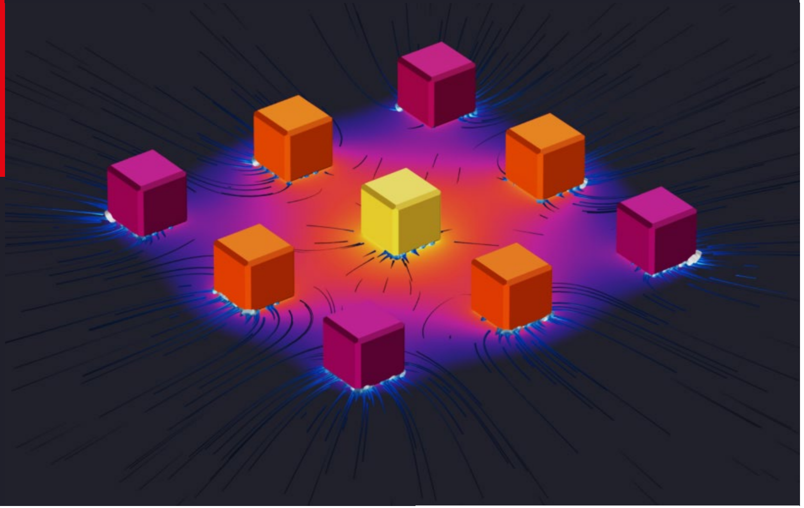
Heat and Mass Transfer
ME-341

Instructor: Giulia Tagliabue



École
polytechnique
fédérale
de Lausanne

Spring Semester

Practical Information about the course

Lectures on:

- Tuesday 9:15 – 10:00
- Wednesday **9:10 – 9:55**
- Wednesday **10:10 – 10:55**

In-person Lectures (please attend)
PAST recordings on SwitchTube (see Moodle)
Live streaming available but not optimized

Exercise Sessions on Tuesday 8:15 – 9:00

TAs available in person for questions

Forum for questions on Moodle

Instructors:

- Prof. Giulia Tagliabue
- TAs :
  - Milad Sabzehparvar (milad.sabzehparvar@epfl.ch)
  - Matteo Bevione (matteo.bevione@epfl.ch)
  - Ibrahim Elhagali (ibrahim.elhagali@epfl.ch)
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  - Yan Meng (yan.meng@epfl.ch)
  - Gloria Davidova (gloria.davidova@epfl.ch)
  - German Garcia Martinez (german.garciamartinez@epfl.ch)

Practical Information about the course

Textbook:

Incropera et al. – Fundamentals of Heat and Mass Transfer – 6th Ed.

- Slides will be posted on Moodle before the class.
- Exercises are assigned weekly, solutions are available before the weekend, TAs can respond to questions on the NEXT Tuesday.

Exercises are not graded but they reflect the difficulty level of the exam. Practice them!

Grade will be determined by the final written examination (exercises are not graded)

Weekly Course Plan

	Week Topic	H1 (Tue 8-9)	H2 (Tue 9-10)		H3 (Wed 9-10)	H4 (Wed 10-11)
Week 1	Intro + Steady State Heat Conduction	**W1L1** - Intro	**W1L2 -** Heat diffusion equation		**W1L3 -** Boundary Conditions; 1D planar & cylindrical solutions	**W1L4 -** Concept of Thermal Resistance; Bi Number; Intro to Thermal Circuits
Week 2	Steady State Heat Conduction wth/without Sources	exercises - HW 1	**W2L1 -** Thermal Circuits and Overall Heat Transfer Coefficient		**W2L2 -** 1D steady-state Heat Conduction With Heat Sources;	**W2L3 -** Problems on 1D Steady State with Heat sources; 2D Conduction
Week 3	Fins	exercises - HW 2	**W3L1** - Fins : Introduction to Extended surfaces concept		**W3L2** - Fins : Boundary Conditions, Fin temperature Profiles, Heat transfer from a Fin; solved exercises	**W3L3** - Fins: Fin Performance and Fin Arrays
Week 4	Transient Heat Conduction	exercises - HW 3	**W4L1 -** Transient Heat: Lumped capacitance Model		**W4L2** - Transient Heat: Generalized Solution for Planar/ Radial/ Spherical Geometries	**W4L3 -** Transient Heat: Infinite Solid; Periodic Heating
Week 5	Intro to Convection +Forced External Flow	exercises - HW 4	**W5L1** - Intro Convection; Recap of Fluid Dynamics; Thermal boundary layer concept, Nu and the problem of convection		**W5L2** - thermal boundary Layer Eqns; dimensionless numbers; problem of physical properties	**W5L3** - External forced convection: flat horizontal plate (local and aerage values); Other Correlations; General Methodology for Convection (Example)
Week 6	Forced Internal Convection	exercises - HW 5	**W6L1 -** Forced Internal Convection: fluiddynamics and thermodynamics aspects		**W6L2 -** Temperature and Heat flow in internal convection; Laminar Flow In Circular Tubes;	**W6L3 -** Correlations for Internal forced convection; circular VS non-circular pipes; a note on the entrance; RECAP and Questions
Week 7	Natural Convection	exercises - HW 6	**W7L1** - Intro Free convection; Governing Equations; Gr and Ra numbers		**W7L2** - Free COnvection over a Vertical Plate and other correlations	**Dr. Narmada Gopal - COMSOL LECTURE 1 (natural convection)**

