [W/m ² K]
Roof	0.4	0.6
Wall	0.4	0.6
Floor	0.4	0.6
Windows, door	2.4	2.4
Blind casing	2	2

Building element	Envelope element adjacent to exterior [W/m ² K]		Envelope elements adjacent to unheated premises [W/m ² K]	
	<i>renovation</i>	<i>new</i>	<i>renovation</i>	<i>new</i>
Opaque elements	0.25	0.17	0.28	0.25
Windows	1.0	1.0	1.3	1.3
Door	1.2	1.2	1.5	1.5
Blind casing	0.5	0.5	0.5	0.5

- Illustration for new constructions:

***Standardized boundary conditions:**
 Indoor: +20°C
 Outdoor: -10°C



Surface Thermal Resistance

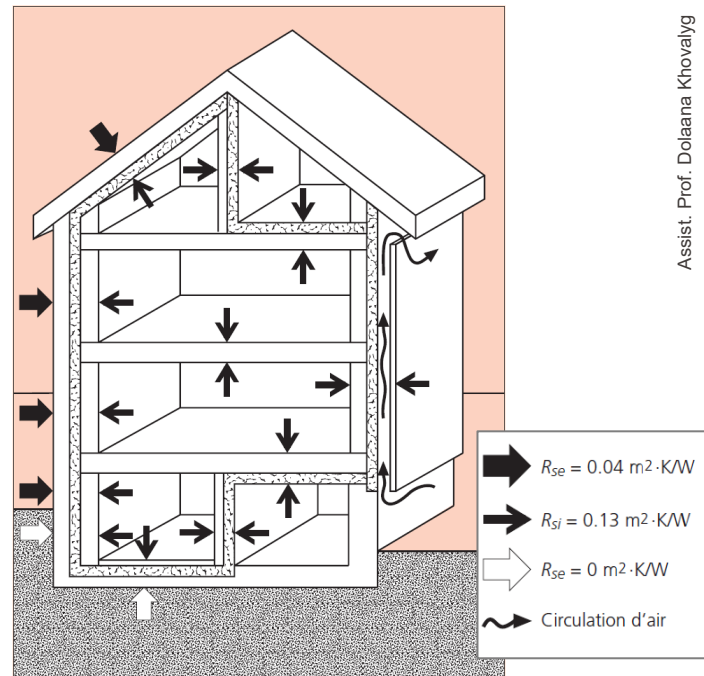
■ Design surface resistance (ISO 6946):

Values of *external* and *internal* film surface resistance depending on heat flow direction:

Surface resistance (m ² K/W)	Direction of heat flow		
	Upwards ↑	Horizontal →	Downwards ↓
Interior R_{si}	0.1	0.13	0.17
Exterior R_{se}	0.04	0.04	0.04

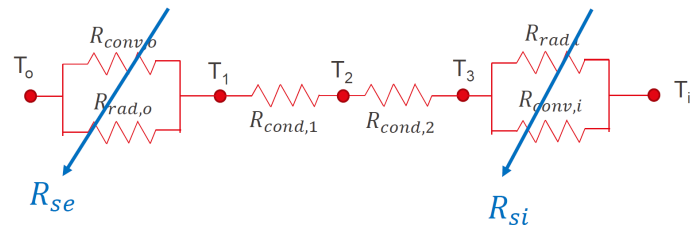
Design values are considered for the following conditions:

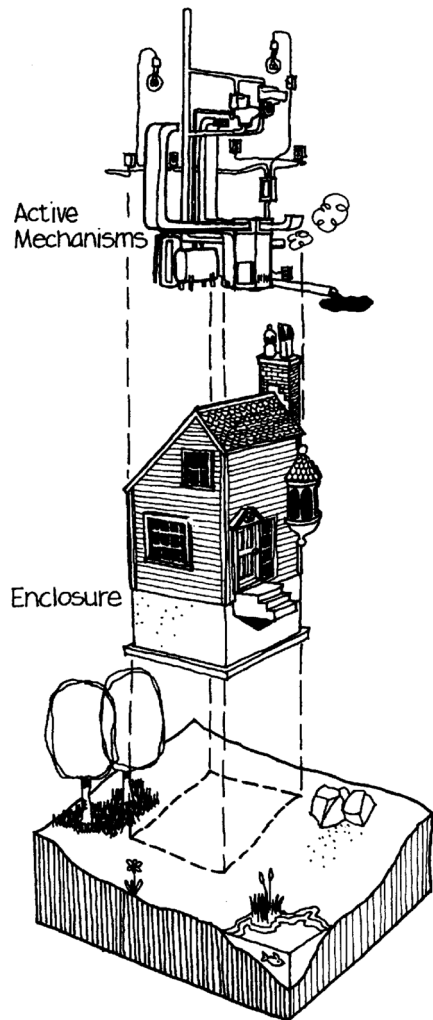
- internal surface resistance is calculated for $\varepsilon = 0.9$, h evaluated at 20°C
- external surface resistance is calculated for $\varepsilon = 0.9$, h evaluated at -10°C, $v = 4 \text{ m/s}$



- If surface resistances are known, the example for a composite wall on slide 19 simplifies as follows:

$$U_{tot} = \frac{1}{R_{tot}} = \frac{1}{R_{se} + R_{1-3} + R_{si}}$$





Source: Edward Allen «How Buildings Work» (2005)

