EPFL

CIVIL-309: URBAN THERMODYNAMICS

Assist. Prof.
Dolaana Khovalyg

Lecture 03:

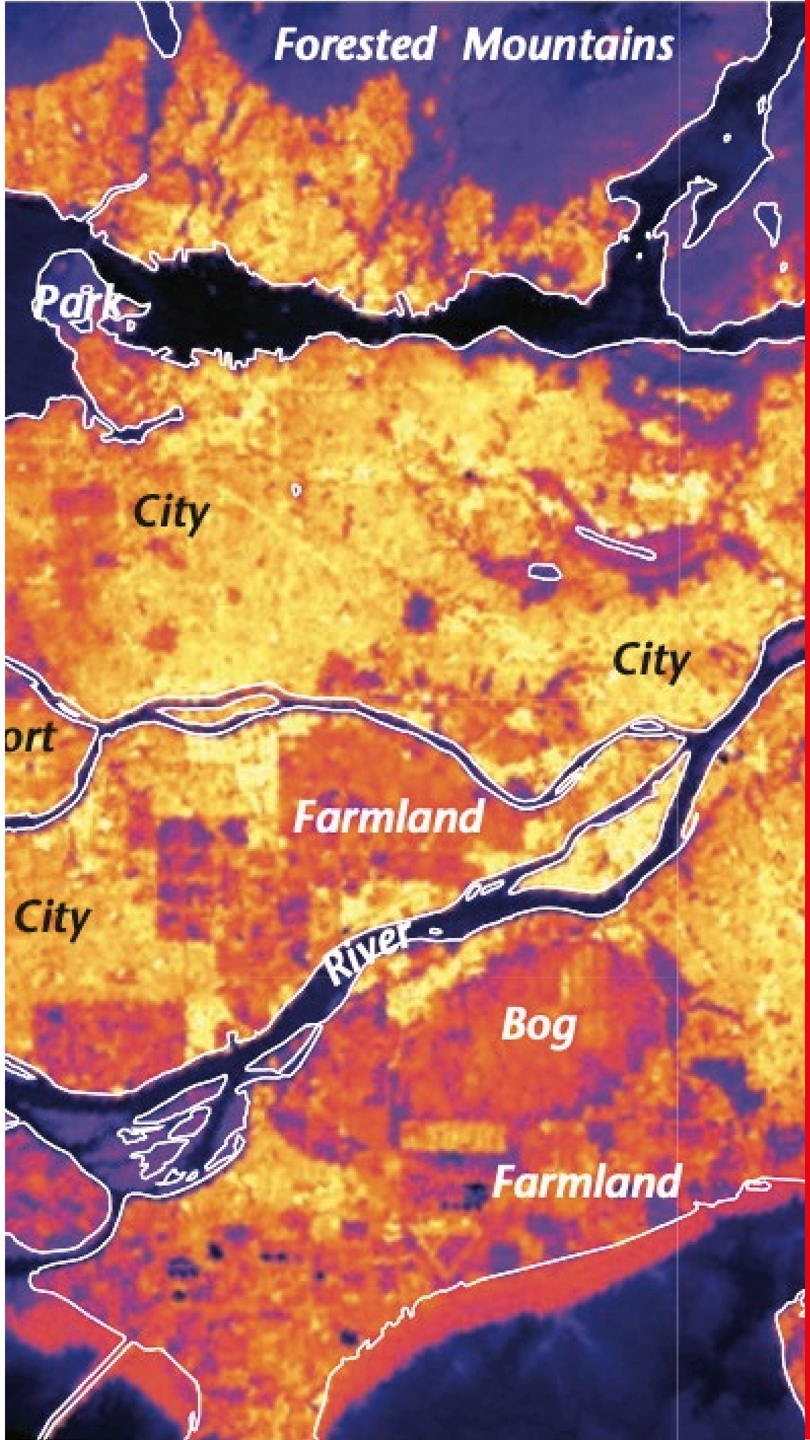
Heat Transfer and Thermal Properties: Conduction and Radiation

30 September 2024

Course Schedule

Lectures (L) 15:15-17:00, practice sessions (P) 17:15-18:00, room INJ218

Week	Date	Time	ID	Topics	Responsible
1	09.09	2 x 45’	**L1**	**Course overview** (content, evaluation, group project). **Urban characteristics**, **Urban Heat Island (UHI) effect.**	DK
		1 x 45’	**P1**	Exercises based on materials in lecture L1	KL
2	16.09			**No class (holiday)**	
3	23.09	2 x 45’	**L2**	Overview of **physical parameters. Urban environment** and **urban modeling**.	DK, KL
		1 x 45’	**P2**	**Workshop** on how to use the simulation tool **ENVI-met** (basic functions, geometry input, etc.) Exercises based on materials in lecture L2 [HW]	KL
4	30.09	2 x 45’	**L3**	**Heat Transfer**: Conduction and radiation	DK
		1 x 45’	**P3**	Exercises based on materials in lecture L3	KL
5	07.10	2 x 45’	**L4**	**Heat Transfer:** Convection and evaporation	DK
		1 x 45’	**P4**	Exercises based on materials in lecture L4	KL
6	14.10	90’	**Q**	**Quiz** (open book exam, based on lectures L1-L4)	DK, KL
		1 x 45’	**V**	**Case study site (EPFL Innovation park) visit**, overview of important urban features	DK, KL
7	21.10			**Fall Break (no classes)**	



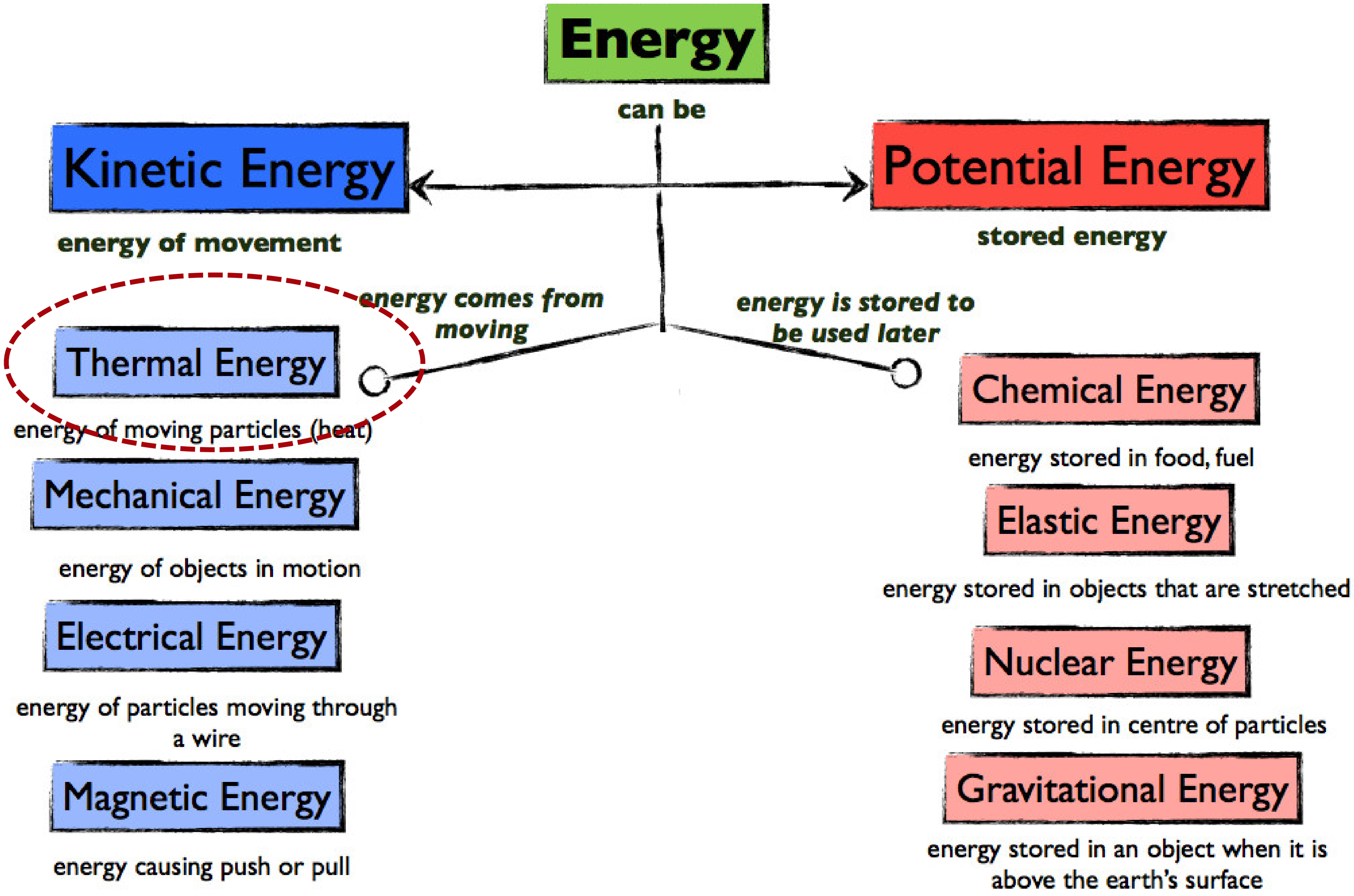
CONTENT:

I. Introduction (overview of basic concepts)

II. Conduction
- Heat conduction (Fourier's Law)
- Thermal resistance
- Conduction properties

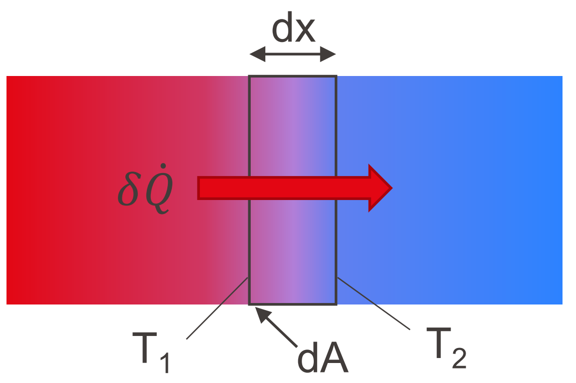
III. Radiation
- Definitions
- Radiative heat exchange
- Radiative properties
- Surface radiation budget

Introduction



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.*



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

- **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.

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

- **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*.**

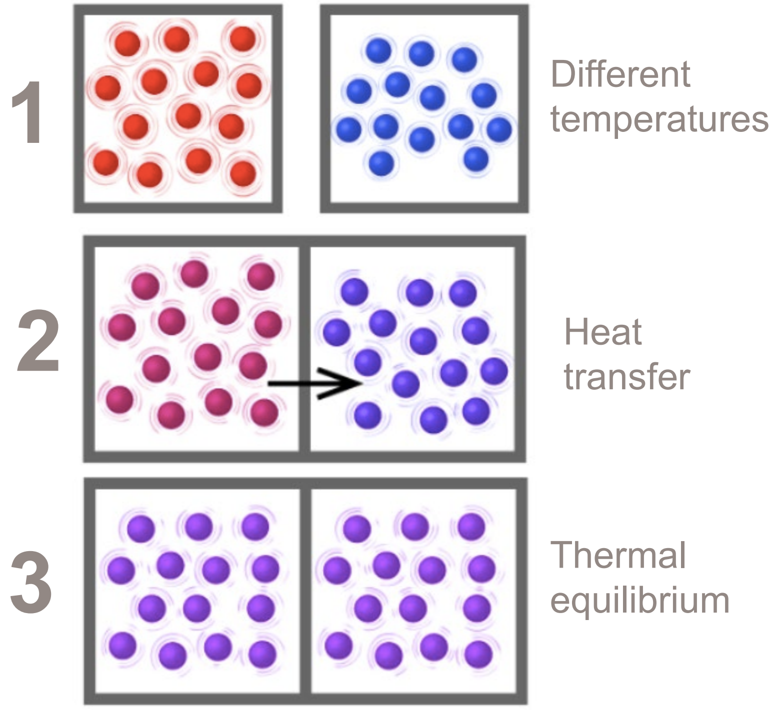
$$h = \frac{\dot{q}}{\Delta T} \quad (3\text{-}3)$$

