



CIVIL-309: URBAN THERMODYNAMICS

**Assist. Prof.
Dolaana Khovalyg**

Lecture 03:

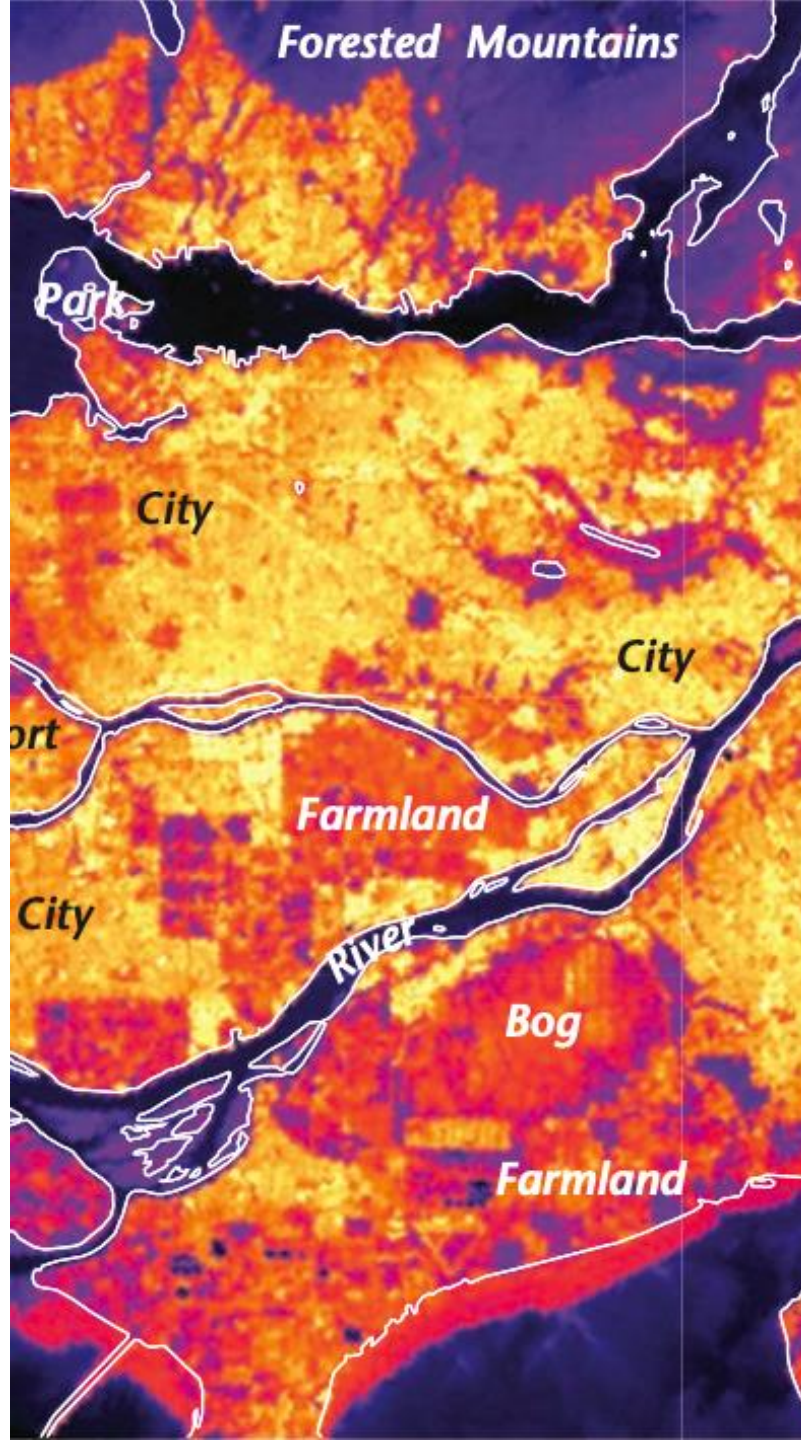
**Heat Transfer and Thermal Properties:
Conduction and Radiation**

26 September 2025

EPFL Course Schedule

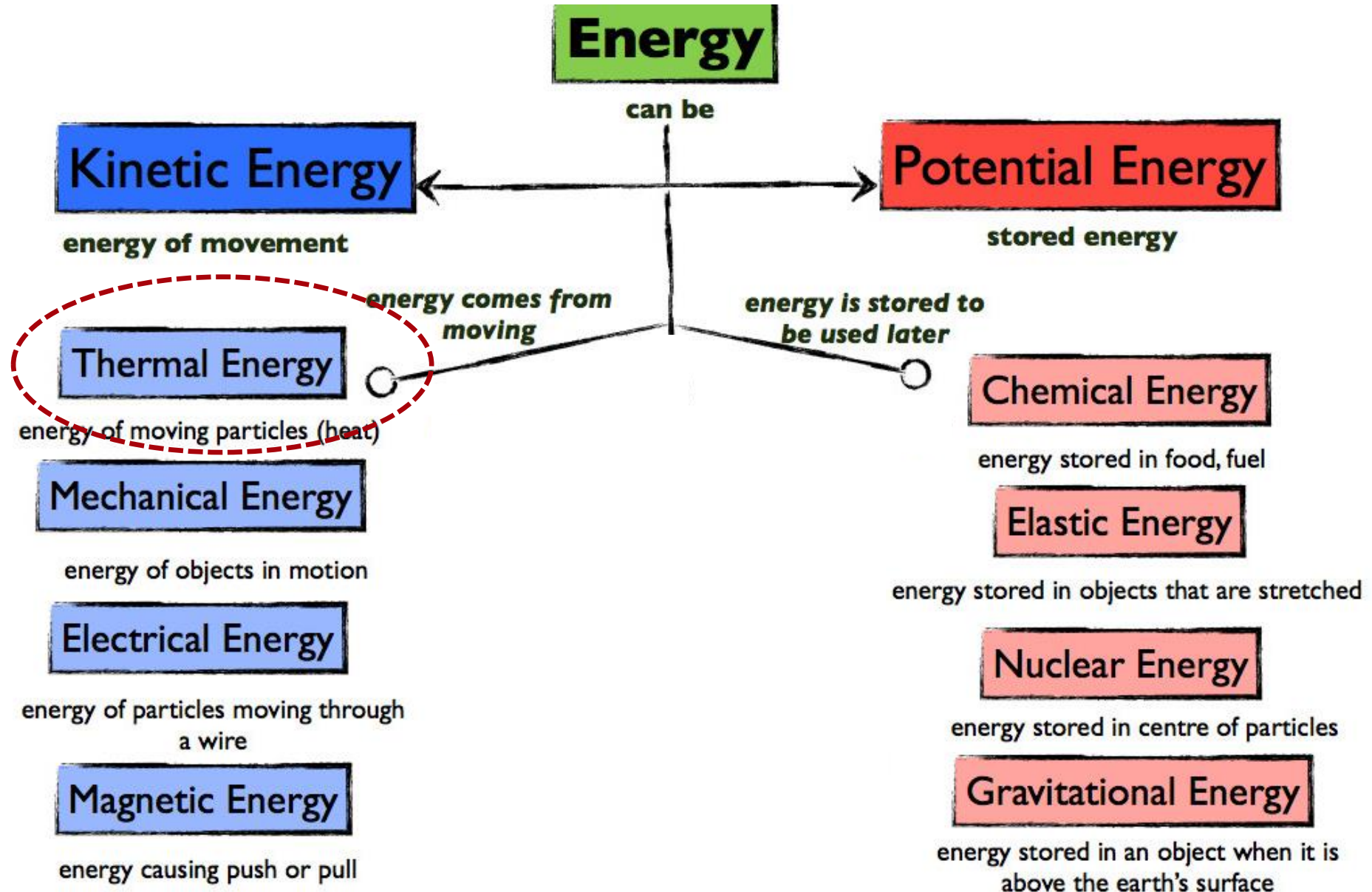


Week	Date	Time	Topics	Instructor
1	12.09	2 x 45'	Course overview: content, evaluation, topics Urban characteristics, Urban Heat Island (UHI) effect	DK
		1 x 45'	Introduction to the web tool CityTherm (part I)	DK
2	19.09	1 x 45'	Overview of physical parameters	DK
		1 x 45'	Introduction to the course project I	DK, JY
		1 x 45'	Supervised work on the course project I	JY
3	26.09	2 x 45'	Heat Transfer: Conduction and radiation	DK
		1 x 45'	Supervised work on the course project I	JY
4	03.10	2 x 45'	Heat Transfer: Convection and evaporation	DK
		1 x 45'	Supervised work on the course project I	JY
5	10.10	1 x 45'	Campus walk: exploring urban thermodynamics	DK, JY
		2 x 45'	Supervised work on the course project I	JY
6	17.10	3 x 45'	Supervised work on the course project I Course project I submission deadline: 16:00 on October 17	JY
7	24.10		BREAK	



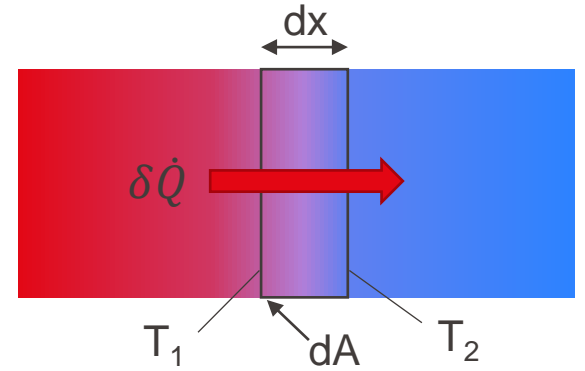
CONTENT:

- I. Introduction (overview of basic concepts)
- II. Conduction
 - Heat conduction (Fourier's Law)
 - Thermal resistance
 - Conduction properties
- III. Radiation
 - Definitions
 - Radiative heat exchange
 - Radiative properties
 - Surface radiation budget



Heat transfer: Basic Definitions

- **Thermal Energy = Heat.**
- **Heat transfer** - transport of **thermal energy** due to the **temperature gradient**. Heat transfer in a system occurs until reaching **thermal equilibrium**.
- **Heat transfer rate \dot{Q}** ($W = J/s$) – the amount of heat transferred *per unit of time*.



$$\delta \dot{Q} = h(T_1 - T_2)dA \quad (3-1)$$

- **Heat flux density \dot{q}** (W/m^2) – the **rate of heat transfer per unit area from or to a surface**.
Eqn. 3-2 is for the cases when \dot{Q} is uniform over the area A.

$$\dot{q} = \frac{\dot{Q}}{A} \quad (3-2)$$

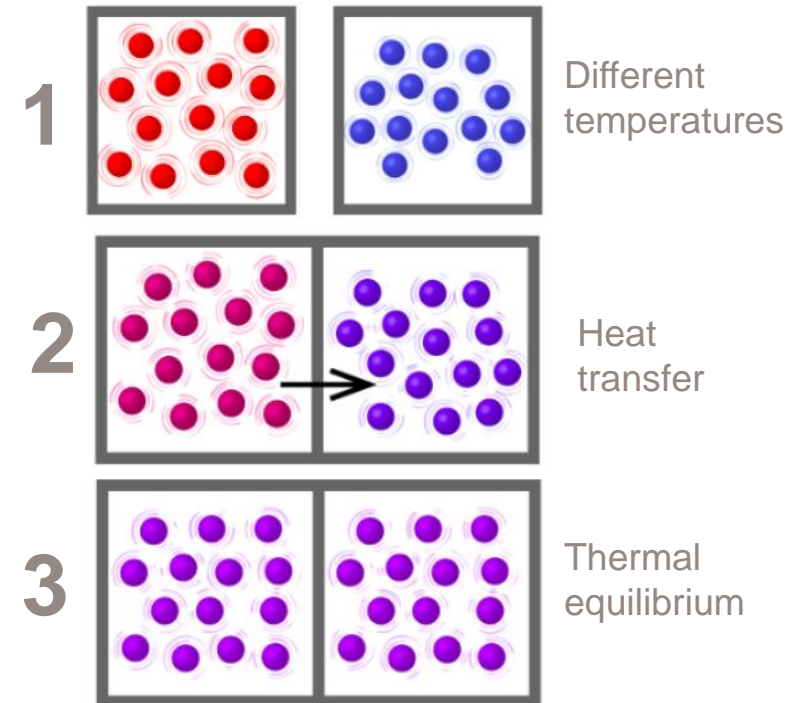
- **Heat transfer coefficient h** ($\frac{W}{m^2 \cdot K}$) – *heat flux density per unit temperature difference*, defines the **intensity of the transport of heat**.

$$h = \frac{\dot{q}}{\Delta T} \quad (3-3)$$

- **Total amount of heat transfer Q** (J) during a time interval Δt :

$$Q = \int_0^{\Delta t} \dot{Q} dt \quad (3-4a)$$

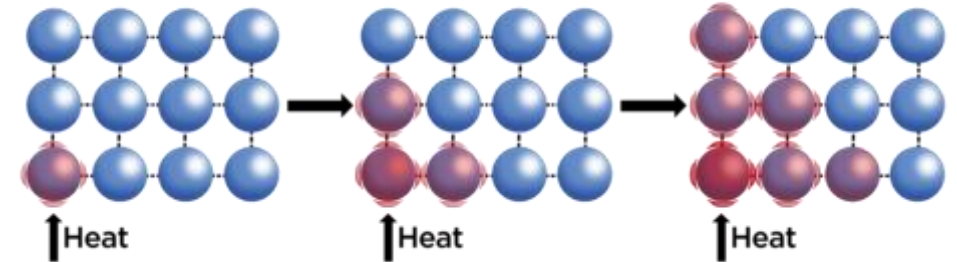
$$\xrightarrow[\dot{Q} = \text{constant}]{\text{when}} Q = \dot{Q} \cdot \Delta t \quad (3-4b)$$



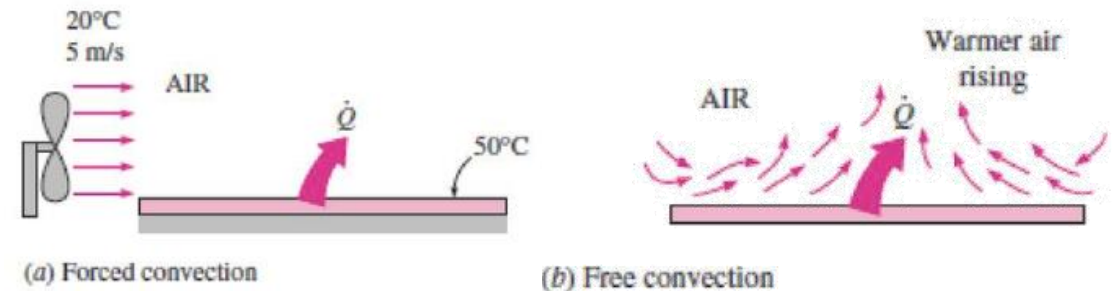
Heat transfer: Mechanisms

- **Sensible (“visible”) heat transfer** - energy transferred as heat, require the existence of a temperature difference. There are 3 modes of heat transfer.

