Universität
Bremen

Fachbereich 4
Produktionstechnik
Maschinenbau &
Verfahrenstechnik

People 4
Production

Heat Happens: Thermodynamics in Daily Life

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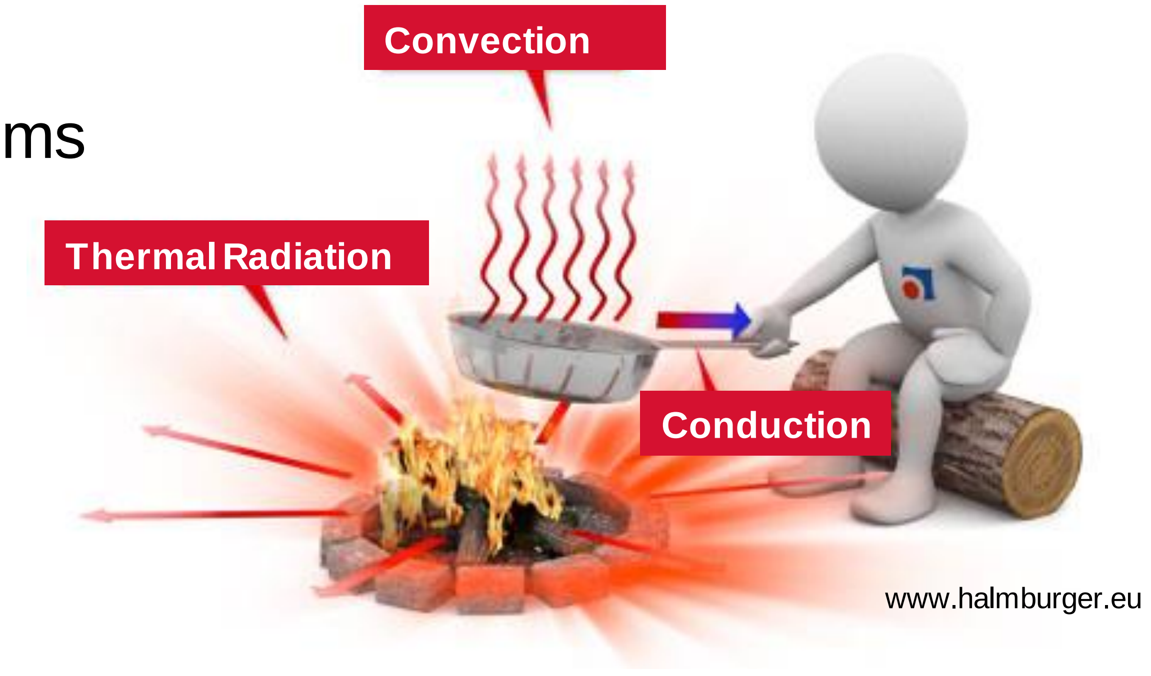
Outline

- Introduction to Heat as a Form of Energy
- Relationship between Thermodynamics and Heat Transfer
- Introduction to the 3 Types/Mechanisms of Heat Transfer
  - Conduction
  - Convection
  - Thermal Radiation



www.halmburger.eu

Forms of Energy: Heat and Work

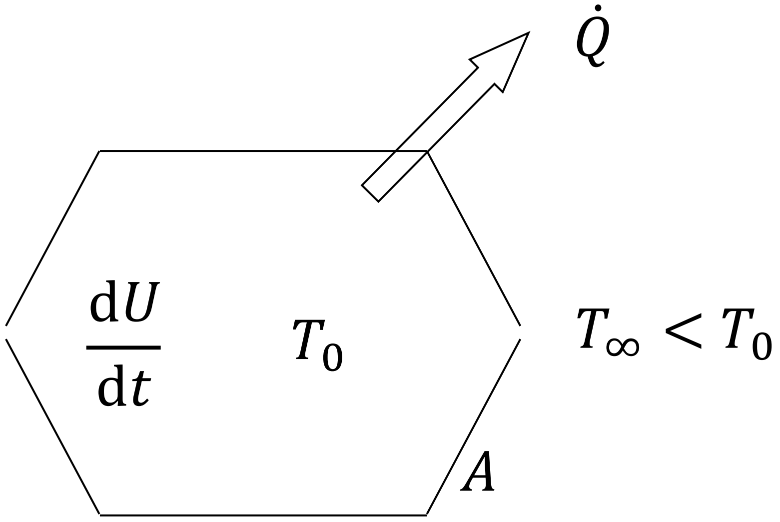
- Heat and work appear only during a process while crossing the system boundary.
  They change the energy content of the system (internal energy *U* or enthalpy *H*, kinetic energy, potential energy) → law of energy conservation (First Law of Thermodynamics)

- Heat and work are process quantities (not state quantities; there is no “heat content” or “work content” of a system), since the heat or work transferred across the system boundary depends on the chosen process

- According to the general convention:
  - Energy supplied to a system has a positive sign
  - Energy removed from a system has a negative sign

Form of Energy: Heat

- Heat is energy that crosses the system boundary between the system and the surroundings solely due to a temperature difference and without work being involved
- Heat is transferred only in the direction of decreasing temperature (this follows from the Second Law of Thermodynamics)
- The common symbol for heat (*Wärme*) is *Q*
  Unit: [*Q*] = J (joule)
- Heat flow rate (*Wärmestrom*) $\dot{Q}$: heat transferred per unit time
  Unit: [$\dot{Q}$] = J/s = W (watt)