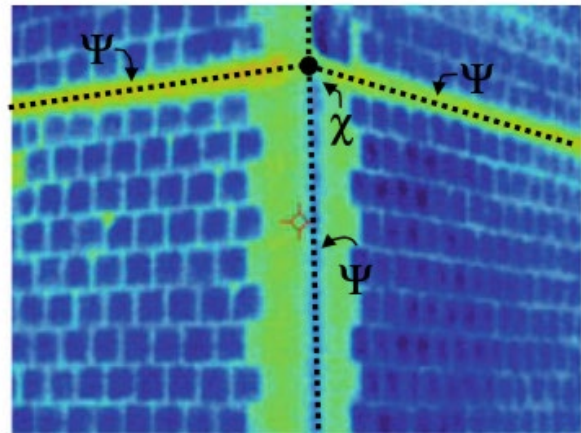
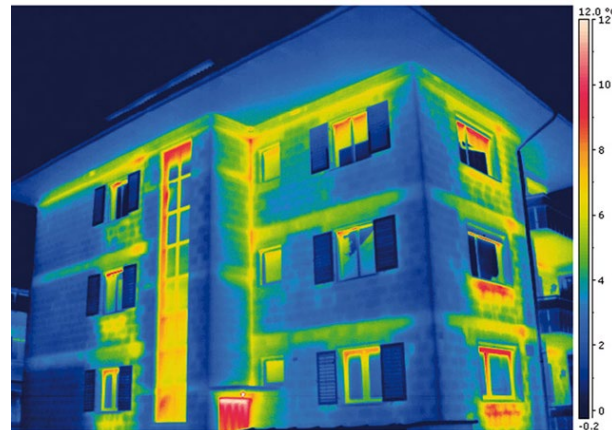
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- Total specific heat flux through the **opaque elements** of the building envelope [W/K]:

$$H = \underbrace{\sum_i A_i \cdot U_i}_{1\text{-dimensional}} + \underbrace{\sum_j l_j \cdot \psi_j}_{2\text{-dimensional}} + \underbrace{\sum_k \chi_k}_{3\text{-dimensional}}$$

- A_i [m²] - area of element i of the building envelope
- U_i [W/(m²·K)] - thermal transmittance of element i -th of the building envelope
- l_j [m] - length of the j -th linear thermal bridge
- ψ_j [W/(m·K)] - linear thermal transmittance of linear j -th thermal bridge
- χ_k [W/K] - point thermal transmittance of the k -th point thermal bridge



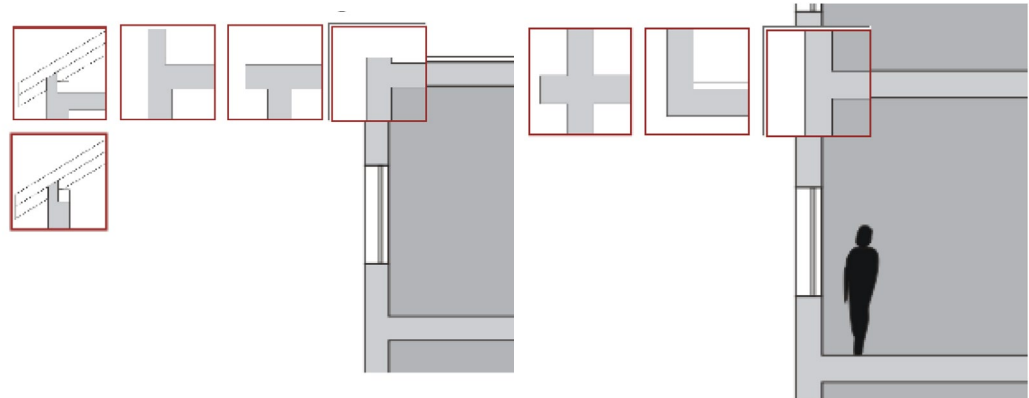
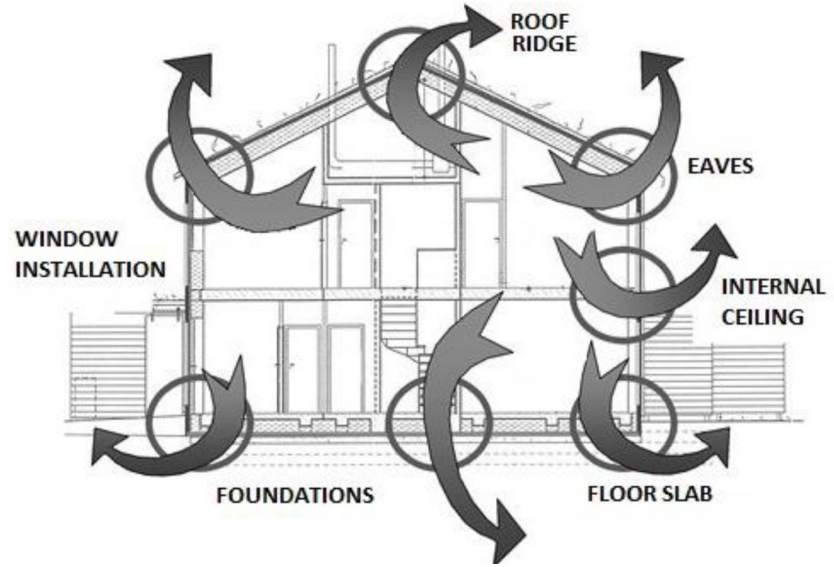
Source: Medved, Building Physics

