EPFL

ENG-445
Building Energetics

Building Envelope

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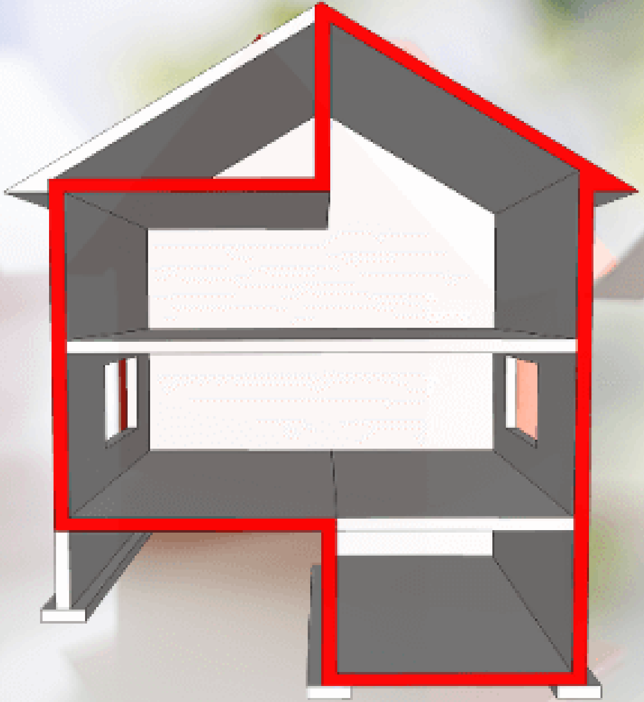
Session ID: **ENG445DK**



Assist. Professor
Dolaana KHOVALYG

7 November 2024

smart living lab

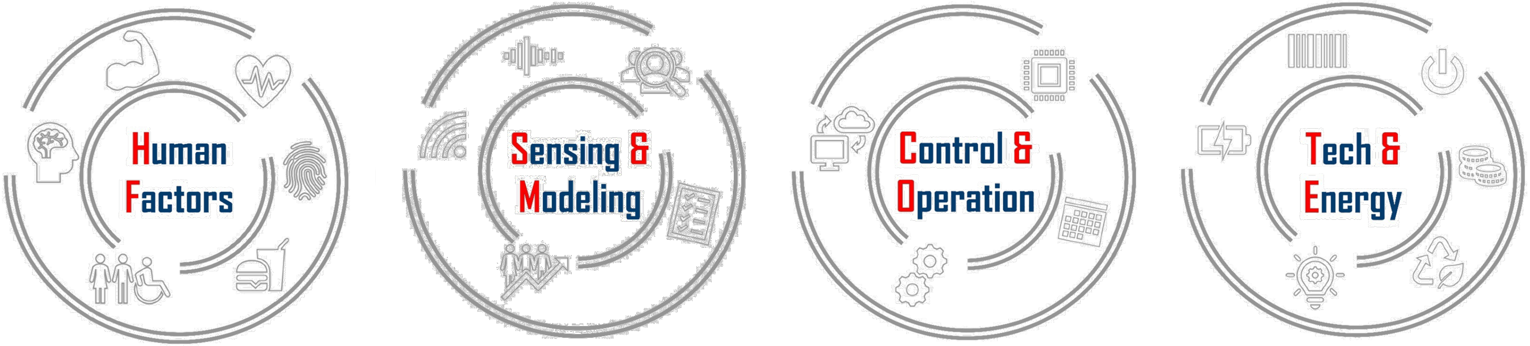
Integrated Comfort Engineering Laboratory

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:

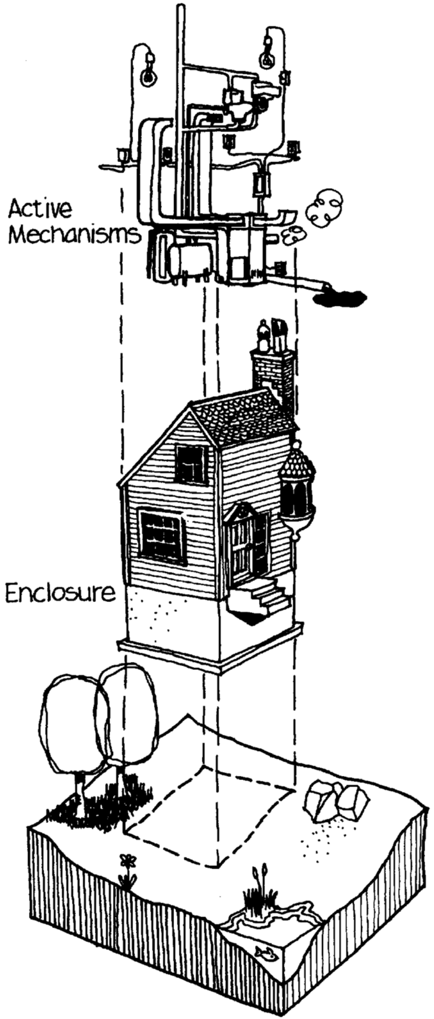


More details on the ICE activities online: https://www.epfl.ch/labs/ice/

Course Information

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)

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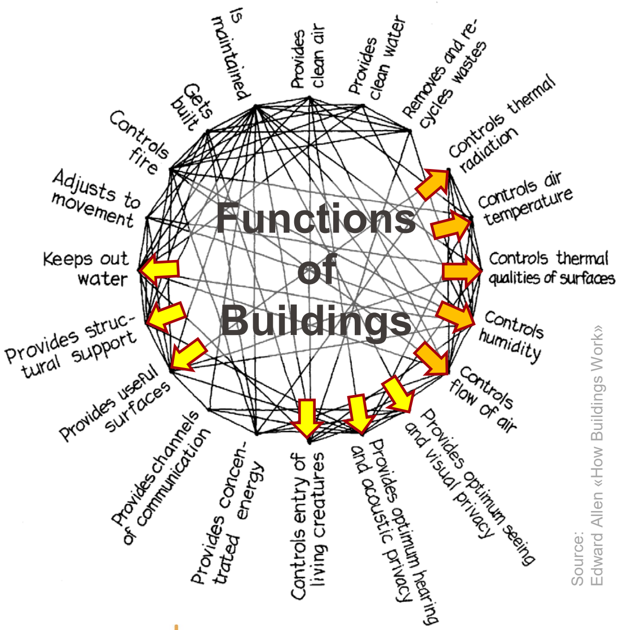
Building Envelope

- 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



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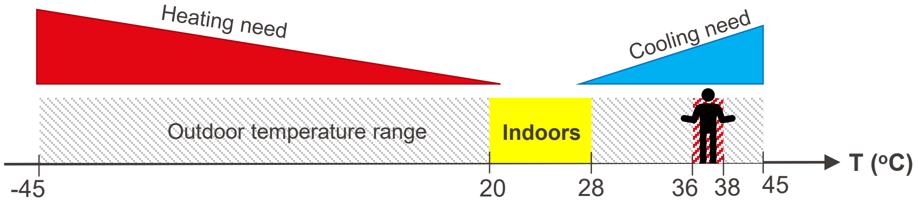
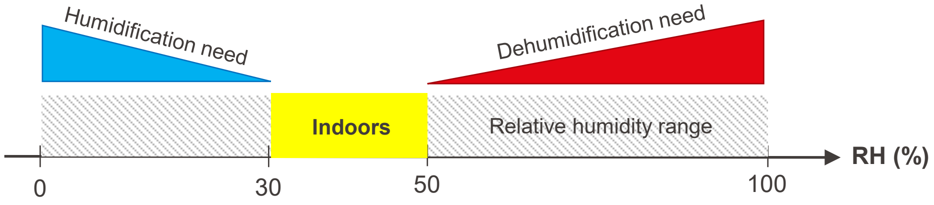




Elements of the Building Envelope

- **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**

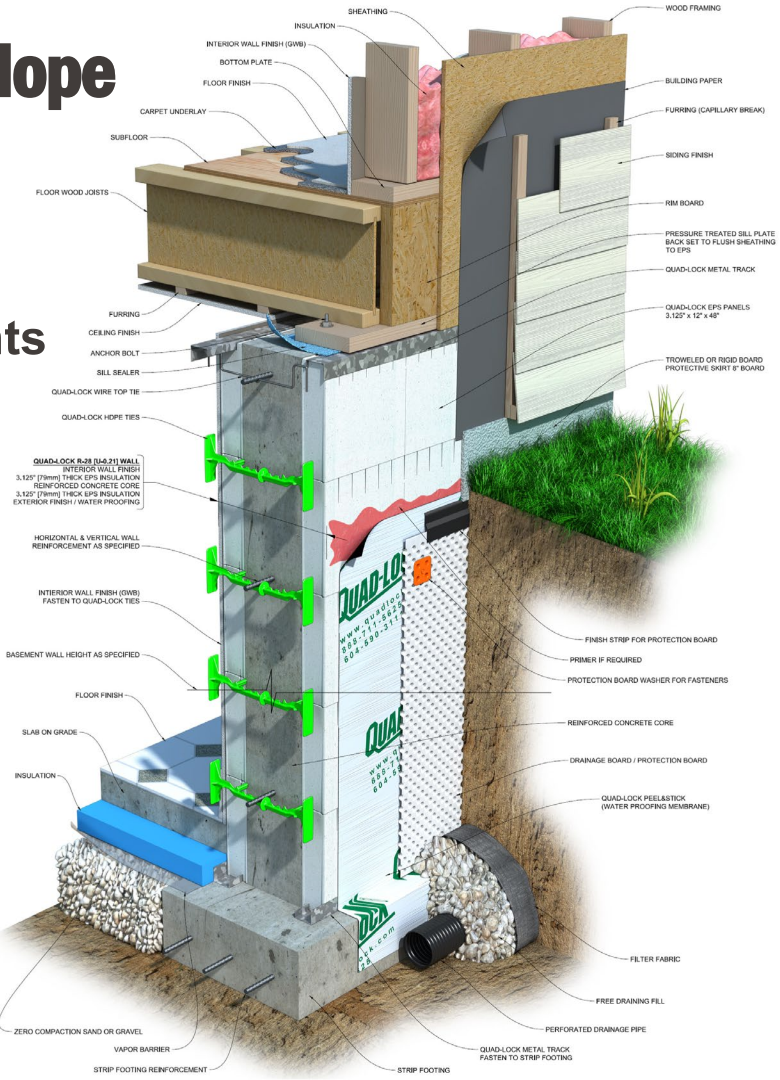
  wraps, membranes, *etc.*

- **Finishing**

  interior finishing, external façade

- **Connections**

  joints, ties, battens, *etc.*



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Source: https://www.quadlock.com