	Week Topic	H1 (Tue 8-9)	H2 (Tue 9-10)		H3 (Wed 9-10)	H4 (Wed 10-11)
Week 8	Boiling	exercises - HW 7	**W8L1** - Intro to Boiling and Condensation; Boiling Modes and Curve for Saturated Pool Boiling		**W8L2** - Correlations for Nucleate and FIlm Pool Biling; Exercises	**W8L3** - Forced Boiling (external and Internal)
Week 9	Condensation	exercises - HW 8	**W9L1** - Introduction to COndensation; Equation of Condensation on a Vertical Plate		**W9L2** - Correlations for Condensation and RECAP of Boiling and COndensation	**W9L3** - Introduction to Heat Exchangers; The problem of the overall Heat Transfer Coefficient; recap of critical concepts
Easter break						
Week 10	Heat Exchanger 1	exercises - HW 9	**W10L1 -** Fouling; Calculation of the Overall Heat Trasfer Coefficient		**W10L2** - Parallel & Counter Flow Heat Exchanger; Temperature Profile and Heat Transfer	**W10L3 -** Special Operating Conditions; Exercises
Week 11	Heat Exchanger 2	exercises - HW 10	**W11L1** - Effectiveness-NTU Method		**W11L2** - Exercises on Heat Exchanger Design	**W11L3** - Introduction to Radiation
Week 12	Radiation	exercises - HW 11	**W12L1** - Emission of Thermal Radiation		**W12L2** - Interaction of Thermal Radiation with Matter; Black Body; Real Surfaces (Kirchoff's laws etc.)	**Dr. Narmada Gopal - COMSOL LECTURE 2**
Week 13	Radiation	exercises - HW 12	**W12L3** - Exercises on Radiation		**W13L2 - Video Recording** Radiation Exchange betwwen Surfaces - view Factors	**W13L3 - Video Recording** Net radiation exchange at a surface and in a 2-surface enclosure - Electrical Analogy
Week 14	RECAP	exercises - HW 13	**W14L1** - Q&A on prior Week; Radiation Exchange on a Multi-surface Enclosure		**W14L2 -** RECAP Radiation; General Q&A about the course	**W14L3 -** RECAP Exercises

Introduction to Heat Transfer

- Where and how is energy transferred from inside to outside?
- What drives the energy transfer and in what direction does energy flows ?
- What can you do to reduce the costs of heating/cooling ?

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Where and how is energy transferred from inside to outside?

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What drives the energy transfer and in what direction does energy flow ?

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What can you do to reduce the costs of heating/cooling ?

bungee jumping
running
hiking
ice fishing
jogging
video games
weight lifting
swimming
kayaking
rock climbing

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Introduction to Heat Transfer

Q1. **What** is heat transfer?

Q2. **Why/When** does heat transfer happen?

Q3. **How** does heat transfer happen?

Introduction to Heat Transfer

Q1. **What** is heat transfer?

A1. Heat transfer is thermal energy in transit.

Q2. **Why/When** does heat transfer happen?

A2. Heat transfer happens when there is a temperature difference

Q3. **How** does heat transfer happen?

A3. Heat transfer happens in three different ways: through solids, across solid/fluid interfaces and via radiation

Heat Transfer Mechanisms

Conduction

Heat flows within solids
(or stationary fluids)

Convection

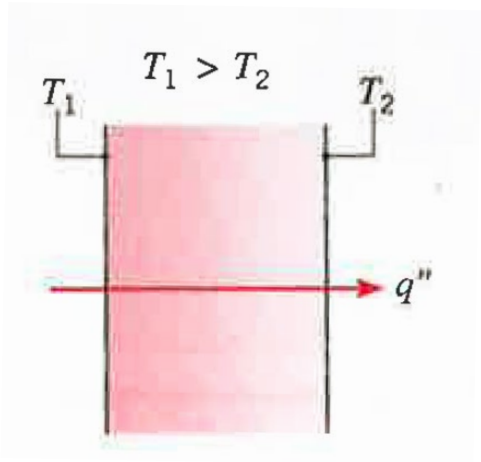
Heat flows between a moving fluid and a solid