Thermal Bridge

(cold bridge, heat bridge) –

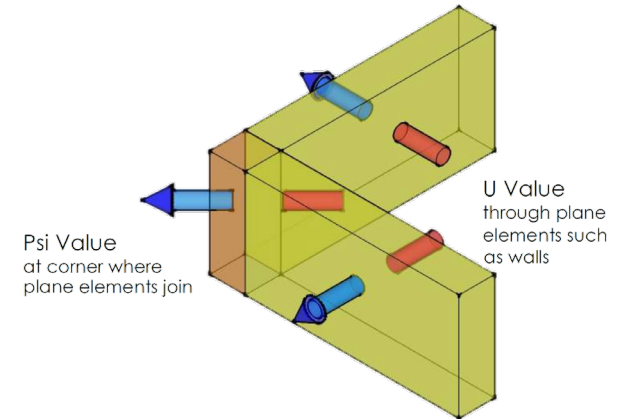
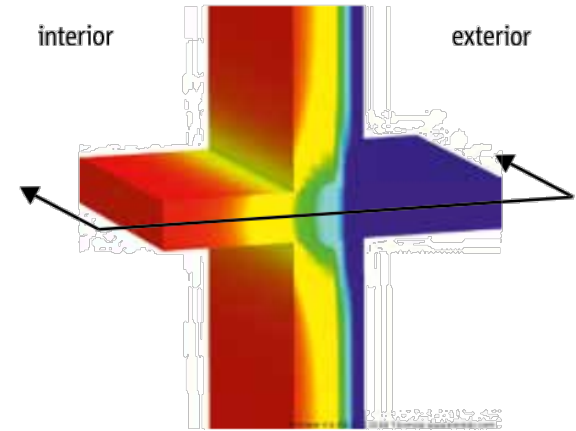
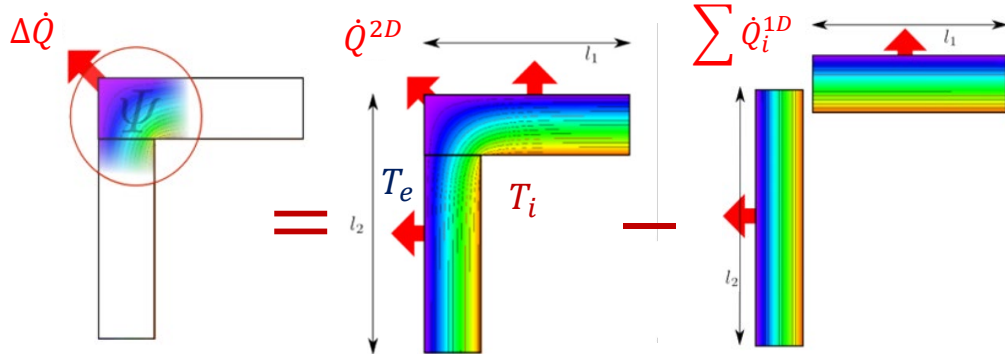
a localized area of the building envelope where the heat flow is different (usually increased) in comparison with adjacent areas if there is a *temperature gradient* between the inside and the outside.

The heat leak *occur due to the higher thermal conductivity of the area* compared *to the surrounding materials* creating a path *of least resistance for heat transfer*.

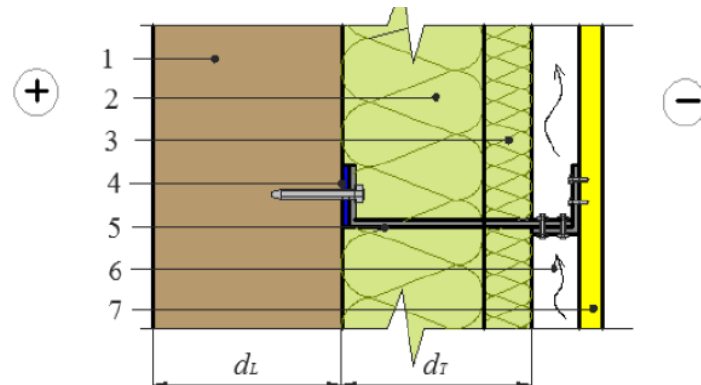
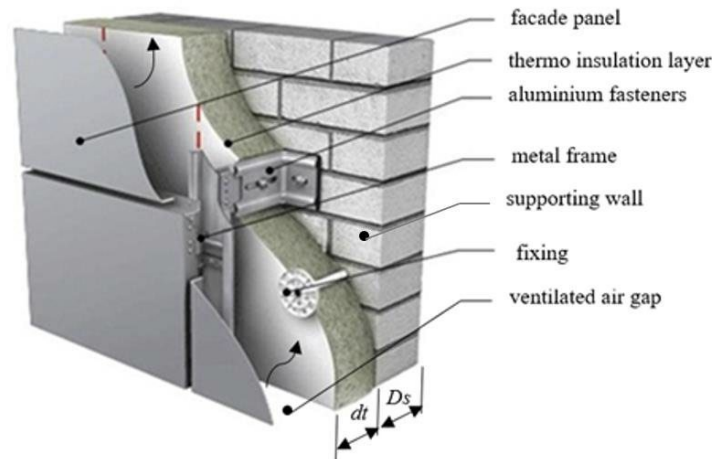


Linear Thermal Bridge (2D)

- **Linear Thermal Bridge** emerges at joints *over the length* of building components
- **Linear thermal transmittance, Psi-value** [ψ , W/m²*K] – an indicator of the *heat loss across a given junction* between the *external wall* and *another element* for every linear **1 m** of that junction and **1 K** difference between inside and outside.
- The thermal transmittance due to *the thermal bridge* is **the difference** between **the thermally interrupted** and the **uninterrupted** components



- **ENG-445 / BUILDING ENVELOPE**



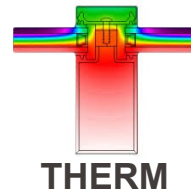
EPFL Thermal Bridges: **Standardized Requirements**

Limiting values per SIA 380/1 of thermal transmittance of thermal bridges in **new buildings**:

Linear Thermal Bridges		ψ (W/m ² *K)
Type 1	Protruding parts (balconies eaves)	0.30
Type 2	interruption of the insulating envelope by walls, floors and ceilings	0.20
Type 3	Interruption of the insulating envelope by the horizontal or vertical edges	0.20
Type 5	Window still	0.15
Point Thermal Bridges		χ (W/K)
Type 6	Point element passing through the thermal insulation	0.30

Methods to calculate thermal bridges

Method	Accuracy	Considerations
Numerical calculations	±5%	○ Description elaborated in ISO 10211:2017
Thermal bridge catalogues	±20%	○ Have essentially fixed parameters (e.g. fixed dimensions and materials) ○ Less flexible than calculations ○ Do not exactly match the actual detail being considered
Manual calculations	±20%	○ Performed by simple computer software ○ Apply only to a specific type of thermal bridge (e.g. constructions with sheet metal) ○ It can be very inaccurate outside of the range of the specified range of application
Default values	0 % to 50%	○ Calculated for parameters representing worst-case situations ○ Based on two-dimensional numerical modelling in accordance to ISO 10211:2017 ○ To be used in the absence of more specific data for the thermal bridges concerned



and more..