Building Façades

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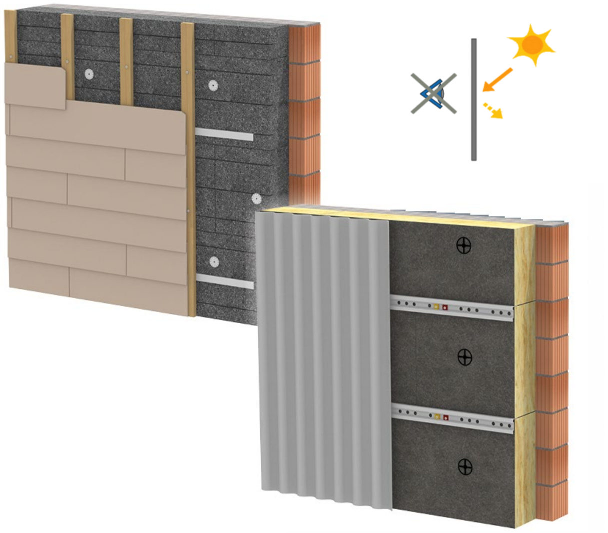
Opaque

(traditional façade)

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



Source: www.swisspor.ch

Curtain Wall

(double-skin façade)

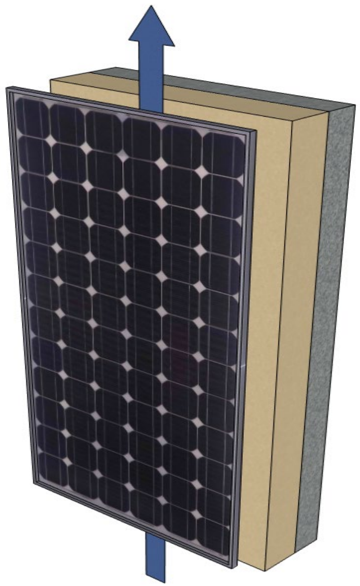
reduced DSF, closed cavity façade, internal sunshield

Source: R. Miller, pinterest

BIPV

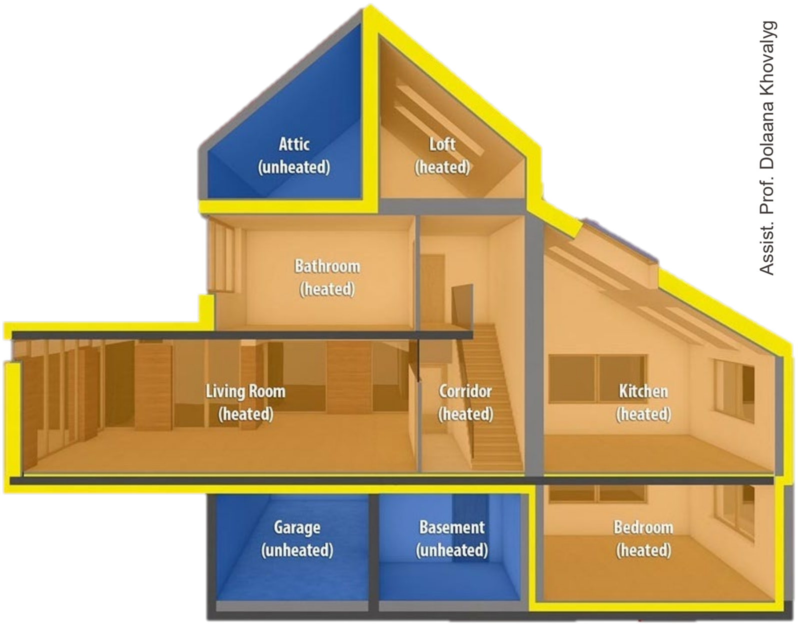
(active façade)

opaque, translucent, transparent



Thermal Boundary

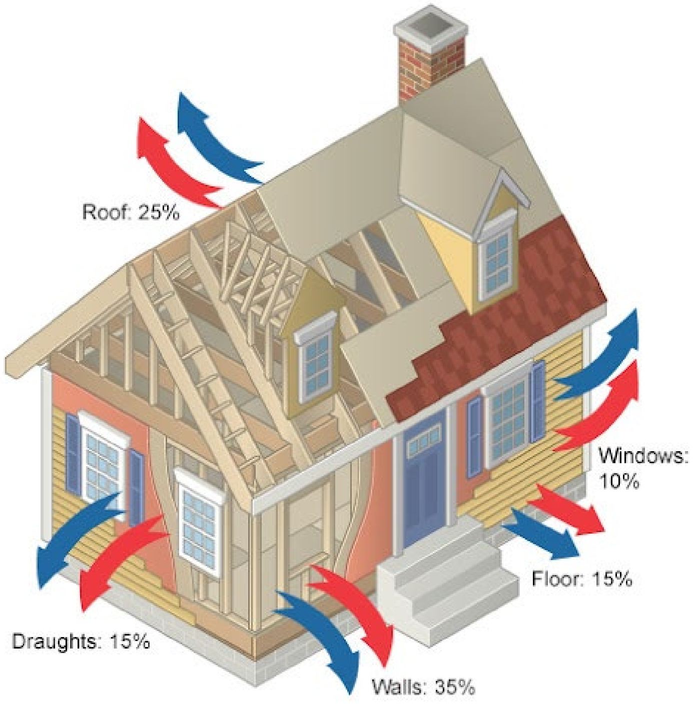
- A boundary where **heat losses** and **heat gains** are *accounted* and *effectively* **controlled**
- It *fully wraps* the **indoor conditioned space**, it often located *over the building outer envelope*.
- A **well-thought design of the thermal boundary** is *a crucial factor* for ***enhanced building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

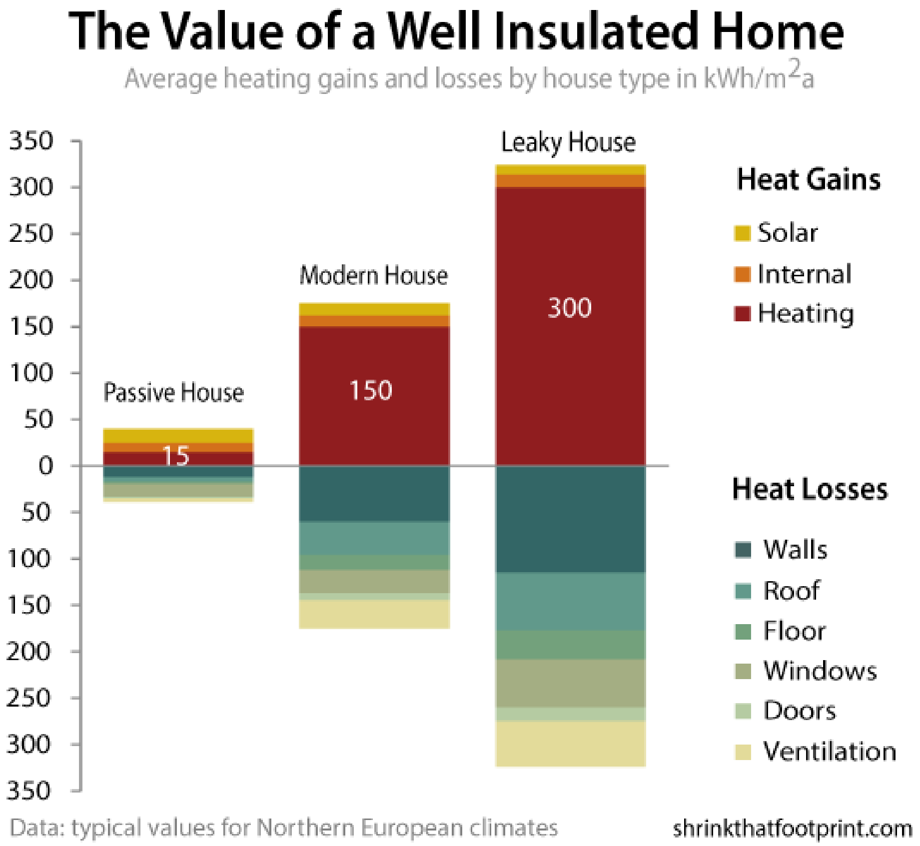


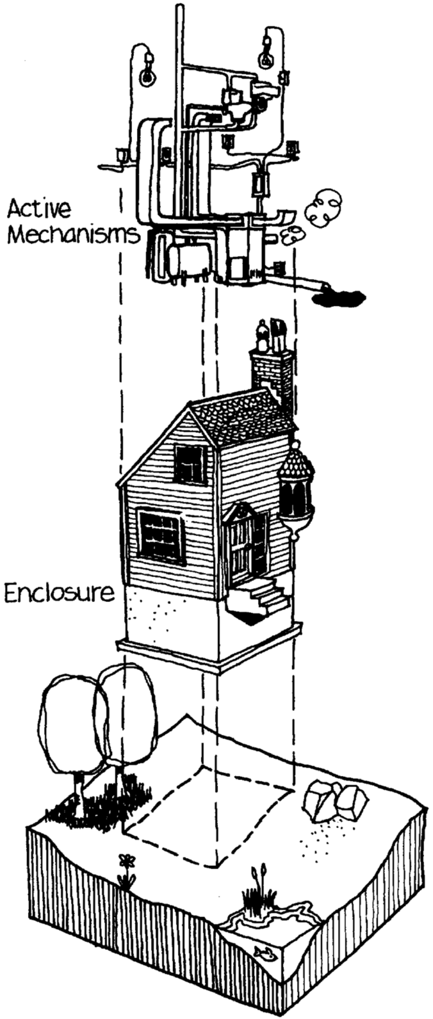
Where to Insulate?