Radiation

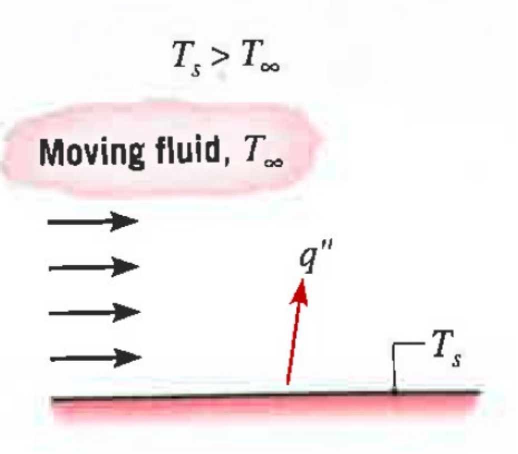
Heat flows without a medium (electromagnetic wave)

Heat Transfer Mechanisms

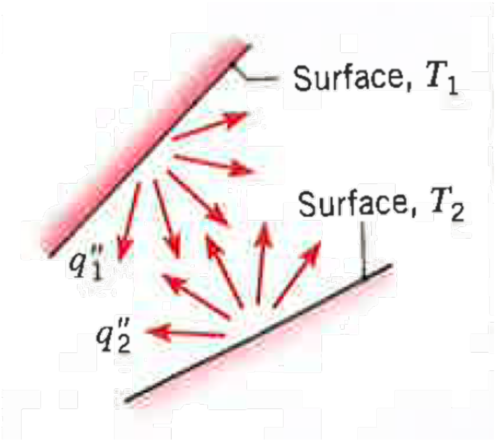
Conduction



Convection



Radiation



Involves mass transport

Involve physical contact

Introduction to Heat Transfer

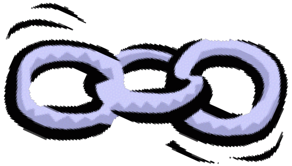
- ✓ Heat Transfer Mechanisms
- ❑ From Thermodynamics to Heat Transfer
- ❑ Overview of Transport Laws

Learning Objectives:

- ✓ From real-world to model:
  - identify the system and its boundaries
  - Identify heat transfer mechanisms involved
- ❑ Solve basic heat transfer problems

From Thermodynamics to Heat Transfer

Thermodynamics



Heat Transfer

- Energy conversion processes
- System progresses through *equilibrium* states
- Work and heat

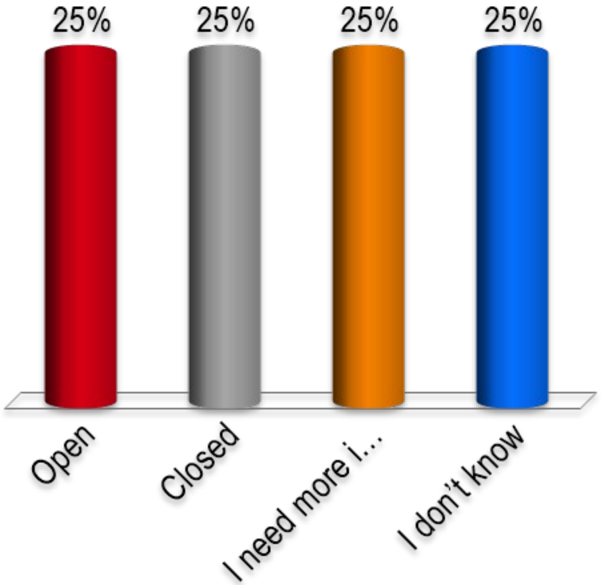
- Rate of thermal energy transfer

From Thermodynamics to Heat Transfer

- Are these houses open or closed systems?

Are these houses open or closed systems?