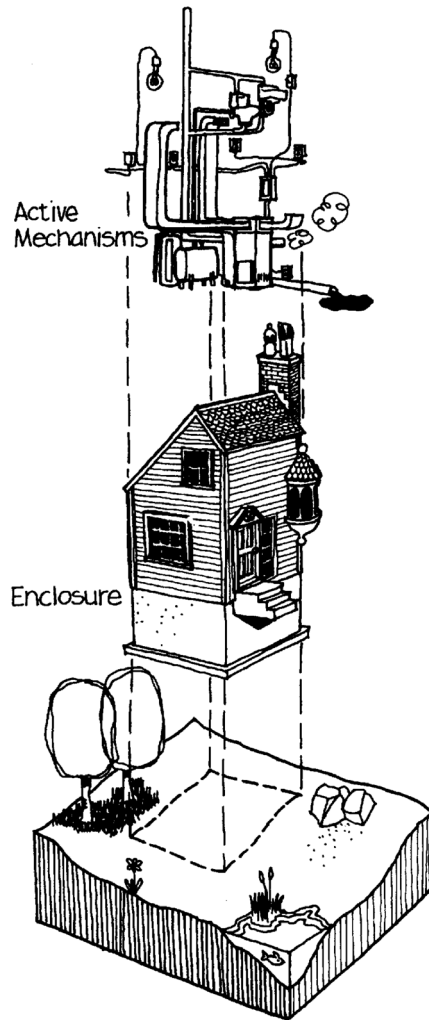
How much could be the contribution of thermal bridges in the overall thermal balance of new buildings?

- A. < 1%
- B. 1-5%
- C. 5-10%
- D. 10-20%
- E. >20%

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Source: Edward Allen «How Buildings Work» (2005)

CONTENT:

- Introduction to the Building Envelope
- Modes of Heat Transfer and their Properties
- Thermal Properties of the Building Elements:
 - Opaque Elements (walls, roofs)
 - Thermal Bridges (linear and point)
 - Transparent Elements (windows)

■ Radiation:

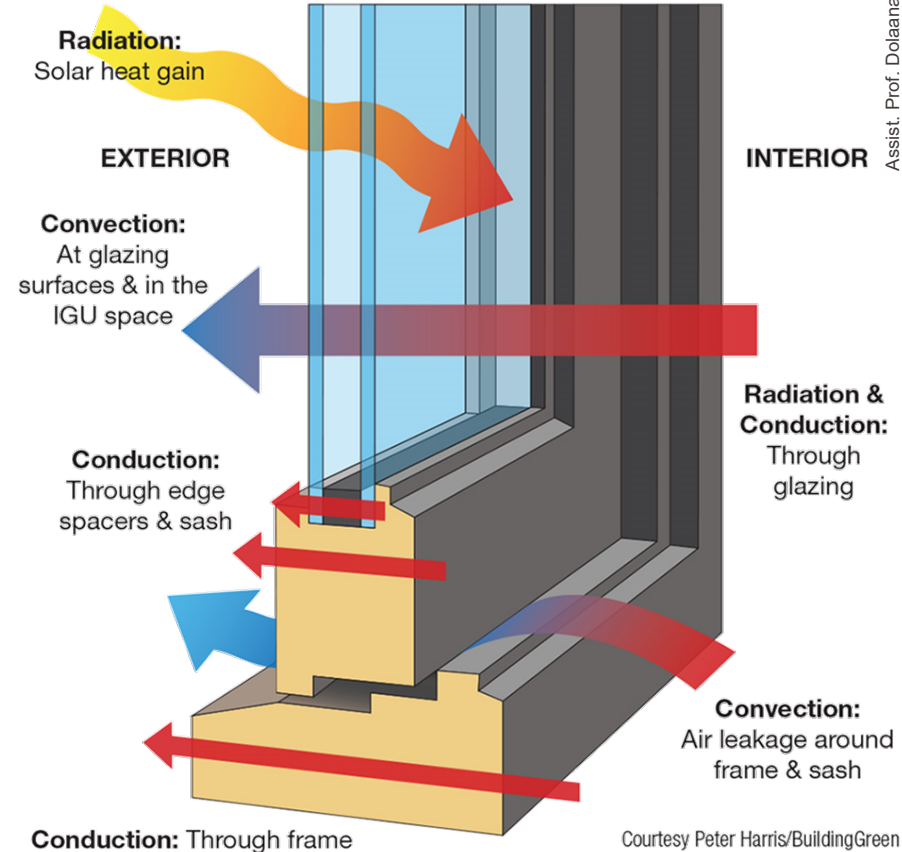
- Short-wave solar radiation (< 2500 nm) incident on the fenestration
- Long-waver radiative heat exchange (> 2500 nm) between fenestration and its surroundings

■ Convection:

- At the outward surface of the outer pane
- At the inward surface of the inner pane
- In the inter-pane space
- Air leakage around frame and edges (infiltration)

■ Conduction:

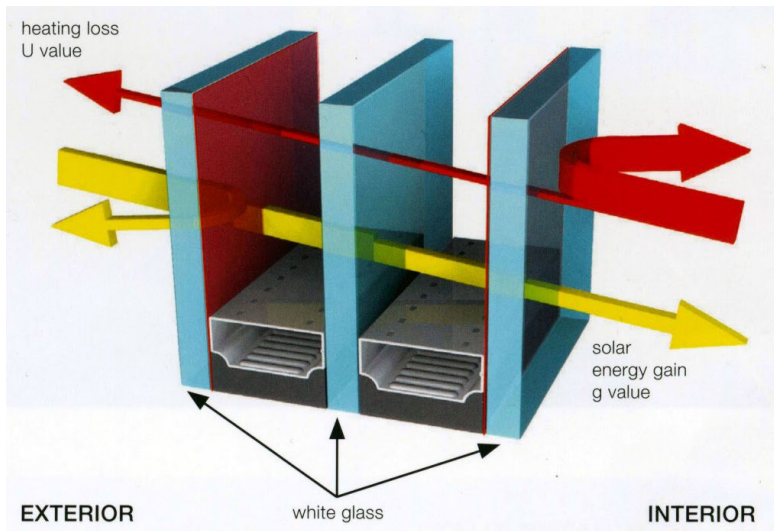
- Through the frame, glass, edge spaces and sash



$$\dot{Q} = U_w \cdot A_{pf} \cdot (T_{out} - T_{in}) + g \cdot A_{pf} \cdot I + AL \cdot A_{pf} \cdot \rho \cdot C_p \cdot (T_{out} - T_{in}), \quad [\text{W}]$$

Heat transfer due to conduction
 Heat transfer due to solar radiation
 Heat transfer caused by air leakage

Overall **U-value** of the window
 Total projected area of fenestration
 Solar Heat Gain Coefficient (**g-value**)
 Incident solar irradiance $[\text{W}/\text{m}^2]$
 Air leakage through the frame $[\text{m}^3/\text{s} \cdot \text{m}^2]$



Source: ASHRAE HOF 2017, Chapter 15

 World's Best Window Co. Series "2000" Casement Vinyl Clad Wood Frame Double Glazing • Argon Fill • Low E ABC-X-1-00001-00001	
ENERGY PERFORMANCE RATINGS	
U-Factor (U.S. / I-P)	Solar Heat Gain Coefficient
0.35	0.32
ADDITIONAL PERFORMANCE RATINGS	
Visible Transmittance	Air Leakage (U.S. / I-P)
0.51	≤ 0.3
Manufacturer stipulates that these ratings conform to applicable NFRC procedures for determining whole product performance. NFRC ratings are determined for a fixed set of environmental conditions and a specific product size. NFRC does not recommend any product and does not warrant the suitability of any product for any specific use. Consult manufacturer's literature for other product performance information. www.nfrc.org	

Thermal Transmittance of Windows

Factors defining **overall U-value of the window** (U_w):

- U-value of the **glazing** (U_g)
- U-value of the **frame** (U_f)
- Thermal bridges (l_g and Ψ_g)

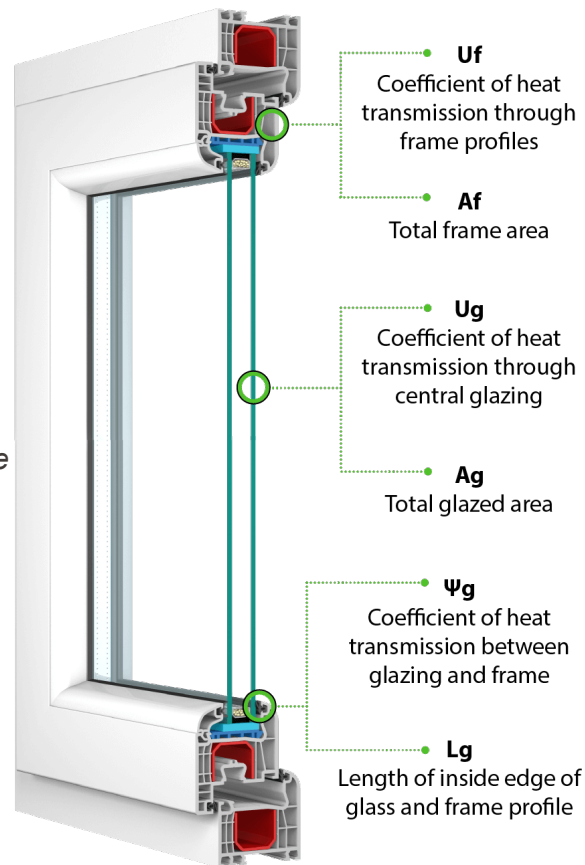
linear thermal transmittance of the insulated glazing edge seal