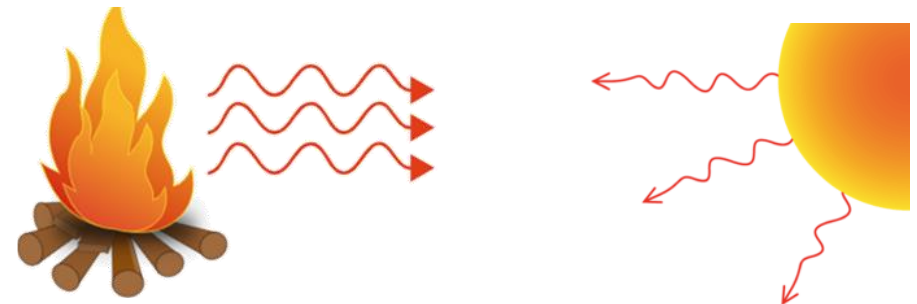
- **Conduction** – the transfer of thermal energy *from the more energetic particles of a substance to the adjacent less energetic ones* as a result of *interactions between particles*.



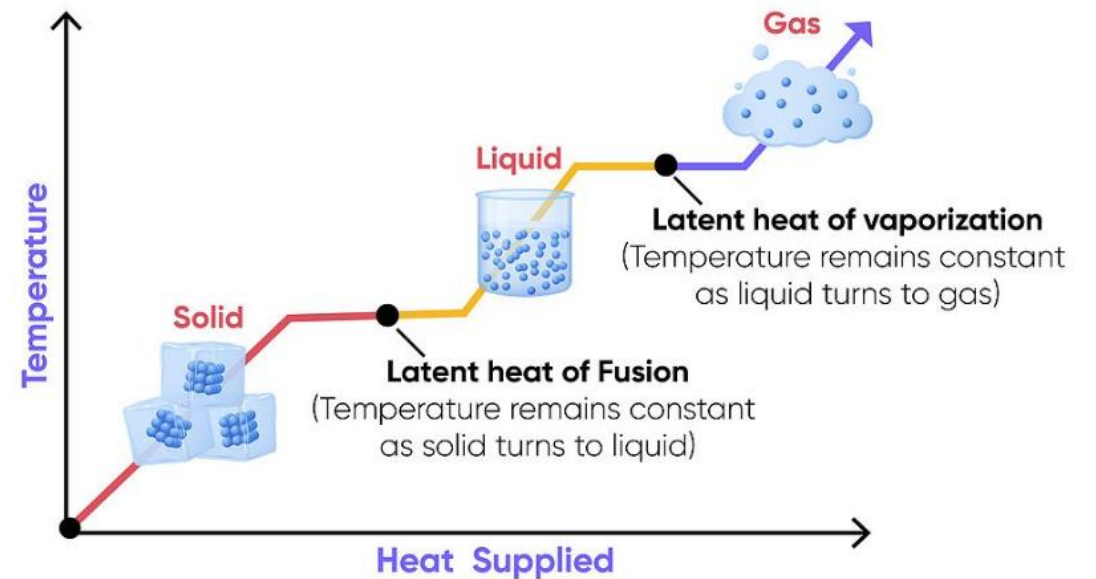
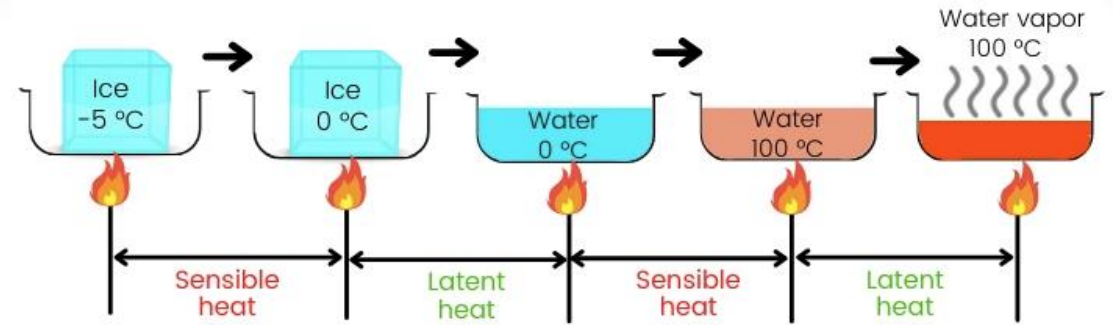
- **Convection** – the transfer of thermal energy *between a solid surface and the adjacent liquid or gas that is in motion* (the faster the fluid motion, the greater the convection heat transfer).

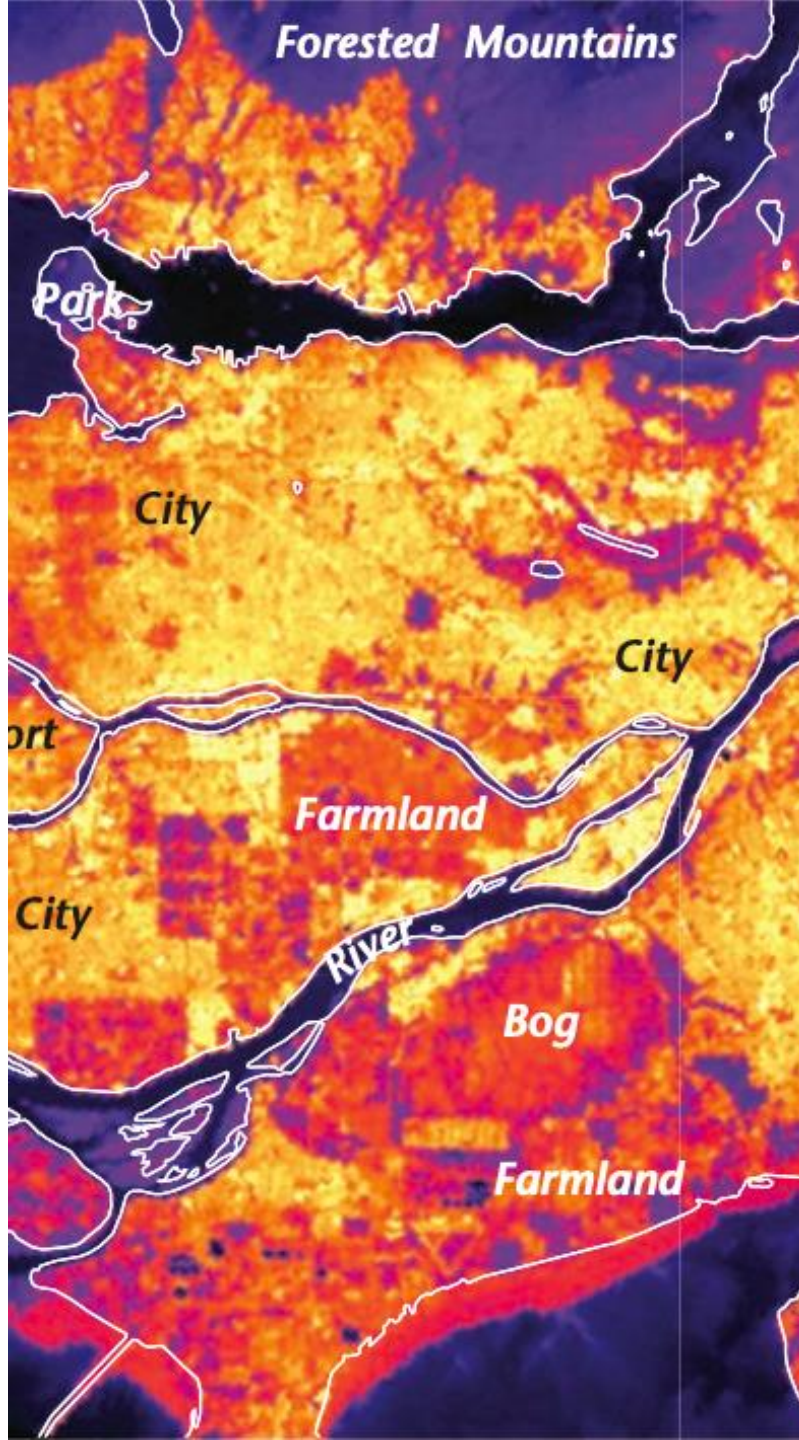


- **(Thermal) Radiation** – the energy emitted by matter in the form of *electromagnetic waves* (transfer at the speed of light).



- **Latent (“hidden”) heat** – energy released/absorbed by a thermodynamic system during a **constant-temperature process** of **changing the state** (e.g., phase change such as *condensation* and *evaporation*)
 - **Heat of vaporization** – the energy required *to change* an amount of substance from the *liquid* to *gas state* (about 2260 kJ/kg for water)
 - **Heat of condensation** – the energy *released* when an amount of substance *condenses* (transforms from *gas state* to the *liquid*).
- As condensation is a *reverse process* to evaporation, *the same amount of heat* as in vaporization should be removed to trigger condensation.





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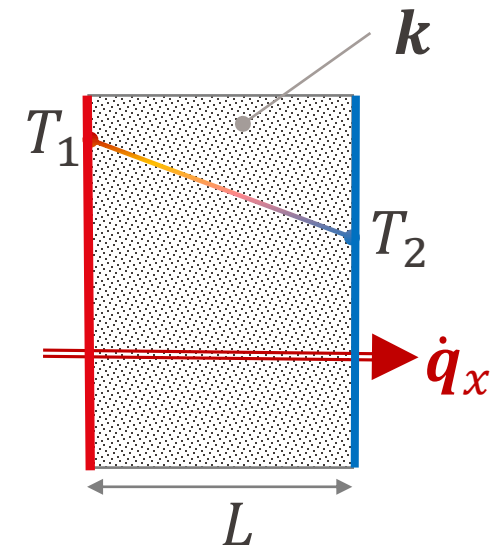
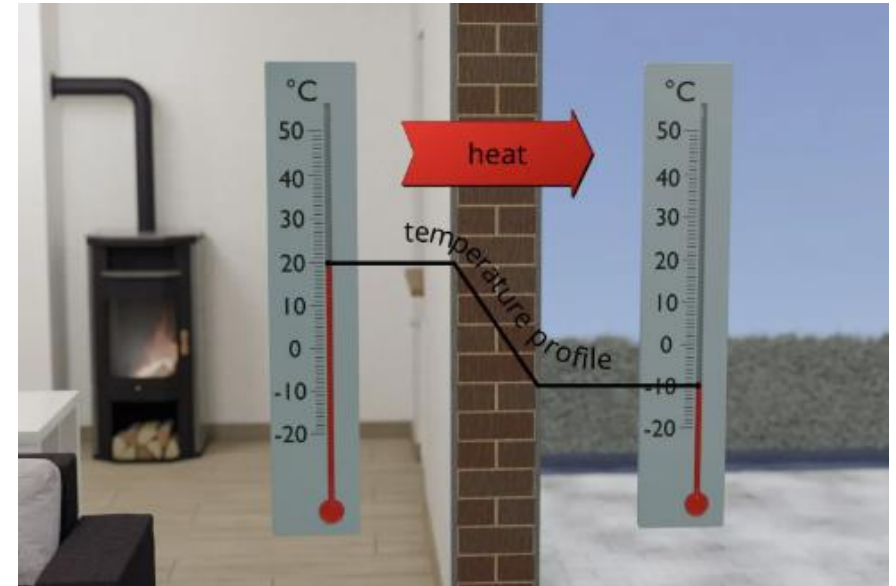
EPFL Heat Conduction: Fourier's Law

- **Conduction** - energy transfer from *molecule* to *molecule* is due to *the temperature gradient*

Fourier's Law: $\dot{q}_x = -k \cdot \frac{dT}{dx}$ (3-5a)

$\xRightarrow[steady\ state]{1D}$ $\dot{q}_x = k \cdot \frac{T_1 - T_2}{L}$ (3-5b)

- **Fourier's Law:** heat flux density \dot{q} ($\frac{W}{m^2}$) in a certain direction (e.g., in x) per unit area perpendicular to the direction of transfer, is *proportional to the temperature gradient* in this direction.
- The coefficient of proportionality k is a *transport property* known as **thermal conductivity**, it is a *characteristic* of the material.
 - Thermal conductivity can be expressed as *the combination of other thermal properties*, highlighting different thermal behavior of the material.