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

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

when $\dot{Q}$ *= constant* →

$$Q = \dot{Q} \cdot \Delta t \quad (3\text{-}4b)$$

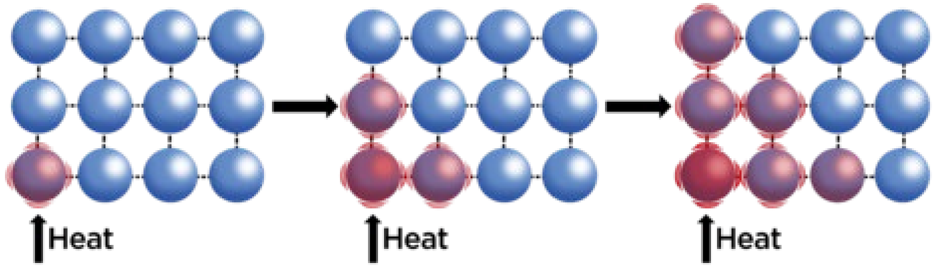


Assist. Prof. Dolaana Khovalyg

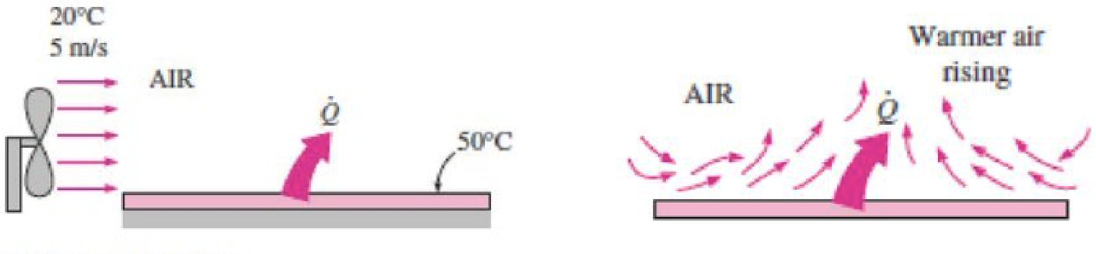
Heat transfer: Mechanisms

- **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.*

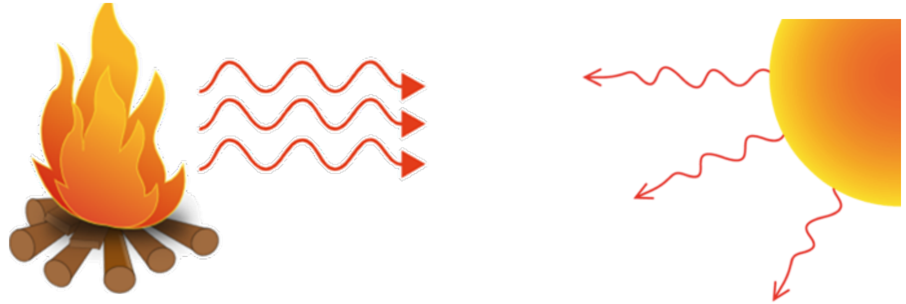


  - **Convection** – the transfer of thermal energy *between a solid surface* and *the adjacent liquid* or *gas* that is *in motion* (the faster the fluid motion, the greater the convection heat transfer).



(*a*) Forced convection (*b*) Free convection

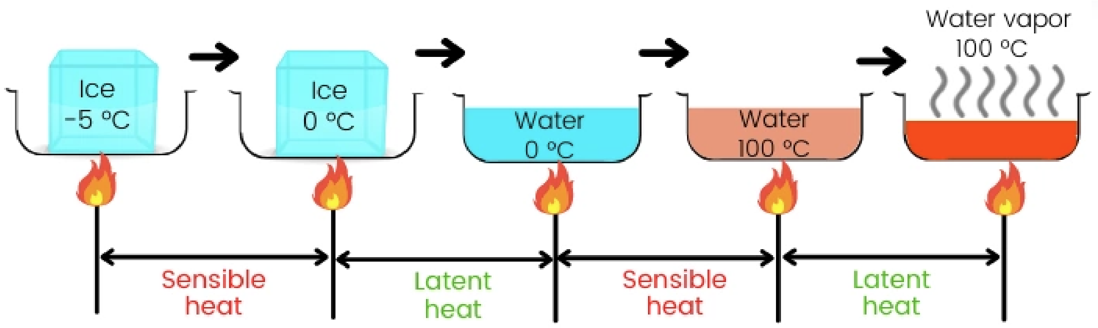
  - **(Thermal) Radiation** – the energy emitted by matter in the form of *electromagnetic waves* (transfer at the speed of light).

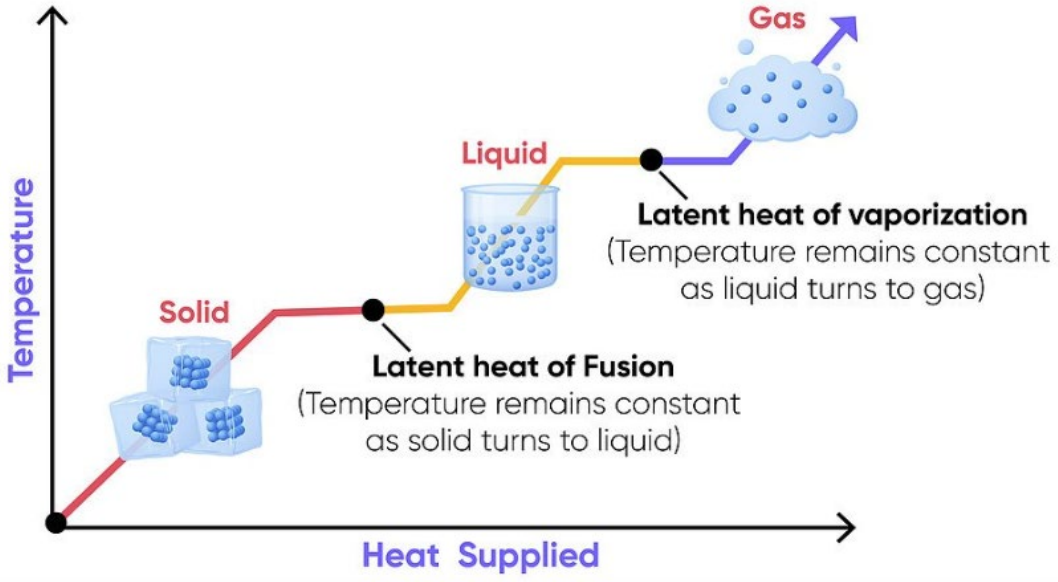


Latent Heat

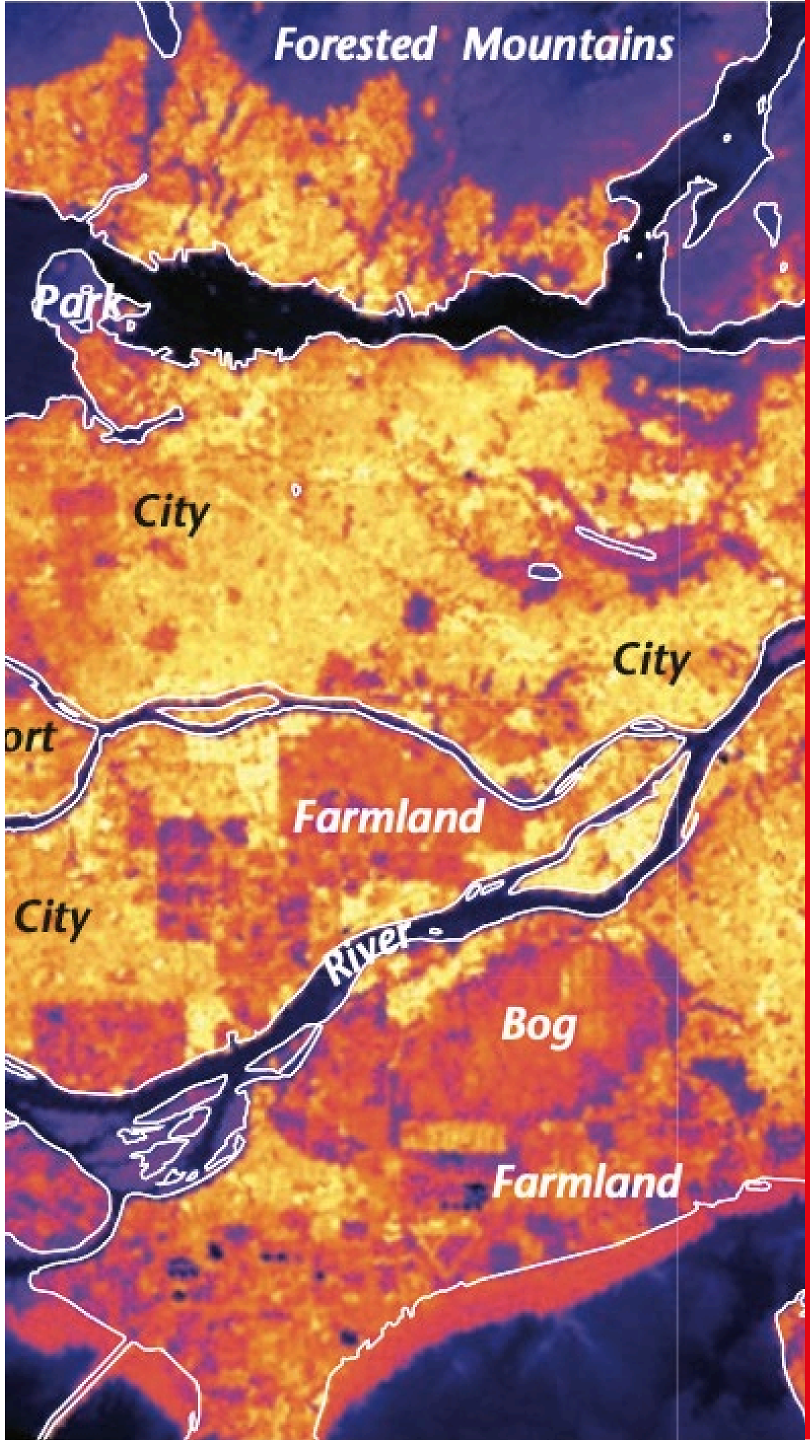
- **Latent ("hidden") heat** – energy **released/absorbed** by a thermodynamic system during **a constant-temperature process** of **changing** the **state** (e.g., phase change such as *condensation* and *evaporation*)
  - **Heat of vaporization** – the energy required *to change* an amount of substance 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.





Assist. Prof. Dolaana Khovalyg



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 Conduction: Fourier's Law

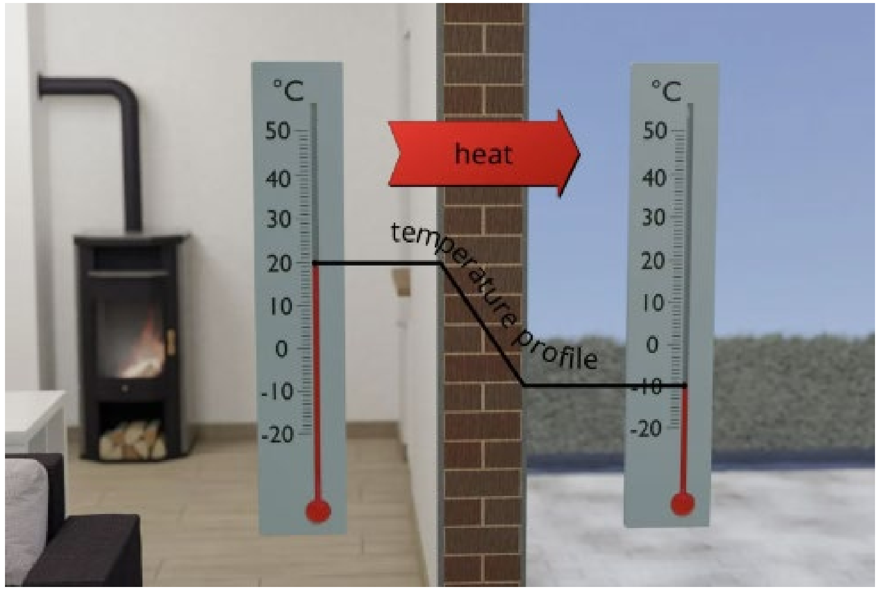
- **Conduction** - ***energy transfer*** from ***molecule*** to ***molecule*** is due to ***the temperature gradient***

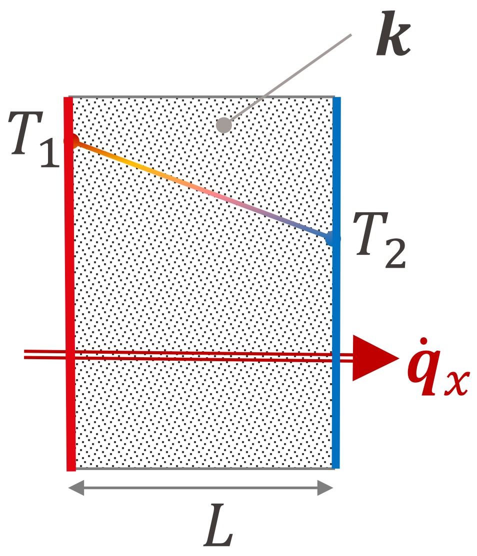
Fourier's Law: $$\dot{q}_x = -k \cdot \frac{dT}{dx} \quad (3\text{-}5a)$$

$$\overset{1D}{\underset{\text{steady state}}{\Rightarrow}} \quad \dot{q}_x = k \cdot \frac{T_1 - T_2}{L} \quad (3\text{-}5b)$$

- **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.