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**

Sources of Heat Losses in Buildings







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Overview of Heat Transfer Modes

1 D, steady state

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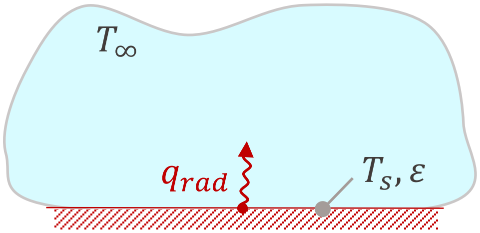
Radiation

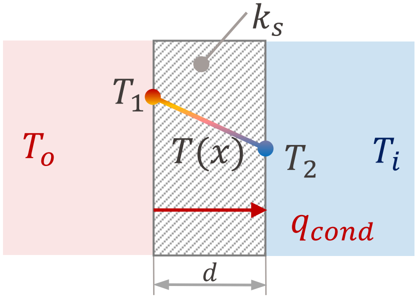
energy transfer in the space by electro-magnetic waves (no need in a medium)



All objects at $T_s > 0\ K$ spontaneously emit electromagnetic waves

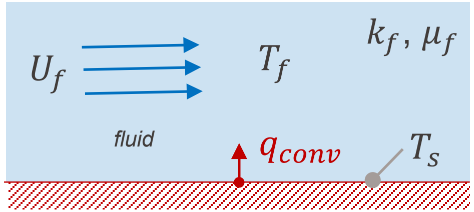
Conduction

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*



If $T_s > T_f$, the convection heat flux is transferred from the surface

Heat flux $q (W/m^2)$

Stefan – Boltzmann's Law:

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

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

Fourier's Law:

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

Newton's Law of Cooling:

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

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

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

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

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

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

Properties defining intensity of Heat Transfer

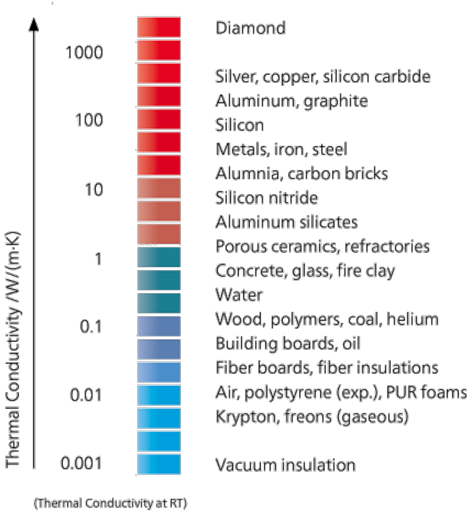
Radiation

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

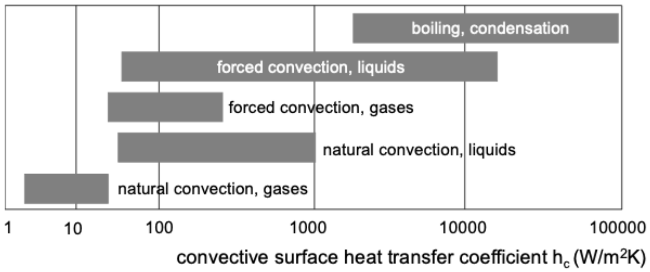
Conduction

Thermal Conductivity k or λ (W/m*K): **amount of heat** than can be **conducted** during **1 second** through **1 m²** of a ***homogeneous*** **layer of material** subjected to **a temperature gradient 1 K/m**.



Convection

Convective heat transfer coefficient h_{conv} (W/m²*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: Overview

- **Insulation materials restrict the flow of heat**

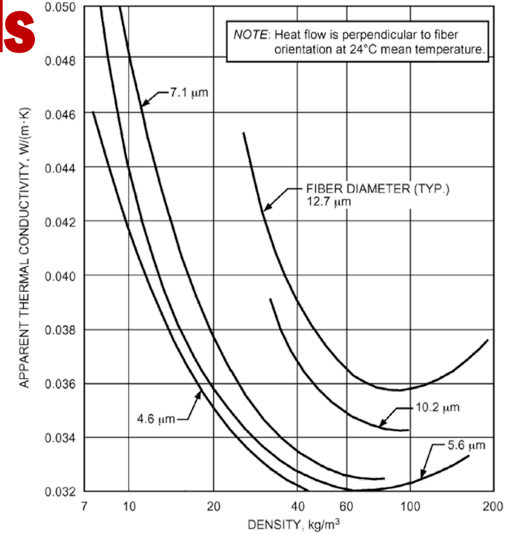
  (which in turn **reduces** ability of **building assemblies *to dry out*** when **wet**)

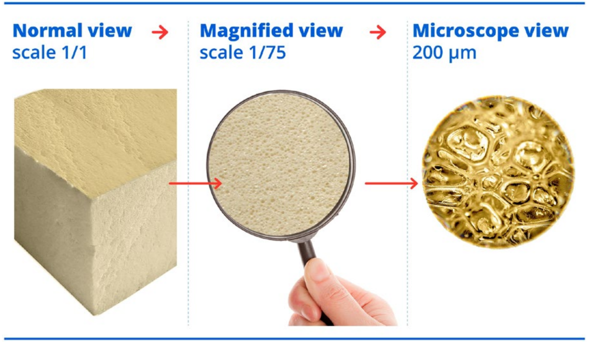
- Thermal Insulation
  - Inorganic
    - Cellular materials — calcium silicate, bonded perlite, vermiculite, and ceramic products.
    - Fibrous materials — glass wool, rock wool, and slag wool.
  - Organic
    - Fibrous materials — cellulose, cotton, sheep wool, wood, pulp, cane, or synthetic fibers.
    - Cellular materials — cork, foamed rubber,polystyrene, polyethylene, polyurethane, polyisocyanurate, and other polymers.
  - Metallic/Metalized reflective membranes — rolled foil (usually aluminum), reflective paint, reflective metal shingles, or foil-faced plywood sheathing
  - Advanced material — transparent materials (Aerogel), phase change materials

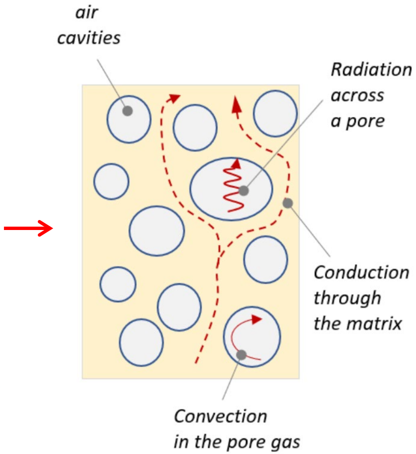
Source: Sadineni et. al. (2011), Renewable and Sustainable Energy Reviews vol. 15

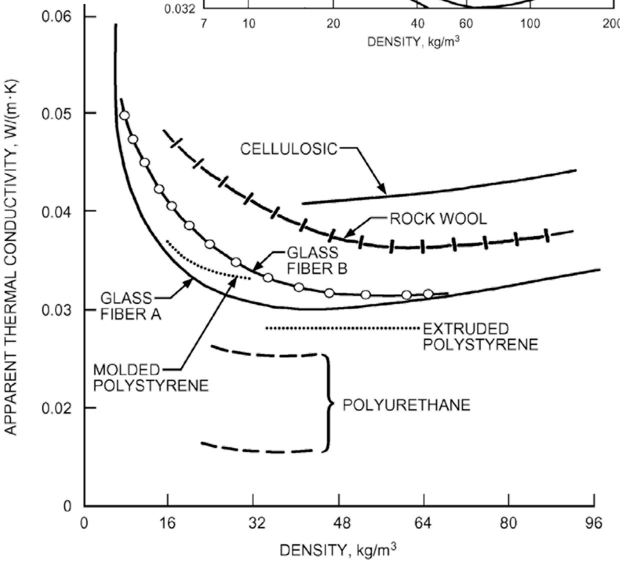
Conductive Properties: Insulation Materials

- ***Apparent* Thermal Conductivity** (W/m*K) – **amount of heat** than can be **conducted** during **1 second** through **1 m²** 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*









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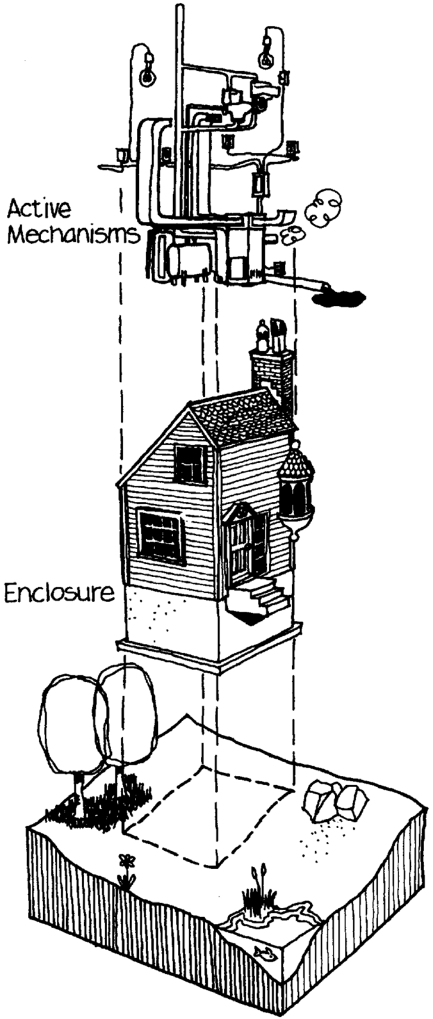
Source: *ASHRAE Handbook 2017. Fundamentals. Chapter 26.*



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Thermal Resistance and Thermal Transmittance

- **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

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

- **Thermal Resistance** (**R-value**, m²K/W) – the capacity of a material to ***resist* heat flow**

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

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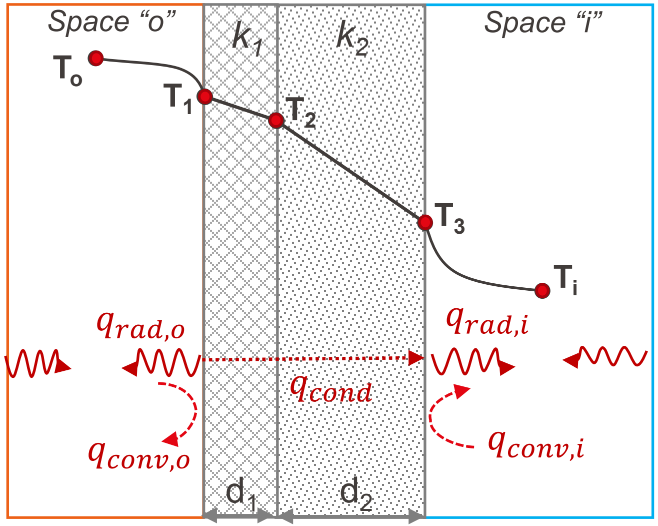
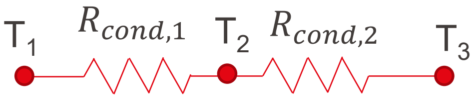
Network of Thermal Resistances