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

- Heat transfer is analogous to an electrical current $\dot{q} \leftrightarrow I$
- Temperature difference is analogous to a potential difference $\Delta T \leftrightarrow \Delta \phi$
- The inverse of the *conductive heat transfer coefficient* is analogous to a *resistance*

- Thermal resistance R** ($\frac{m^2 \cdot K}{W}$) – a measure of a material's resistance to heat flow

- If two thermal resistances **in series**:

$$R_{tot} = R_1 + R_2 \quad (3-6)$$

- If two thermal resistances **in parallel**:

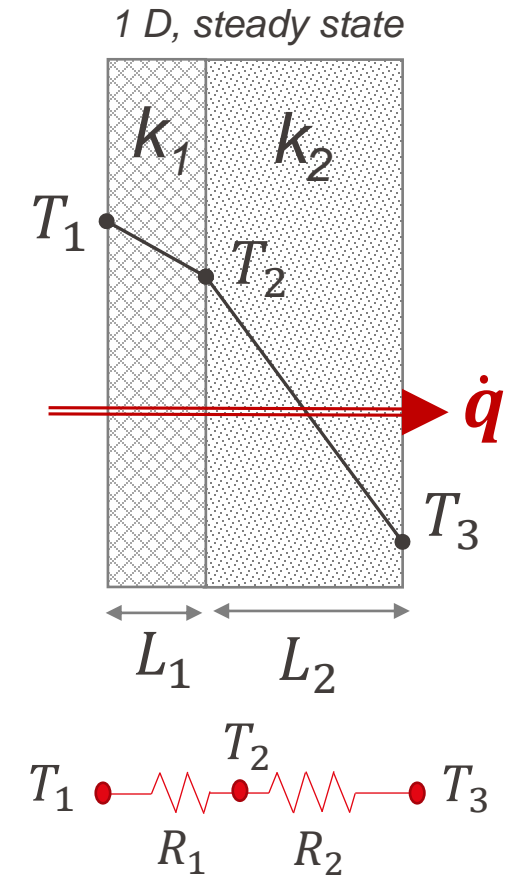
$$\frac{1}{R_{tot}} = \frac{1}{R_1} + \frac{1}{R_2} \quad (3-7)$$

- A **single thermal resistance** of a wall with *multiple* solid layers:

$$\dot{q} = U_{tot} \cdot \Delta T = \frac{1}{R_{tot}} \cdot \Delta T \quad (3-8)$$

$$U = \frac{1}{R} \quad (3-9)$$

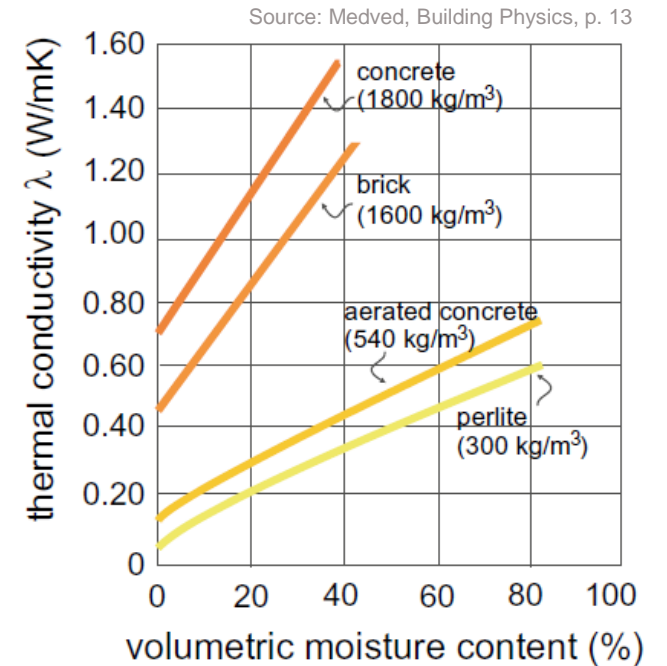
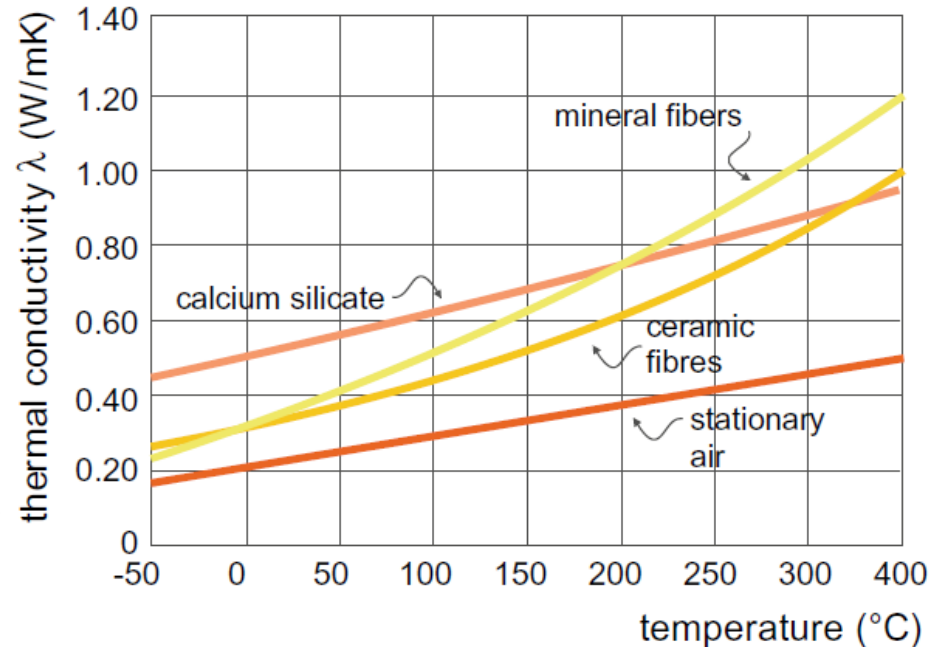
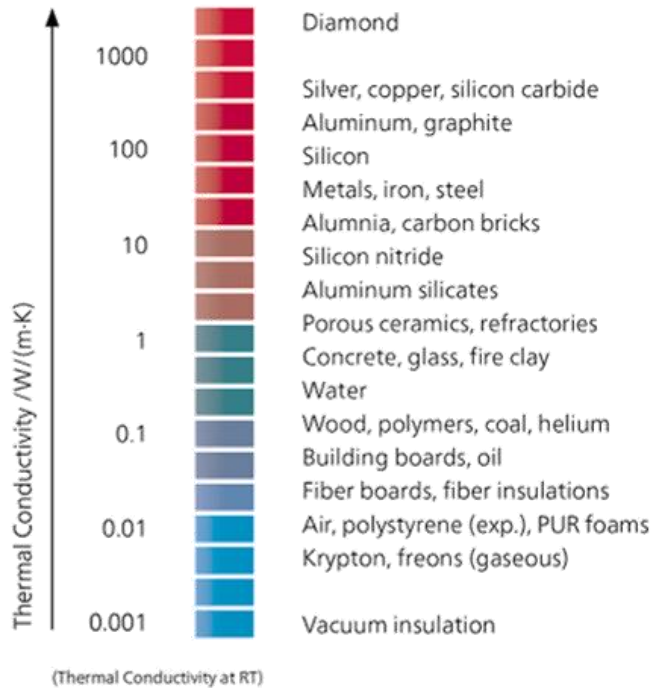
$$R_{cond,i} = \frac{L_i}{k_i} \quad (3-10)$$



- Thermal transmittance U** ($\frac{W}{m^2 \cdot K}$) – the rate of heat transfer through a matter

Conduction Properties: Thermal Conductivity

- **Thermal conductivity, k or λ** ($\frac{W}{m \cdot K}$): the rate of heat transfer (in 1 sec) through a unit of thickness (1 m) of the material per unit area (1 m²) per unit temperature difference (1 K/m).
- **Construction materials** are considered as **thermally isotropic** (have the same thermal conductivity in all direction). **Ground properties** are **anisotropic**.
- Thermal conductivity depends on *temperature* and *moisture content*.



Construction materials:

Material	k or λ ($\frac{W}{m \cdot K}$)
Concrete aerated	0.08
Wood light	0.09
Wood dense	0.19
Plaster	0.46
Adobe	0.57
Gypsum board	0.57
Glass	0.74
Asphalt road	0.75
Brick	0.83
Clay tiles	0.84
Stone ballast	0.86
Concrete dense	1.51
Stone	2.19
Steel	53.3

Insulation materials:

Material	k or λ ($\frac{W}{m \cdot K}$)
Extruded polystyrene	0.038
Expanded polystyrene	0.039
Cellulose	0.040
Sheep wool	0.040
Glass wool	0.040
Mineral wool	0.040
Cork	0.041
Coconut fibre	0.042
Perlite	0.045
Expanded clay	0.055

Natural materials:

Material	k or λ ($\frac{W}{m \cdot K}$)
Air (10°C still)	0.025
Snow	0.08
Clay soil dry	0.25
Sandy soil dry	0.3
Water (4°C, still)	0.57
Clay soil saturated	1.58
Sandy soil saturated	2.2
Ice	2.24

EPFL Conduction Properties

- **Thermal conductivity** can be expressed as *the combination of other thermal properties*, highlighting different thermal behavior of the material.
- **Thermal diffusivity, α** ($\frac{m^2}{s}$): **time at which temperature change travels and depth of the layer involved in thermal changes**, represents how fast heat diffuses through a material. A material with low thermal diffusivity, such as sand, doesn't store much of the thermal energy.
- **Specific heat capacity (isobaric), c_p** ($\frac{J}{kg \cdot K}$): ability of a material to store heat. Energy absorbed by 1 kg of material when its temperature increases by 1 K, highly dependent on temperature.
- **Heat capacity (isobaric), C_p** ($\frac{J}{m^3 \cdot K}$): specific heat capacity expressed in terms of the volume.
- **Thermal admittance, μ** ($\frac{J}{m^2 \cdot K \cdot s^{1/2}}$): ability of the system to store heat and response of the surface temperature to a temperature change in the air, it is a surface property. Related both to the ability of the system to store heat and the amplitude of the diurnal wave of surface temperature change in response to energy forcing.

$$k = \alpha \cdot C_p \quad (3-11)$$

$$\alpha = \frac{k}{\rho \cdot c_p} \quad (3-12)$$

$$\alpha = \frac{\text{Heat conduction}}{\text{Heat Storage}}$$

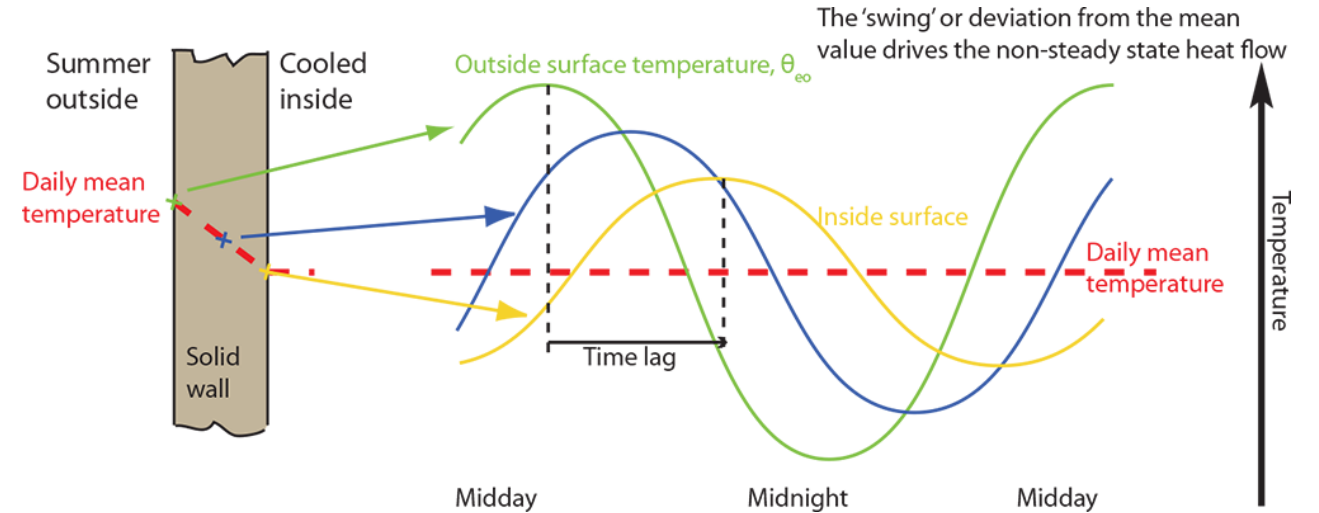
$$C_p = \rho \cdot c_p \quad (3-13)$$

$$\mu = \sqrt{k \cdot C_p} \quad (3-14a)$$

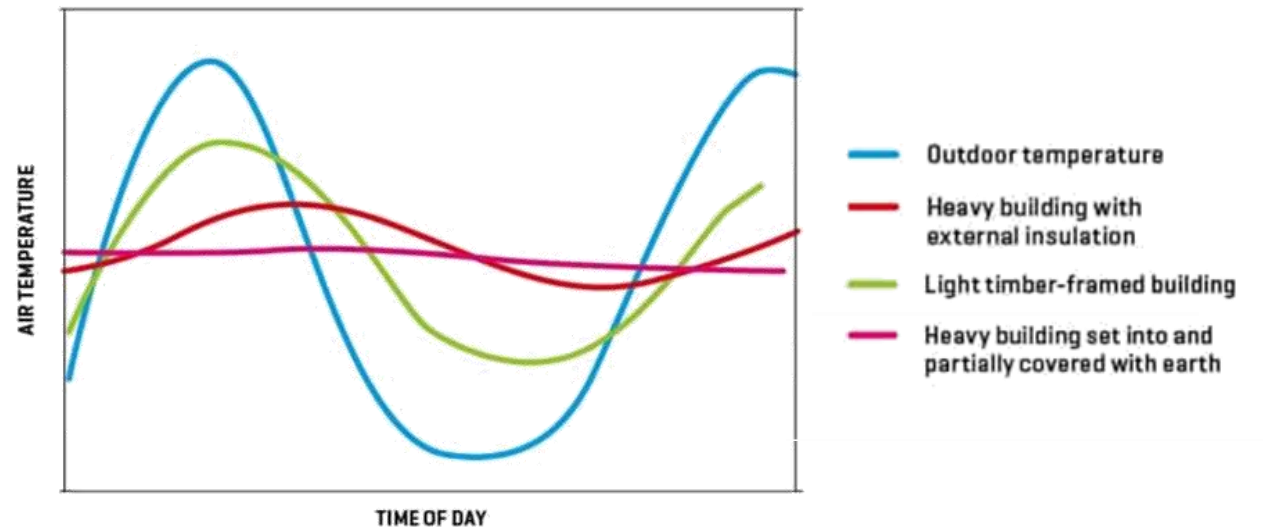
$$\mu = C_p \sqrt{\alpha} \quad (3-14b)$$

- **Daily temperature profiles** at both surfaces of a building material depend on *the outdoor conditions* and *thermal admittance*

- **If μ is large:** sequester heat *within* the material and there is *relatively small change* in the *surface temperature* throughout the day (it has a small diurnal range).
- **If μ is small:** heat is *less readily stored*, the surface temperature *has large amplitude* and these surfaces *shed large amount of heat* to the neighboring *air*.