Assist. Prof. Dolaana Khovalyg

Thermal Resistance and Transmittance

- 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*

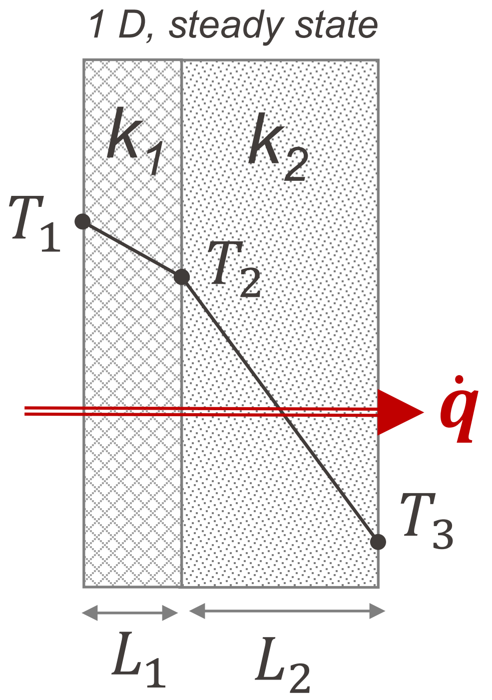
- **Thermal resistance *R*** $\left(\frac{m^2 \cdot K}{W}\right)$ – a measure of a material's resistance to heat flow
  - If two thermal resistances **in series:** $\boldsymbol{R_{tot}} = R_1 + R_2$ (3-6)
  - If two thermal resistances **in parallel:** $\frac{1}{\boldsymbol{R_{tot}}} = \frac{1}{R_1} + \frac{1}{R_2}$ (3-7)
  - A **single thermal resistance** of a wall with *multiple* solid layers:

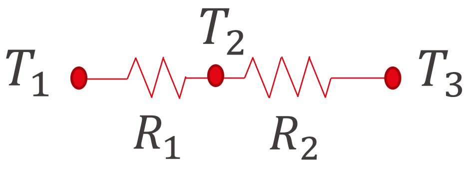
$$\dot{q} = U_{tot} \cdot \Delta T = \frac{1}{R_{tot}} \cdot \Delta T \quad (3\text{-}8)$$

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

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

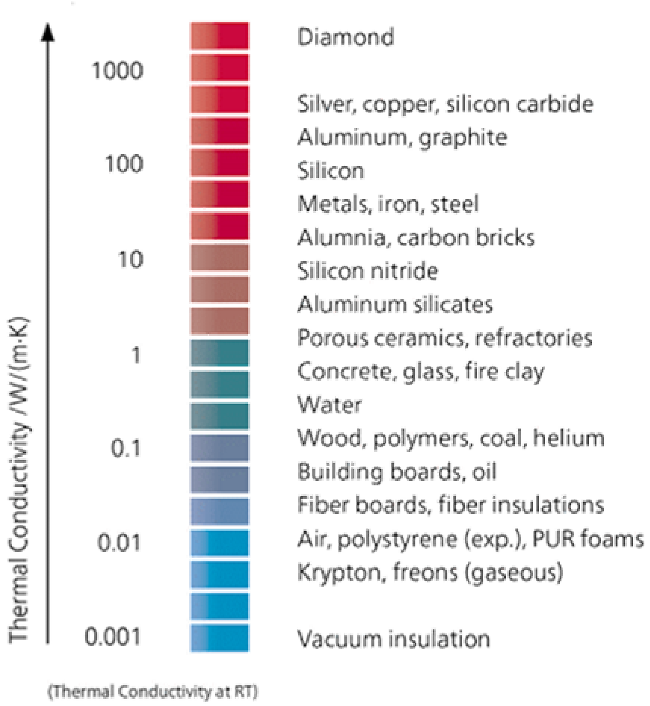
- **Thermal transmittance *U*** $\left(\frac{W}{m^2 \cdot K}\right)$ – the rate of heat transfer through a matter

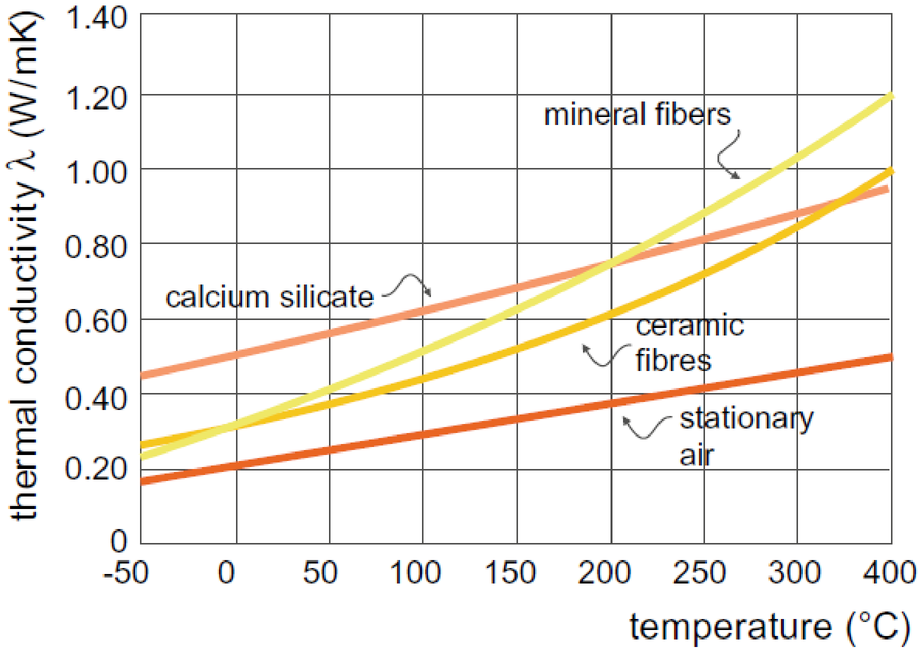




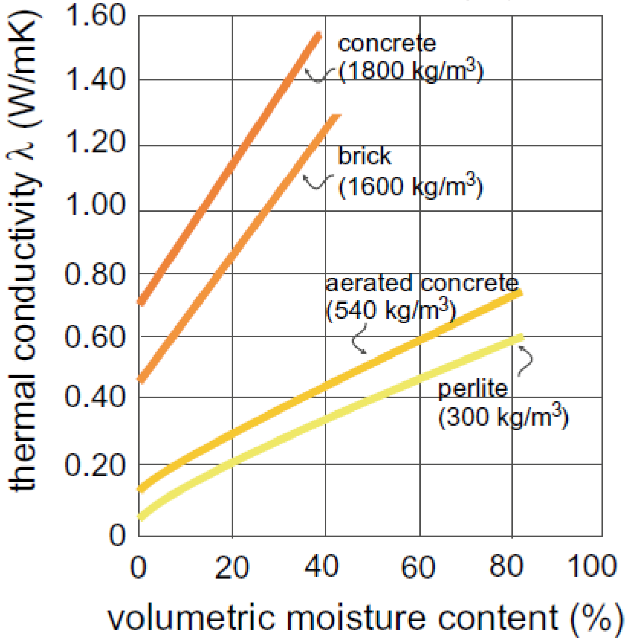
Conduction Properties: Thermal Conductivity

- **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 m^2) 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*.





Source: Medved, Building Physics, p. 13



Assist. Prof. Dolaana Khovalyg

Conduction Properties: Thermal Conductivity

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

Conduction Properties

- **Thermal conductivity** can be expressed *as the combination of other thermal properties*, highlighting different thermal behavior of the material.

$$\boldsymbol{k} = \alpha \cdot C_p \quad (3\text{-}11)$$

- **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.

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

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

- **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.

$$\boldsymbol{C_p} = \rho \cdot c_p \quad (3\text{-}13)$$

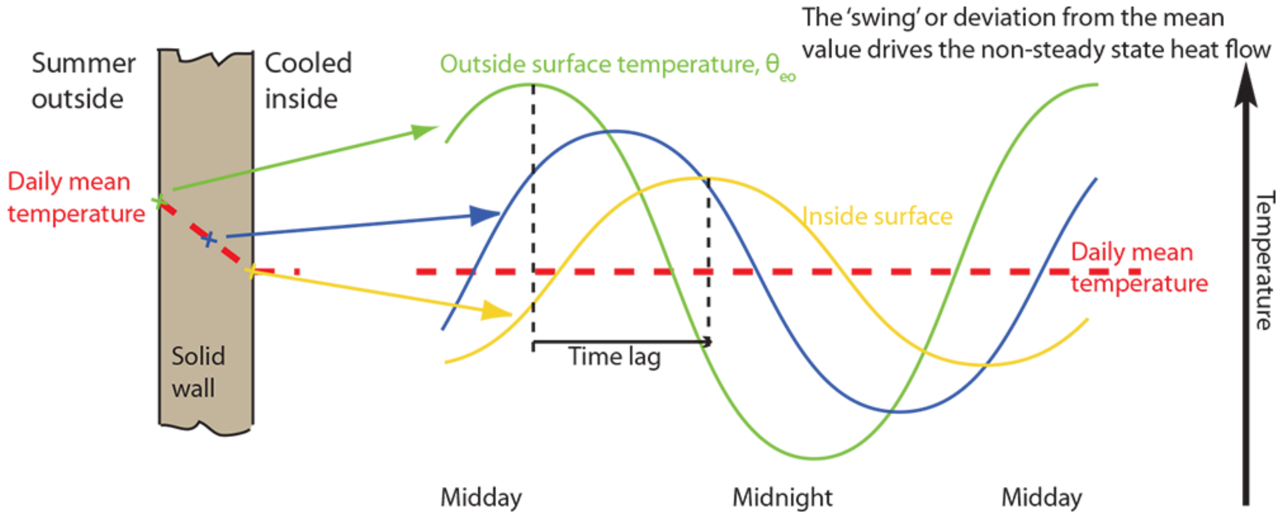
- **Thermal admittance, μ** ($\frac{J}{m^2 \cdot K \cdot s^{1/2}}$): ability of the system *to store heat* and *response of the surface temperature* to *a temperature change* in the air, it is a surface property. Related both to the ability of the system to store heat and the amplitude of the diurnal wave of surface temperature change in response to energy forcing.

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

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

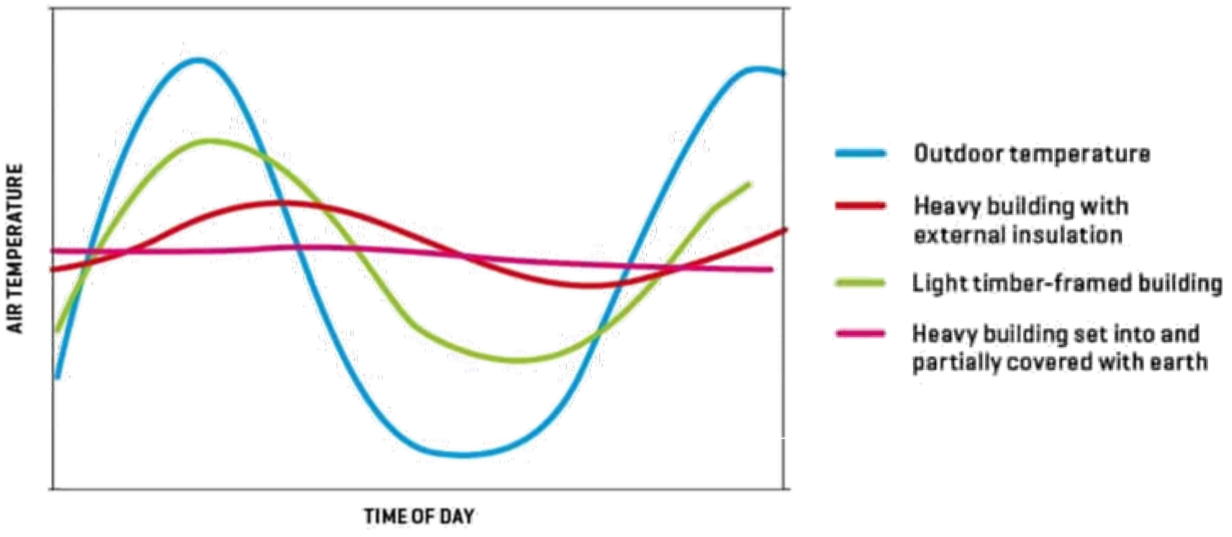
Conduction Properties: Thermal Admittance

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



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

- **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.*



Conduction Properties

Source: Oke, Urban Climates, p. 169

Material	State	Heat capacity C (MJ m^{-3} K^{-1})	Thermal conductivity k (W m^{-1} K^{-1})	Thermal diffusivity κ (m^2 s^{-1} × 10^{-6})	Thermal admittance μ_s (J m^{-2} s$^{-1/2}$ 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