Relationship Between Thermodynamics & Heat Transfer

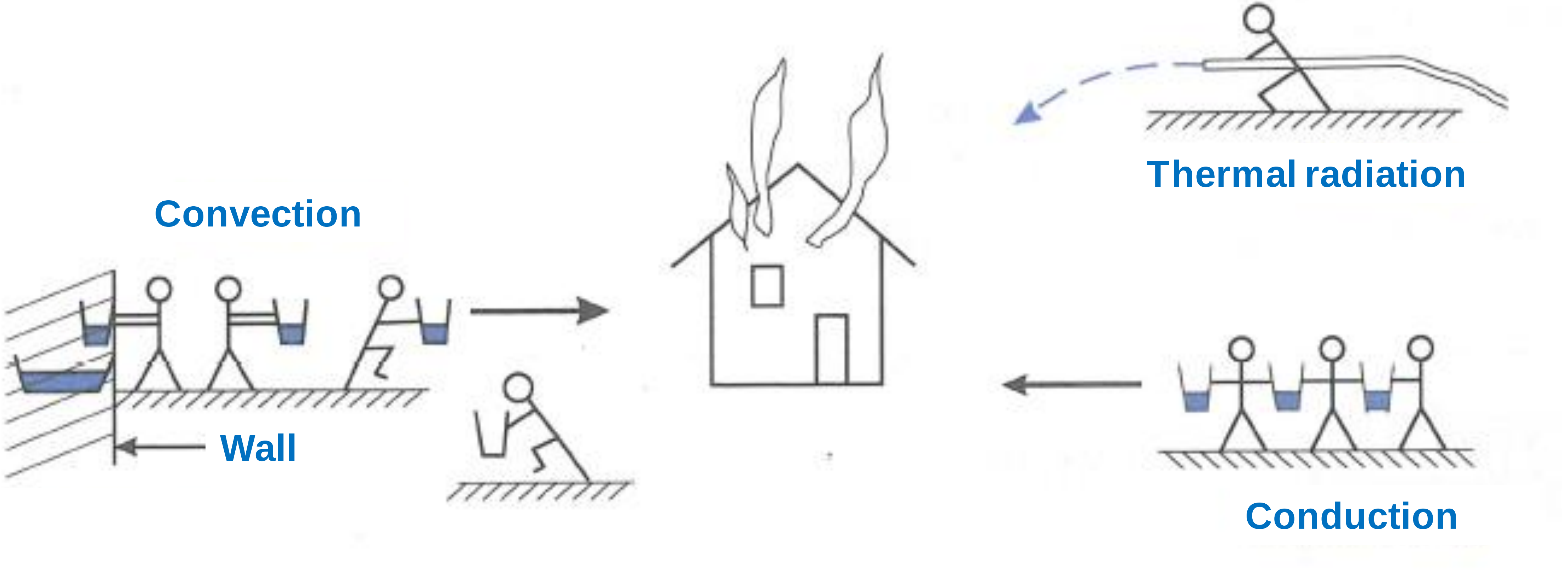
Thermodynamics

- Heat Q is a form of energy
- Heat Q crosses the system boundary only during a process due to a temperature difference ΔT
- The First Law of Thermodynamics relates heat Q or heat flow rate $\dot{Q}$ to changes in internal energy U or enthalpy H and changes in kinetic and potential energy
- The Second Law of Thermodynamics states that heat always flows across the system boundary from higher to lower temperatures
- **No** statement is made about how the heat flow rate depends on the driving temperature difference
- **No** statement is made about how fast or how intensely the heat transfer process occurs
- **No** quantitative relationship is provided between heat and process conditions (e.g., flow conditions, geometries, materials, etc.)

Heat Transfer

- Description and quantification of the different types/mechanisms of heat transfer (conduction, convection, thermal radiation)
- Determination of the laws governing heat transport
- Volume and mass elements of a solid body or a fluid are considered as small systems (continuum theory)
- Therefore, there is no contradiction with thermodynamics when heat flows occur within a solid body or within a fluid (liquid or gas)

Mechanisms of Heat Transport



Thermal radiation

Convection

Wall

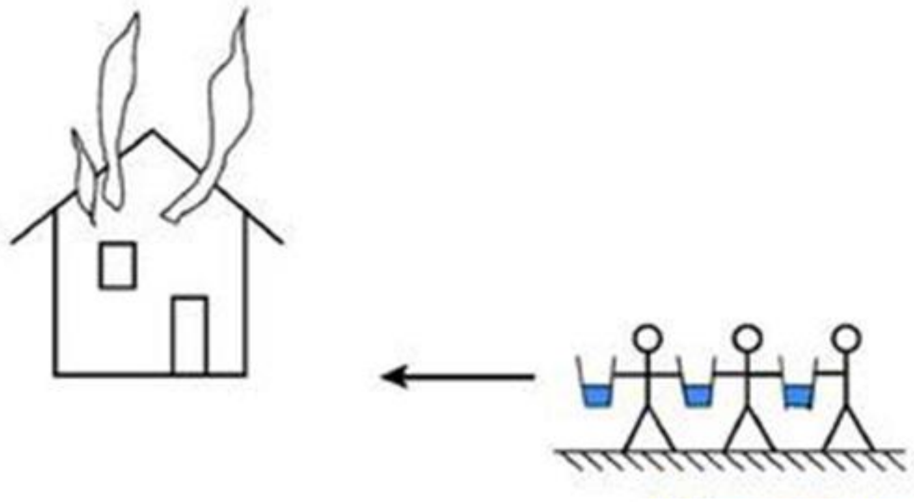
Conduction

(W. Polifke, J. Kopitz, Wärmeübertragung, 2009)

The three heat transport mechanisms illustrated by analogy with water transport in firefighting

Conduction (1)

- **Conduction is the transport of energy between neighboring atoms due to a temperature difference within the material**
- **Atomic/molecular interactions**
- In metals, free electrons also transfer energy
- In opaque solids (= not transparent to thermal radiation), heat is transferred internally only by conduction
- In gases and liquids, conduction is superimposed by energy transport due to fluid motion (convection) and by thermal radiation



(W. Polifke, J. Kopitz, Wärmeübertragung, 2009)