Source: <https://www.cibsejournal.com/cpd/modules/2013-01/>



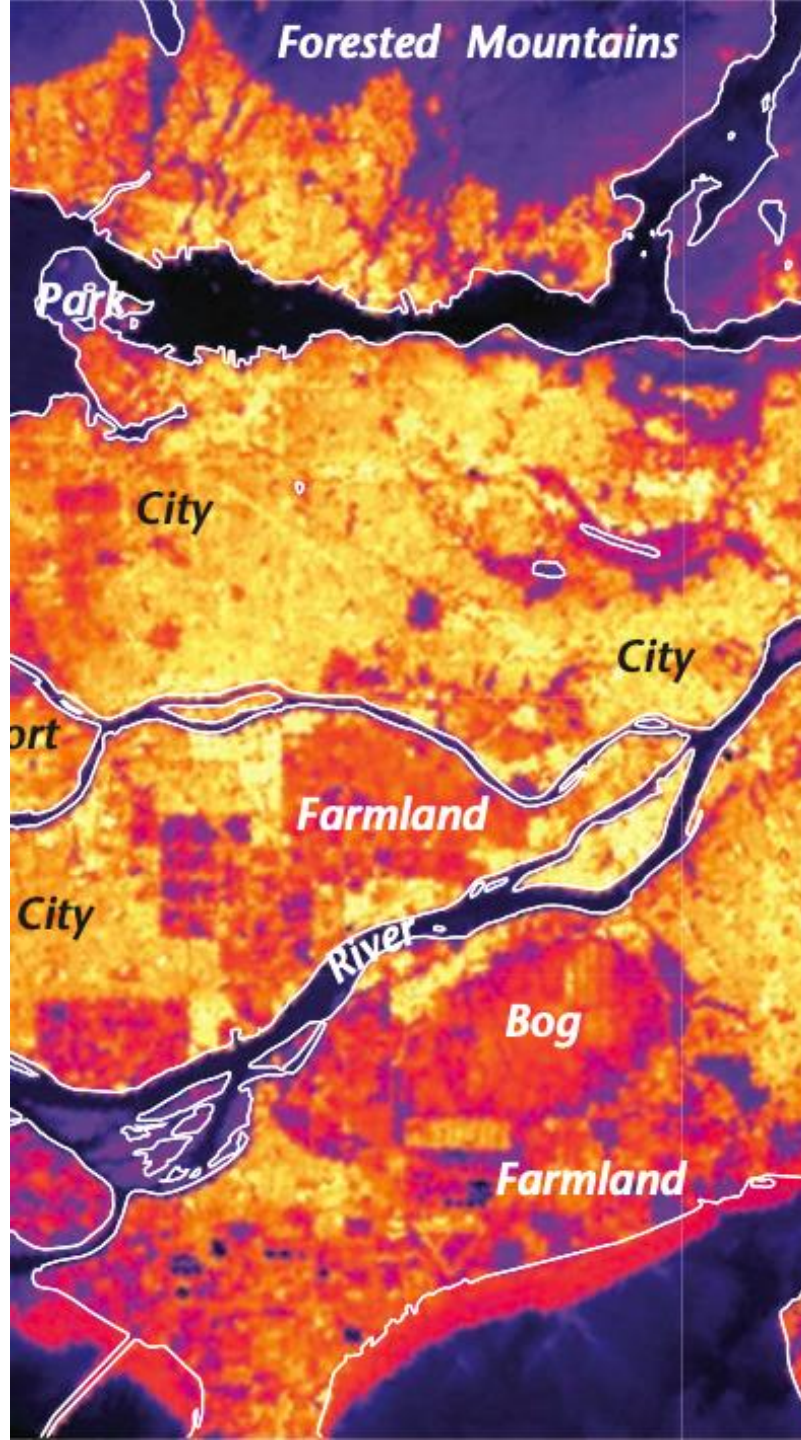
Source: Oke, Urban Climates, p. 169

Material	State	Heat capacity C ($\text{MJ m}^{-3} \text{K}^{-1}$)	Thermal conductivity k ($\text{W m}^{-1} \text{K}^{-1}$)	Thermal diffusivity κ ($\text{m}^2 \text{s}^{-1} \times 10^{-6}$)	Thermal admittance μ_s ($\text{J m}^{-2} \text{s}^{-1/2} \text{K}^{-1}$)
Construction and building materials in dry state (built sites)					
Asphalt road	Range	1.92–2.10	0.74–1.40	0.38–1.04	1,205–1,960
	Typical	1.94	0.75	0.38	1,205
Concrete	Aerated	0.28	0.08	0.29	150
	Dense	2.11	1.51	0.72	1,785
Stone	Typical	2.25	2.19	0.97	2,220
Brick	Typical	1.37	0.83	0.61	1,065
Adobe		1.50	0.57	0.38	922
Clay tiles		1.77	0.84	0.47	1,220
Stone ballast	40% void	1.30	0.86	0.66	1,058
Wood	Light	0.45	0.09	0.20	200
	Dense	1.52	0.19	0.13	535
Steel		3.93	53.3	13.6	14,475
Glass		1.66	0.74	0.44	1,110
Plaster	Gypsum	1.40	0.46	0.33	795
Gypsum board	Typical	1.49	0.27	0.18	635
Insulation	Polystyrene	0.02	0.03	1.50	25
	Cork	0.29	0.05	0.17	120

Source: Oke, Urban Climates, p. 169

Material	State	Heat capacity C ($\text{MJ m}^{-3} \text{K}^{-1}$)	Thermal conductivity k ($\text{W m}^{-1} \text{K}^{-1}$)	Thermal diffusivity κ ($\text{m}^2 \text{s}^{-1} \times 10^{-6}$)	Thermal admittance μ_s ($\text{J m}^{-2} \text{s}^{-1/2} \text{K}^{-1}$)
Natural materials (rural and undeveloped urban sites)					
Sandy soil (40% porosity)	Dry	1.28	0.3	0.24	620
	Saturated	2.96	2.2	0.74	2,550
Clay soil (40% porosity)	Dry	1.42	0.25	0.18	600
	Saturated	3.10	1.58	0.51	2,210
Peat soil (80% porosity)	Dry	0.58	0.06	0.10	190
	Saturated	4.02	0.5	0.12	1,420
Snow	Fresh	0.21	0.08	0.10	130
	Old	0.84	0.42	0.40	595
Ice	0°C, pure	1.93	2.24	1.16	2,080
Water ¹	4°C, still	4.18	0.57	0.14	1,545
Air ¹	10°C, still	0.0012	0.025	21.5	5
	Turbulent	0.0012	~125	~10 × 10 ⁶	390

¹ Properties depend on temperature

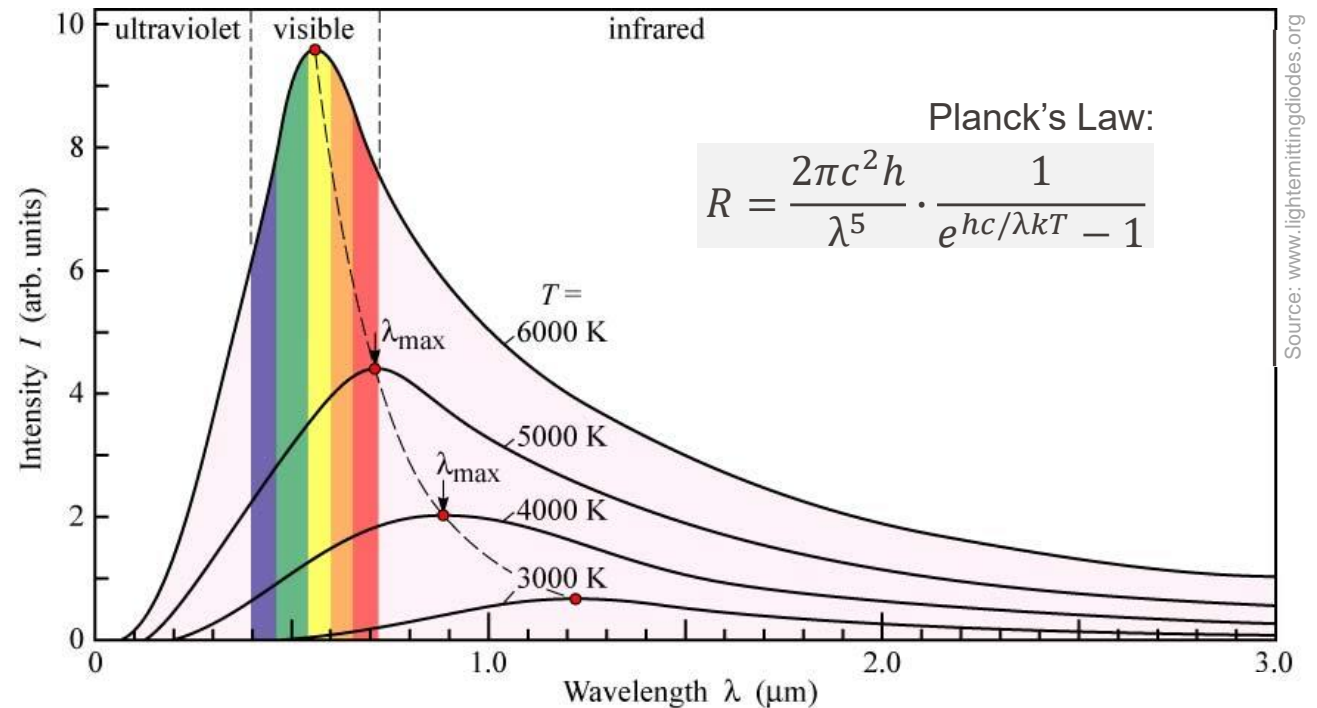
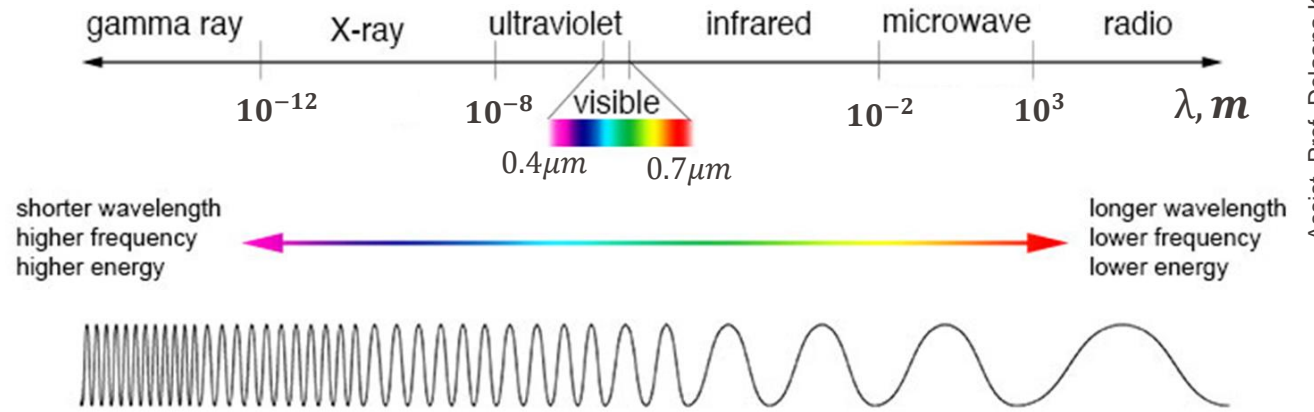


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Radiation: Definitions

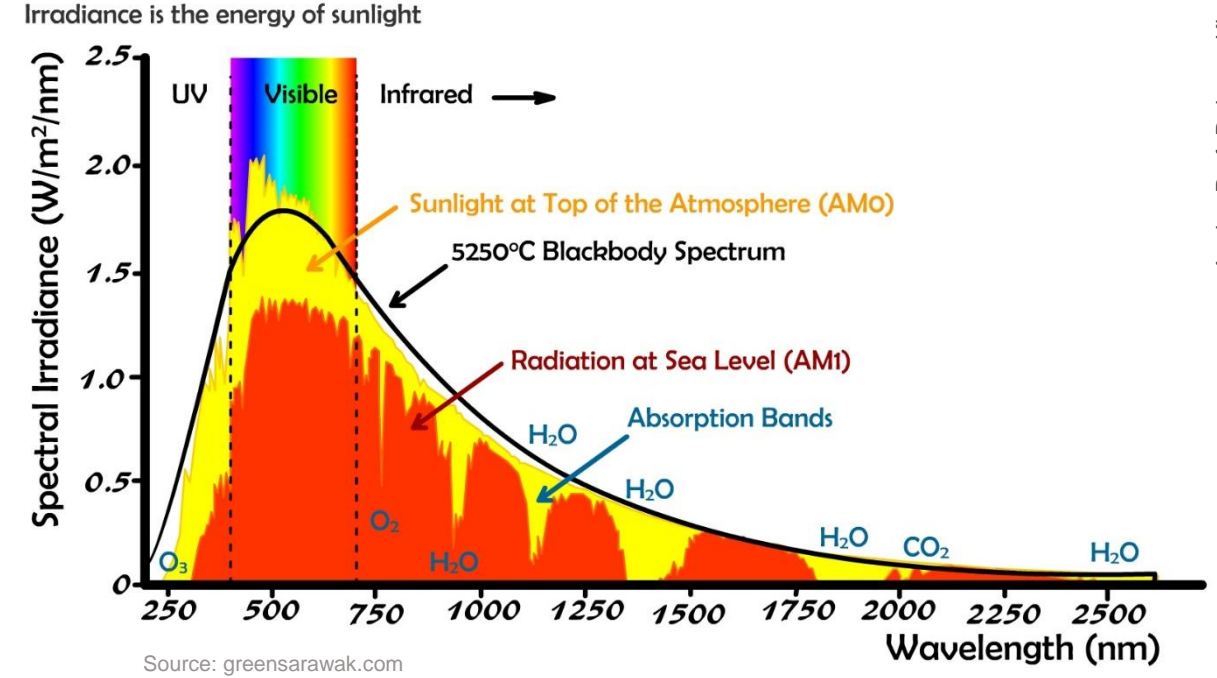
- **Radiation** – the energy emitted by matter in the form of **electromagnetic waves (photons)** and propagated through the space **at the speed of light**.
- **Thermal radiation** – the form of radiation emitted by bodies *because of their temperature*.
- All objects at **$T > 0\text{K}$** spontaneously emit **electromagnetic waves**. The *spectrum of thermal radiation varies with the temperature*.
- **Planck's Radiation Law** describes the **spectral density of electromagnetic radiation emitted by a black body in thermal equilibrium**.
- **Black body** is an *idealized body absorbing all incident radiation with no reflecting power* (perfect absorber and radiator of energy).