Assist. Prof. Dolaana Khovalyg

Conduction Properties

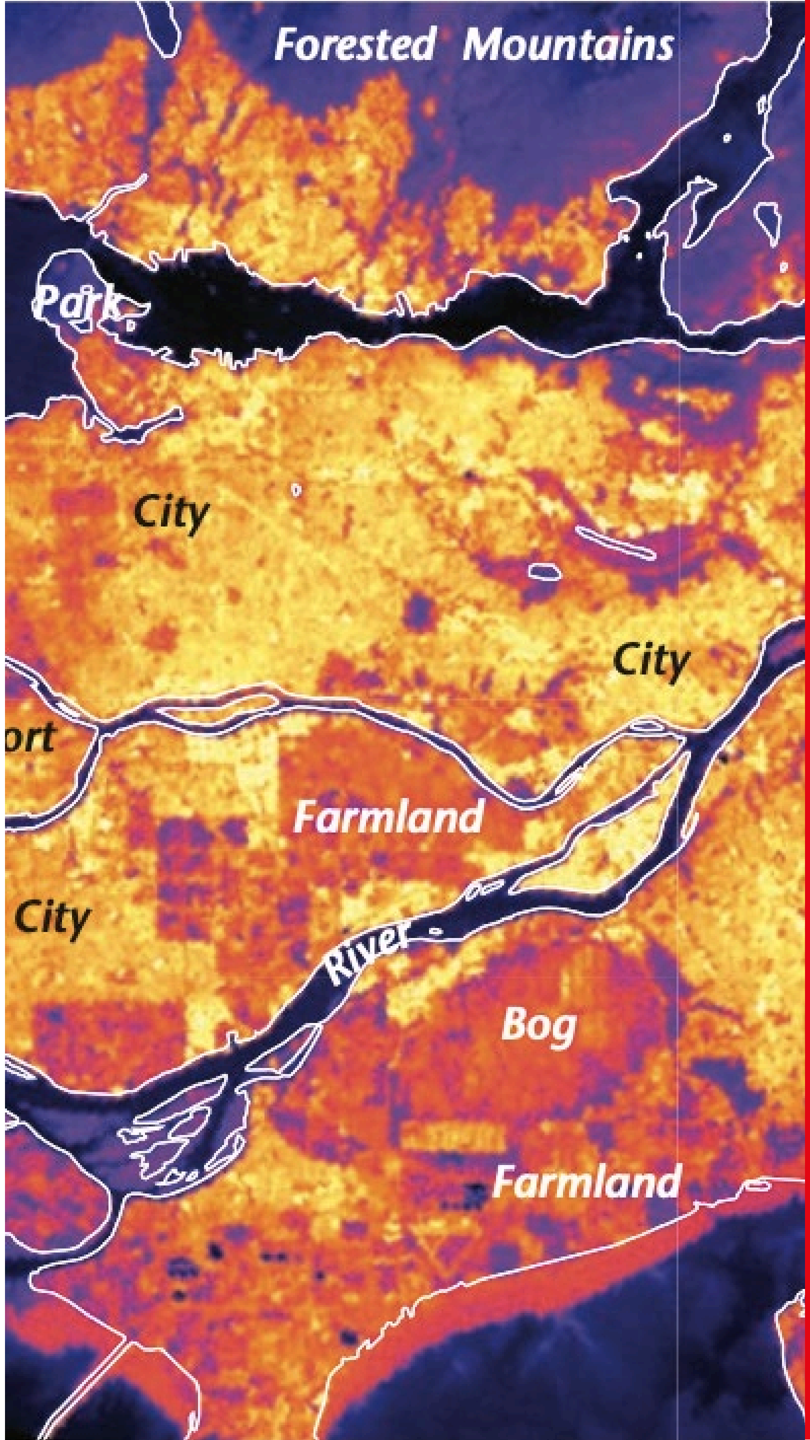
Source: Oke, Urban Climates, p. 169

Material	State	Heat capacity C ($MJ\ m^{-3}\ K^{-1}$)	Thermal conductivity k ($W\ m^{-1}\ K^{-1}$)	Thermal diffusivity κ ($m^2\ s^{-1} \times 10^{-6}$)	Thermal admittance μ_s ($J\ m^{-2}\ s^{-1/2}\ K^{-1}$)
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	$\sim 10 \times 10^6$	390

[1] Properties depend on temperature

Assist. Prof. Dolaana Khovalyg

EPFL



CONTENT:

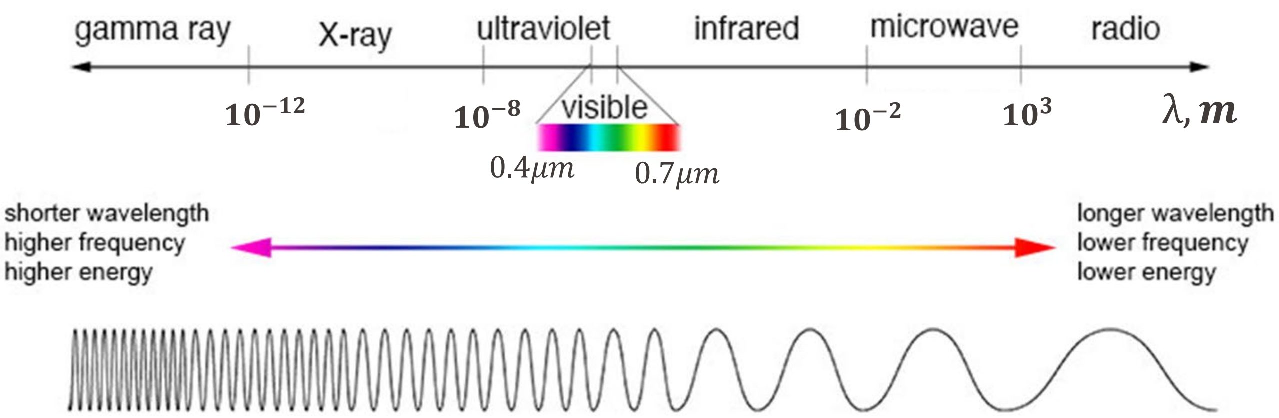
I. Introduction (overview of basic concepts)

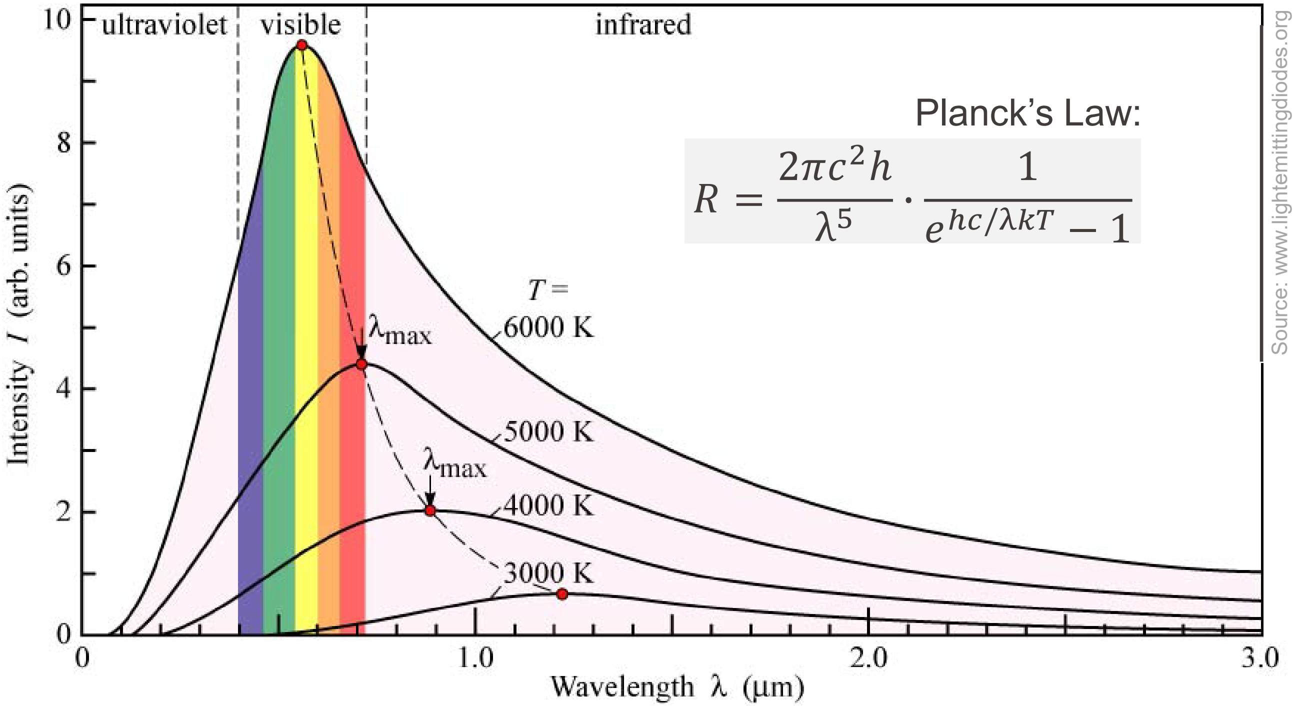
II. Conduction
- Heat conduction (Fourier’s Law)
- Thermal resistance
- Conduction properties

III. Radiation
- Definitions
- Radiative heat exchange
- Radiative properties
- Surface radiation budget

Radiation: Definitions

- **Radiation – the energy emitted by matter** in the form of **electromagnetic waves (photones)** 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 > 0K** 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).





$$R = \frac{2\pi c^2 h}{\lambda^5} \cdot \frac{1}{e^{hc/\lambda kT} - 1}$$

Source: www.lightemittingdiodes.org

Assist. Prof. Dolaana Khovalyg

Radiation: Shortwave vs. Longwave

Assist. Prof. Dolaana Khovalyg

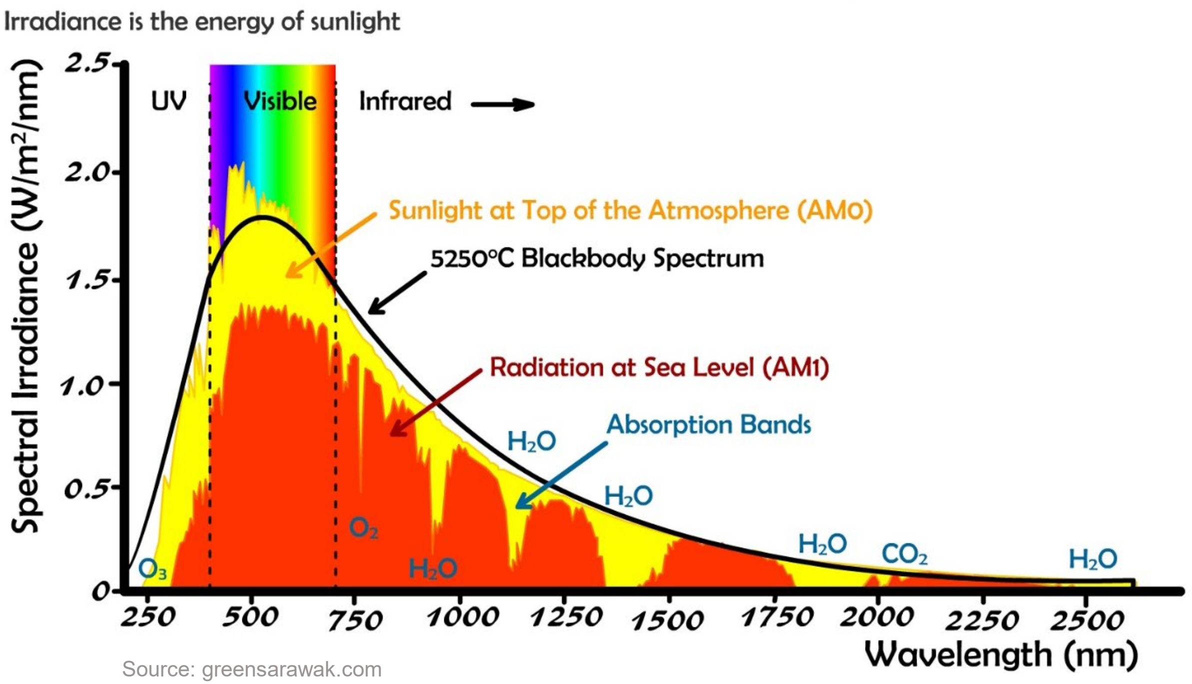
- The **Sun** emits radiation in the range of $\boldsymbol{\lambda = 0.1 - 3\ \mu m}$ (peak at $\boldsymbol{0.47\ \mu m}$), and it is called **shortwave radiation (K)** or **"solar".**

  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 $\boldsymbol{\lambda = 3 - 100\ \mu m}$ (peak at $\boldsymbol{10\ \mu m}$), it is called **longwave radiation (L)** or **"terrestrial"** (thermal IR).