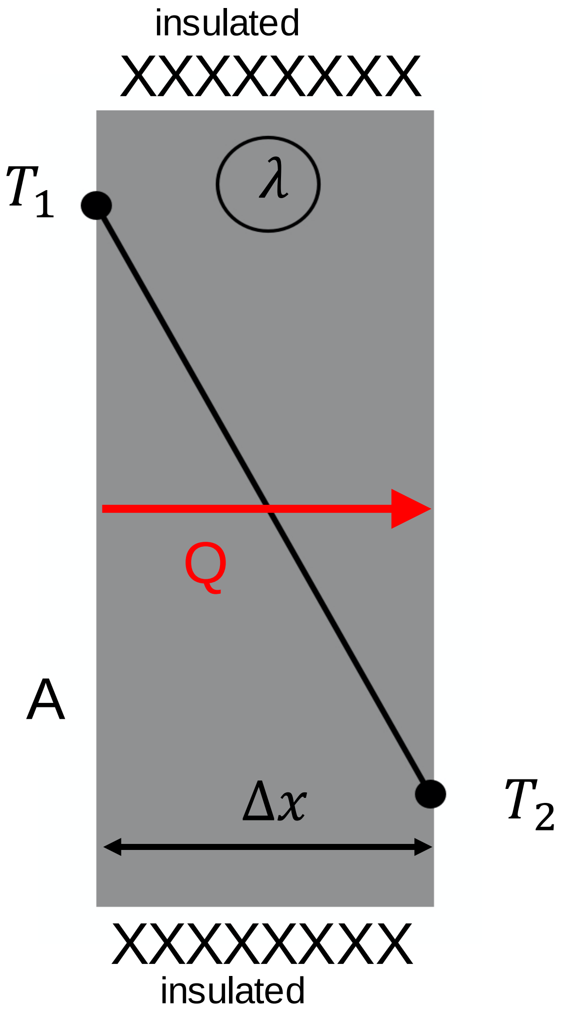
Conduction illustrated by analogy with water transport in firefighting

Conduction (2)

Example: Steady-state conduction through a plane wall with insulated lateral surfaces

- One surface is maintained at temperature T_1, the opposite surface at T_2
- The heat Q transferred through the wall from the side at temperature T_1 to the side at temperature T_2 is
  - proportional to the temperature difference $(T_1 - T_2)$
  - proportional to the area A
  - proportional to the time interval Δt
  - inversely proportional to the wall thickness Δx
  - strongly dependent on the wall material

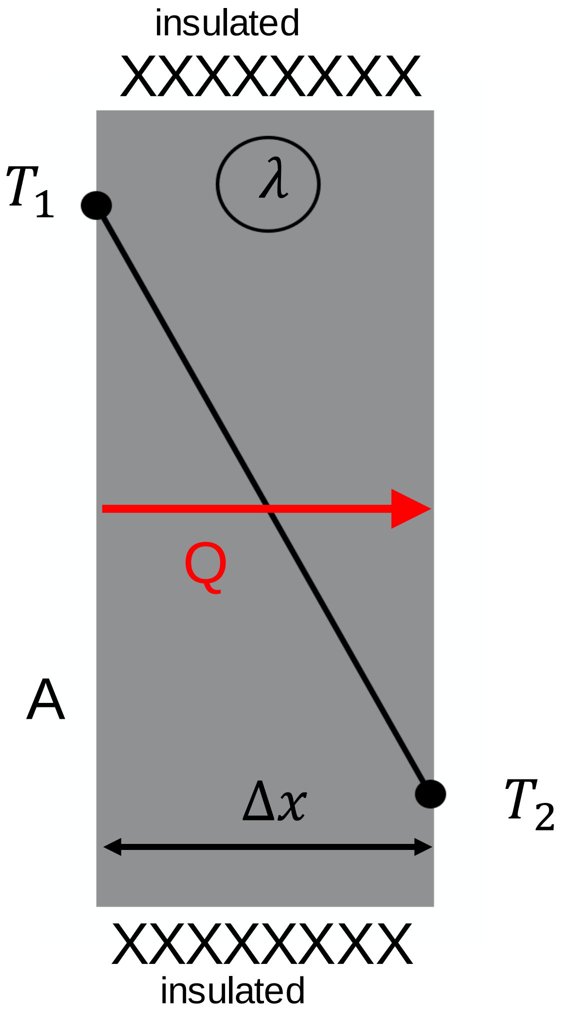
$$\boxed{Q = \lambda \cdot \frac{T_1 - T_2}{\Delta x} \cdot A \cdot \Delta t}$$



Conduction (3)

$$\boxed{Q = \lambda \cdot \frac{T_1 - T_2}{\Delta x} \cdot A \cdot \Delta t}$$

- The proportionality factor λ is a material property: **thermal conductivity (*Wärmeleitfähigkeit*)**
- Unit of thermal conductivity: $[\lambda] = \frac{\mathrm{W}}{\mathrm{m\,K}}$



Conduction (4)

$$\boxed{Q = \lambda \cdot \frac{T_1 - T_2}{\Delta x} \cdot A \cdot \Delta t}$$

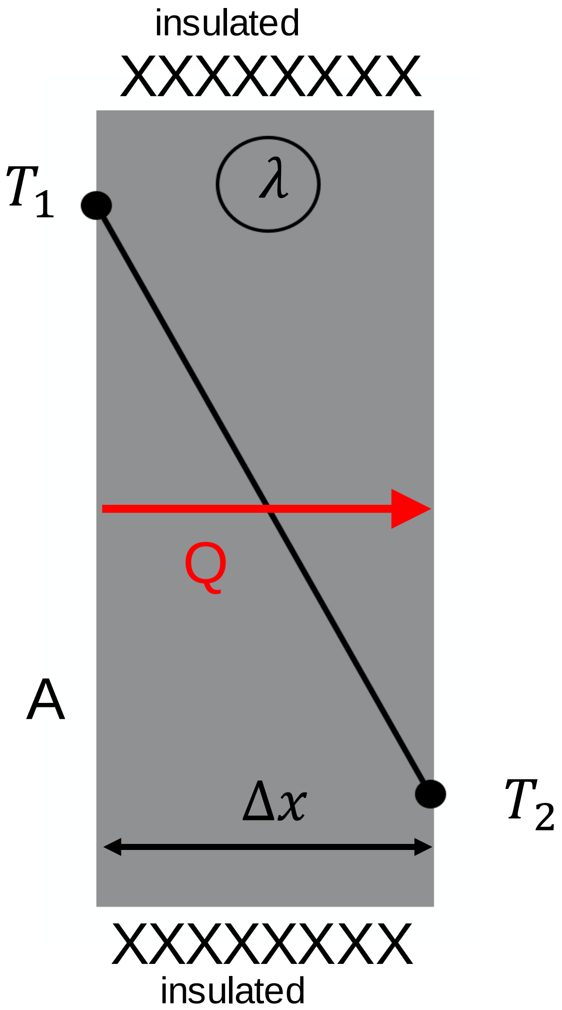
$$\frac{Q}{\Delta t\, A} = \lambda \cdot \frac{T_1 - T_2}{\Delta x}$$