length of inside edge of frame profile

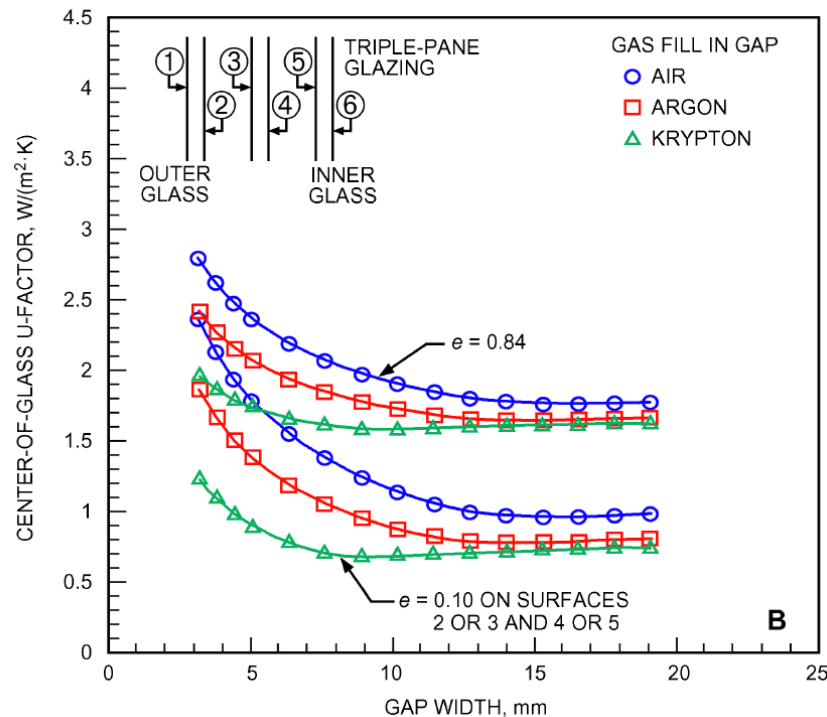
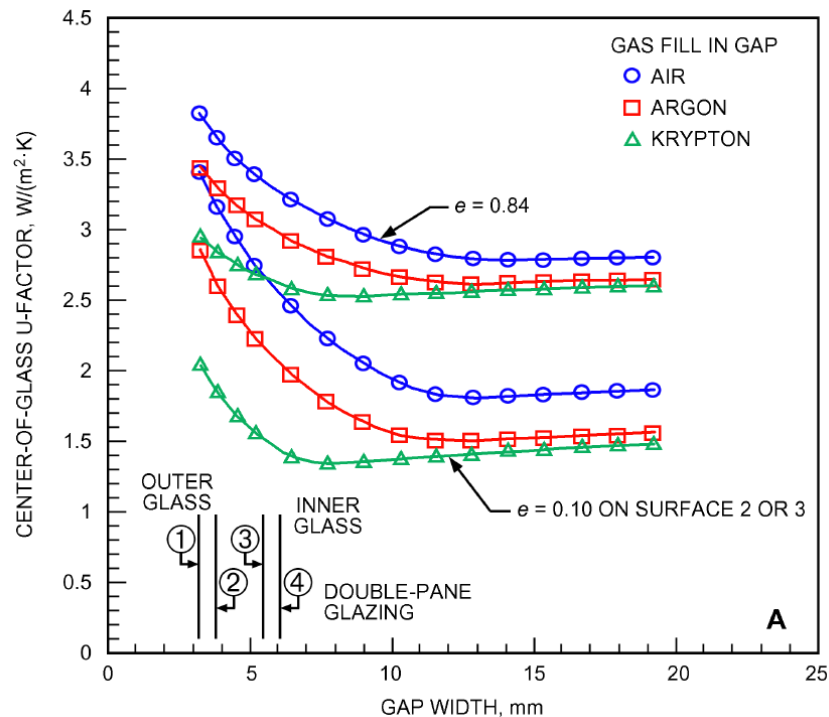
$$U_w = \frac{(U_g \cdot A_g + U_f \cdot A_f + \psi_g \cdot l_g)}{(A_g + A_f)}$$

glass area

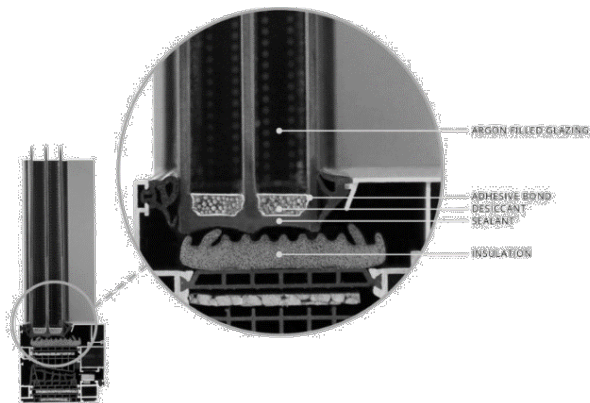
area of the frame



U-factor of the glass (U_g) for vertical **double-** and **triple-pane** glazing units



- Linear thermal transmittance ψ_g value depends on the **frame type** (e.g., material and presence of a thermal break) and **glazing type** (e.g., gas-filling).



- Thermal transmittance of the frame U_f is *the highest* for frames with **metal core** and decreases with *the number of hollow chambers*.

Frame type	Linear thermal transmittance for different types of glazing ψ_g	
	Double or triple glazing uncoated glass air- or gas-filled	Double ^a or triple ^b glazing low-emissivity glass air- or gas-filled
Wood or PVC	0,06	0,08
Metal with a thermal break	0,08	0,11
Metal without a thermal break	0,02	0,05

^a One pane coated for double glazed.
^b Two panes coated for triple glazed.

ISO 10077-1:2017

Table F.1 — Thermal transmittances for plastic frames with metal reinforcements

Frame material	Frame type	U_f W/(m ² ·K)
Polyurethane	with metal core thickness of PUR ≥ 5 mm	2,8
PVC-hollow profiles ^a	two hollow chambers external  internal	2,2
	three hollow chambers external  internal	2,0

^a With a distance between wall surfaces of each hollow chamber of at least 5 mm

Which window type would have the lowest U_w value?

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A double-glazed window with a wooden frame ($U_g = 1.1 \text{ W/m}^2\text{K}$, $U_f = 1.3 \text{ W/m}^2\text{K}$, identical for 3 options), the total projected area of each window is the same.