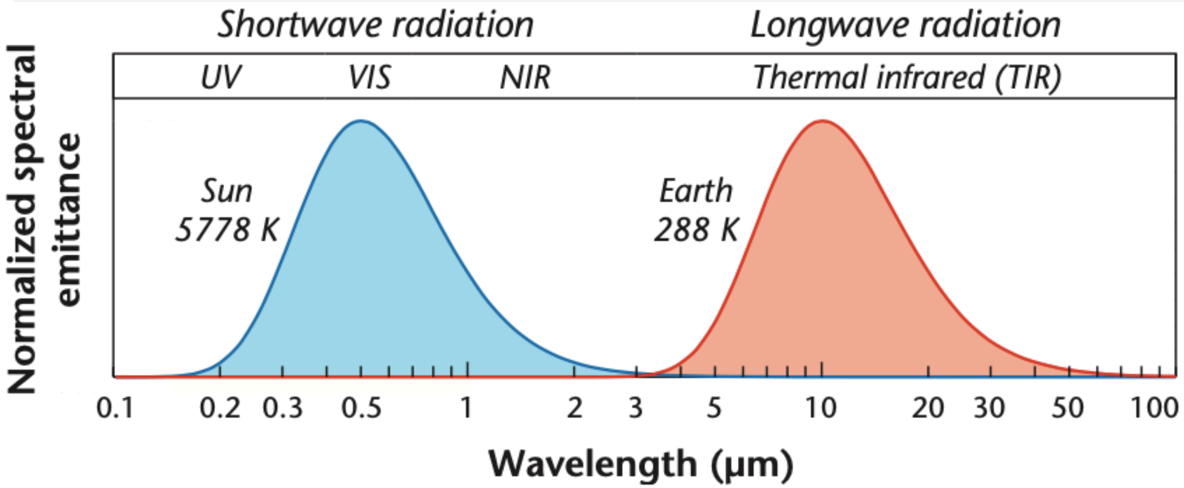
- For common ambient temperatures **~293 K** (20°C) the emitted spectrum is located in the **thermal infrared region**. Thermographic (IR) cameras are able to take images in this region.

- 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*, $30 - 1000\ \mu m$)



Source: greensarawak.com

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



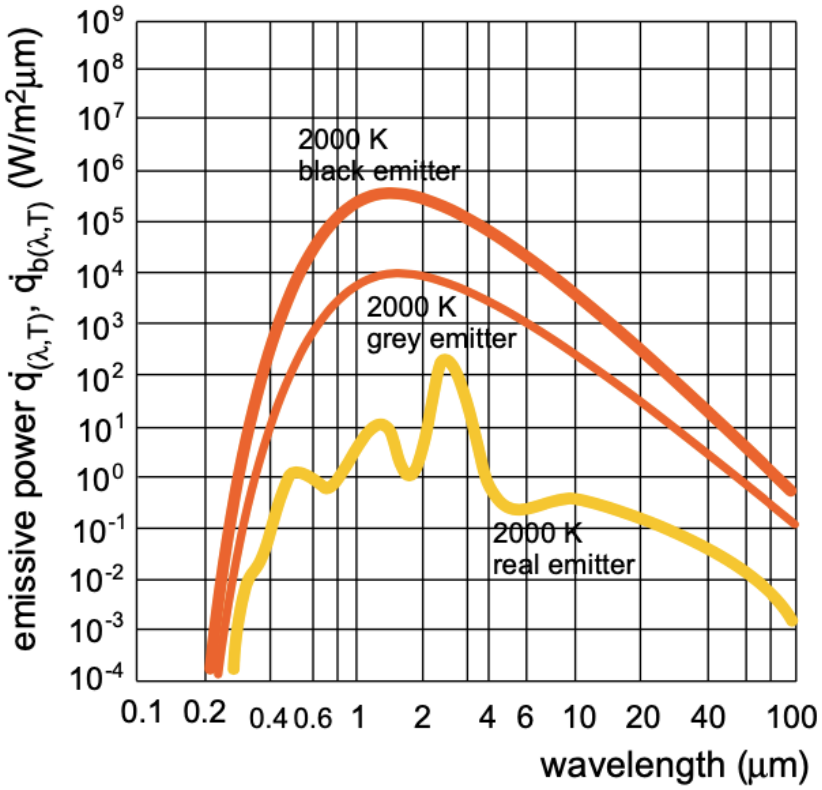
Source: Oke, Urban Climates, p. 124

Radiation: Stefan-Boltzmann Law

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



Source: Medved, Building Physics, p. 27

- **Emissivity ε** (-): property of *the emitter's surface*, characterizes **the effectiveness** of **a surface** in **emitting energy** as **thermal infrared radiation** ($3 \le \lambda \le 100\ \mu m$).
  - 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: $0 \le \varepsilon < 1$ for grey/real bodies and $\varepsilon = 1$ for a blackbody

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

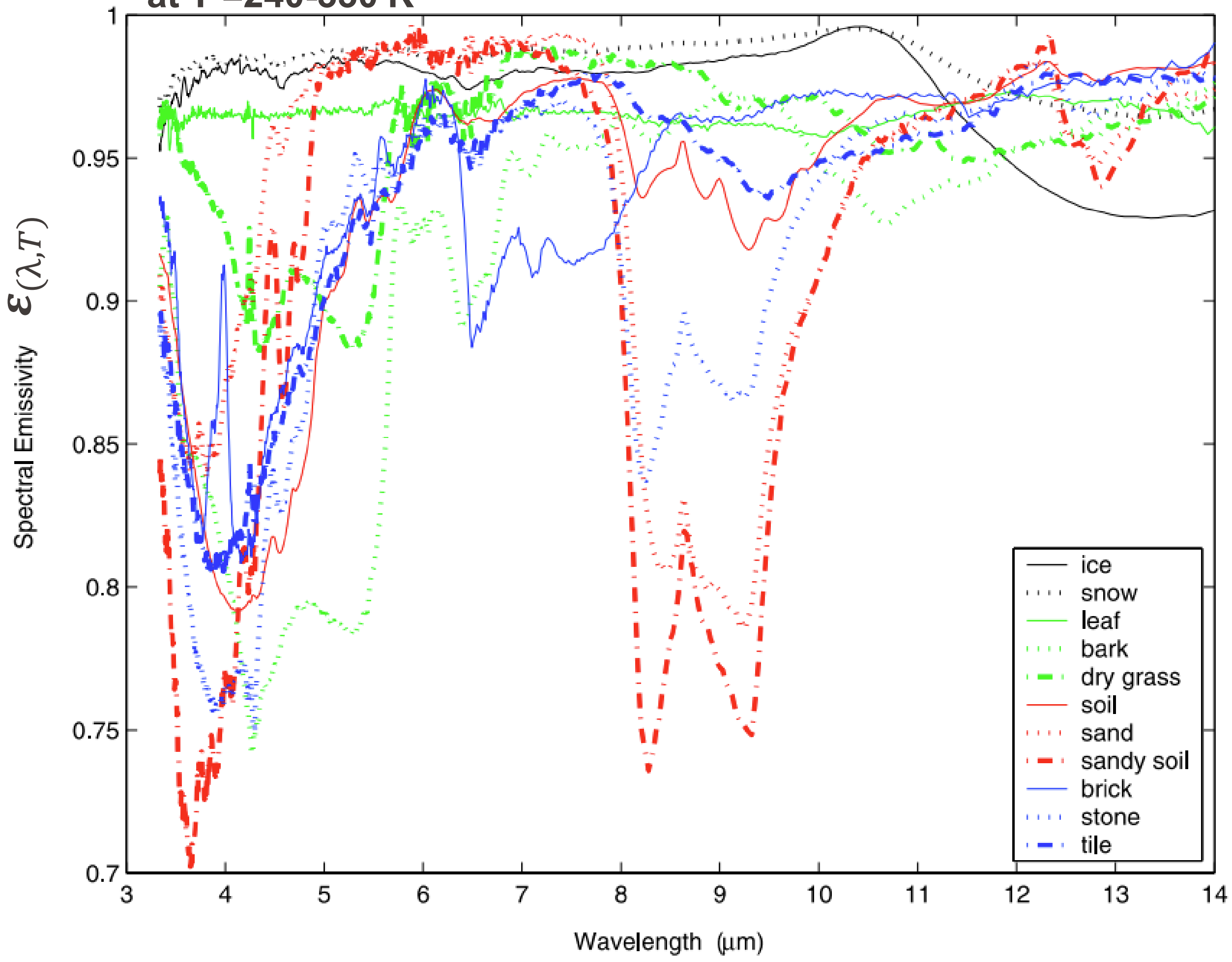
$$\varepsilon_{(\lambda,T)} = \frac{\dot{q}_{(\lambda,T)}}{\dot{q}_{b(\lambda,T)}} \quad \text{(3-17b)}$$

Assist. Prof. Dolaana Khovalyg

Radiative Properties: Emissivity

Average emissivity of urban areas is ≈ 0.94-0.96.

at T =240-330 K



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

Emissivities of different kind of materials:

Anthropogenic materials:	
Paper	0.7 – 0.95
Glass	0.76 – 0.94
Wood	0.8 – 0.95
Plastic	0.8 – 0.95
Stone	0.85 – 0.95
Rubber	0.86 – 0.94
Asphalt	0.89 – 0.96
Brick	0.9 – 0.92
Concrete	0.93 – 0.96
Carbon	0.96

Source: Oke, Urban Climates, p. 130

Natural surfaces:	
Sand or rock	0.84 – 0.92
Soil	0.89 – 0.98
Grass	0.9 – 0.98
Ice	0.9 – 0.98
Trees	0.9 – 0.99
Water	0.92 – 0.97
Human skin	0.98

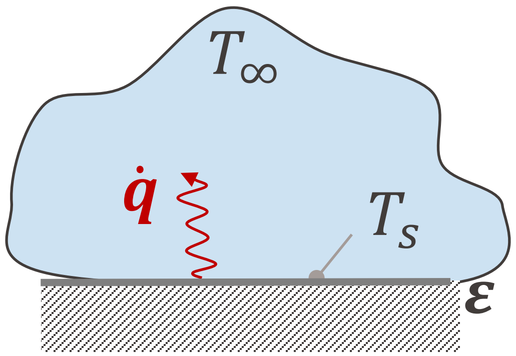
Metal surfaces:	
Silver	0.01 – 0.07
Zinc	0.02 – 0.28
Gold	0.02 – 0.37
Aluminium	0.02 – 0.40
Copper	0.02 – 0.74
Brass	0.03 – 0.61
Tin	0.04 – 0.08
Nickel	0.05 – 0.46
Lead	0.06 – 0.63
Steel	0.07 – 0.85

Assist. Prof. Dolaana Khovalyg

EPFL

Net Radiation Heat Transfer (Stefan-Boltzmann Law)

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



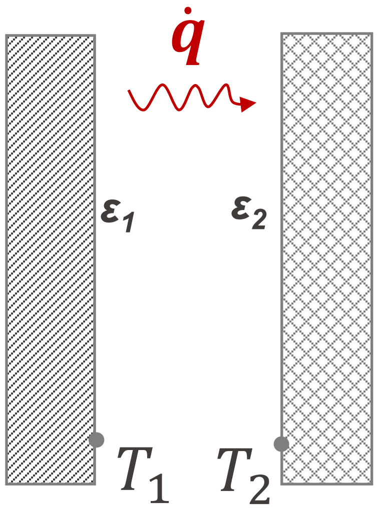
$$\dot{q} = \varepsilon \cdot \sigma \cdot (T_s^4 - T_\infty^4) \quad \text{(3-18a)}$$

$$\dot{q} = h_{rad} \cdot (T_s - T_\infty) \quad \text{(3-18b)}$$

Radiative heat transfer coefficient:

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

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



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

Radiative heat transfer coefficient:

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

Simplification for $T_1 - T_2 < 50\ K$:

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

Effective emissivity:

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

Radiative thermal resistance:

$$R_{rad} = \frac{1}{h_{rad}} \quad \text{(3-23)}$$

Assist. Prof. Dolaana Khovalyg

Radiative Properties

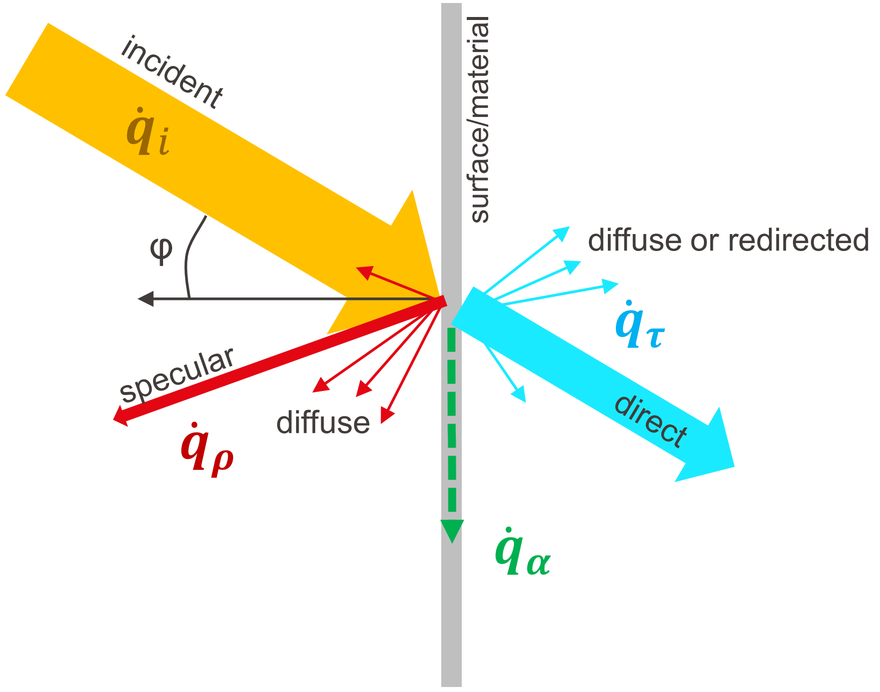
- All bodies **radiate energy** in the form of **photons moving in a random direction**, with random phase and frequency.
- When photons reach **another surface** (*incident* radiation), they may be:
  - **Reflected** (specular or diffuse)
  - **Transmitted** (direct or diffuse)
  - **Absorbed** (converted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