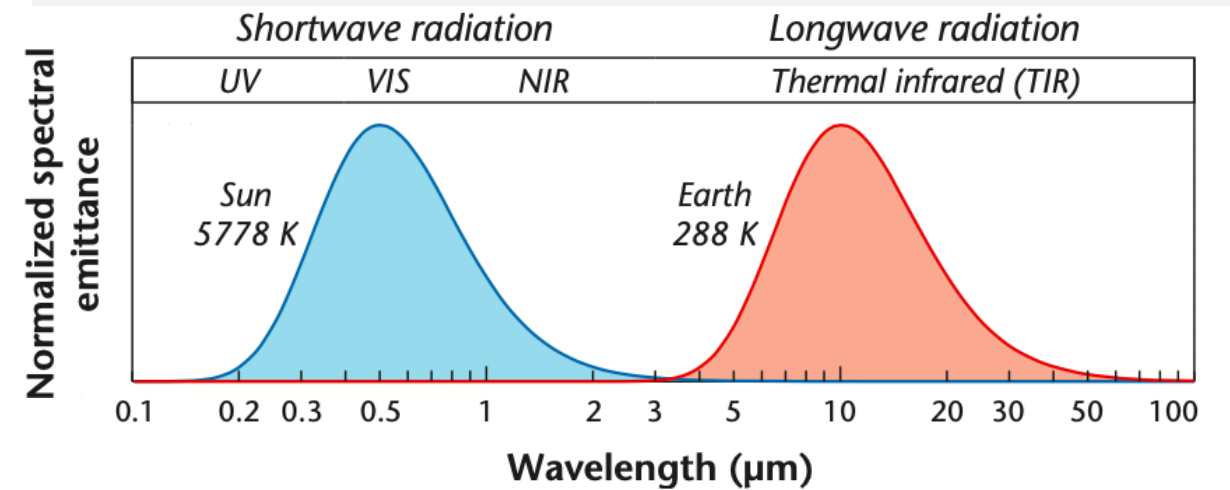
Radiation: Shortwave vs. Longwave

- The **Sun** emits radiation in the range of $\lambda = 0.1 - 3 \mu m$ (peak at $0.47 \mu m$), and it is called **shortwave radiation (K)** or “**solar**”.

At sea level, solar energy is distributed as **3% UV, 55% Visible, 42% IR**.
- The **Earth-Atmosphere System (EAS)** emits radiation in the wavelength range of $\lambda = 3 - 100 \mu m$ (peak at $10 \mu m$), it is called **longwave radiation (L)** or “**terrestrial**” (thermal IR).
- For common ambient temperatures $\sim 293 \text{ K}$ (20°C) the emitted spectrum is located in the **thermal infrared region**. Thermographic (IR) cameras are able to take images in this region.
- The **infrared (IR)** band is subdivided into three regions: **near (NIR, $0.75 - 3 \mu m$)**, **middle (MWIR, $3 - 30 \mu m$)**, and **far (FIR, $30 - 1000 \mu m$)**



Radiation curves of blackbody emitters at the temperatures of the Sun and EAS



- All bodies radiate energy in the form of photons moving in a random direction, with random phase and frequency.
- The total radiant heat flux \dot{q} (W/m^2) over the entire range of wavelength emitted by a body is defined by the **Stefan-Boltzmann Law**:

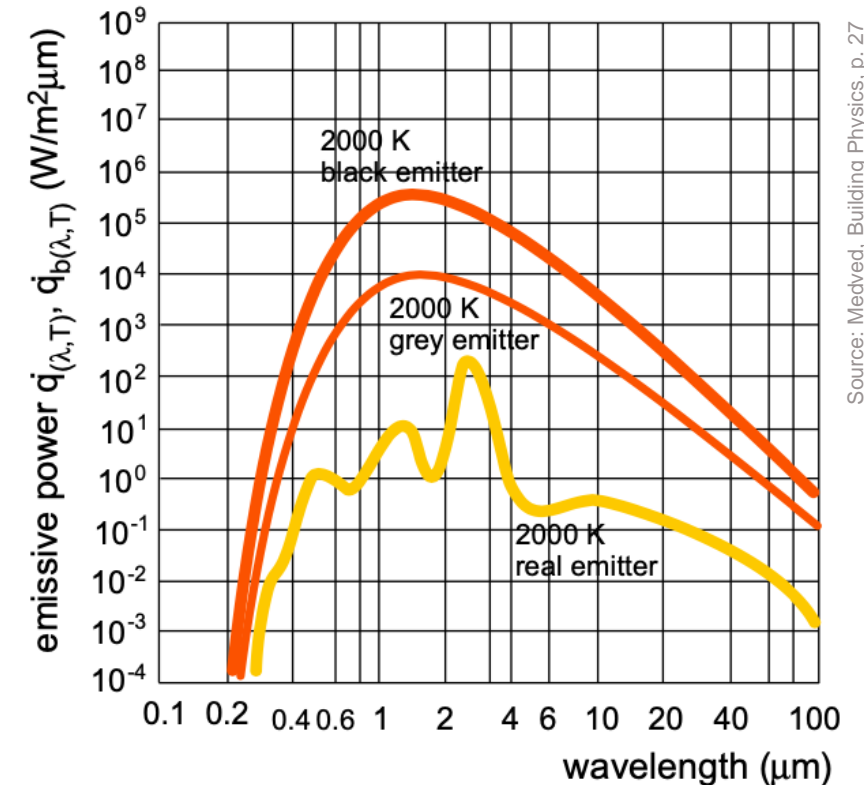
- for a black body $\dot{q}_b = \sigma \cdot T^4$ (3-15)

- for a grey/real body $\dot{q} = \varepsilon \cdot \sigma \cdot T^4$ (3-16)

Stefan-Boltzmann constant: $\sigma = 5.67 \cdot 10^{-8} \text{ W/m}^2\text{K}^4$

- Emissivity ε** (-): property of the emitter's surface, characterizes the effectiveness of a surface in emitting energy as thermal infrared radiation ($3 \leq \lambda \leq 100 \mu\text{m}$).

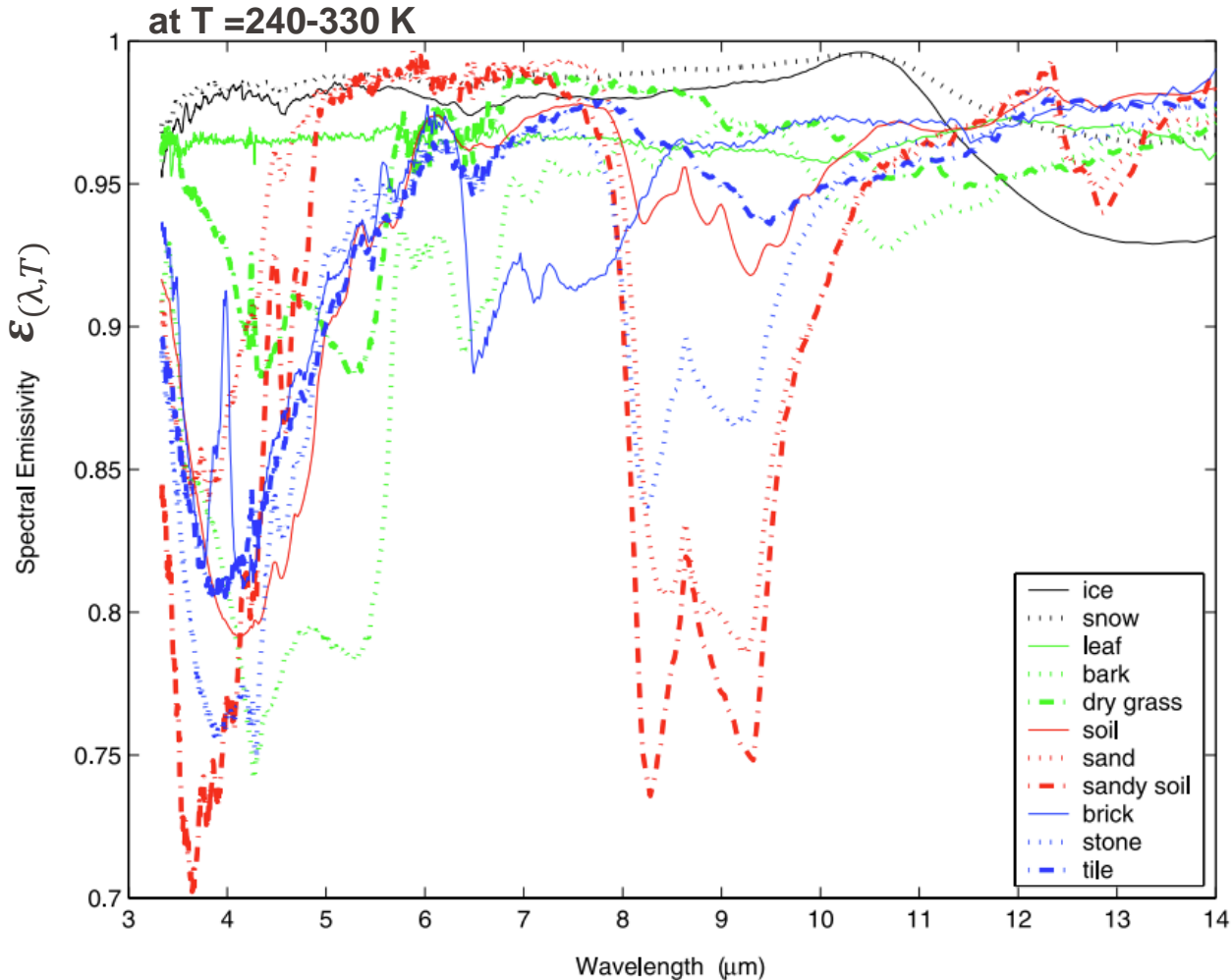
- The ratio of the total radiant energy emitted per unit time per unit area of a surface at a specified wavelength and temperature to that of a blackbody under the same conditions.
- It depends on the wavelength as well as on the object's temperature
- Values: $0 \leq \varepsilon < 1$ for grey/real bodies and $\varepsilon = 1$ for a blackbody



$$\varepsilon = \frac{\dot{q}}{\dot{q}_b} \quad (3-17a)$$

$$\varepsilon_{(\lambda,T)} = \frac{\dot{q}_{(\lambda,T)}}{\dot{q}_{b(\lambda,T)}} \quad (3-17b)$$

Average emissivity of urban areas is $\approx 0.94-0.96$.



Emissivities of different kind of materials:

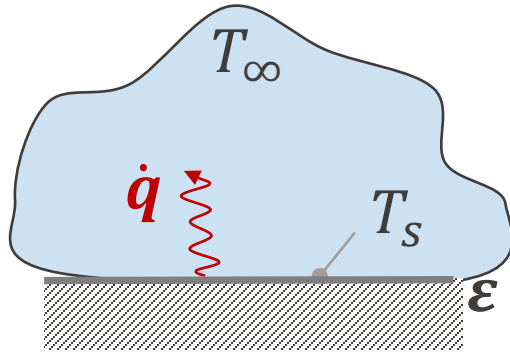
Anthropogenic materials:		Natural surfaces:	
Paper	0.7 – 0.95	Sand or rock	0.84 – 0.92
Glass	0.76 – 0.94	Soil	0.89 – 0.98
Wood	0.8 – 0.95	Grass	0.9 – 0.98
Plastic	0.8 – 0.95	Ice	0.9 – 0.98
Stone	0.85 – 0.95	Trees	0.9 – 0.99
Rubber	0.86 – 0.94	Water	0.92 – 0.97
Asphalt	0.89 – 0.96	Human skin	0.98
Brick	0.9 – 0.92	Metal surfaces:	
Concrete	0.93 – 0.96	Silver	0.01 – 0.07
Carbon	0.96	Zinc	0.02 – 0.28
		Gold	0.02 – 0.37
		Aluminium	0.02 – 0.40
		Copper	0.02 – 0.74
		Brass	0.03 – 0.61
		Tin	0.04 – 0.08
		Nickel	0.05 – 0.46
		Lead	0.06 – 0.63
		Steel	0.07 – 0.85

Source: Oke, Urban Climates, p. 130

Source: Wang et al. (2005) , 10.1029/2004JD005566

Net Radiation Heat Transfer (Stefan-Boltzmann Law)

- From a single surface at T_S enclosed by a uniform environment at T_∞ :

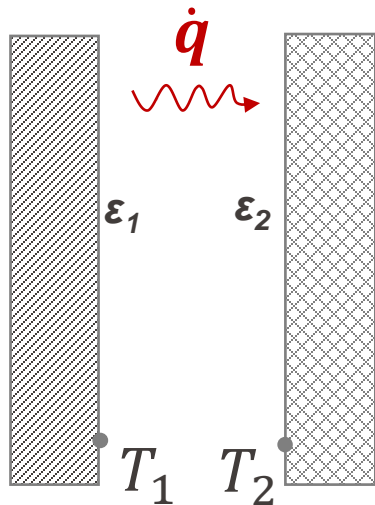


$$\dot{q} = \varepsilon \cdot \sigma \cdot (T_S^4 - T_\infty^4) \quad (3-18a) \quad \dot{q} = h_{rad} \cdot (T_S - T_\infty) \quad (3-18b)$$

Radiative heat transfer coefficient:

$$h_{rad} = \varepsilon \cdot \sigma \cdot (T_S^2 + T_\infty^2) \cdot (T_S + T_\infty) \quad (3-19)$$

- Between two parallel surfaces at T_1 (emissivity ε_1) and T_2 (emissivity ε_2):



Radiative heat transfer coefficient:

$$\dot{q} = h_{rad,12} \cdot (T_2 - T_1) \quad (3-20)$$

$$h_{rad,12} = \varepsilon_{12} \cdot \sigma \cdot (T_1 + T_2) \cdot (T_1^2 + T_2^2) \quad (3-21a)$$

Simplification for
 $T_1 - T_2 < 50 \text{ K}$:

$$h_{rad,12} = 4 \cdot \varepsilon_{12} \cdot \sigma \cdot \left(\frac{T_1 + T_2}{2} \right)^3 \quad (3-21b)$$