1 D, steady state



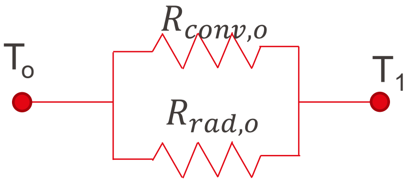
- Using *the electrical circuit analogy*, **heat transfer problems** can be analyzed using **network of thermal resistances** forming **a thermal circuit**
- Example for a simple **composite wall**:

Linear network:



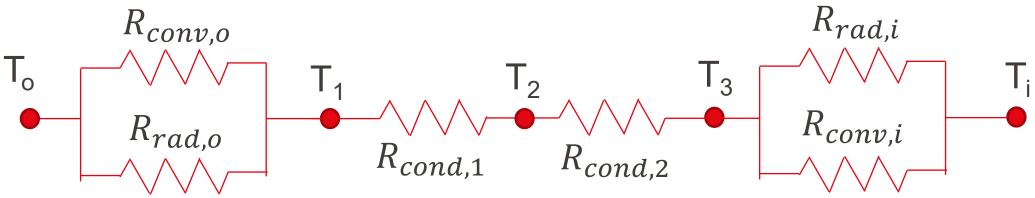
$$R_{1-3} = \frac{d_1}{k_1} + \frac{d_2}{k_2}$$

Parallel network:



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

Overall network:



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

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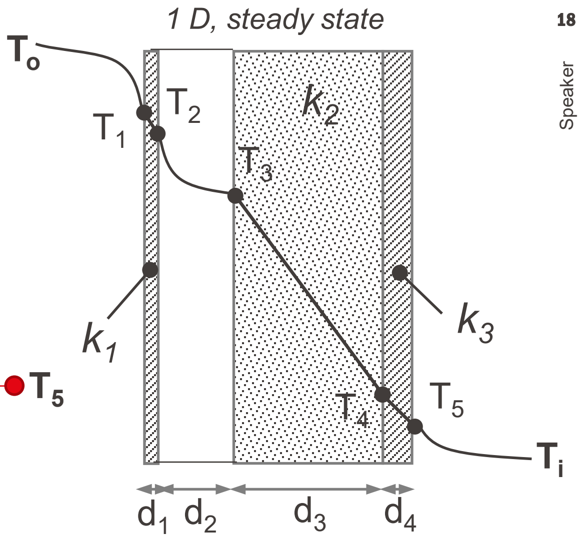
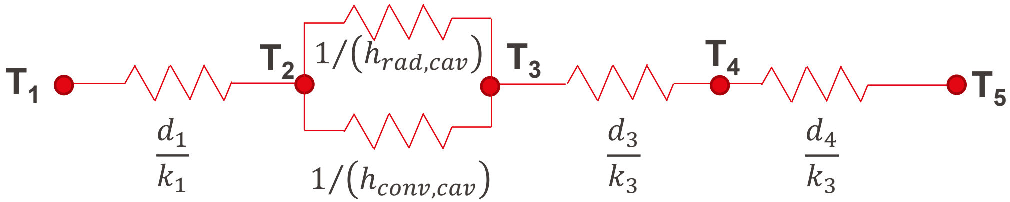
Network of Thermal Resistances

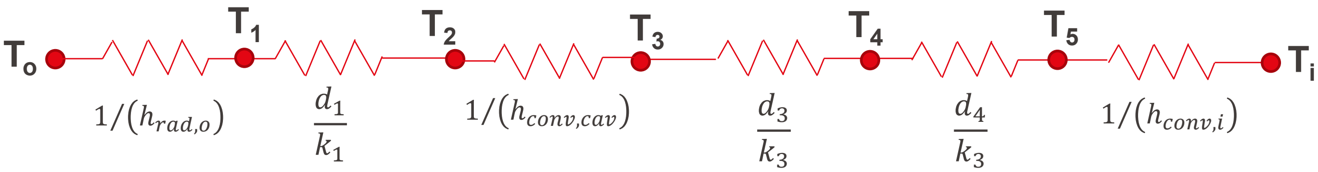
Which of the following thermal circuits corresponds to the **overall thermal resistance** through **a composite wall** with **a sealed air cavity**?



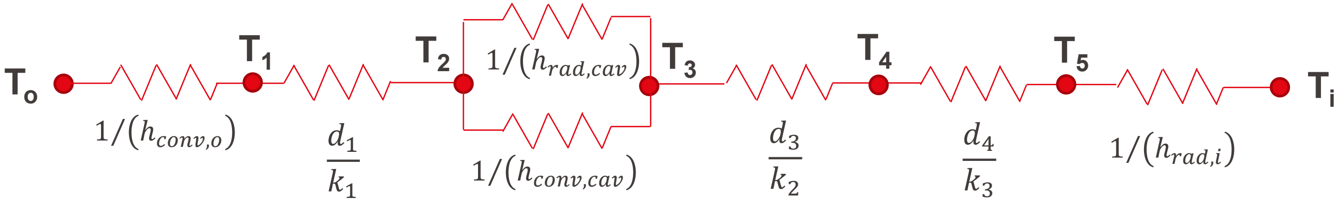
A.



B.



C.



D. NONE ABOVE

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

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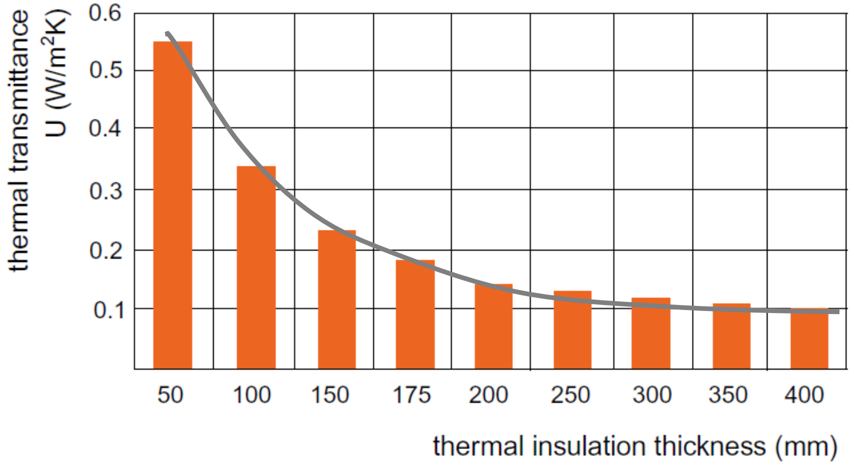
Session ID: **ENG445DK**

A. Yes

B. No

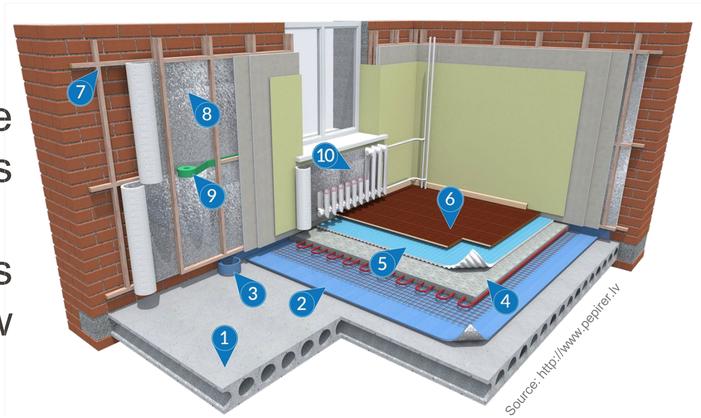
C. Not sure

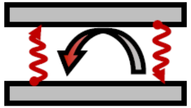


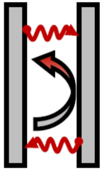
Source: Medved, Building Physics, p. 44

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*







Air gap thickness	Horizontal gap (e.g., roof): *NO reflective insulation*	Horizontal gap (e.g., roof): *WITH reflective insulation*	Vertical gap (e.g., wall): *NO reflective insulation*	Vertical gap (e.g., wall): *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

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Building Envelope Performance: Standards

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 – Tabuated 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

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Requirements per SIA standards

- Maximum permitted **U-values** (SIA 180)

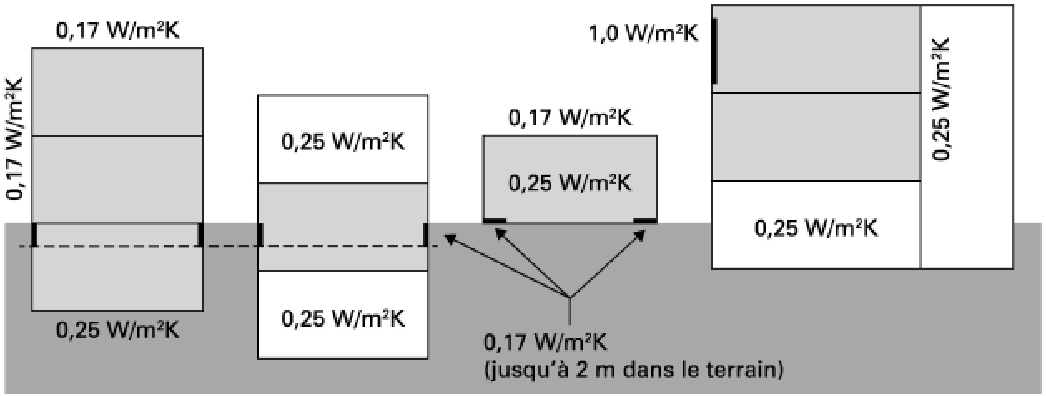
Building element	Envelope adjacent to exterior [W/m²K]	Envelope element adjacent to unheated premises [W/m²K]
Roof	0.4	0.6
Wall	0.4	0.6
Floor	0.4	0.6
Windows, door	2.4	2.4
Blind casing	2	2

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

Building element	Envelope element adjacent to exterior [W/m²K]		Envelope elements adjacent to unheated premises [W/m²K]	
	renovation	*new*	*renovation*	*new*
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**