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

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

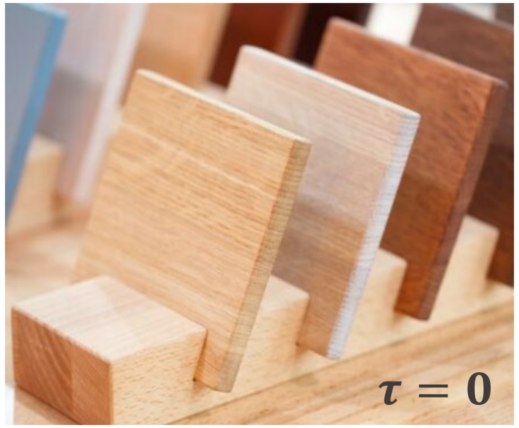
$$\frac{\dot{q}_\rho}{\dot{q}_i} + \frac{\dot{q}_\tau}{\dot{q}_i} + \frac{\dot{q}_\alpha}{\dot{q}_i} = 1 \quad \text{(3-25a)} \Rightarrow \rho + \alpha + \tau = 1 \quad \text{(3-25b)}$$

ρ - reflectivity, α - absorptivity, τ - transmissivity



Transparent material

Opaque material



Assist. Prof. Dolaana Khovalyg

Radiative Properties

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

- **Reflectivity** ρ (-):

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

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

- **Absorptivity** α (-):

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

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

- **Transmissivity** τ (-):

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

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

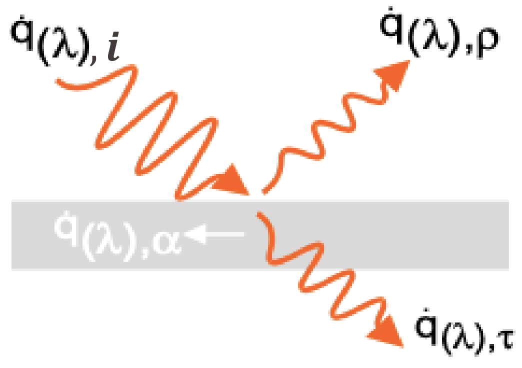
- **Kirchhoff's law: spectral absorptivity** of an *emitter surface* **is equal** to the **spectral emissivity** at a *given wavelength* and *temperature*

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

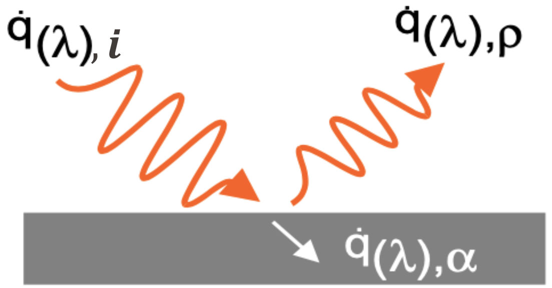
  For opaque bodies:

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

Transparent material:



Opaque material:



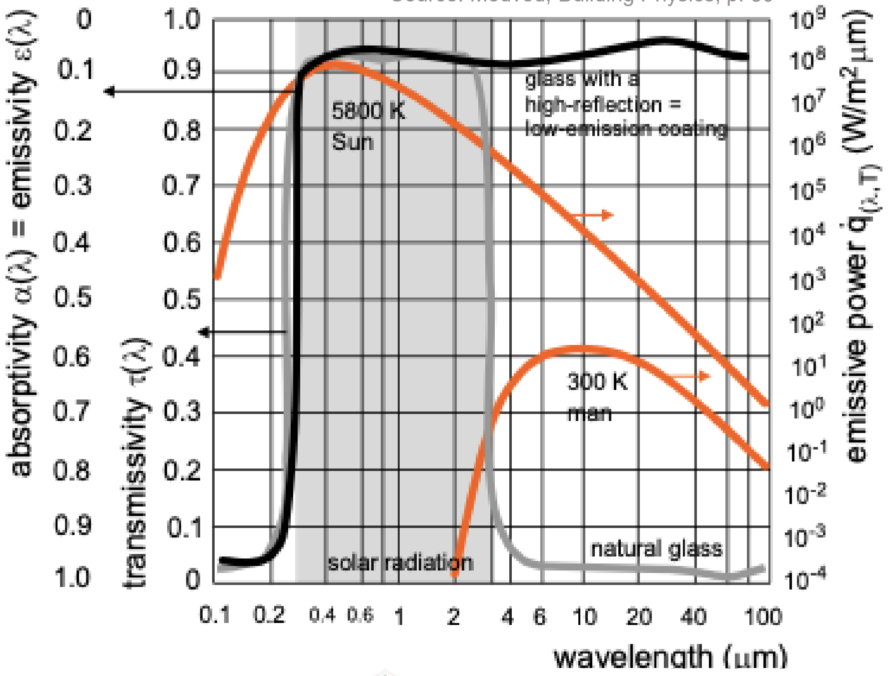
Source: Medved, Building Physics, p. 28

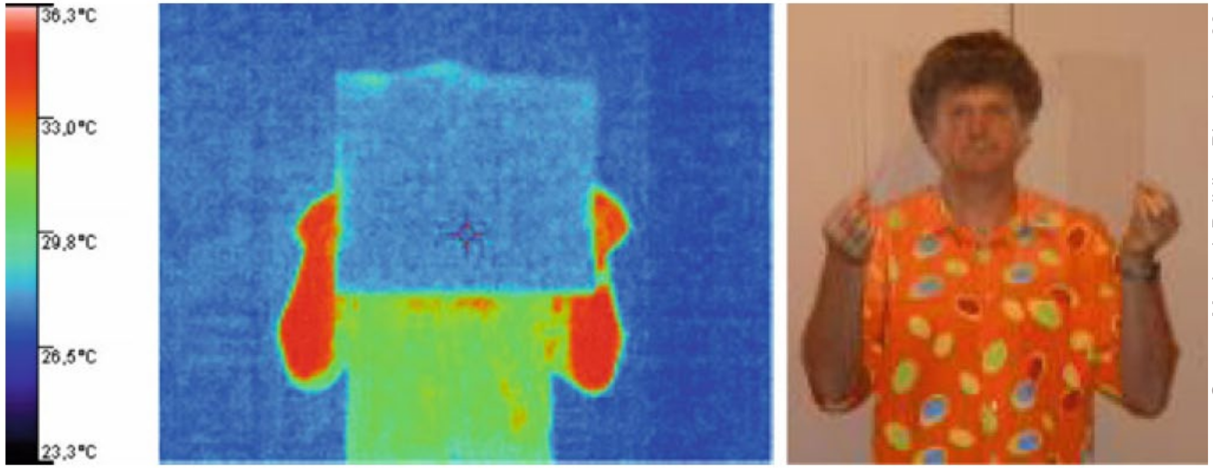
Assist. Prof. Dolaana Khovalyg

Radiative Properties

- **Radiative properties** of materials **depending on the wavelength** λ are called **selective radiative properties**.
- **Natural glass is selective**:
  - *short wavelengths* ($\lambda < 3\ \mu m$) are *transmitted*
  - *long wavelengths* ($\lambda > 5\ \mu m$) 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.)

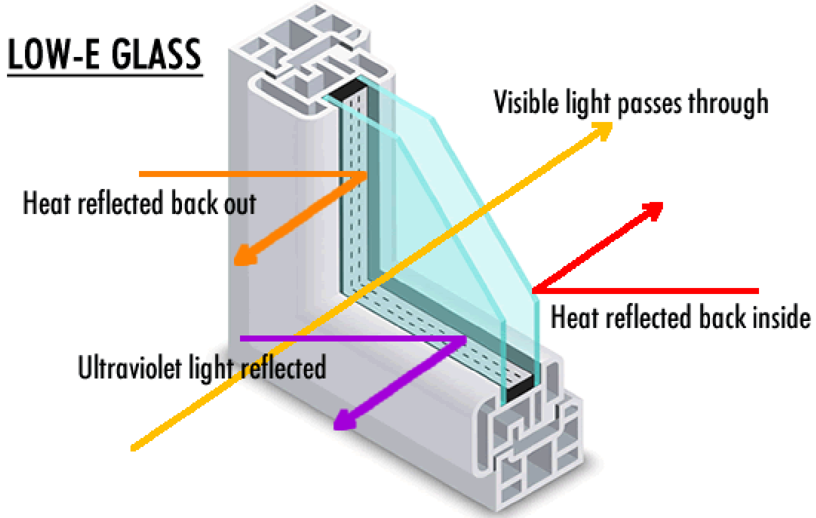
Source: Medved, Building Physics, p. 30





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)



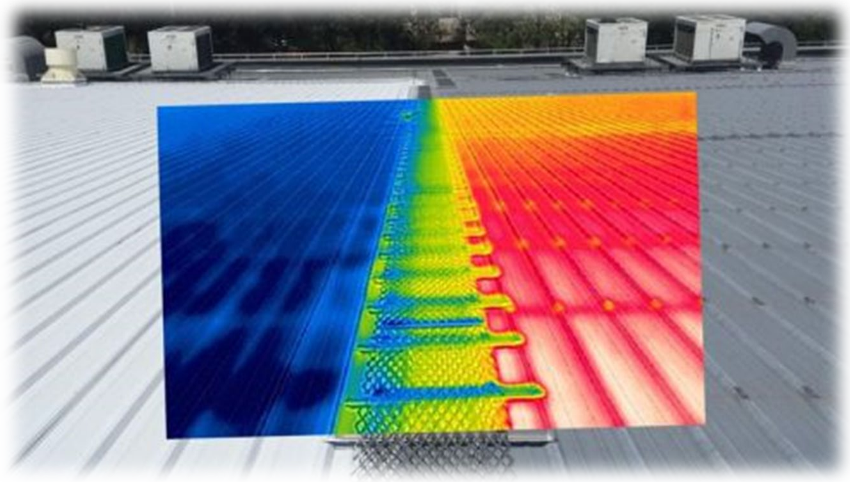
Source: Low Emissivity Glass | Planibel A Coating (prestonglassfix.co.uk)

Assist. Prof. Dolaana Khovalyg

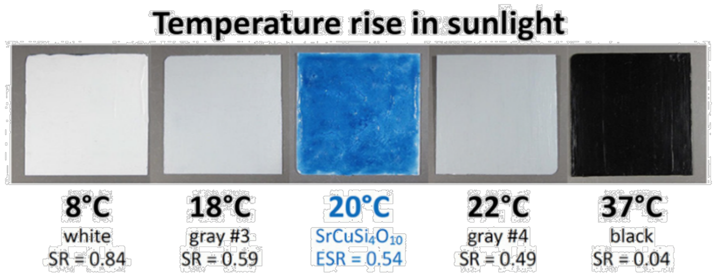
Radiative Properties

- 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.

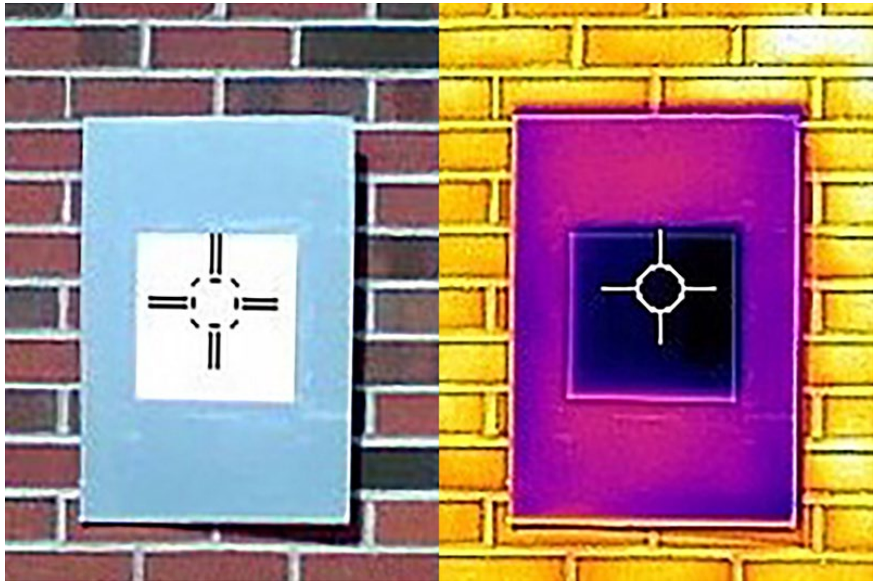


Source: https://newscenter.lbl.gov/2018/10/09/



- **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.