A. Open
B. Closed
C. I need more information
D. I don't know



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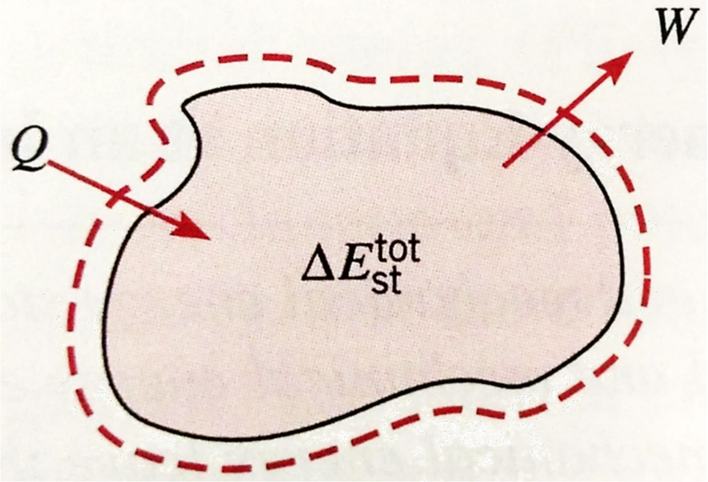
1st Law of Thermodynamics (Conservation of Total Energy) - 1

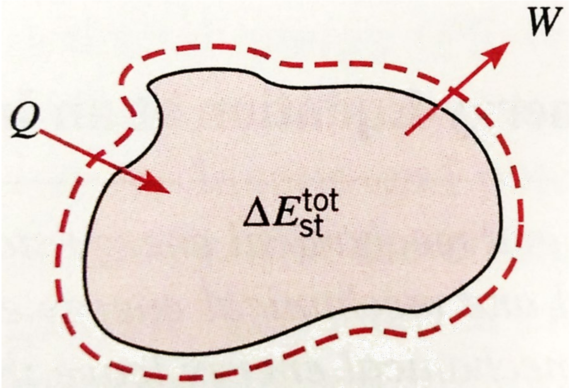
- Assumption: **Closed** System (NO mass flow across the boundary)



control volume

1st Law of Thermodynamics (Conservation of Total Energy) - 1

- Assumption: **Closed** System



control volume

thermal + chemical + electrical + nuclear

~ 0

mechanical + internal energy

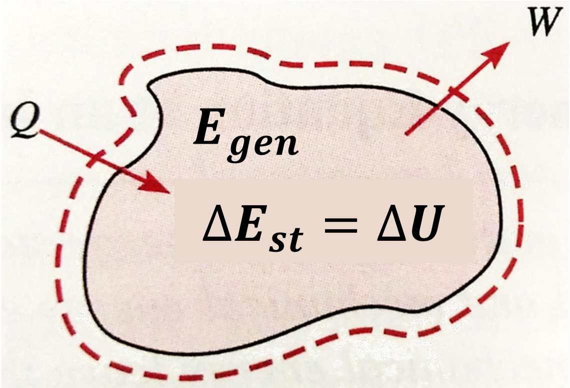
$$\Delta U = Q - W$$

Q>0 enters the system
Q<0 exits the system

W>0 done BY the system
W<0 done ONTO the system

1st Law of Thermodynamics (Conservation of Total Energy) - 1

- Assumption: **Closed** System



control volume

W>0 done BY the system
W<0 done ONTO the system

Q>0 enters the system
Q<0 exits the system

Eg>0 heat released
Eg<0 heat absorbed

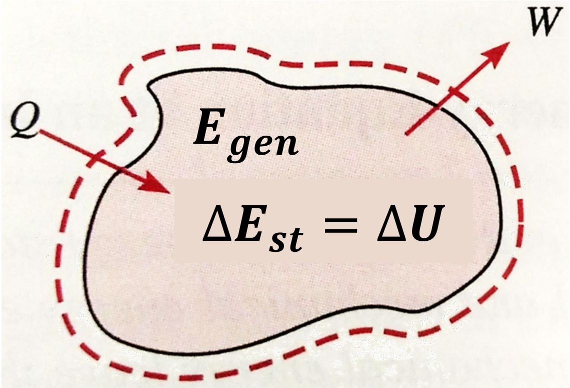
$$\Delta U = Q - W + E_{gen} \quad \text{[Joule]}$$

ΔU: thermal internal energy

E_{gen}: Heat Sources & Sinks (chemical, electrical, ..)

1st Law of Thermodynamics (Conservation of Total Energy) - 1

- Assumption: **Closed** System



control volume

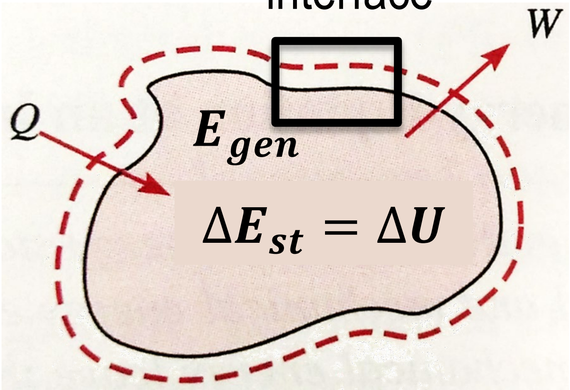
$$\frac{dE_{st}}{dt} = \dot{U} = Q - W + \dot{E}_{gen}$$