$$\dot{q}_\mathrm{x} = \frac{Q}{\Delta t\, A} = \lambda \cdot \frac{T_1 - T_2}{\Delta x}$$

Heat flux (*Wärmestromdichte*) $\dot{q}$: heat transferred per unit area and unit time

Fourier's law of conduction
(one-dimensional in the x-direction):

$$\dot{q}_\mathrm{x} = -\lambda \cdot \frac{\mathrm{d}T}{\mathrm{d}x}$$



Conduction (5)

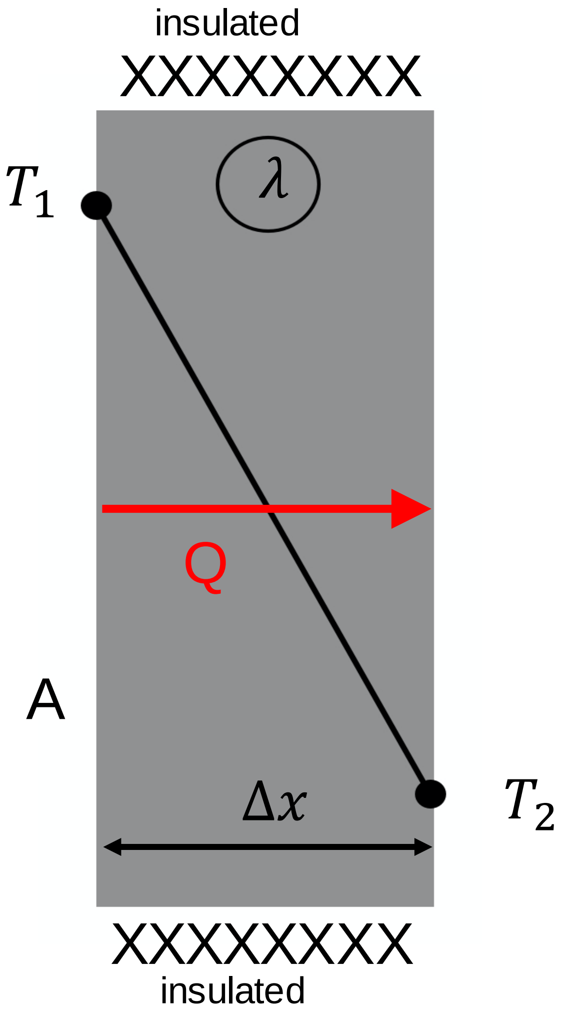
Fourier's law of conduction
(one-dimensional in the x-direction):

$$\dot{q}_\mathrm{x} = -\lambda \cdot \frac{\mathrm{d}T}{\mathrm{d}x}$$

Unit of heat flux: $[\dot{q}]$ = J/(s m²) = W/m²

Unit of thermal conductivity: $[\lambda]$ = W/(m K)

Minus sign: heat flux in the direction of decreasing temperature is positive (Second Law of Thermodynamics)



Thermal Conductivity (1)

- **Thermal conductivity decreases from solids to liquids to gases** because the average distance between particles increases and energy transfer by molecular interactions becomes less effective
- **Metals:** very high thermal conductivities (free electrons also transfer energy)
- **Solid electrical insulators:** lower thermal conductivities
- **Liquids and especially gases:** very low thermal conductivities
- **Thermal conductivity λ at 20 °C and 1 bar:**
  - **Copper:** **$\lambda = 399$ W/(m K)**
  - **Water:** **$\lambda = 0.6$ W/(m K)**
  - **Air:** **$\lambda = 0.026$ W/(m K)**

Material class	**λ in W/(m K)**
Gases at 1 bar	0.007 – 0.17
Insulation materials	0.02 - 0.20
Non-metallic liquids	0.08 - 0.70
Non-metallic solids (stone, concrete)	0.03 - 2.1
Liquid metals	8 - 70
Alloys	13 - 120
Pure metals	50 - 400

Thermal Conductivity (2)

- **Thermal conductivity depends on temperature and pressure $\boldsymbol{\lambda = \mathrm{f}(T, p)}$**
- **Pressure dependence** must only be considered for gases and liquids
- **Temperature dependence is often weak,** so λ can often be assumed constant over a temperature range
- **Isotropic materials:** thermal conductivity is the same in all directions
- **Anisotropic materials:** direction-dependent thermal conductivity (e.g., wood)