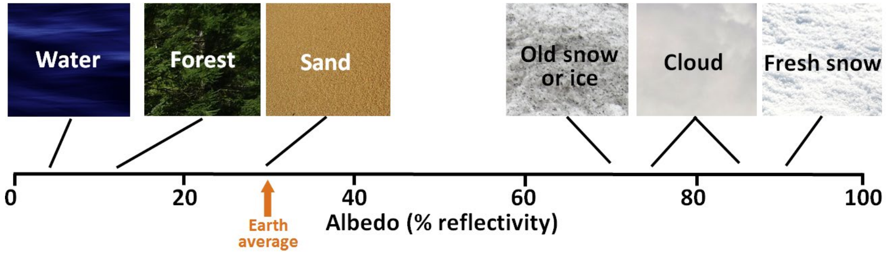


Source: The whitest paint is here – and it's the coolest. Literally. - Purdue University News

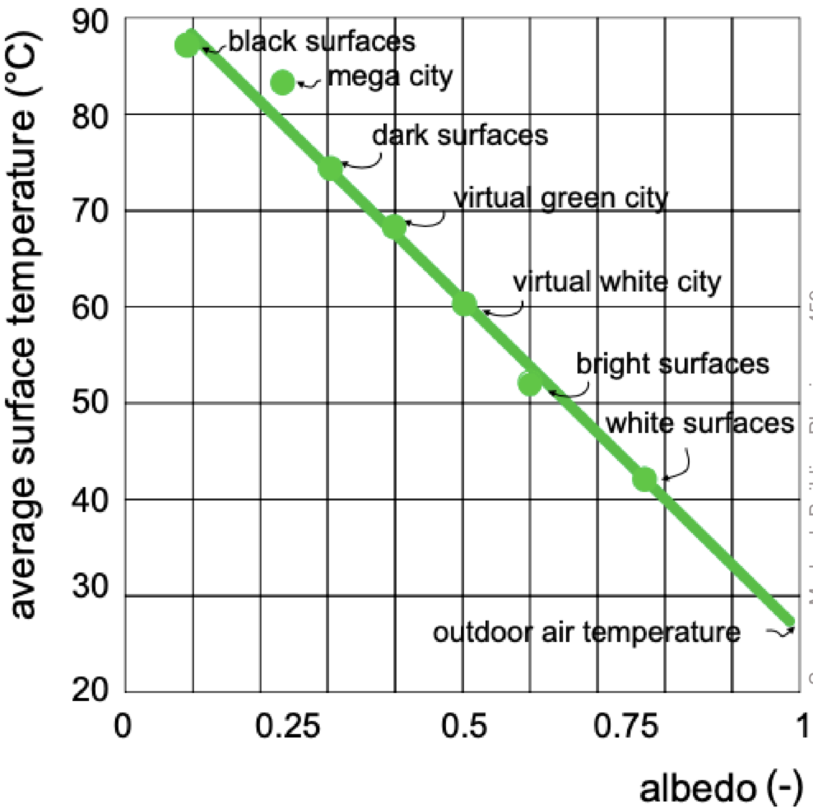
Radiative Properties: Albedo

- **Albedo, a - reflectivity** of **shortwave radiation:**

$$a = \rho_{(0.1 \leq \lambda \leq 3\ \mu m)} \quad (3\text{-}31)$$



- 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

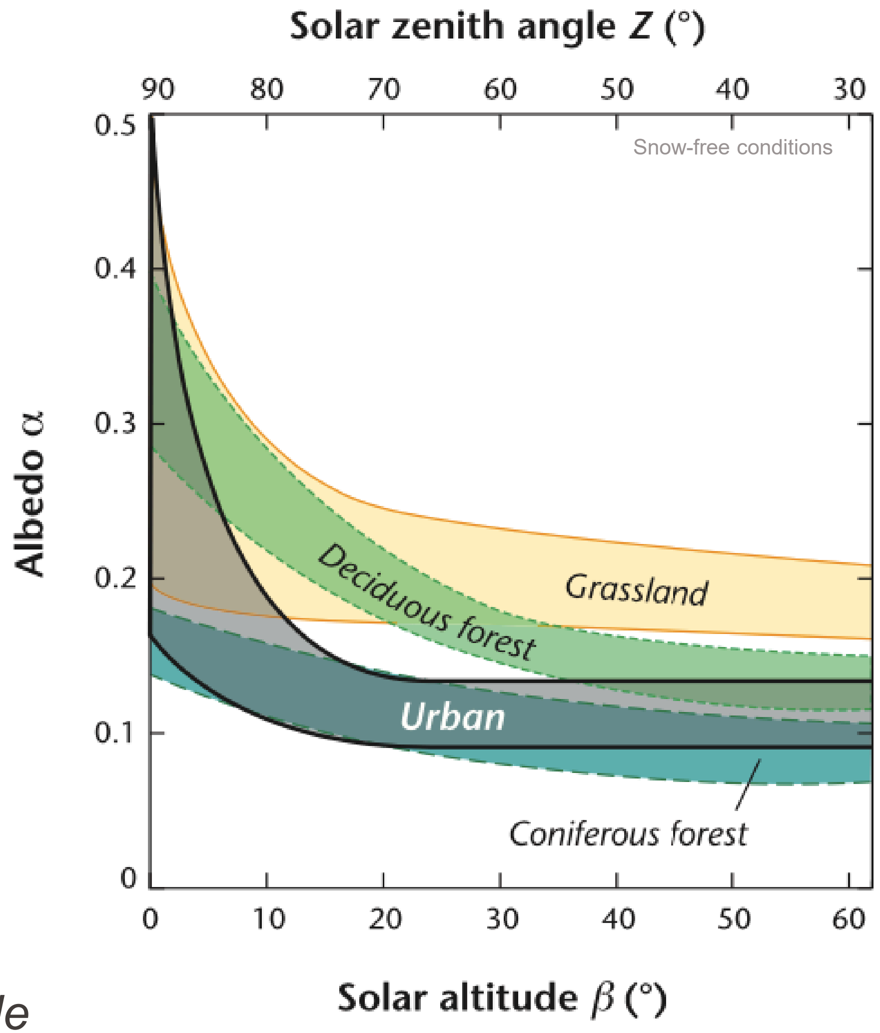
Source: Oke, Urban Climates, p. 129

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

Assist. Prof. Dolaana Khovalyg

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*.



Source: Oke, Urban Climates, p. 142

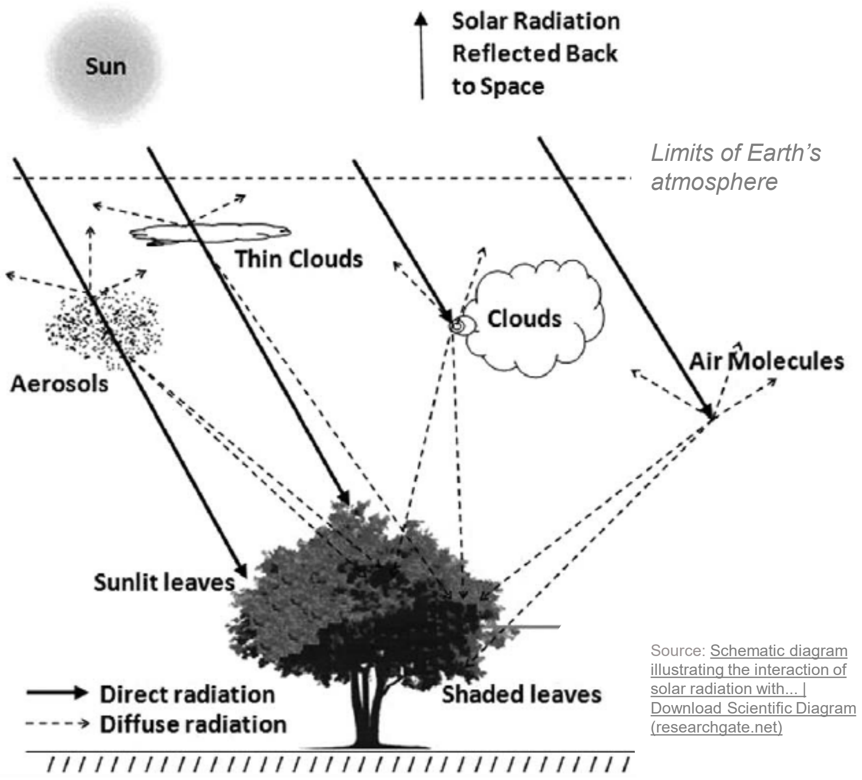
Relation between surface albedo and solar altitude angle or zenith angle for snow-free conditions (urban data include cities of Hamilton, St. Louise, Vancouver, Basel)

Solar Irradiance

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

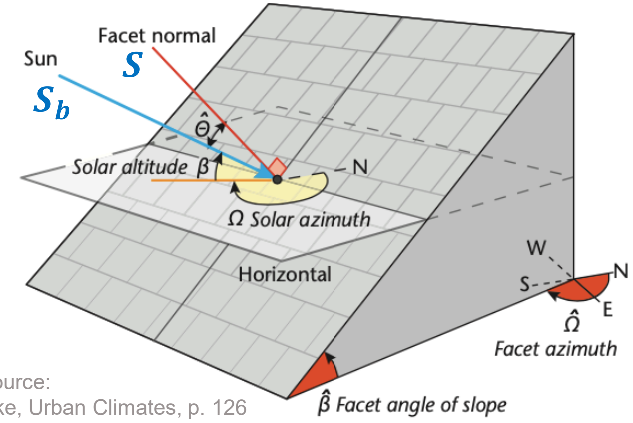
$$K_\downarrow = S + D \quad (3\text{-}32)$$

  - **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*)



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

- The amount of **direct irradiance S** incident on a surface depends *on its inclination*:

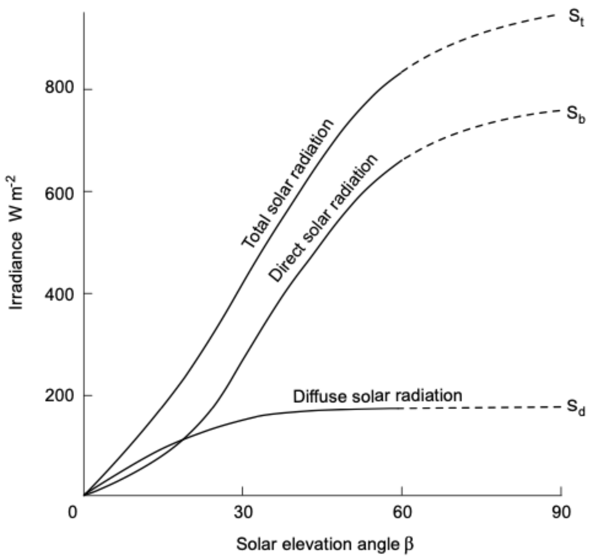


Source: Oke, Urban Climates, p. 126

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

- 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

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



← 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** $\boldsymbol{Q^*}$ *at any surface* is **the sum** of the budget of **net shortwave** $\boldsymbol{K^*}$ and **net longwave** $\boldsymbol{L^*}$ radiation flux.