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Surface Thermal Resistance

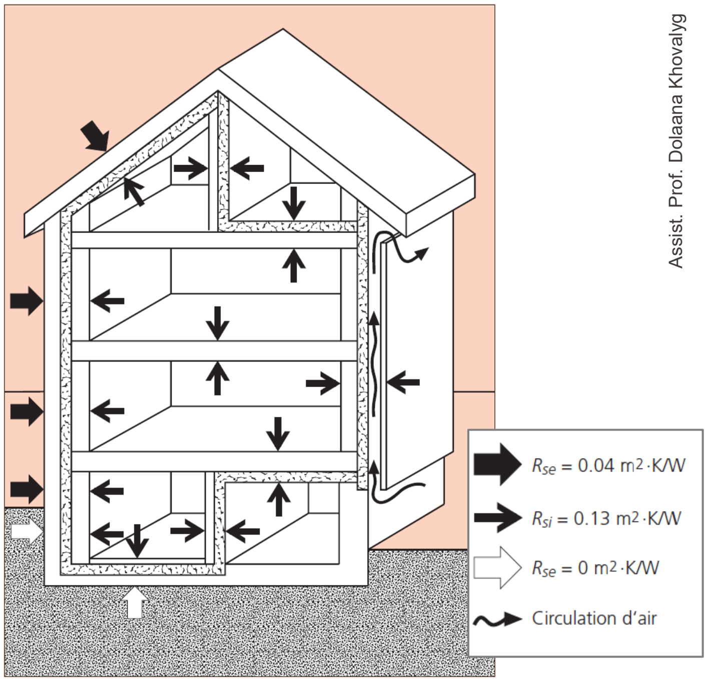
- **Design surface resistance** (ISO 6946):

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

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

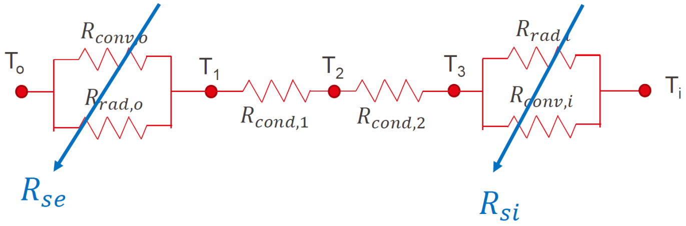
Design values are considered for the following conditions:

- 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, $v = 4\ m/s$



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

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



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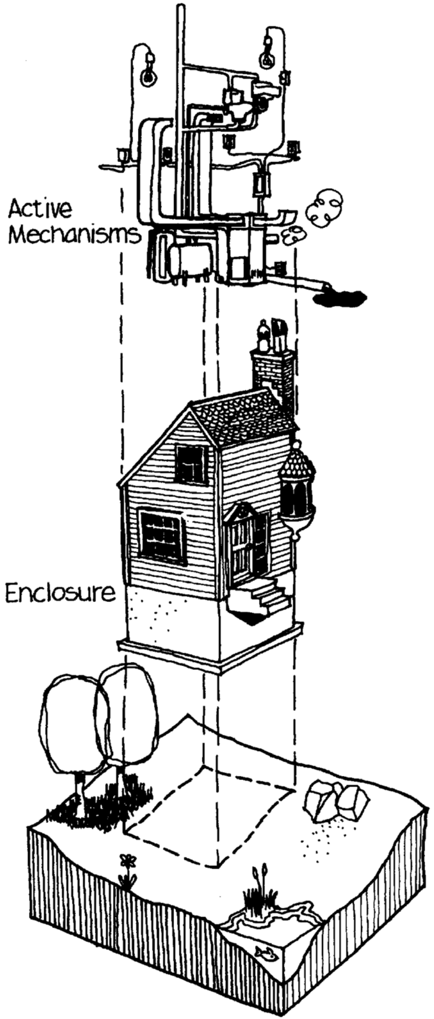

Source: Edward Allen «How Buildings Work» (2005)

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)

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Opaque Building Elements: Transmission Heat Flow

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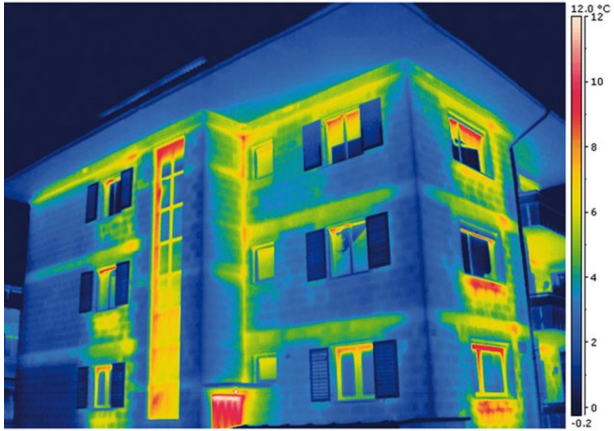
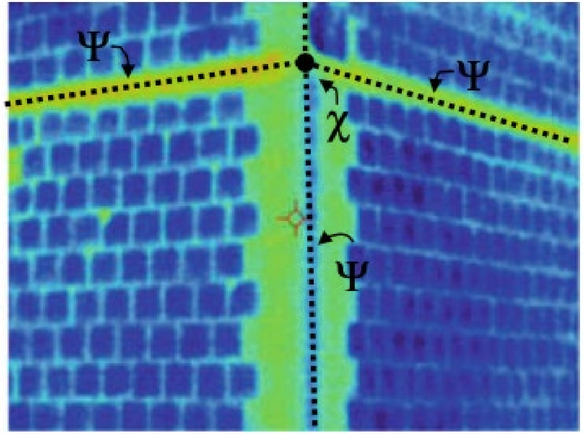
- **Total** **specific** **heat flux** through **the opaque elements** **of the building envelope** [W/K]:

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



- 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

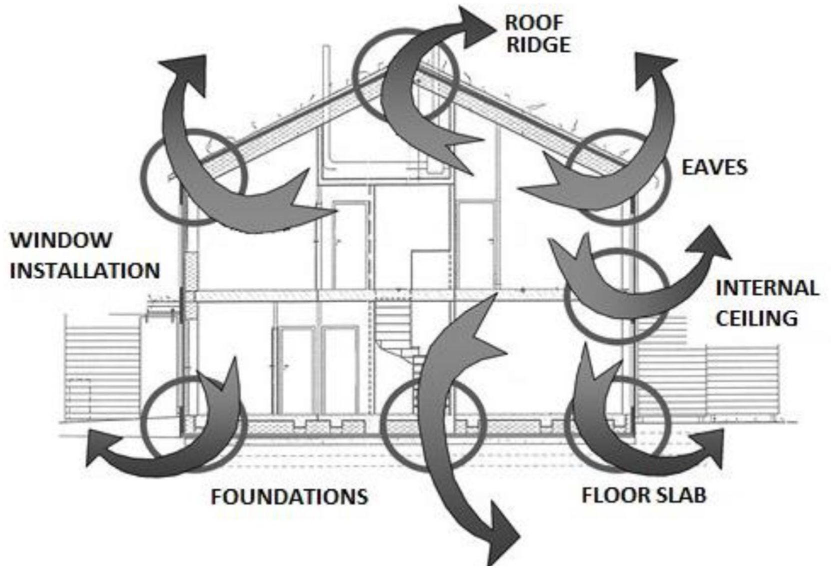
Thermal Bridges

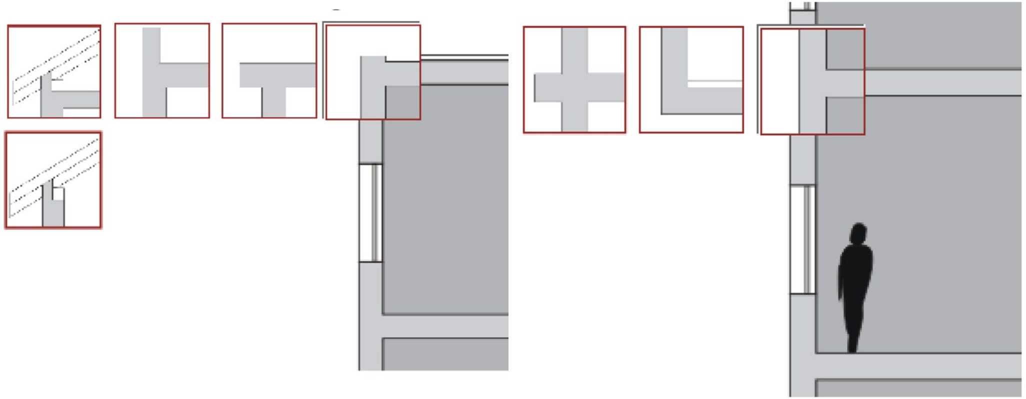
Thermal Bridge

(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***.

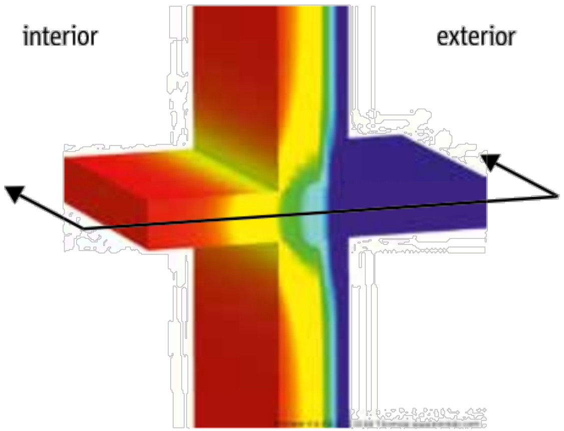




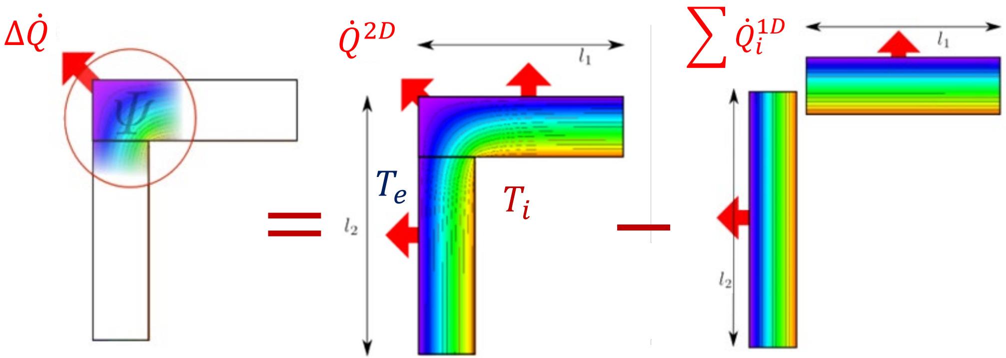
Images from Passive House Institute and LESOSAI

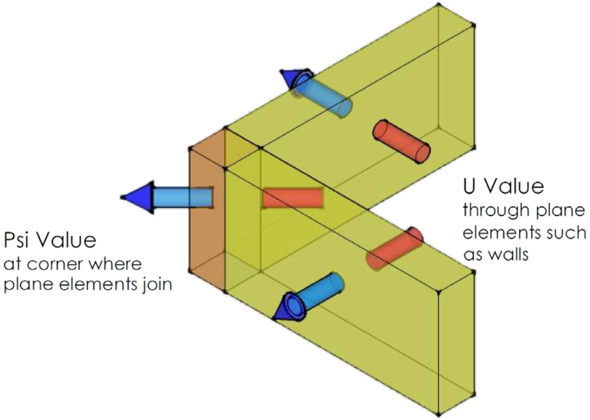
Linear Thermal Bridge (2D)