Effective emissivity:

$$\frac{1}{\varepsilon_{12}} = \frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1 \quad (3-22)$$

Radiative thermal resistance:

$$R_{rad} = \frac{1}{h_{rad}}$$

(3-23)

EPFL Radiative Properties

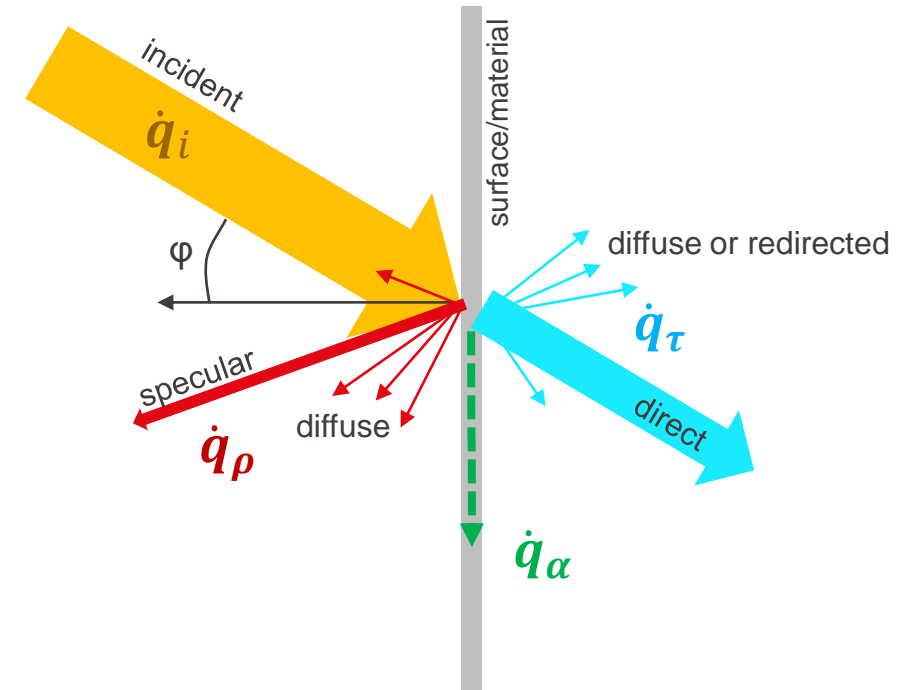
- All bodies radiate energy in the form of photons moving in a random direction, with random phase and frequency.
- When photons reach another surface (*incident radiation*), they may be:
 - Reflected (specular or diffuse)
 - Transmitted (direct or diffuse)
 - Absorbed (converted to heat)
- The **energy conservation** at a surface:

$$(3-24) \quad \dot{q}_\rho + \dot{q}_\tau + \dot{q}_\alpha = \dot{q}_i \quad (W/m^2)$$

- The relation between the **spectral radiative quantities**:

$$\frac{\dot{q}_\rho}{\dot{q}_i} + \frac{\dot{q}_\tau}{\dot{q}_i} + \frac{\dot{q}_\alpha}{\dot{q}_i} = 1 \quad (3-25a) \quad \Rightarrow \quad \rho + \alpha + \tau = 1 \quad (3-25b)$$

ρ - reflectivity, α - absorptivity, τ - transmissivity



Transparent material



Opaque material



EPFL Radiative Properties

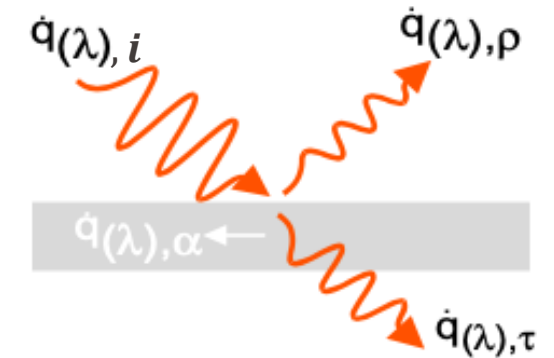
All radiative (optical) properties depend on *the radiation wavelength*:

- **Reflectivity ρ** (-):

the ratio between the *reflected* and *incident* spectral radiant thermal flux

$$\rho(\lambda) = \frac{\dot{q}(\lambda),\rho}{\dot{q}(\lambda),i} \leq 1 \quad (3-26)$$

Transparent material:

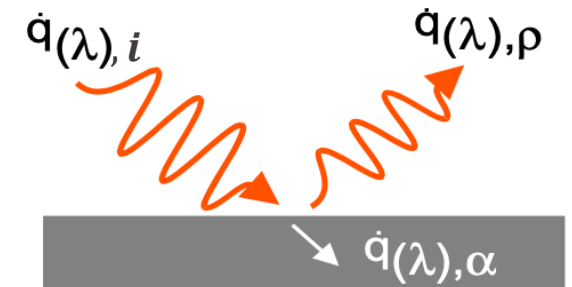


- **Absorptivity α** (-):

the ratio between the *absorbed* and *incident* spectral radiant thermal flux

$$\alpha(\lambda) = \frac{\dot{q}(\lambda),\alpha}{\dot{q}(\lambda),i} \leq 1 \quad (3-27)$$

Opaque material:



Source: Medved, Building Physics, p. 28

- **Transmissivity τ** (-):

the ratio between the *transmitted* and *incident* spectral radiant thermal flux

$$\tau(\lambda) = \frac{\dot{q}(\lambda),\tau}{\dot{q}(\lambda),i} \leq 1 \quad (3-28)$$

- **Kirchhoff's law:** spectral absorptivity of an *emitter surface* is equal to the **spectral emissivity** at a *given wavelength* and *temperature*

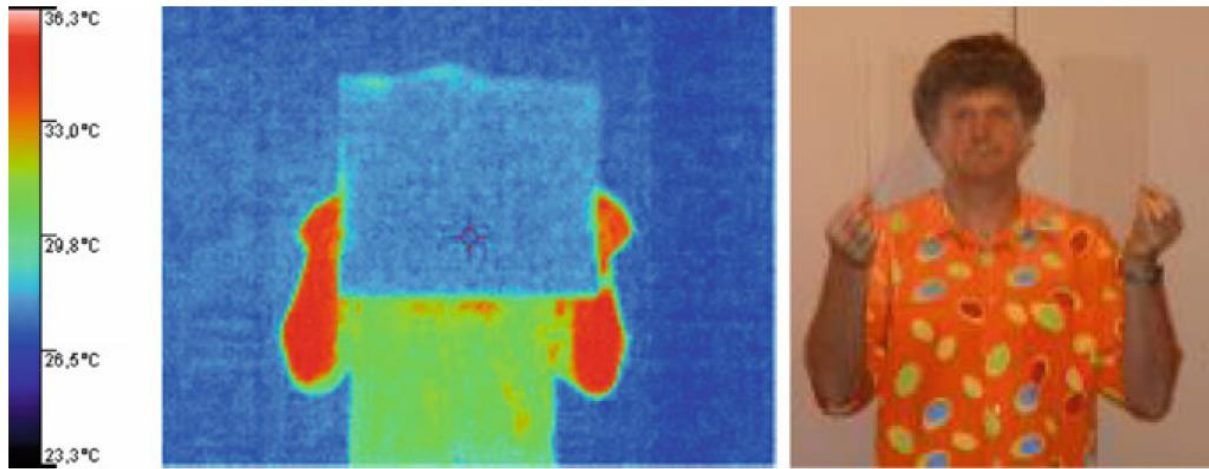
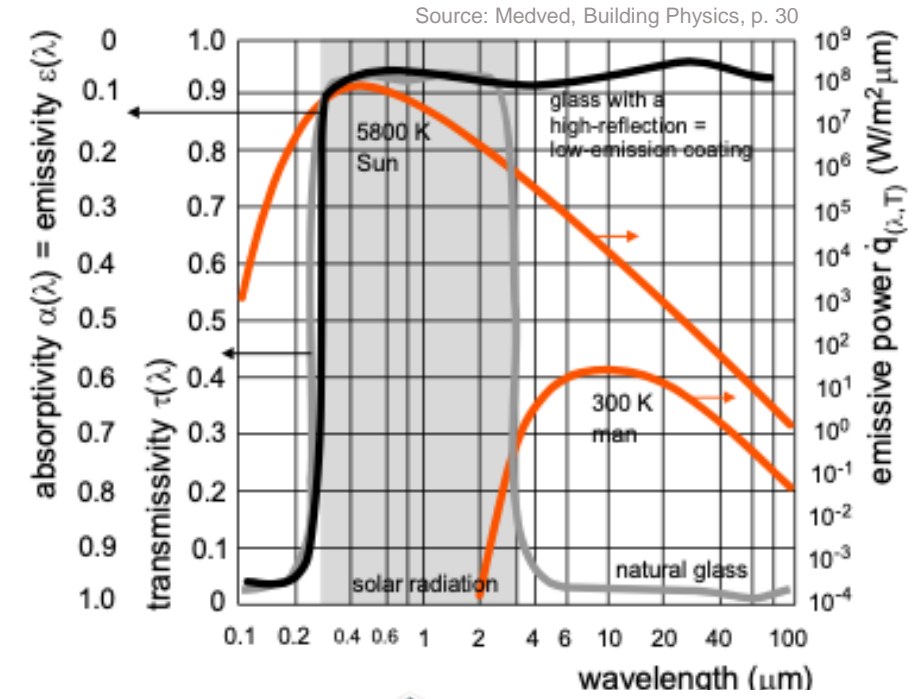
$$\varepsilon(\lambda) = \alpha(\lambda) \quad (3-29)$$

For opaque bodies:

$$\tau = 0 \rightarrow \alpha(\lambda) = 1 - \rho(\lambda) \rightarrow \varepsilon(\lambda) = 1 - \rho(\lambda) \quad (3-30)$$

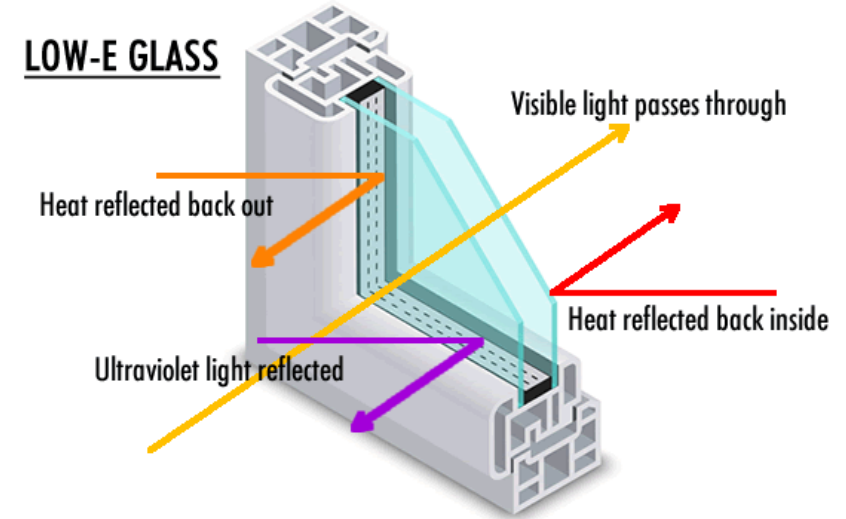
Radiative Properties

- Radiative properties of materials depending on the wavelength λ are called **selective radiative properties**.
- Natural glass is selective:
 - short wavelengths ($\lambda < 3 \mu\text{m}$) are transmitted
 - long wavelengths ($\lambda > 5 \mu\text{m}$) mostly absorbed
- IR glass properties can be *improved* by applying a thin layer increasing reflectivity of the material such as **low-e coatings** (e.g., oxides SiO_2 , metals Ag, Au, Sn, etc.)



Source: Medved, Building Physics, p. 30

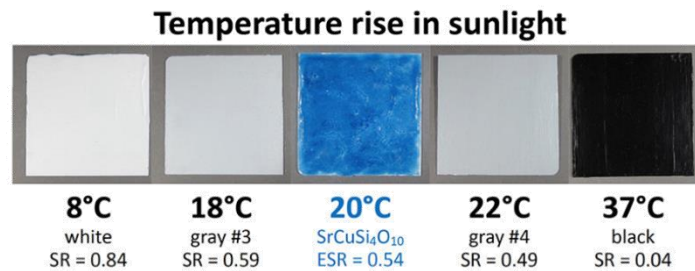
The glass is opaque for the long wavelength radiation emitted by the surface of the skin (left), but transmits well the shortwave radiant thermal flux (right)



Source: Low Emissivity Glass | Planibel A Coating (prestonglassfix.co.uk)

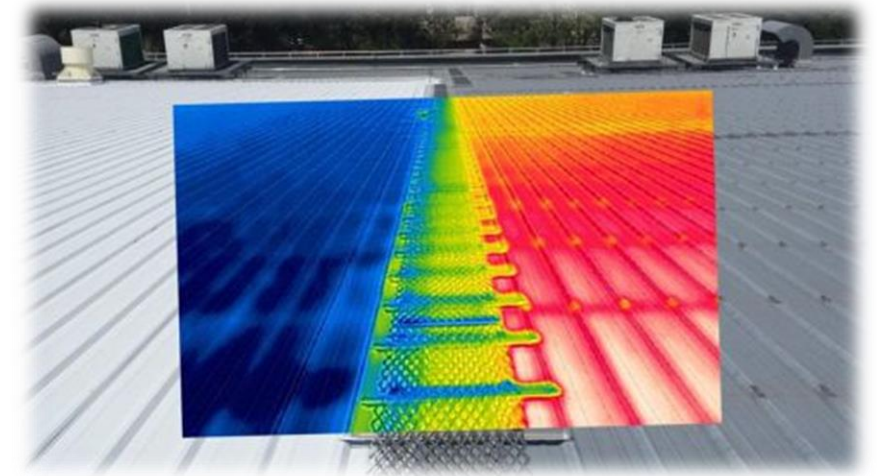
Radiative Properties

- Other material's properties can be also be modified by the addition of a **painting layer** (selective coating) with low emissivity (i.e., low absorptivity) of *thermal radiation*. It is particularly important for *building walls and roofs*.
- Selective coatings** are usually *transparent* or *white*. The *whiter* and *more reflective* the coating is, the more **efficient to thermally insulate** the building.