[J/s] = **[W]**

1st Law of Thermodynamics (Conservation of Total Energy) - 1

- Assumption: **Closed** System
- Control volume encompasses only the interface

interface



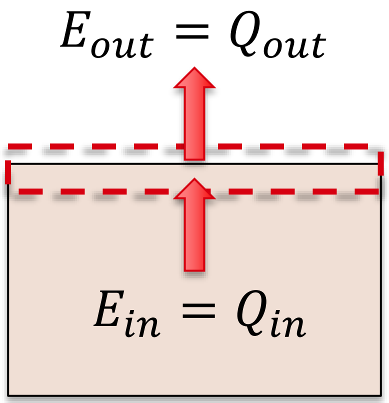
control volume

$$\frac{dE_{st}}{dt} = \dot{U} = Q - W + \dot{E}_{gen}$$

- Interface has no mass
  - ➢ No thermal capacity
  - ➢ No work
  - ➢ No sources

1st Law of Thermodynamics (Conservation of Total Energy) - 1

- Assumption: **<u>Closed</u>** System
- Control volume encompasses only the interface



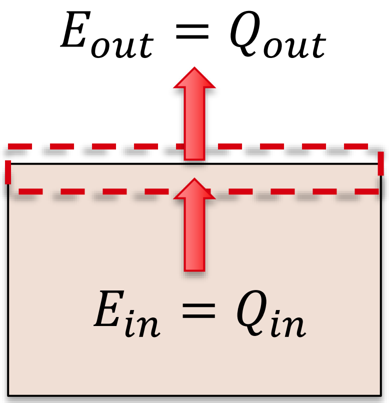
control volume

$$\frac{dE_{st}}{dt} = \dot{U} = Q - W + \dot{E}_{gen}$$

- Interface has no mass
  - No thermal capacity
  - No work
  - No sources

1st Law of Thermodynamics (Conservation of Total Energy) - 1

- Assumption: **Closed** System
- Control volume encompasses only the interface



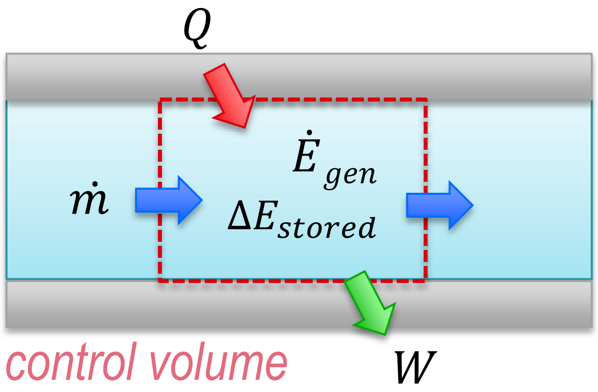
control volume

$$0 = E_{in} - E_{out} = \sum Q \qquad [\ J/s\ ] = [\ W\ ]$$

- Interface has no mass
  - No thermal capacity
  - No work
  - No sources

1st Law of Thermodynamics (Conservation of Total Energy) - 2

- Assumption: **Open** System → **advection** of energy must be included



$$\frac{dE_{stored}}{dt} = \dot{E}_{stored} = \dot{E}_{in} - \dot{E}_{out} + \dot{E}_{gen}$$

$$\dot{m}\left(u + pv + \frac{1}{2}V^2 + gz\right)_{in} - \dot{m}\left(u + pv + \frac{1}{2}V^2 + gz\right)_{out} + Q - W$$

$\dot{m}$: [kg/s]

u: [J/kg]

$u + pv$: Enthalpy *h*

$Q - W$: [W]

Important relationships

IDEAL GAS

- Change in enthalpy $h_{in} - h_{out} = c_p(T_{in} - T_{out})$
- Change in internal energy $u_{in} - u_{out} = c_v(T_{in} - T_{out})$

$$\frac{dE_{st}}{dt} = \dot{U} = mc_{(v)}\frac{dT}{dt} = Q - W + \dot{E}_{gen}$$

INCOMPRESSIBLE FLUID *(i.e. liquid)*

$$c_p = c_v$$

2nd Law of Thermodynamics

The Clausius Statement of the Second Law: *'It is impossible to construct a cyclically operating device that produces no effect other than the transfer of heat from a lower temperature body to a higher temperature body.'*

Inequality of Clausius:
Whenever a system undergoes a cycle, the integral around the cycle of dQ/T *is less than zero for an irreversible cycle and equal to zero for a reversible cycle or :*