- **Linear Thermal Bridge** emerges **at joints *over the length*** of building components



- **Linear thermal transmittance, Psi-value** [ψ, W/m*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

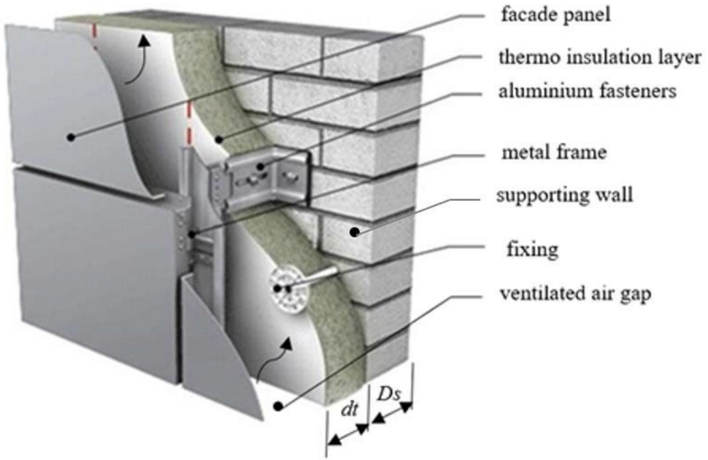


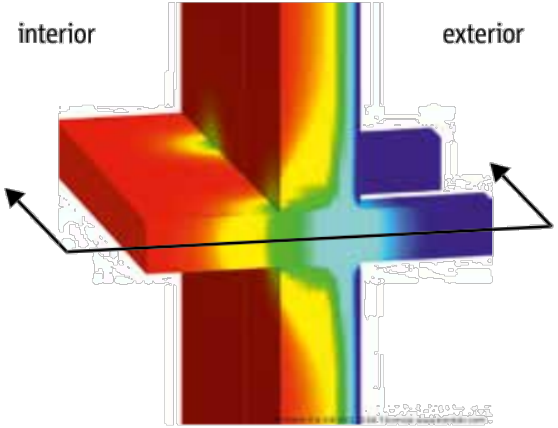


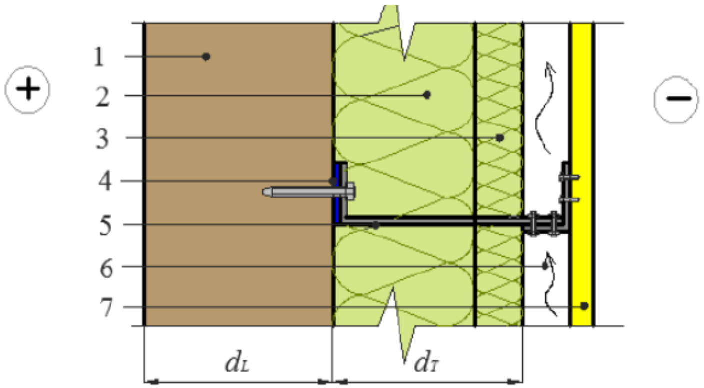
Point Thermal Bridge (3D)

- **Point Thermal Bridge** emerges when a building envelope is **interrupted in a point** (e.g., by a fastener)

- **Point thermal transmittance, Ksi-value** [χ, W/K] – an indicator of the ***heat loss across a given point*** between **the *external wall*** and ***another element*** at **1 K** difference between *inside* and *outside*.







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Thermal Bridges: Standardized Requirements

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

	Linear Thermal Bridges	ψ (W/m*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

HTflux
WUFI®
THERM
PHYSIBEL
and more..

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

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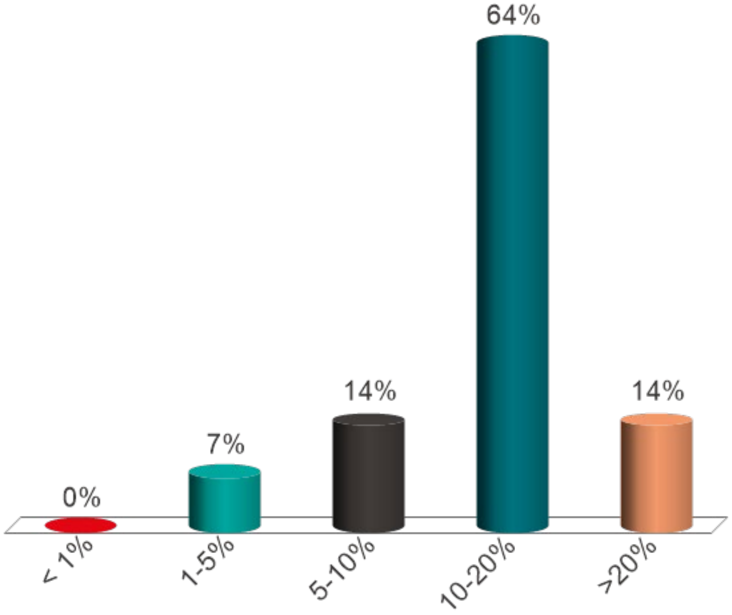
A. < 1%

B. 1-5%

C. 5-10%

D. 10-20%

E. >20%



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Contribution of Thermal Bridges

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Bilan thermique SIA380/1: 2009
380/1 Justificatif (2007,2009,2016)
Nom Projet openoffice-group18 - Variante 1

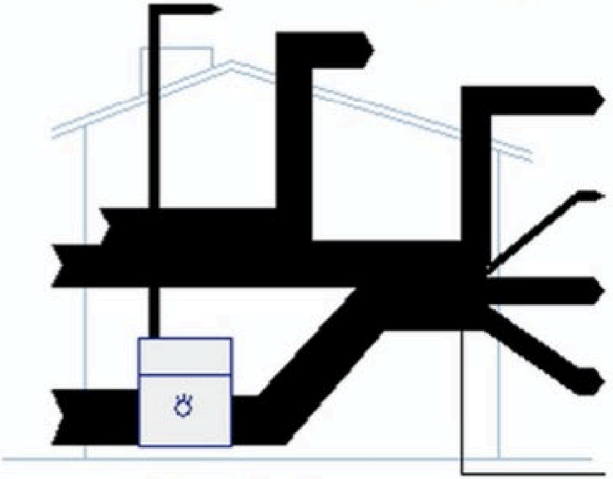
Payerne
Rotation du bâtiment 0 [°]
Surface Ae 912 [m²]

Lesosai 2019
de Janvier à Décembre

Pertes techniques 8,6
Rejets 27,5

Apports thermiques

	[kWh/m²]
Internes	28,8
Solaires	32,7
Chauffage	43,1
	104,6

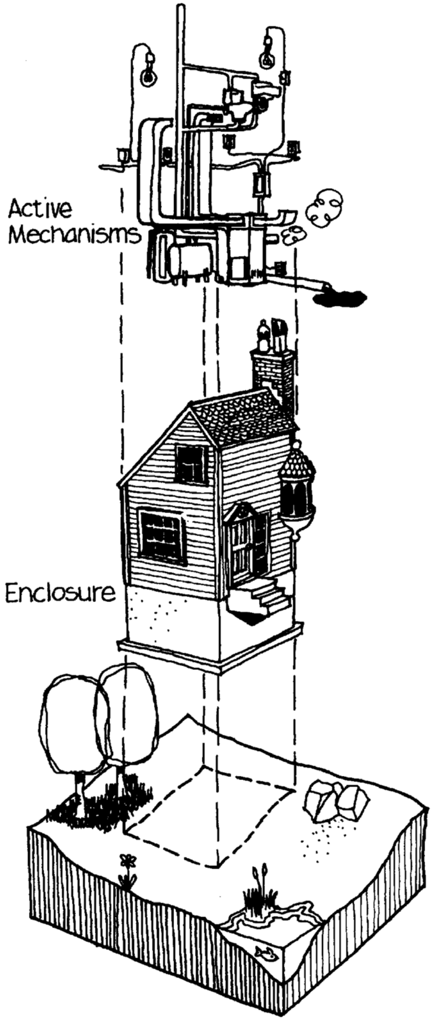


Frac. utile 0,80

Pertes thermiques

	[kWh/m²]	[%]
Toit	22,6	33
Parois	7,1	10,4
Fenêtres	20,1	29,4
Aération	20,7	30,2
Plancher	-2,0	-3
	68,5	100

Dont ponts thermiques: 10,9
Dont ponts thermiques (sans pertes aération): 15,6



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

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Heat Transfer in Buildings: Windows

Radiation:

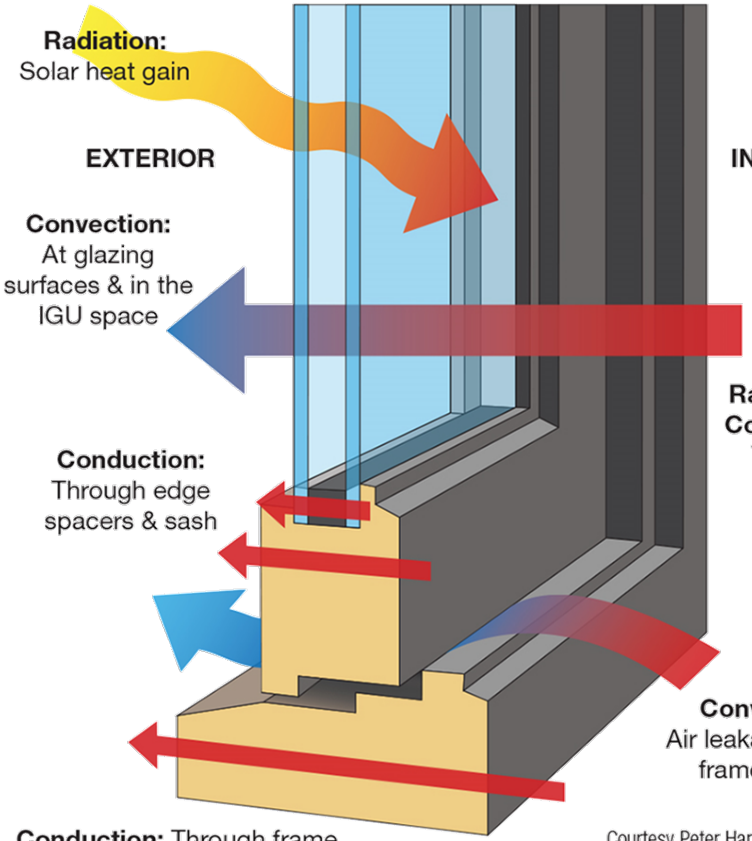
- Short-wave solar radiation (< 2500 nm) incident on the fenestration
- Long-waver radiative heat exchange (> 2500 nm) between fenestration and its surroundings