Material Class	**λ in W/(m K)**
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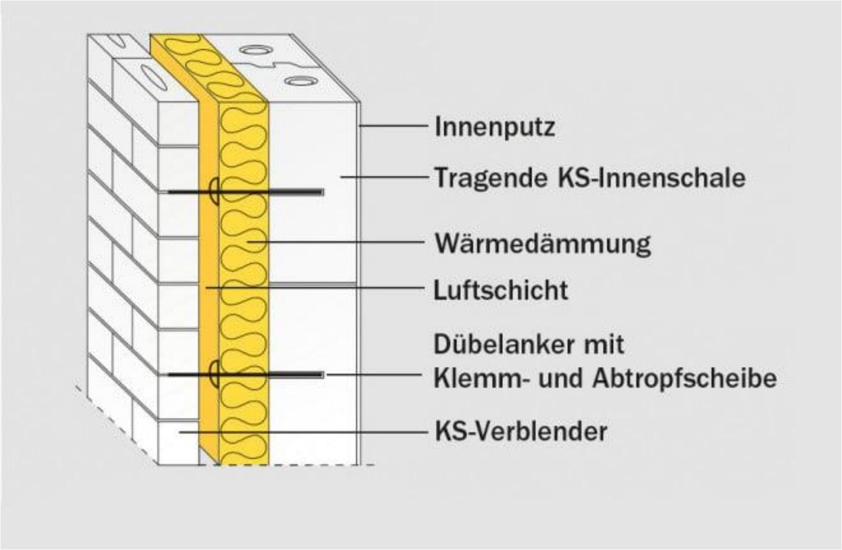
Non-metallic solids (stone, concrete)	0.03 - 2.1
Liquid metals	8 - 70
Alloys	13 - 120
Pure metals	50 - 400

Examples of Heat Conduction in Everyday Life

Heat conduction through a metal spoon in hot tea

www.colourbox.de

Heat conduction through a multi-layer house wall



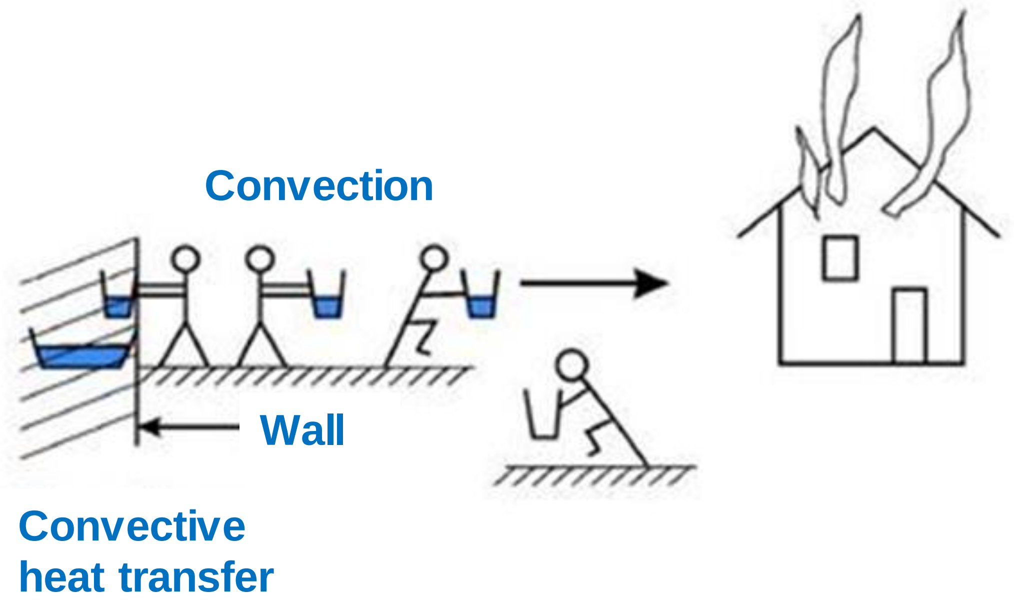
www.baunetzwissen.de

Heat conduction through the metal bottom of a cooking pot on an electric stove

www.dreamstime.com

Convection (1)

- **In a flowing fluid, energy is transported not only by conduction, but also by the macroscopic motion of the fluid**
- **Convection is the transport of energy by the motion of a flowing fluid**



(W. Polifke, J. Kopitz, Wärmeübertragung, 2009)

Convection illustrated by analogy with water transport in firefighting

Convection (2)

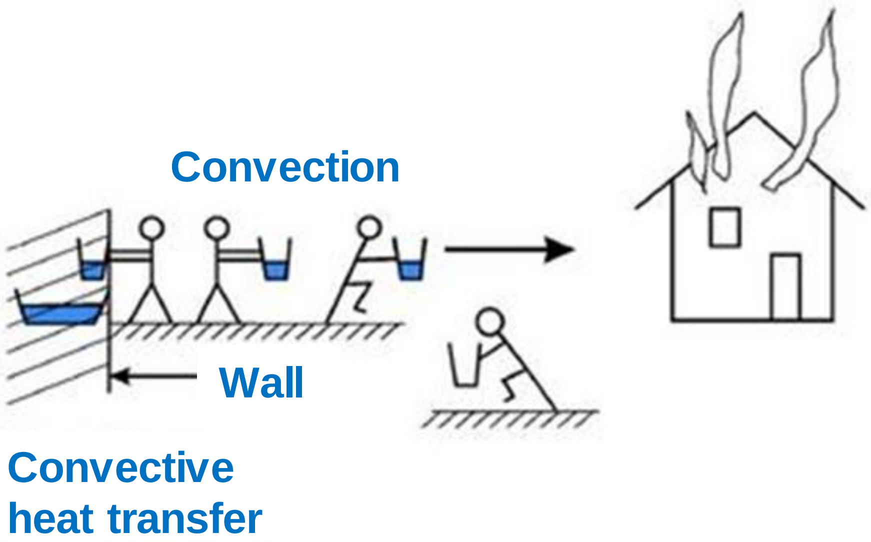
- **Convective heat transfer (*Wärmeübergang*) between a flowing fluid and a wall**
- The fluid layer close to the wall (boundary layer) is of particular importance
- Heat flux at the wall:

$$\dot{q}_\mathrm{w} = \alpha \cdot (T_\mathrm{w} - T_\infty)$$

T_w: Wall temperature

T_∞: Fluid temperature at a sufficiently large distance from the wall

α: (Convective) heat transfer coefficent (*Wärmeübergangskoeffizient*), Unit: $[\alpha] = \mathrm{W/(m^2\,K)}$