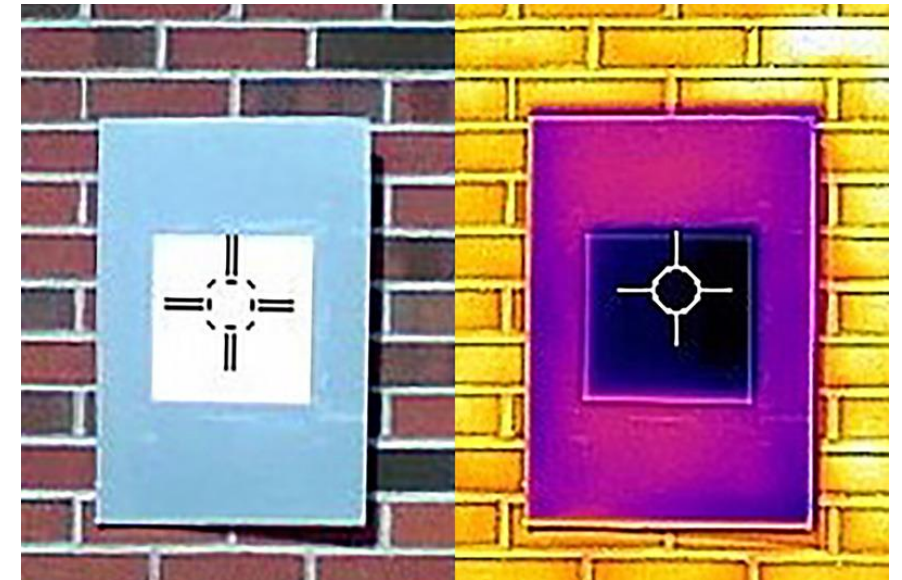


- Reducing the **emissivity** of a material for **thermal radiations** can **decrease the surface temperature** of a material.

The whitest coating developed recently reflects **98.1 %** of sunlight, the coating keeps surfaces **10.6°C** cooler than ambient surroundings at night and **4.4°C** cooler under strong sunlight.



Source: <https://newscenter.lbl.gov/2018/10/09/>



Source: [The whitest paint is here – and it's the coolest. Literally. - Purdue University News](#)

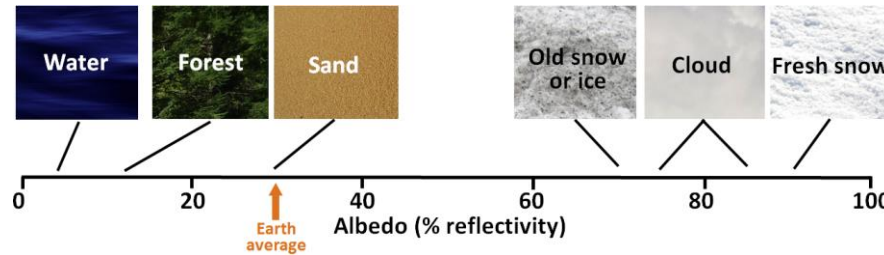
Radiative Properties: Albedo

Source: Oke, Urban Climates, p. 129

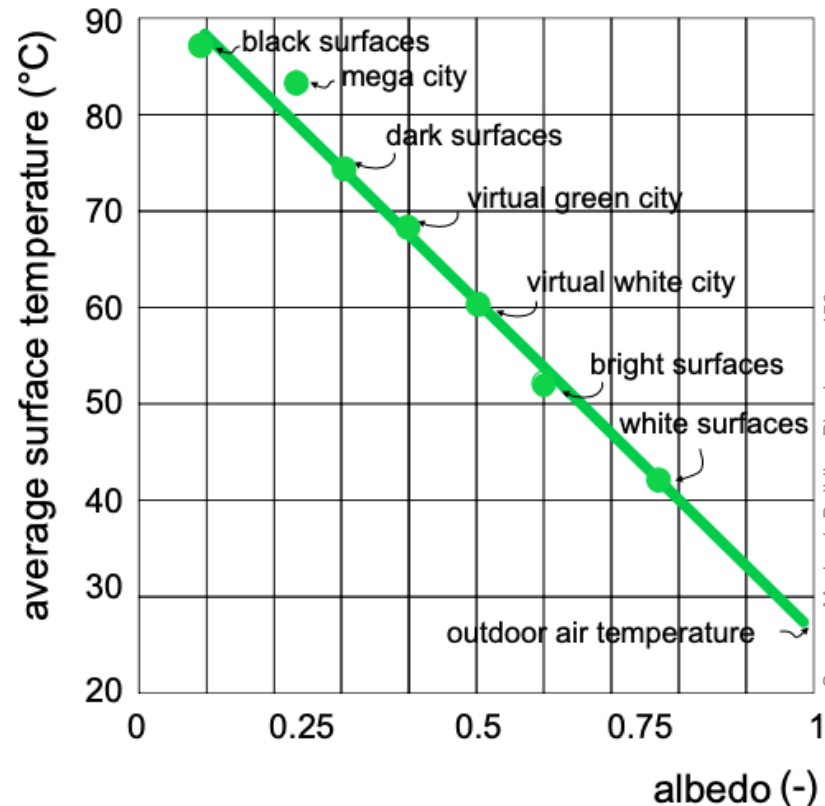
- Albedo, a - reflectivity of shortwave radiation:

(3-31)

$$a = \rho_{(0.1 \leq \lambda \leq 3 \mu m)}$$



- A high albedo means that less solar radiation is absorbed or transmitted by the surface.
- The range of albedo values of surface materials in cities is greater than for rural areas due to the diversity of materials in use.

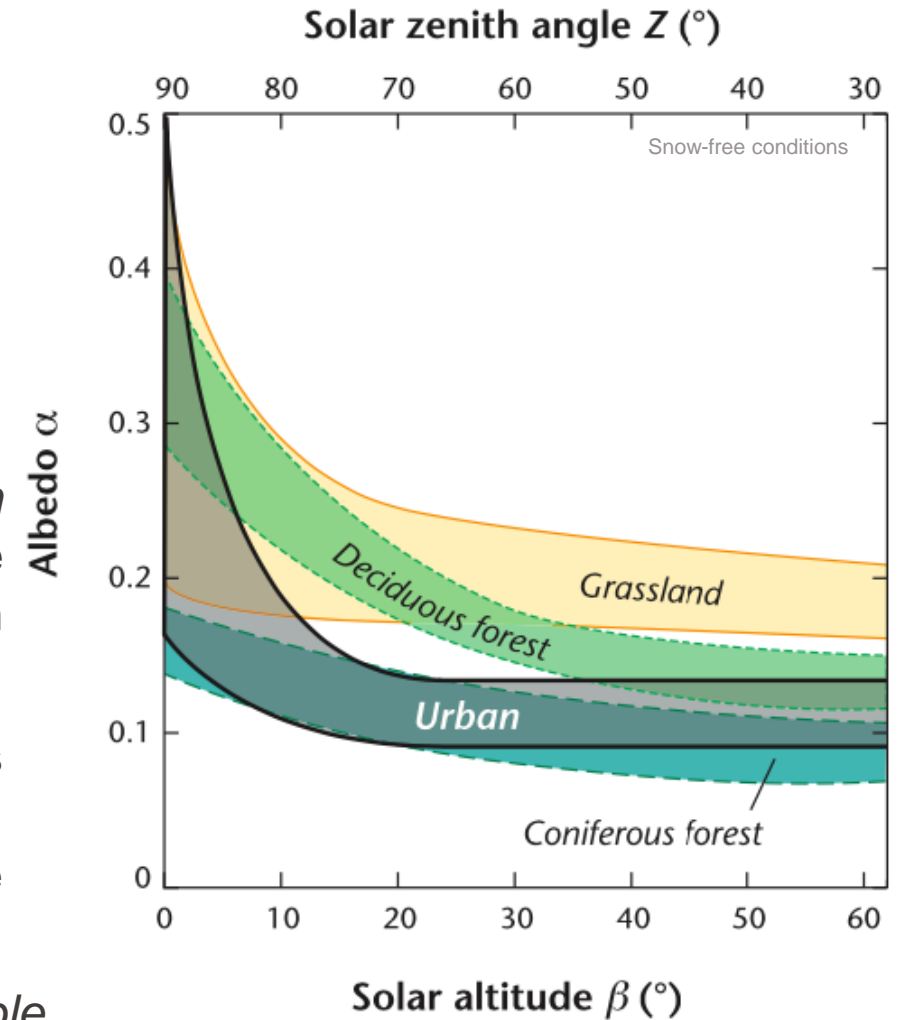


Source: Medved, Building Physics, p. 459

Surfaces	Albedo α
Natural Surfaces	
Soil dark, wet	0.05 – 0.13
Water (overcast)	0.05 – 0.5
Trees	0.11 – 0.3
Soil light, wet	0.12 – 0.30
Grass	0.16 – 0.26
Sand	0.2 – 0.45
Ice	0.2 – 0.9
Anthropogenic Surfaces	
Paint black	0.02 – 0.15
Asphalt	0.05 – 0.27
Tar and gravel	0.08 – 0.18
Clear glass	0.08
Concrete	0.1 – 0.35
Wood	0.22
Stone	0.2 – 0.45
Brick	0.2 – 0.6
Limestone	0.4 – 0.64
Paint white	0.5 – 0.9
Polished metals	0.5 – 0.9

Radiative Properties: **Albedo of Cities**

- *Proper selection of materials with appropriate albedo can help to control radiatively-driven aspects of building climates and urban environments.*
 - Selecting materials having *higher albedo* is one of the main strategies to *reduce the UHI effect*.
 - Benefits of *albedo control* in the summer: less use of energy for cooling
- **Urban albedo** combines the *reflection from all urban elements* (roofs, trees, canyons, open spaces, etc.) The measured **albedo of cities** show a dependence on **solar altitude / zenith angle**.
 - Albedo of **vegetated surfaces** and **natural surfaces** *increases rapidly at higher solar zenith angles*
 - *Urban albedo values are slightly lower (< 0.1) than in the surrounding countryside*
- *The corrugate form of the urban surface favors multiple reflections of shortwave radiation so absorption by the urban surface is increased in comparison with a flat, horizontal surface made of the same material.*



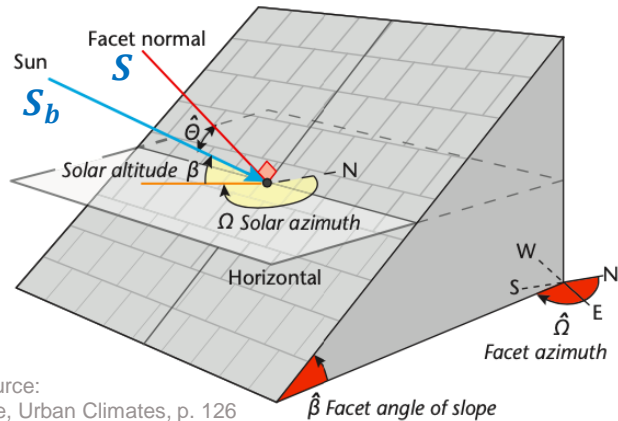
Relation between surface albedo and solar altitude angle or zenith angle for snow-free conditions (urban data include cities of Hamilton, St. Louise, Vancouver, Basel)

Solar Irradiance

- Incoming solar radiation K_{\downarrow} (irradiance) is composed of the *direct* and *indirect* components:

$$K_{\downarrow} = S + D \quad (3-32)$$

- Direct irradiance (S):** radiation from the Sun that reaches an object *with no interposition* of objects
 - Diffuse irradiance (D):** radiation from the Sun that reaches an object *after reflection or passing through other objects* (two main sources – the sky and reflection from the ground)
- The amount of **direct irradiance S** incident on a surface depends on its inclination:

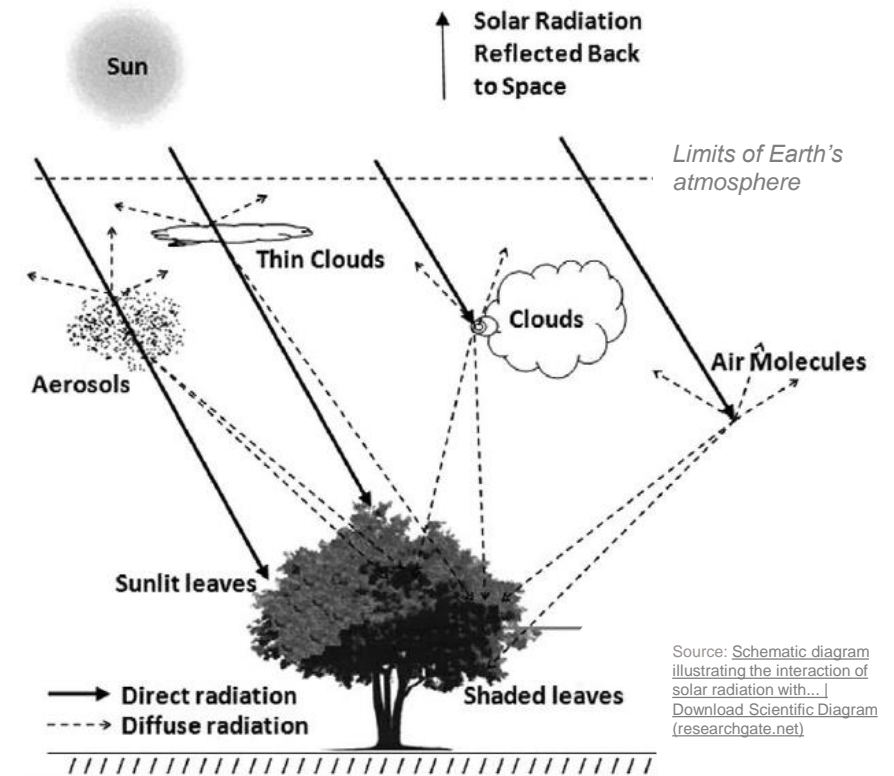


Source: Oke, Urban Climates, p. 126

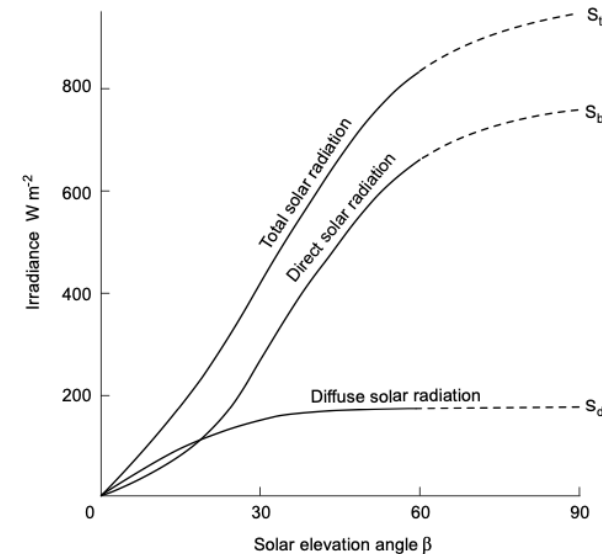
$$S = S_b \cdot \cos \theta \quad (3-33)$$

- S_b - direct-beam irradiance received on a surface perpendicular to the beam
- θ – angle between the beam and an axis perpendicular to the surface

$$\cos \theta = \cos \hat{\beta} \cdot \sin \beta + \sin \hat{\beta} \cdot \cos \beta \cdot \cos(\Omega - \hat{\Omega}) \quad (3-34)$$



Source: Schematic diagram illustrating the interaction of solar radiation with... | Download Scientific Diagram (researchgate.net)



← Total solar radiation incident on a surface as a function of solar altitude (elevation angle)

Source: Rodrigues, Fundamental principals of environmental physics, p.193

Surface Radiation Budget

- Radiation budget Q^* at any surface is the sum of the budget of net shortwave K^* and net longwave L^* radiation flux.