A. Option A

B. Option B

C. Option C



(A)



(B)



(C)

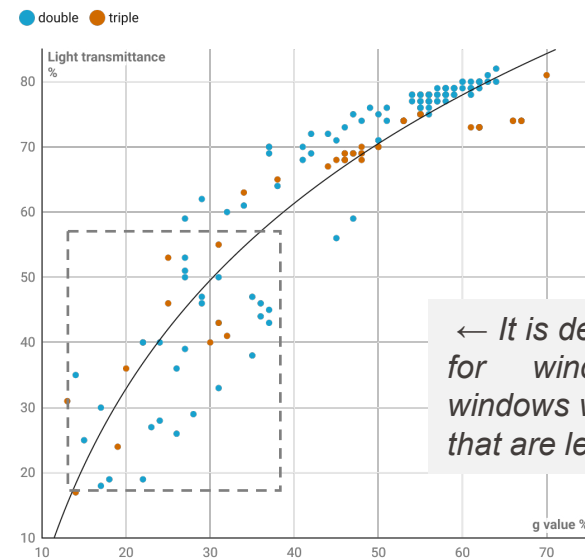
Solar Heat Gain Coefficient (SHGC) or g-value –

the percent of solar energy incident on the glass that is **transferred** indoors both *directly* and *indirectly* through the glass.

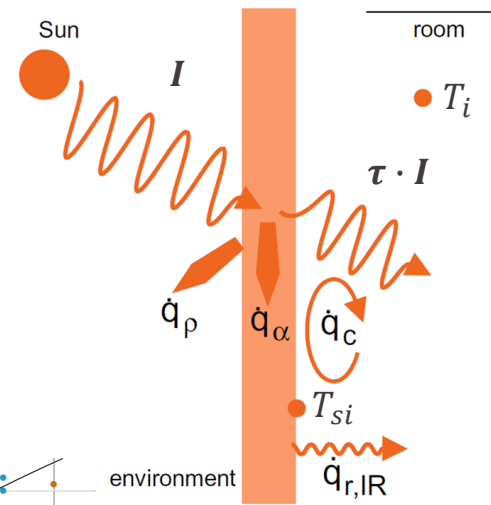
The *direct* gain portion is the **solar energy transmittance**, while the *indirect* is the **fraction of solar energy incident** on the glass (+ blind) that is **absorbed** and **re-radiated** or **transmitted** through convection indoors.

$$g = \frac{\text{solar gains}}{\text{incident radiation}}$$

$$g = \frac{\tau \cdot I + q_c + q_{r,IR}}{I}$$



← It is desired to have the lowest g-value for windows, however engineering windows with low g-value lead to windows that are less transparent.



Source: Medved, Building Physics, p. 65

Which window has **lower** solar heat gain coefficient (**g-value**)?

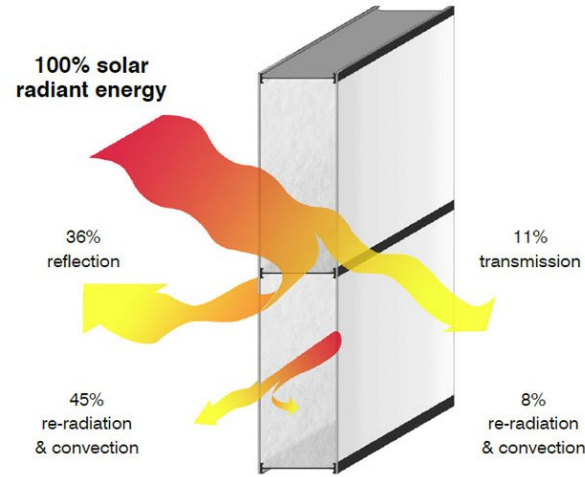
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A. A

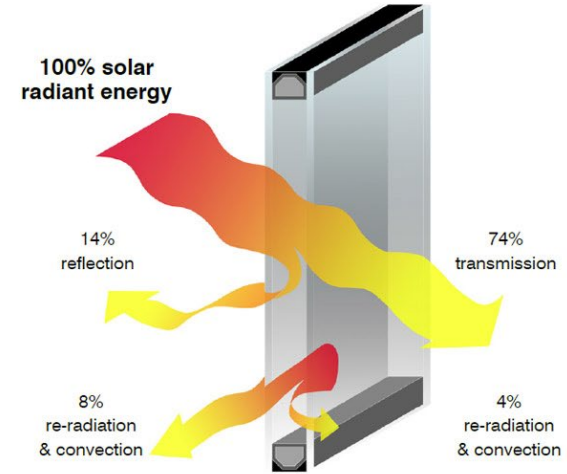
B. B



2-3/4" Crystal-White Kalwall Panel

Option A

VS



1" Clear Insulated Glass Unit (IGU)

Option B

Where is it better to place window blinds to reduce solar heat gains?