(W. Polifke, J. Kopitz, Wärmeübertragung, 2009)

Convection illustrated by analogy with water transport in firefighting

Forced Convection

Fluid flow enforced by a fan or pump, e.g., along a heated flat plate

www.de.weber/blog/fassade-wand/sommerlicher-waermeschutz

Free/Natural Convection

Fluid flow caused by fluid density differences due to temperature differences, e.g., along a vertical heated plate

- Temperature difference

→ Fluid density difference in the Earth‘s gravitation field

→ Upward buoyancy-driven flow

→ Fluid velocity at some distance from the wall (outside the boundary layer) is zero

www.heizung-staudinger.de

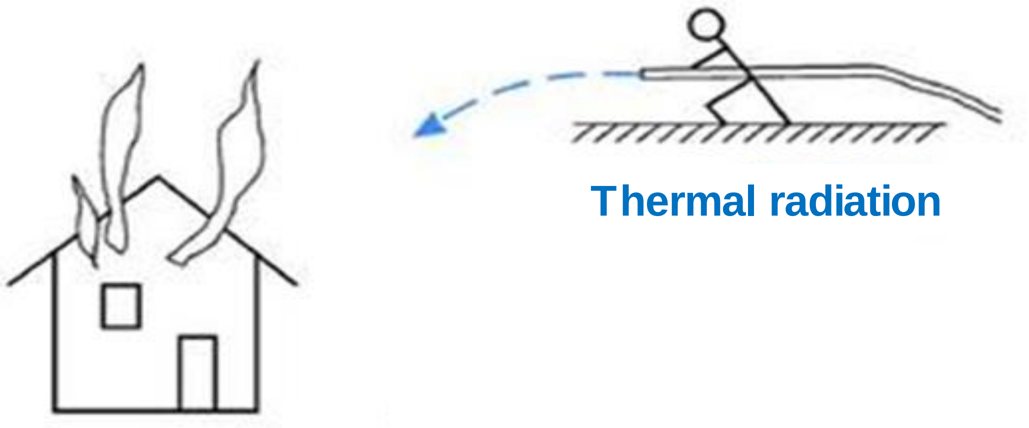
The Heat Transfer Coefficient

- **The heat transfer coefficient α depends on the process and must be calculated!**
- The table only provides an overview of the order of magnitude of the heat transfer coefficient

Vorgang	**α in W/(m² K)**
Air, free convection	2 - 15
Air, forced convection	30 - 200
Water, free convection	200 - 1.000
Water, forced convection	2.000 - 12.000
Boiling	2.000 - 60.000
Condensation	5.000 - 100.000

Thermal Radiation (1)

- **Thermal radiation (thermal emission, temperature radiation) is the transport of energy by electromagnetic waves**
- **Radiation is not bound to matter (it can also propagate through a vacuum)**
- Emission (release of radiation) means conversion of internal energy into energy transported by electromagnetic waves
- When electromagnetic waves strike matter, the energy can be
  - **absorbed** and converted into internal energy,
  - **reflected**,
  - **transmitted** through the material



(W. Polifke, J. Kopitz, Wärmeübertragung, 2009)

Thermal radiation illustrated by analogy with water transport in firefighting

Thermal Radiation (2)

Spectrum of elektromagnetic waves

- Very short wavelengths $\lambda < 10^{-8}$ m:

  Gamma rays and X-rays which are not thermally generated

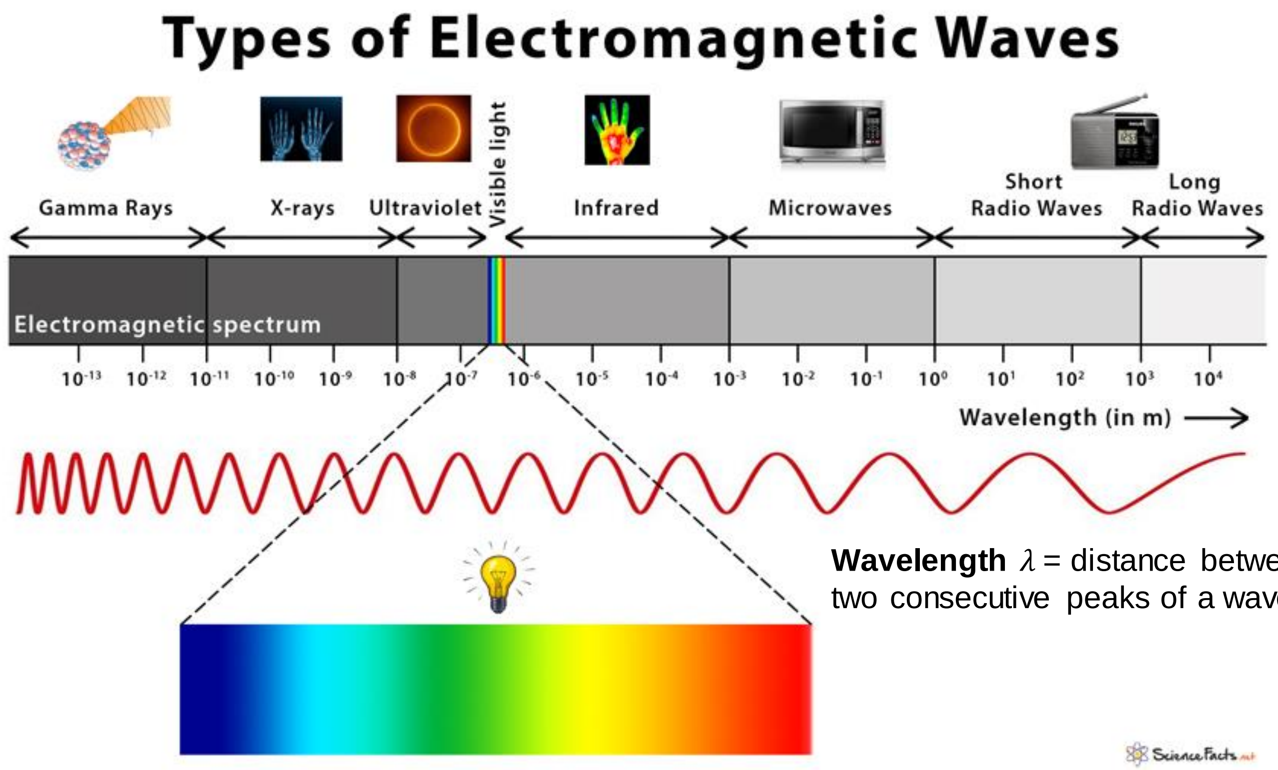
- Very long wavelengths $\lambda > 10^{-3}$ m:

  Microwaves and radio waves, which are not thermally generated

- **Intermediate wavelength range (somewhat arbitrary definition)**
  $\mathbf{10^{-7}\ m} < \boldsymbol{\lambda} < \mathbf{10^{-3}\ m}$:

  Thermal radiation

  - **also includes visible light**
    $\mathbf{0,38\ \mu m\ (violet)} < \boldsymbol{\lambda} < \mathbf{0,78\ \mu m\ (red)}$



Wavelength λ = distance between two consecutive peaks of a wave

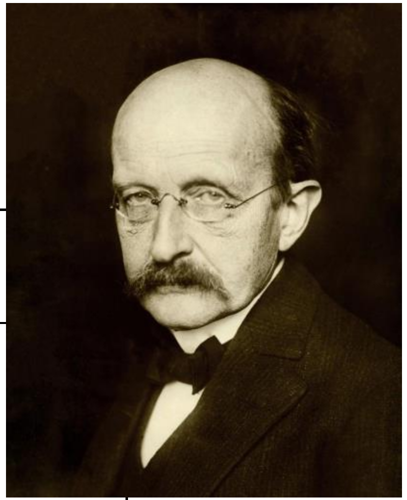
https://www.sciencefacts.net/electromagnetic-waves.html, 30.05.2026

Spectrum of elektromagnetic waves

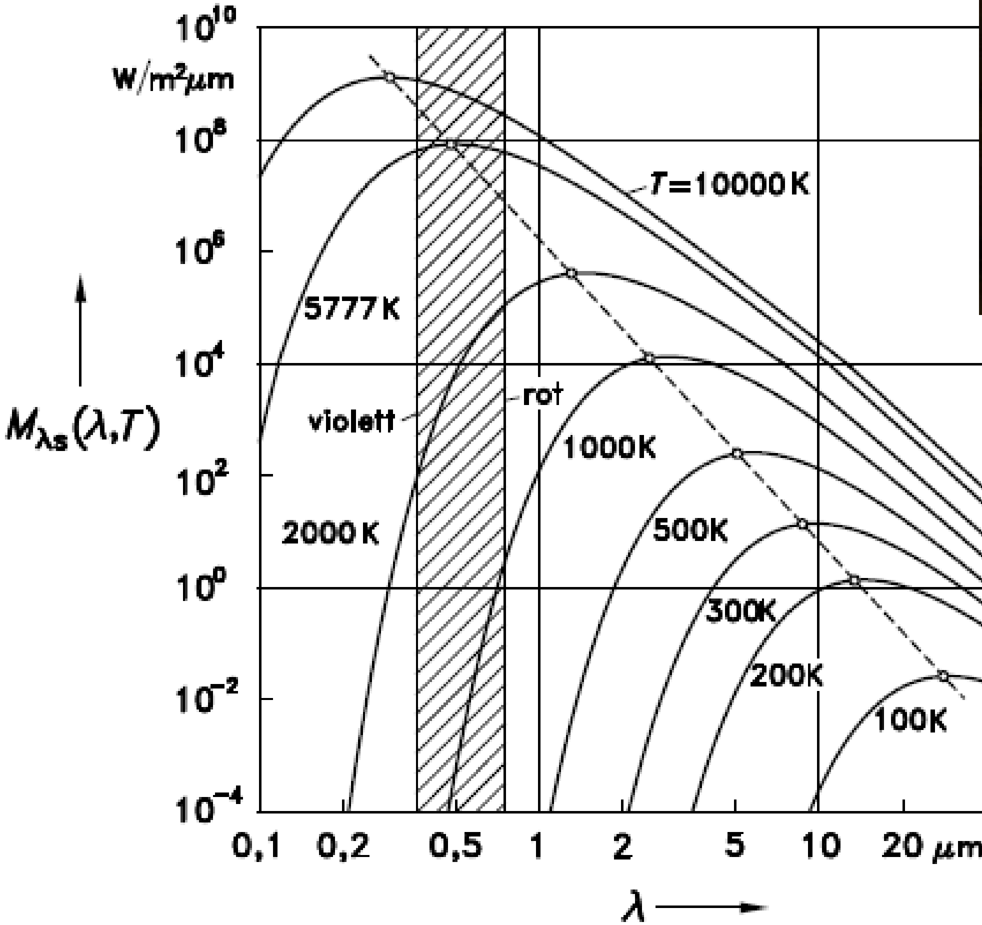
https://alchetron.com/Max-Planck

Thermal Radiation (3)

- **A significant amount of thermal radiation falls within the visible wavelength range only at sufficiently high temperatures.**
- **It is only at the so-called Draper point, at 798 K (525 °C), that a heated body in a dark environment becomes visible to the human eye as a dark red object.**
- The sun emits radiation with a spectral emissive power that closely corresponds to that of a black body at 5777 K. As shown in the Figure, the maximum of spectral emissive power $M_{\lambda,s}$ at this temperature lies within the visible spectral range. The human eye has adapted to this and exhibits its highest sensitivity at these wavelengths.



Max Planck
1858 - 1947



Baehr, Stephan, Wärme- und Stoffübertragung, 2019

Spectral emissive power $M_{\lambda,s}(\lambda,T)$ (*spektrale spezifische Ausstrahlung*) of a black body as predicted by Planck's law, plotted on a logarithmic scale. The shaded wavelength range corresponds to the visible spectrum.