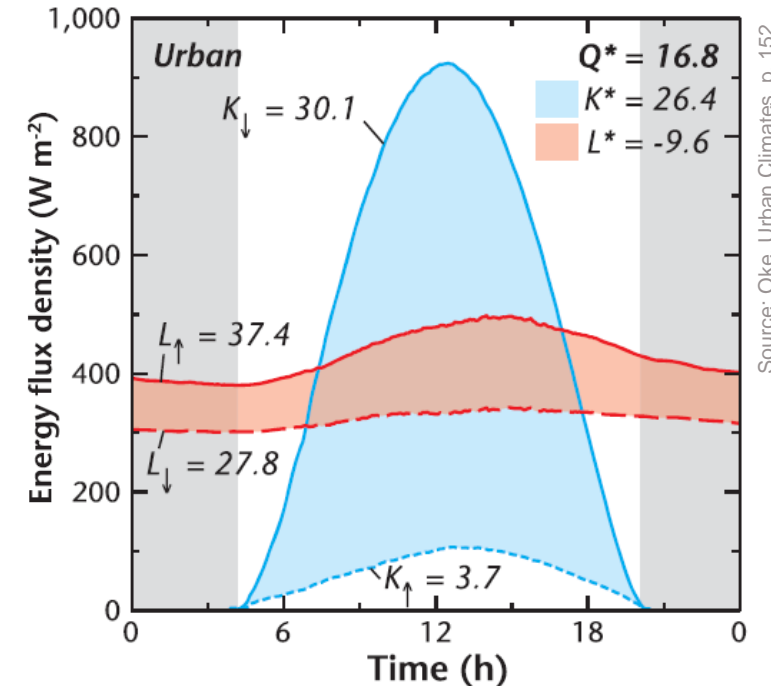
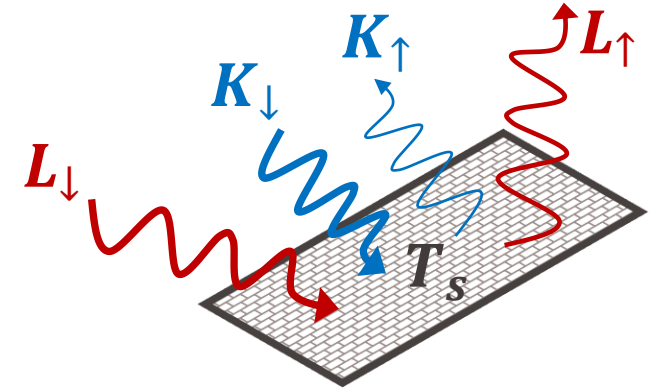
$$Q^* = K^* + L^* \quad (3-35) \quad K^* = K_{\downarrow} - K_{\uparrow} \quad (3-36) \quad L^* = L_{\downarrow} - L_{\uparrow} \quad (3-37)$$

- Upwelling shortwave flux K_{\uparrow} is dominantly due to surface reflectance and it is primarily a function of incident irradiance K_{\downarrow} and the average surface reflectivity (albedo).

$$K_{\uparrow} = a \cdot K_{\downarrow} \quad (3-38)$$

- Incoming longwave radiation L_{\downarrow} depends on the ability of the overlying atmosphere and surrounding surfaces to emit and to smaller extent their ability to reflect toward the surface of interest
- Outgoing longwave radiation L_{\uparrow} from a surface depends on its ability to both emit and reflect longwave radiation

$$L_{\uparrow} = \underbrace{\varepsilon \cdot \sigma \cdot T_s^4}_{\text{emission}} + \underbrace{(1 - \varepsilon) \cdot L_{\downarrow}}_{\text{reflection (small, if } \varepsilon \text{ is large)}} \quad (3-39)$$



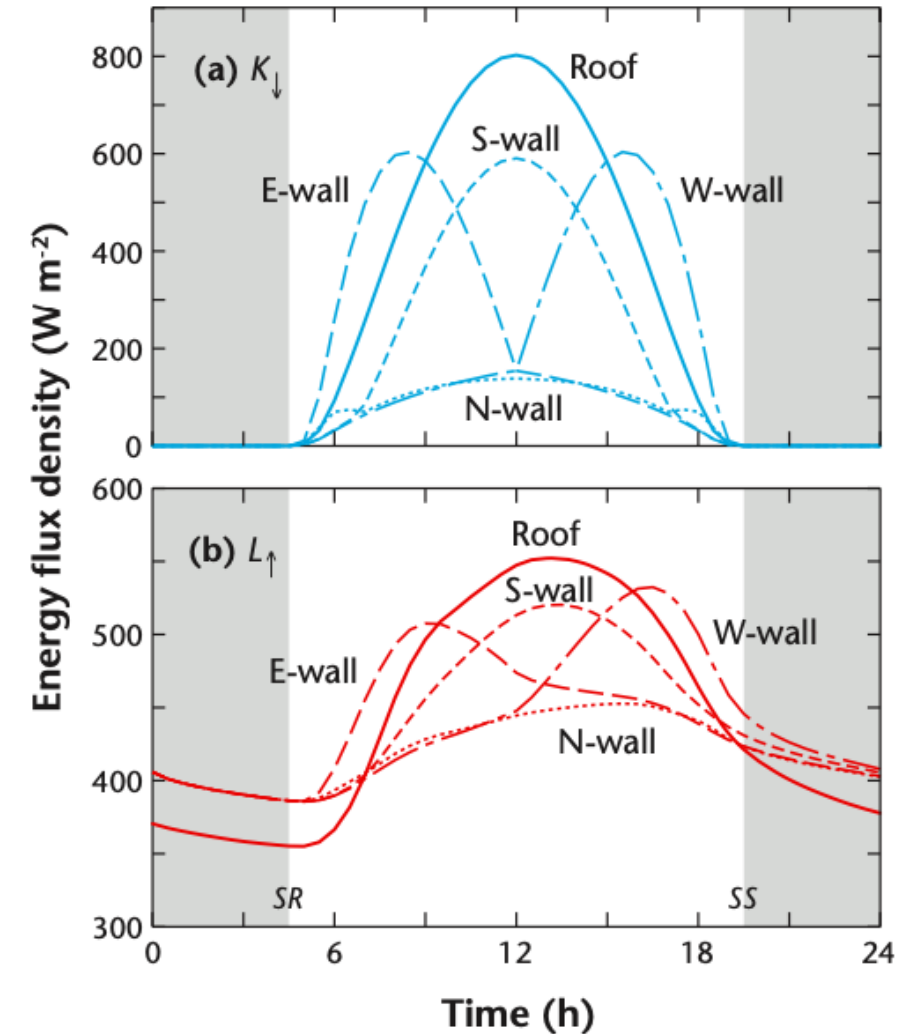
Diurnal course of all radiation component above the urban area (clear sky, city of Vancouver)

- Radiation **received** and **emitted** by surfaces depends on *their orientation* and *time of the day*:
 - A **roof** and the **S wall** have similar patterns but different magnitudes (radiation on the wall is less), the peak is nearly symmetrical around noon
 - The **E wall** has the peak in the *morning*, while the **W wall** has the peak in the *afternoon*.
 - **The N wall**: the solar beam is obstructed by the building itself.

- **Incoming shortwave radiation K_{\downarrow}** :
 - **A flat roof**: an *unimpeded* view of the sky but receives *no radiation from the ground*
 - **All wall facets**: *diffuse shortwave radiation from the sky and reflected from the ground*

- **Outgoing longwave radiation L_{\uparrow}** :
 - **A flat roof**: receives radiation from *the sky* which varies little through a day
 - **All wall facets**: affected by the radiation received from *the ground* and from the *neighboring urban objects* (when the building is not isolated)

Source: Oke, Urban Climates, p. 133

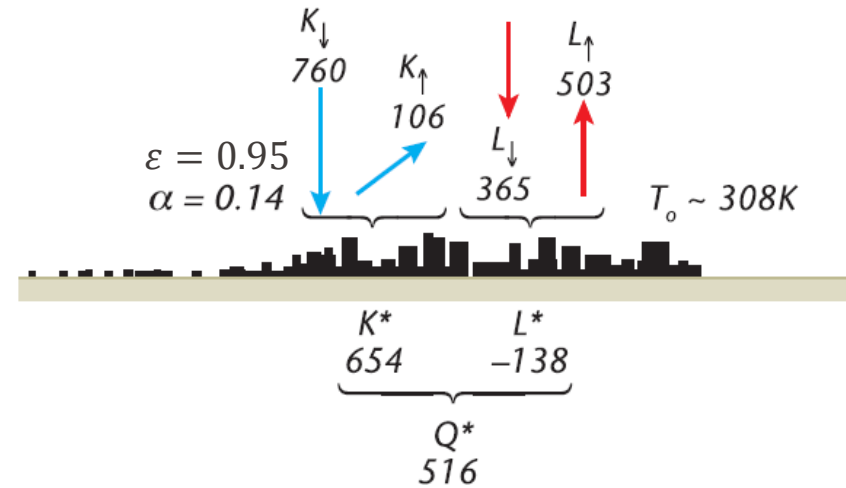
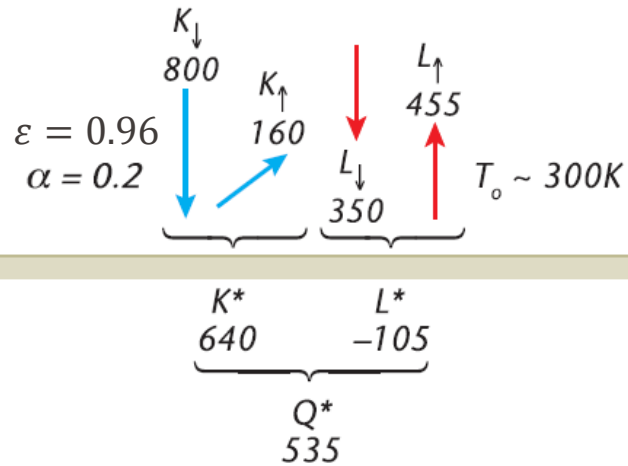


The daily course of (a) incoming shortwave and (b) outgoing longwave radiation fluxes for the walls and roof of an isolated cube-shaped building at 49N on August 15th

Surface Radiation Budget: Urban vs. Rural

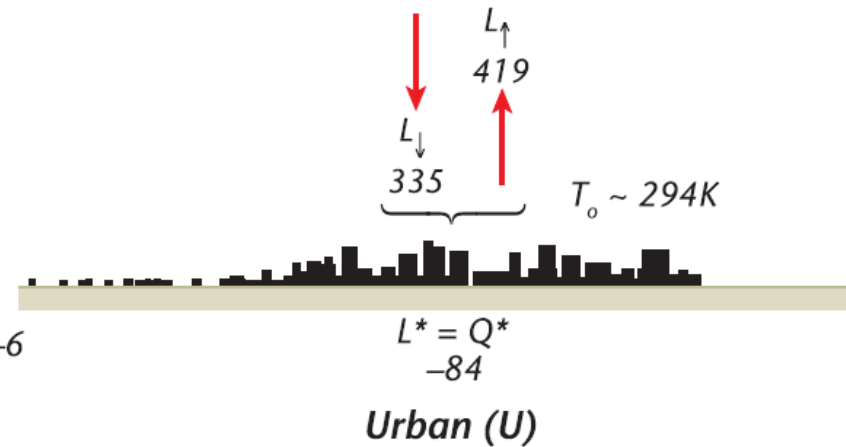
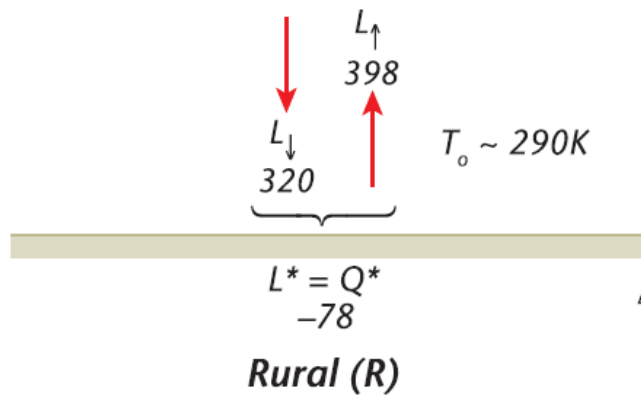
- Surface radiation balances at typical urban and rural sites in the mid-latitude:

(a) Day



$\Delta K^*_{U-R} = 14$
 $\Delta L^*_{U-R} = -33$
 $\Delta Q^*_{U-R} = -19$

(b) Night



$\Delta L^*_{U-R} = \Delta Q^*_{U-R} = -6$

*urban depletion of shortwave irradiance K_{\downarrow} is taken as 5%



**Thank you
for your attention**

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