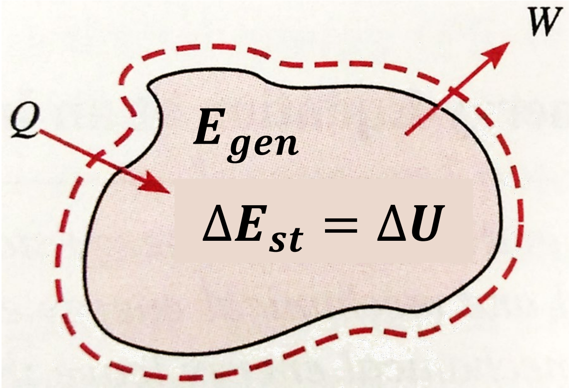
$$\int \frac{dQ}{T} \leq 0 \quad \Rightarrow \quad dS = \frac{dQ}{T}$$

S = entropy

From Thermodynamics to Heat Transfer

$$\dot{U} = Q - W + \dot{E}_{gen}$$

$$Q_{rev} = TdS \neq Q$$



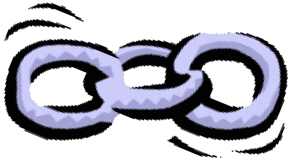
control volume

Real processes are irreversible!

We need **TRANSPORT LAWS**
to determine the heat flux

From Thermodynamics to Heat Transfer

Thermodynamics



Heat Transfer

Although thermodynamics may be used to determine the amount of heat needed for a system to pass from one equilibrium state to another it does not acknowledge that heat transfer is inherently a non-equilibrium process. In fact, for heat transfer to occur there MUST be a TEMPERATURE GRADIENT. (Incropera, Ch. 1.3)

Nomenclature and Units

- $Q = heat\ transfer\ rate\ [W]$
- $\boldsymbol{q" = heat\ flux\ [W/m^2]}$
- $\dot{q} = volumetric\ heat\ source\ [\frac{W}{m^3}]$
- $\boldsymbol{q' = heat\ flux\ unit\ length\ [W/m]}$

Introduction to Heat Transfer

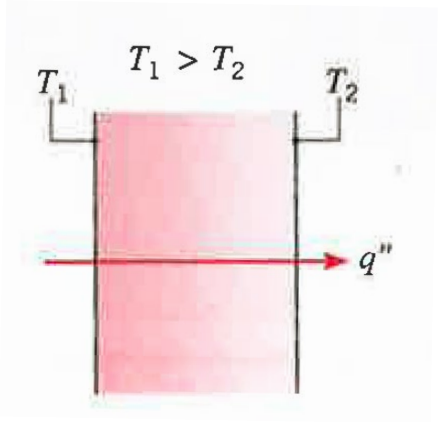
- ❑ Heat Transfer Mechanisms (✓)
- ❑ From Thermodynamics to Heat Transfer (✓)
- ❑ Overview of Transport Laws

Learning Objectives:

- ❑ From real-world to model: (✓)
  - identify the system and its boundaries
  - Identify heat transfer mechanisms involved
- ❑ Solve basic heat transfer problems