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



Courtesy Peter Harris/BuildingGreen

Windows: Instantaneous Energy Flow

Heat transfer due to **conduction**

Heat transfer due to **solar radiation**

Heat transfer caused **by air leakage**

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

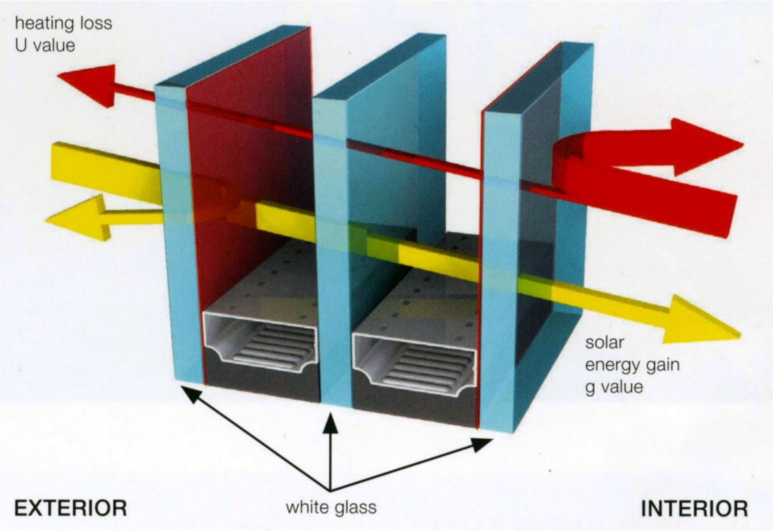
Overall **U-value** of the window

Total projected area of fenestration

Solar Heat Gain Coefficient (**g-value**)

Incident solar irradiance [W/m²]

Air leakage through the frame [m³/s*m²]



Source: ASHRAE HOF 2017, Chapter 15

Thermal Transmittance of Windows

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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)

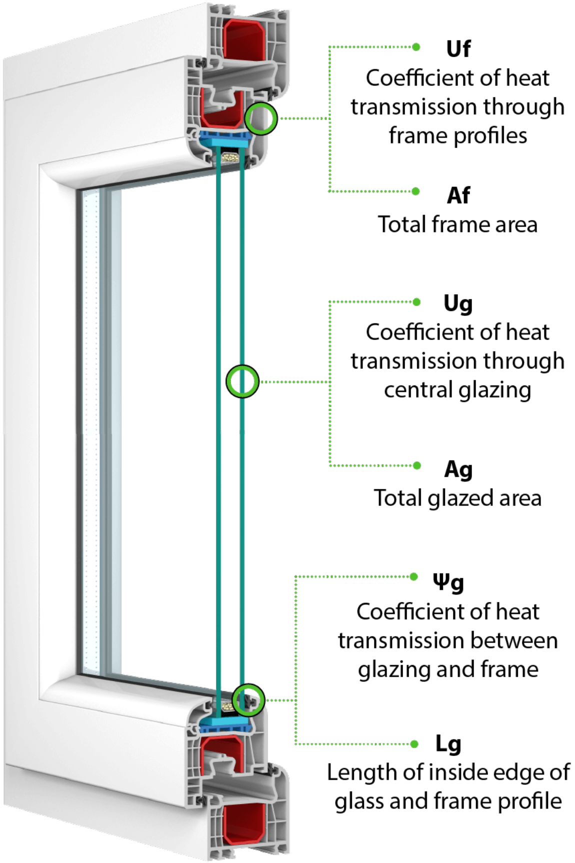
linear thermal transmittance** of the insulated **glazing edge seal

length of inside edge of frame profile

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

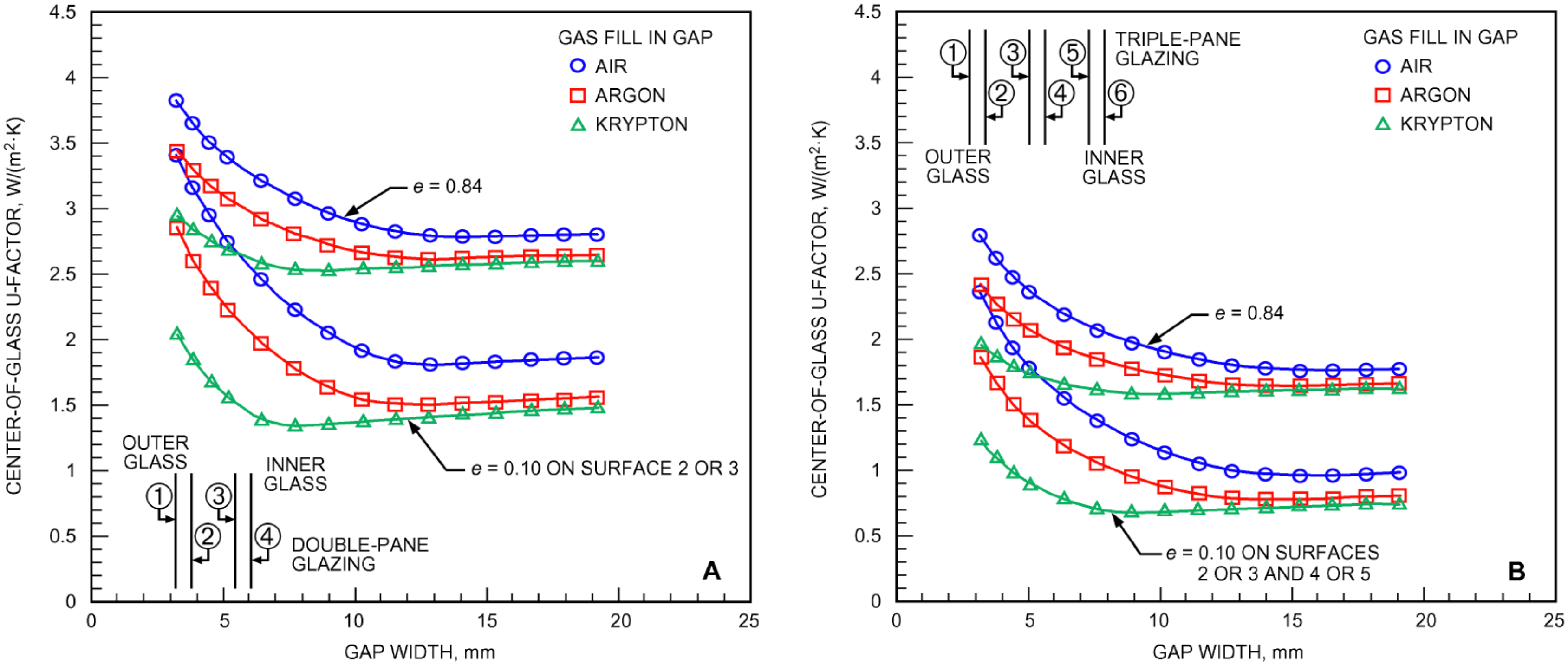
glass area

area of the frame



Thermal Transmittance of Windows

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



Source: ASHRAE HOF 2017, Chapter 15

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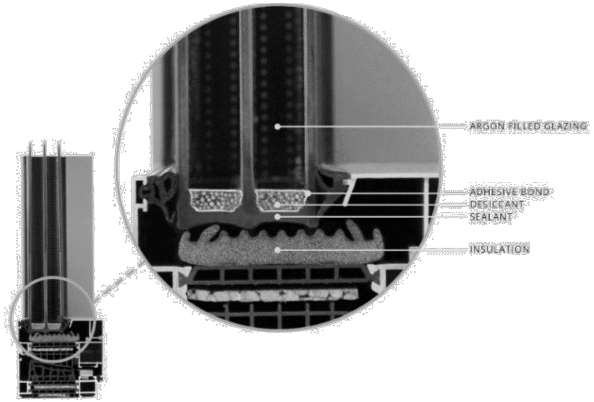
Thermal Transmittance: Standardized values

- 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/(m²·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-grazed window with a wooden frame (U_g = 1.1 W/m²K, U_f =1.3 W/m²K, identical for 3 options), the total projected area of each window is the same.

A. Option A — 80%

B. Option B — 0%

C. Option C

(A) (B) (C)

Solar Heat Gain Control

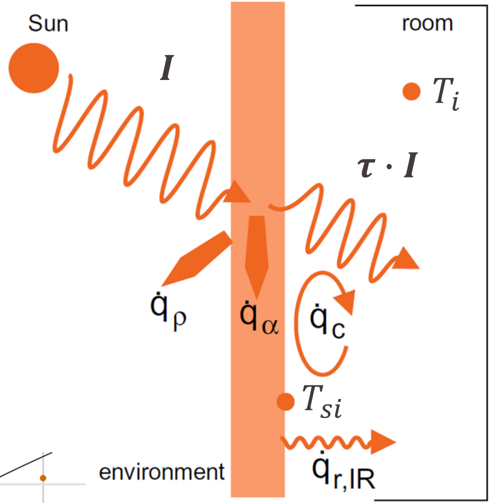
Solar Heat Gain Coefficient (SHGC) or **g-value** –

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

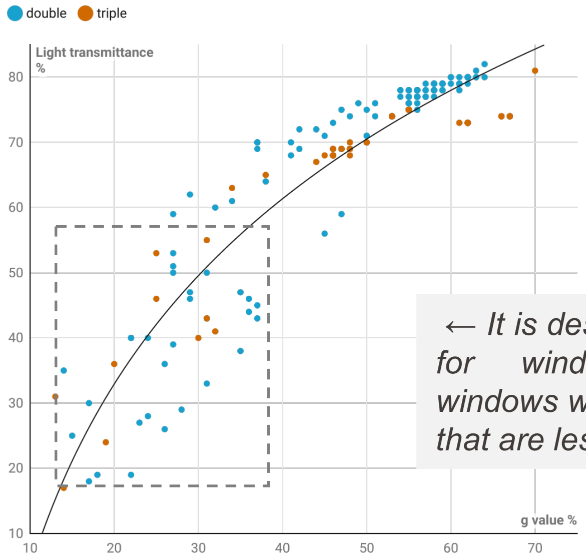
The *direct* gain portion is the **solar energy transmittance**, while the *indirect* is **the fraction of solar energy** ***incident*** on the glass (+ blind) that is ***absorbed*** and ***re-radiated*** or ***transmitted*** through convection indoors.