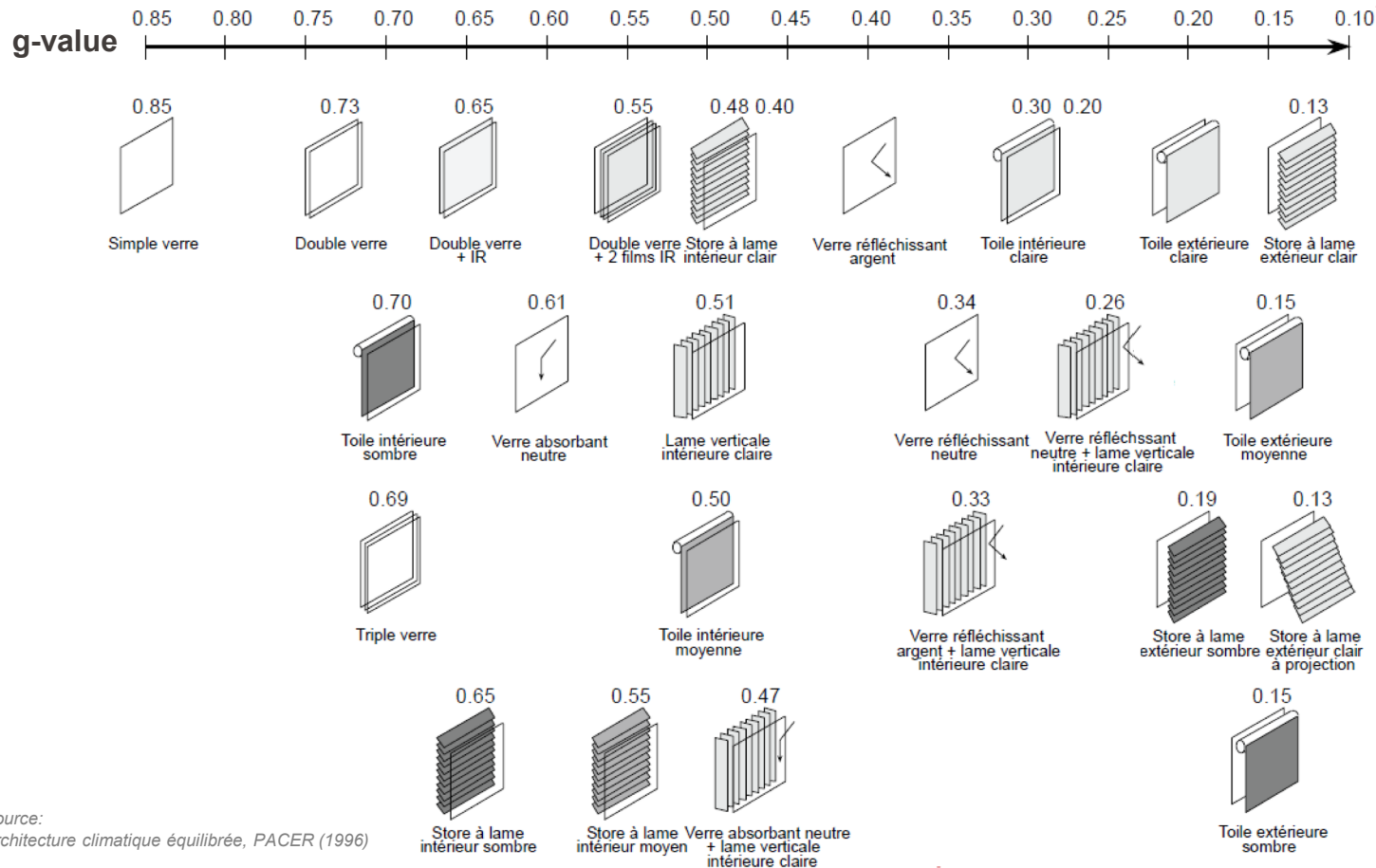
- A. Indoors
- B. Outdoors
- C. Inside the window panes

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Comparison of g and g_{tot} : Effect of Blinds



Source:

Architecture climatique équilibrée, PACER (1996)

EPFL Performance of Transparent Elements: **Standards**

Code	Title
ISO 15099:2003	Thermal performance of windows, doors and shading devices -- <i>Detailed calculations</i>
ISO 10077-1:2017	Thermal performance of windows, doors and shutters -- Calculation of thermal transmittance - Part 1: <i>General</i>
ISO 10077-2:2017	Thermal performance of windows, doors and shutters -- Calculation of thermal transmittance - Part 2: <i>Numerical method for frames</i>
ISO 19467:2017	Thermal performance of windows and doors - <i>Determination of solar heat gain coefficient using solar simulator</i>

Measures to reduce heat transfer:

Which measures are the most efficient for windows?

- A. Increase number of panes (e.g., triple pane)
- B. Addition of the low-e or tinted coatings
- C. Evacuated interpane space
- D. Interpane gas fills (argon, krypton)
- E. Low conductivity spacers

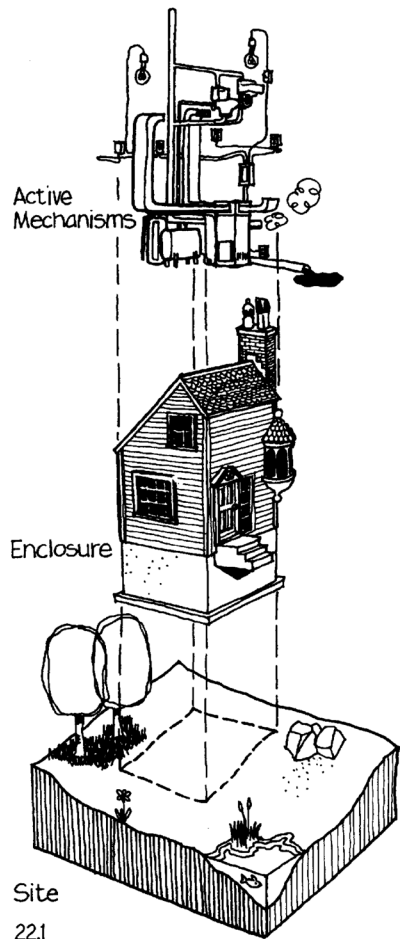
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- Definition of **the thermal boundary**
- **Opaque building elements**
 - Heat transfer modes (q_{cond} , q_{conv} , q_{rad})
 - Concepts of R -value and U -value
 - Network of thermal resistances (R_{tot} and U_{tot})
 - Permitted and limiting U -values according to standards
 - Film surface resistance (internal R_{si} and external R_{se})
 - Thermal bridges, the difference between U , ψ , and χ
 - Measures to reduce the heat transfer through walls
- **Transparent building elements**
 - Heat transfer modes
 - Overall U-value of the window (U_w), contributions of U_g , U_f , ψ_g
 - Solar heat gain coefficient (g) of glasses
 - Linear thermal transmittance (ψ_g) of frames
 - Measures to reduce the heat transfer through windows



Source: Edward Allen «How Buildings Work» (2005)

Thank you for your attention!

Assist. Prof.
Dolaana KHOVALYG
dolaana.khovalyg@epfl.ch

<https://www.epfl.ch/labs/ice/>