Transport Laws

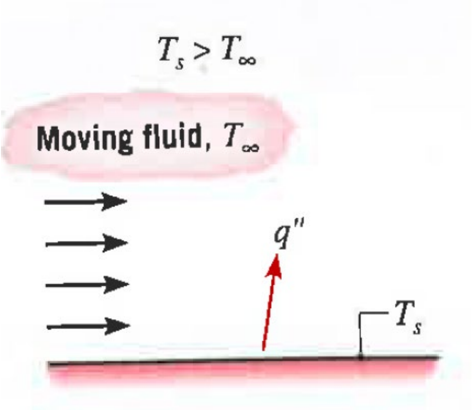
Conduction



Fourier's Law

$$q'' = -k\frac{dT}{dx}$$

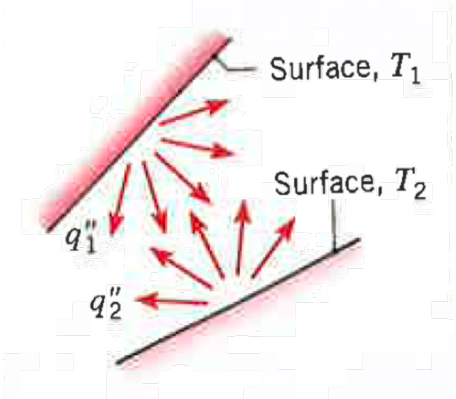
Convection



Newton's Law

$$q'' = \bar{h}\,(T_s - T_\infty)$$

Radiation

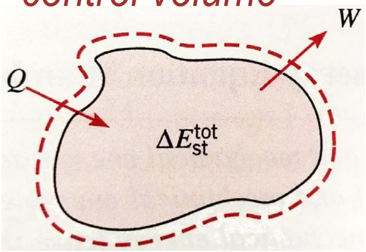


Stefan-Boltzmann Law

$$Q_{rad} = \varepsilon\sigma A_s(T^4 - T^4_{sur})$$

Part I – Fourier's Law and Heat Conduction

control volume

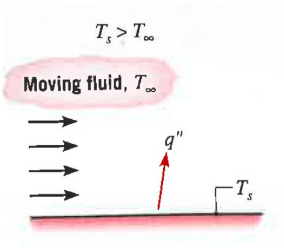


$$\frac{dE_{st}}{dt} = \dot{U} = Q - W + \dot{E}_{gen}$$

$$q" = -k\frac{dT}{dx}$$

- ❑ Heat Diffusion Equation (HDE) 3D
- ❑ HDE Steady-state 1D Solutions with/without Heat Sources
- ❑ Thermal Resistances and Equivalent Electrical Circuits
- ❑ Fins and Arrays of Fins
- ❑ Transient HDE
  - ❑ Lumped Capacitance Model T(t)
  - ❑ 1D Spatial Effects T(X,t)
  - ❑ Semi-Infinite Solid
  - ❑ Periodic BC

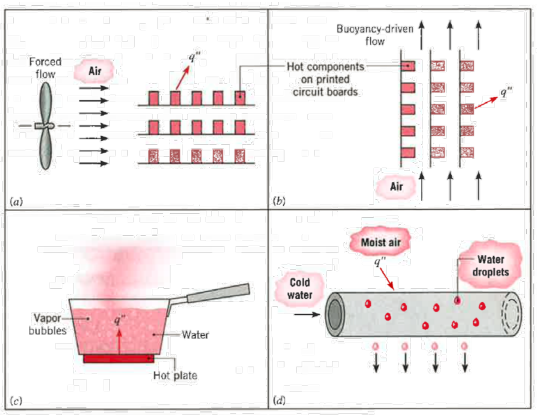
Part II: Newton's Law and Heat Convection



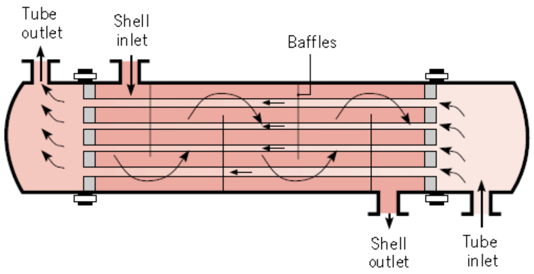
$$q'' = \bar{h}\,(T_s - T_\infty)$$

h = convective heat transfer coefficient, [W/m^2K]

Forced Convection | Free Convection

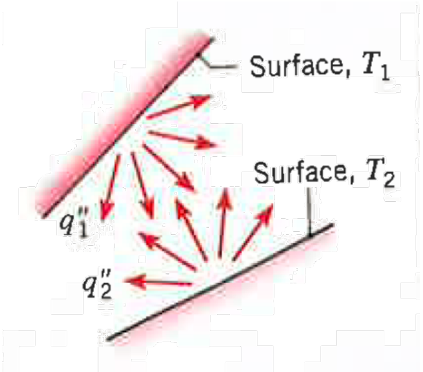


Boiling | Condensation



Heat Exchanger Design and Performance Analysis

Part III: Stefan-Boltzmann's Law and Radiation



$$Q_{rad} = \varepsilon \sigma A_s (T^4 - T_{sur}^4)$$

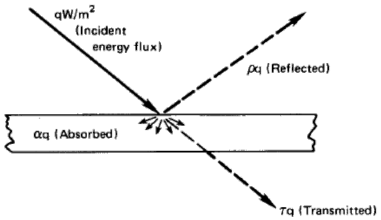
ε = emittance

$0 < \varepsilon < 1$

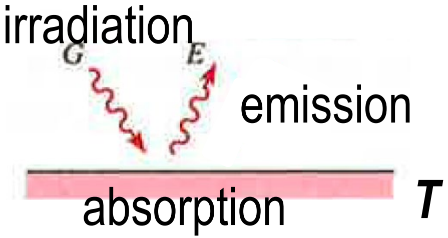
Electromagnetic Radiation Transmission/Reflection/Absorption

$$1 = \alpha_\lambda + \rho_\lambda + \tau_\lambda$$

λ = wavelength [m]



Thermal Absorption/Emission



Transport Laws

- Point to different heat transfer mechanisms in this system and where they occur.
- What temperatures are going to be important?
- What environmental and structural properties are going to play a key role in heat transfer ?