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

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



Source: Medved, Building Physics, p. 65



← 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.

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

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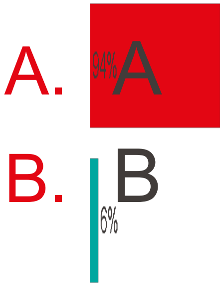
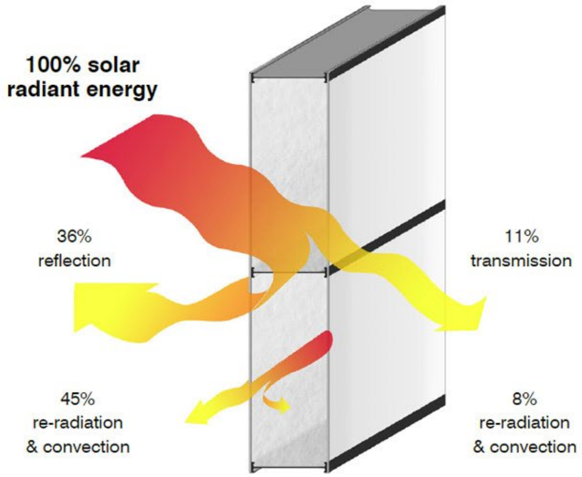
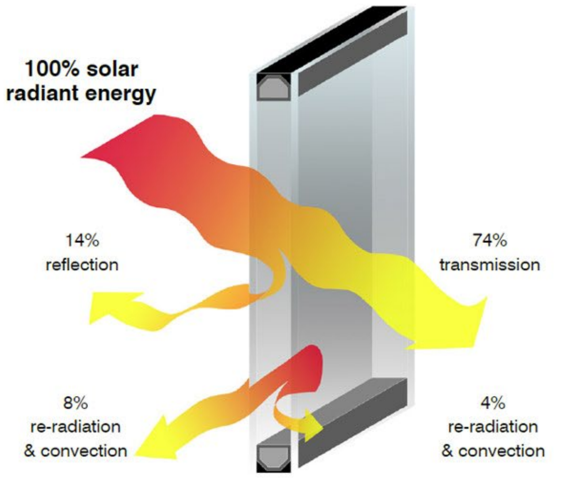




2-3/4" Crystal-White Kalwall Panel

vs



1" Clear Insulated Glass Unit (IGU)

Option A

Option B

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EPFL

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

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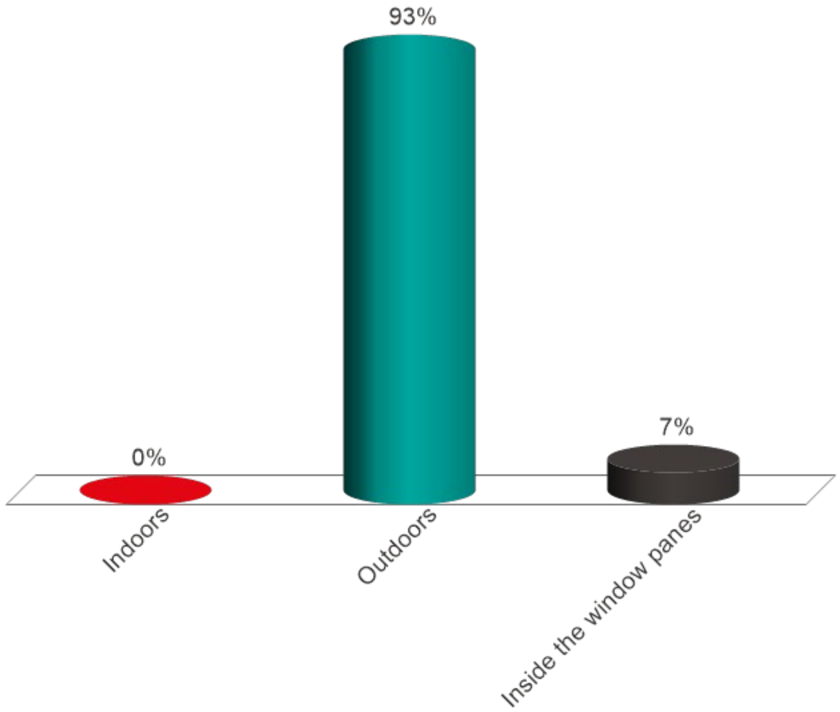
Speaker

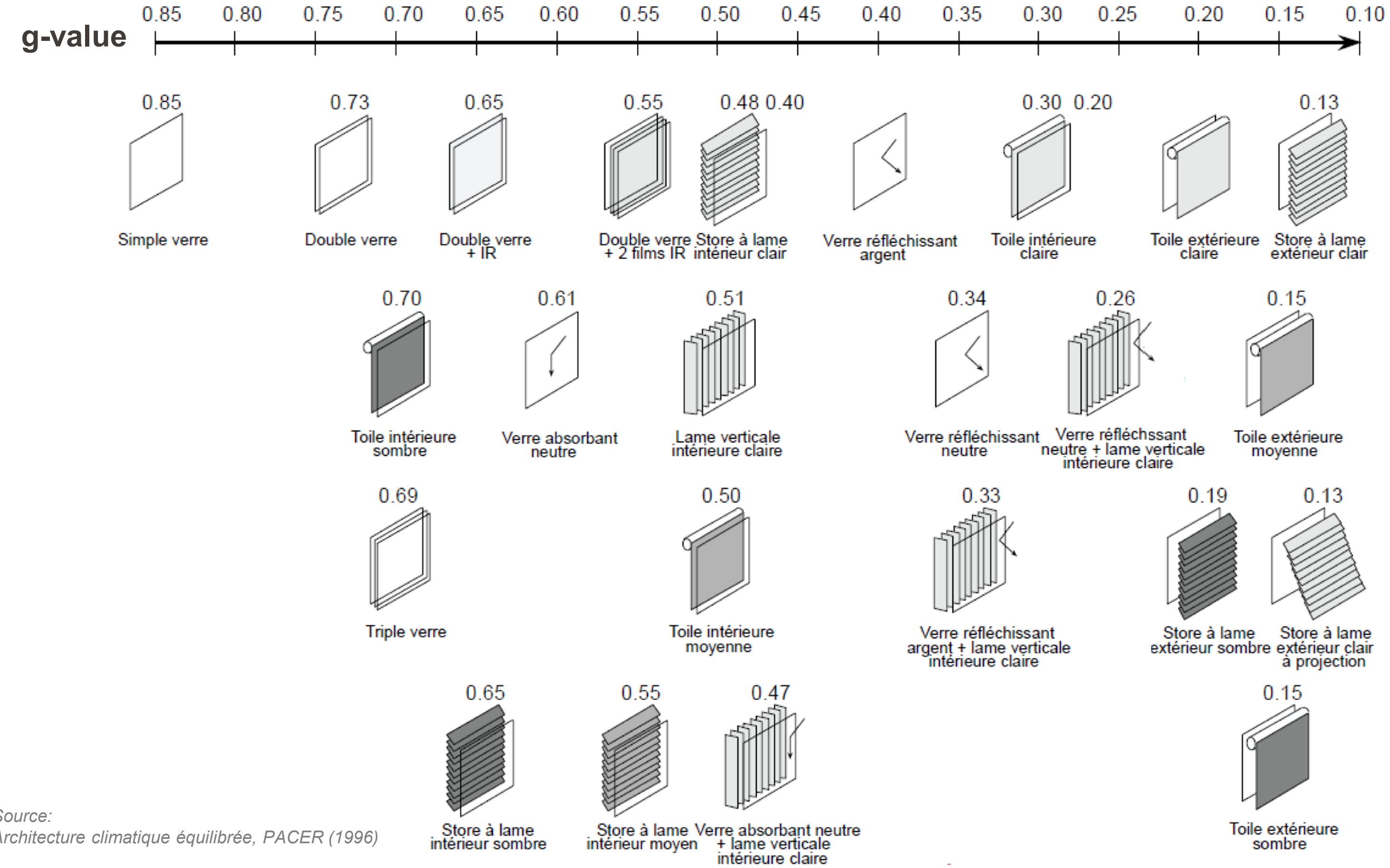
A. Indoors

B. Outdoors

C. Inside the window panes



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



Source:
Architecture climatique équilibrée, PACER (1996)

Performance of Transparent Elements: Standards

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

Measures to reduce heat transfer: Which measures are the most efficient for windows?

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A. Increase number of panes (e.g., triple pane)

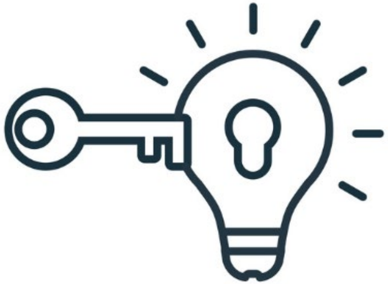
B. Addition of the low-e or tined coatings

C. Evacuated interpane space

D. Interpane gas fills (argon, krypton)

E. Low conductivity spacers

Main Concepts of this Lecture



- 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

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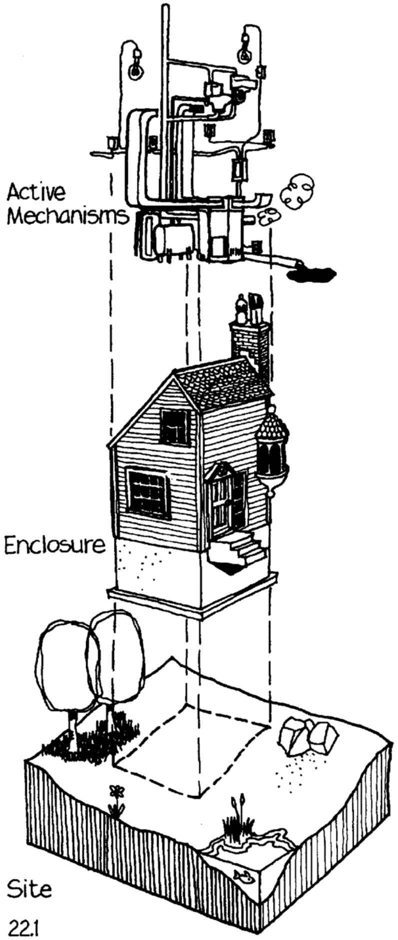

Source: Edward Allen «How Buildings Work» (2005)

Thank you for your attention!

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

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