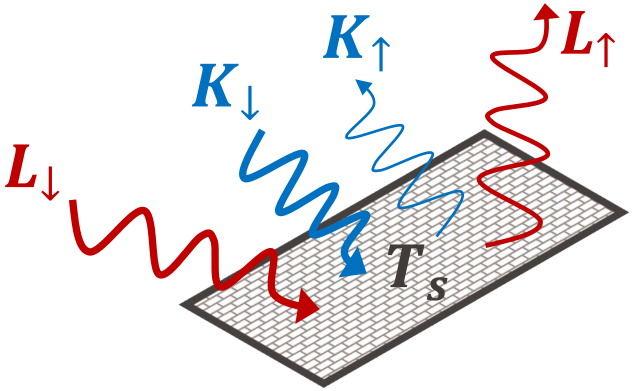
$$Q^* = K^* + L^* \quad (3\text{-}35) \qquad K^* = K_\downarrow - K_\uparrow \quad (3\text{-}36) \qquad L^* = L_\downarrow - L_\uparrow \quad (3\text{-}37)$$

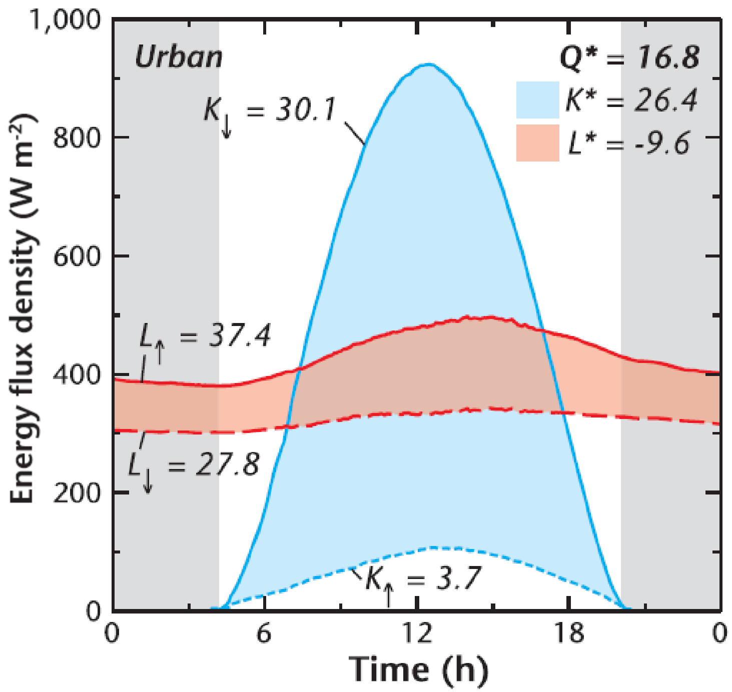
- **Upwelling shortwave flux** $\boldsymbol{K_\uparrow}$ is dominantly due to *surface reflectance* and it is primarily a function *of incident irradiance* $K_\uparrow$ and *the average surface reflectivity* (albedo).

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

- **Incoming longwave radiation** $\boldsymbol{L_\downarrow}$ 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** $\boldsymbol{L_\uparrow}$ from a surface depends on its ability to *both emit* and *reflect longwave radiation*

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





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

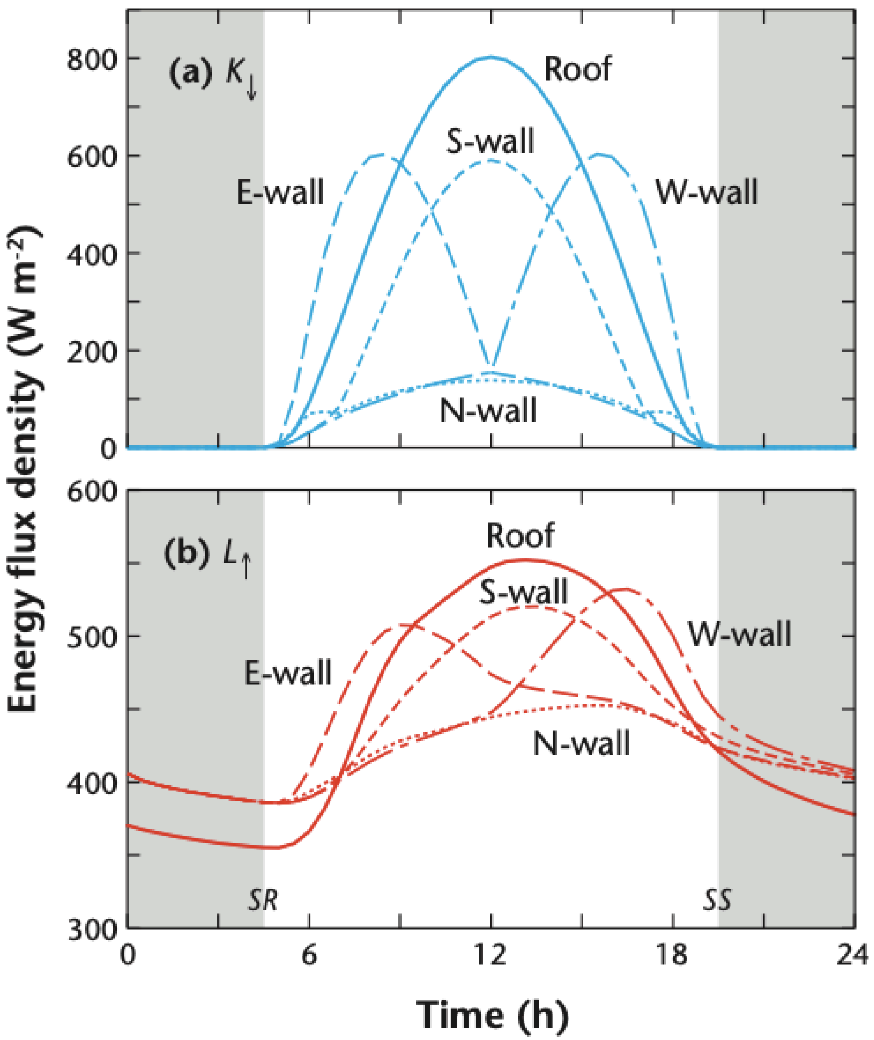
Surface Radiation Budget: Building Surfaces

- 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* form *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

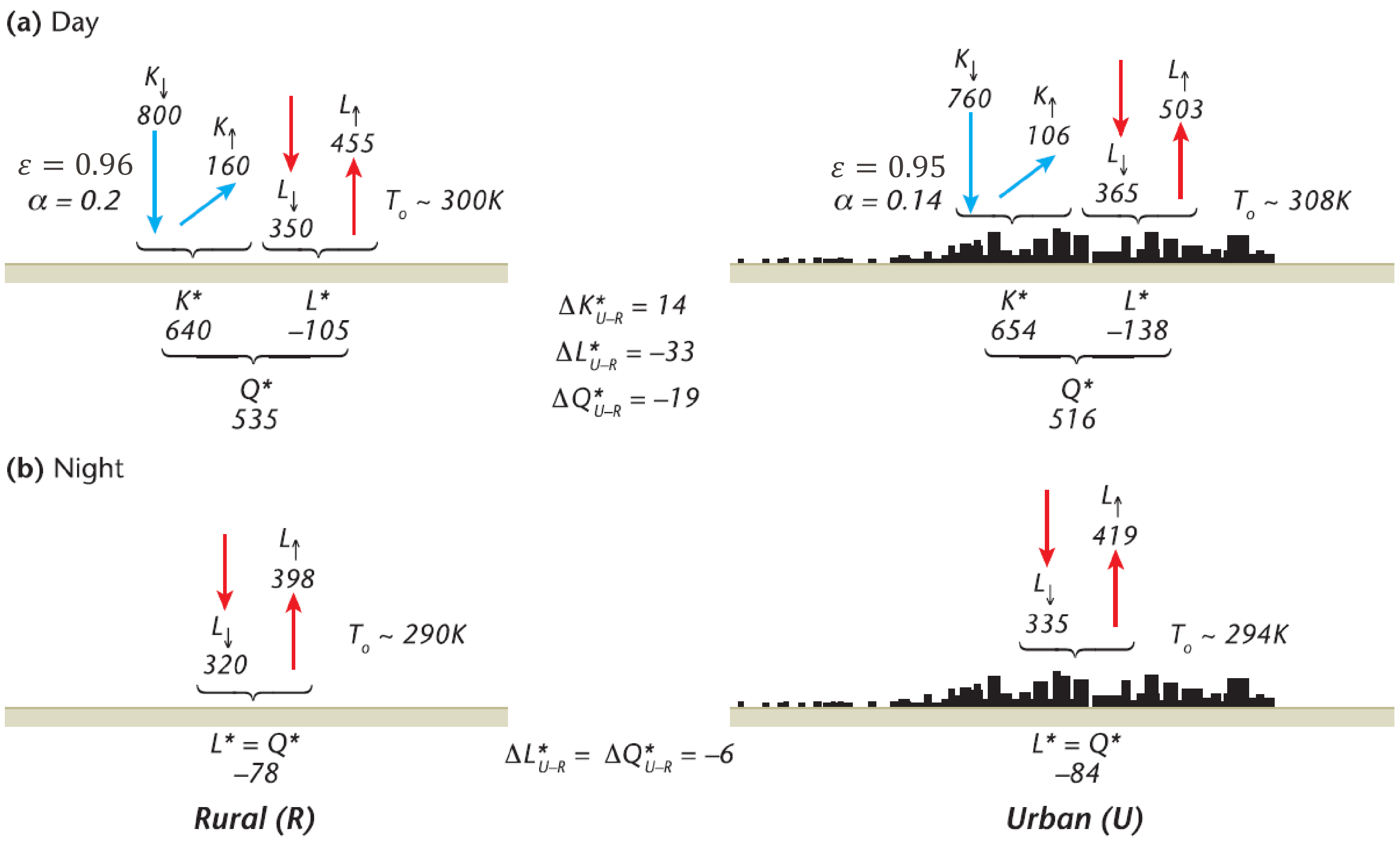


The daily course of (a) incoming shortwave and (b) outgoing longwave radiation fluxes for the walls and roof of an isolated cube-shaped building at 49N on August 15th

Assist. Prof. Dolaana Khovalyg

Surface Radiation Budget: Urban vs. Rural

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

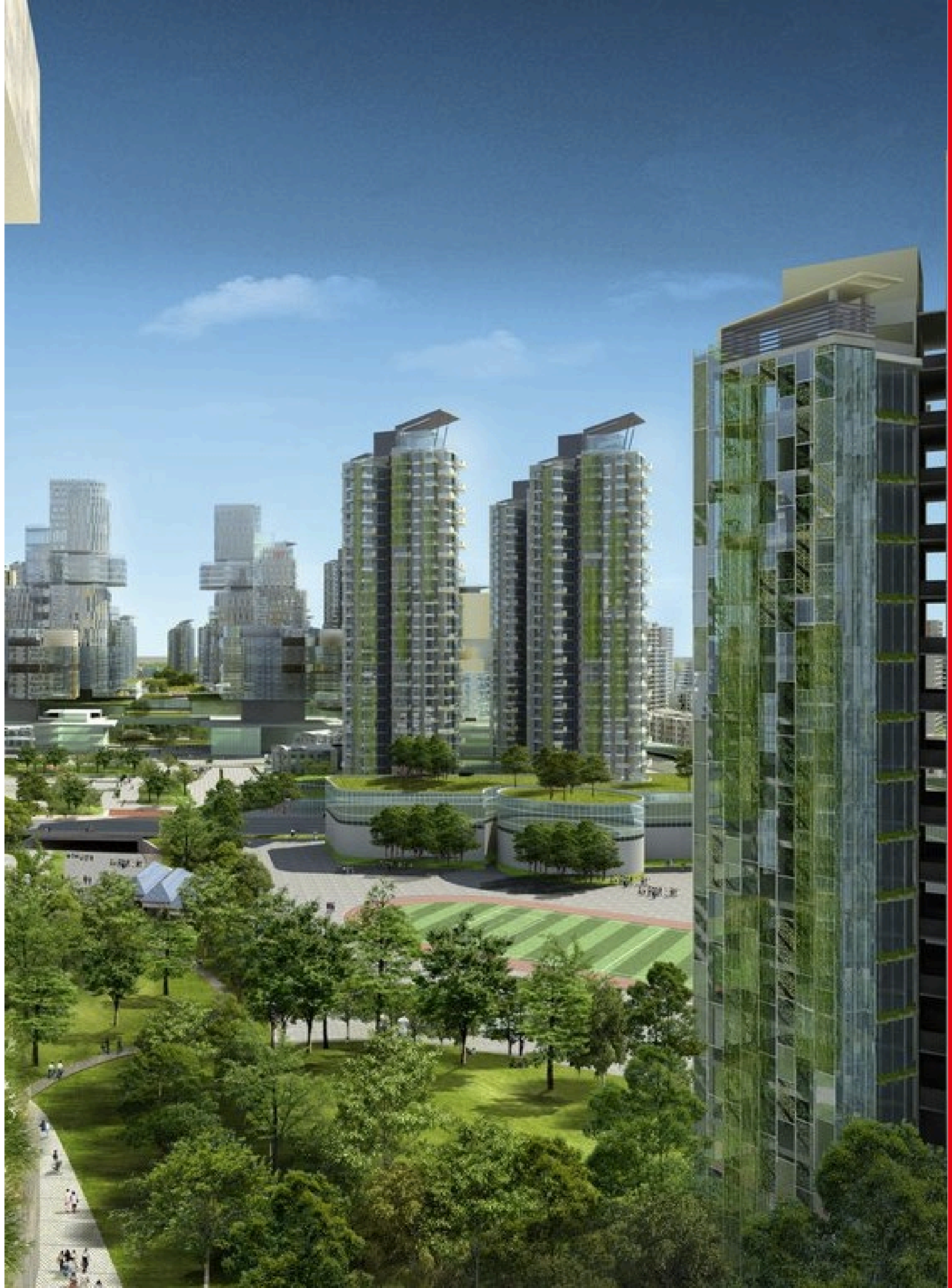


*urban depletion of shortwave irradiance $K_{\downarrow}$ is taken as 5%

Source: Oke, Urban Climates, p. 153

Assist. Prof. Dolaana Khovalyg

EPFL



Thank you for your attention

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