Thermal Radiation (4)

- **Stefan-Boltzmann law:**

  For a **black body** (subscript “b“):

  Heat flux: $\dot{q}_\mathrm{b} = \sigma \cdot T^4$ (T in Kelvin!)

  Stefan-Boltzmann constant σ :

  $\sigma = 5.6704 \cdot 10^{-8}$ W/(m^2 K^4)

- For a **grey body**:

  $\dot{q} = \varepsilon \cdot \sigma \cdot T^4$ (T in Kelvin!)

  ε: emissivity or emission coefficient (*Emissionskoeffizient, Emissionsgrad*)

  $0 < \varepsilon \leq 1$

- Radiation depends on the absolute temperature level

- **Black body:** incident radiation is completely absorbed
- **White body:** incident radiation is completely reflected
- **Grey body:** incident radiation is not completely absorbed; absorption is independent of wavelength
- **Coloured body:** incident radiation is not completely absorbed; absorption depends on wavelength

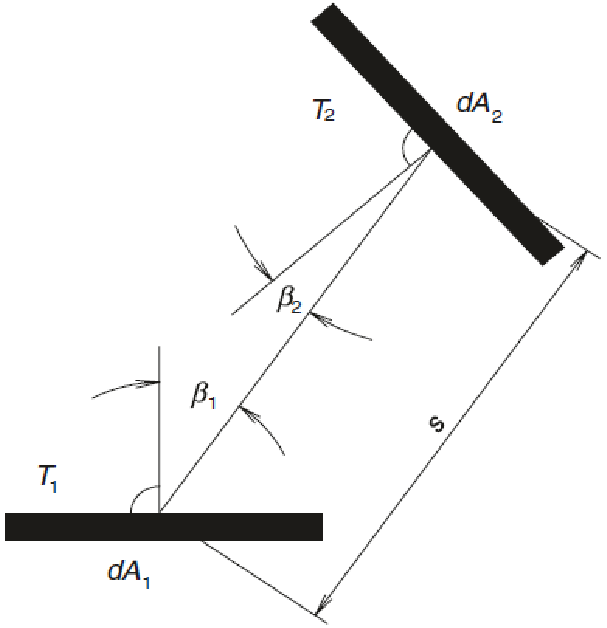
Thermal Radiation (5)

Thermal radiation exchange (*Strahlungsaustausch*) between two grey bodies:

$$\dot{q} = \sigma \cdot F_{12} \cdot (T_1^4 - T_2^4) \quad \text{with } T_1 > T_2$$

$\boldsymbol{F_{12}}$ **accounts for**

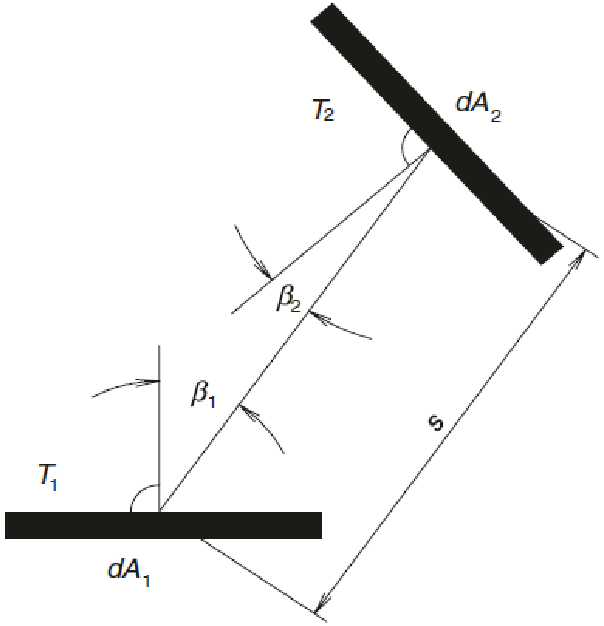
the radiation properties of both bodies ($\boldsymbol{\varepsilon_1}$ **und** $\boldsymbol{\varepsilon_2}$) and
their relative orientation to each other



Thermal Radiation (6)

Thermal radiation differs from conduction and convective heat transfer because it is governed by different physical laws:

- Thermal radiation is **not bound to matter**; electromagnetic waves can transfer energy even through empty space (vacuum)
- Heat transfer by radiation is not governed by temperature gradients or temperature differences, but by **differences in the fourth power of the thermodynamic (absolute) temperatures of the bodies**
- Thermal radiation **depends on wavelength**; the energy emitted by a body is distributed unevenly across the electromagnetic spectrum
- The amount of radiation exchanged between two bodies also **depends on their relative orientation and position**.



$$\dot{q} = \sigma \cdot F_{12} \cdot (T_1^4 - T_2^4)$$

The Three Mechanisms of Heat Transfer

Conduction

Energy transport by atomic/molecular interactions due to a temperature difference

Fourier's law of conduction:

One-dimensional:

$$\dot{q}_{\mathrm{x}} = -\lambda \frac{dT}{dx}$$

$$\dot{Q} = -\lambda\, A \frac{dT}{dx}$$

Convective Heat Transfer

In a flowing fluid, energy is transported by the macroscopic motion of the fluid; always accompanied by energy transport through conduction

Heat transfer between a solid wall and a flowing fluid:

$$\dot{q}_w = \alpha\,(T_w - T_\infty)$$

$$\dot{Q} = \alpha\, A\,(T_w - T_\infty)$$

Thermal Radiation

Energy transport by electromagnetic waves

Stefan-Boltzmann law:

For a black body:

$$\dot{q}_{\mathrm{b}} = \sigma\; T^4$$

For a grey body:

$$\dot{q} = \varepsilon\;\sigma\; T^4$$

Radiation exchange between two grey bodies with $T_1 > T_2$:

$$\dot{q} = \sigma\; F_{12}\,(T_1^4 - T_2^4)$$