Point to different heat transfer mechanisms in this system and where they occur.

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What temperatures are going to be important?

- bungee jumping
- running
- hiking
- ice fishing
- jogging
- video games
- weight lifting
- swimming
- kayaking
- rock climbing

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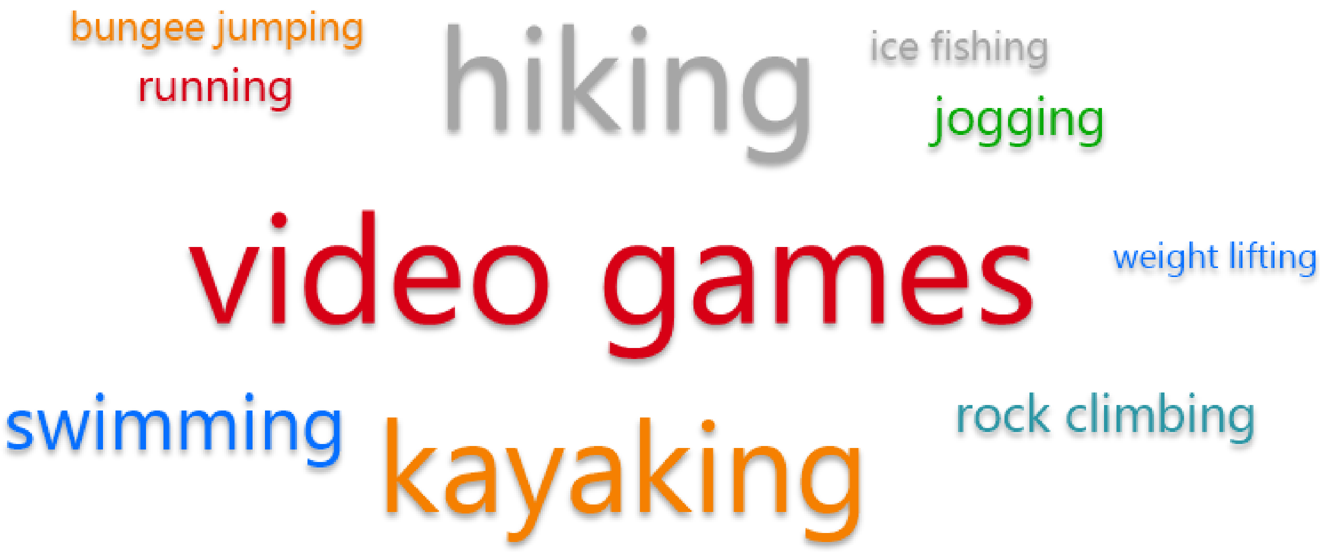
What environmental and structural properties are going to play a key role in heat transfer ?



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Introduction to Heat Transfer

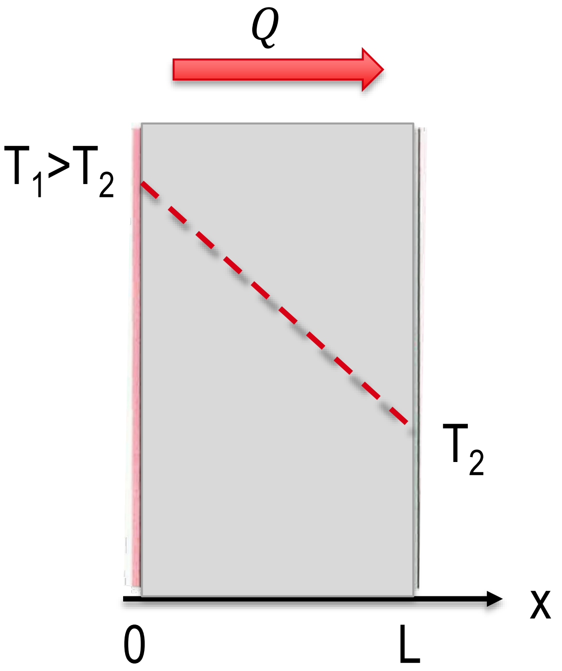
- ☑ Heat Transfer Mechanisms
- ☑ From Thermodynamics to Heat Transfer
- ☑ Overview of Transport Laws

Learning Objectives:

- ☑ From real-world to model:
  - identify the system and its boundaries
  - Identify heat transfer mechanisms involved
- ☑ Solve basic heat transfer problems

Supplementary Slides

Transport Laws 1: Fourier's Law of Heat Conduction



$$Q = -kA\frac{T_2 - T_1}{L} \Rightarrow \frac{Q}{A} = q'' = -k\frac{\Delta T}{L}$$

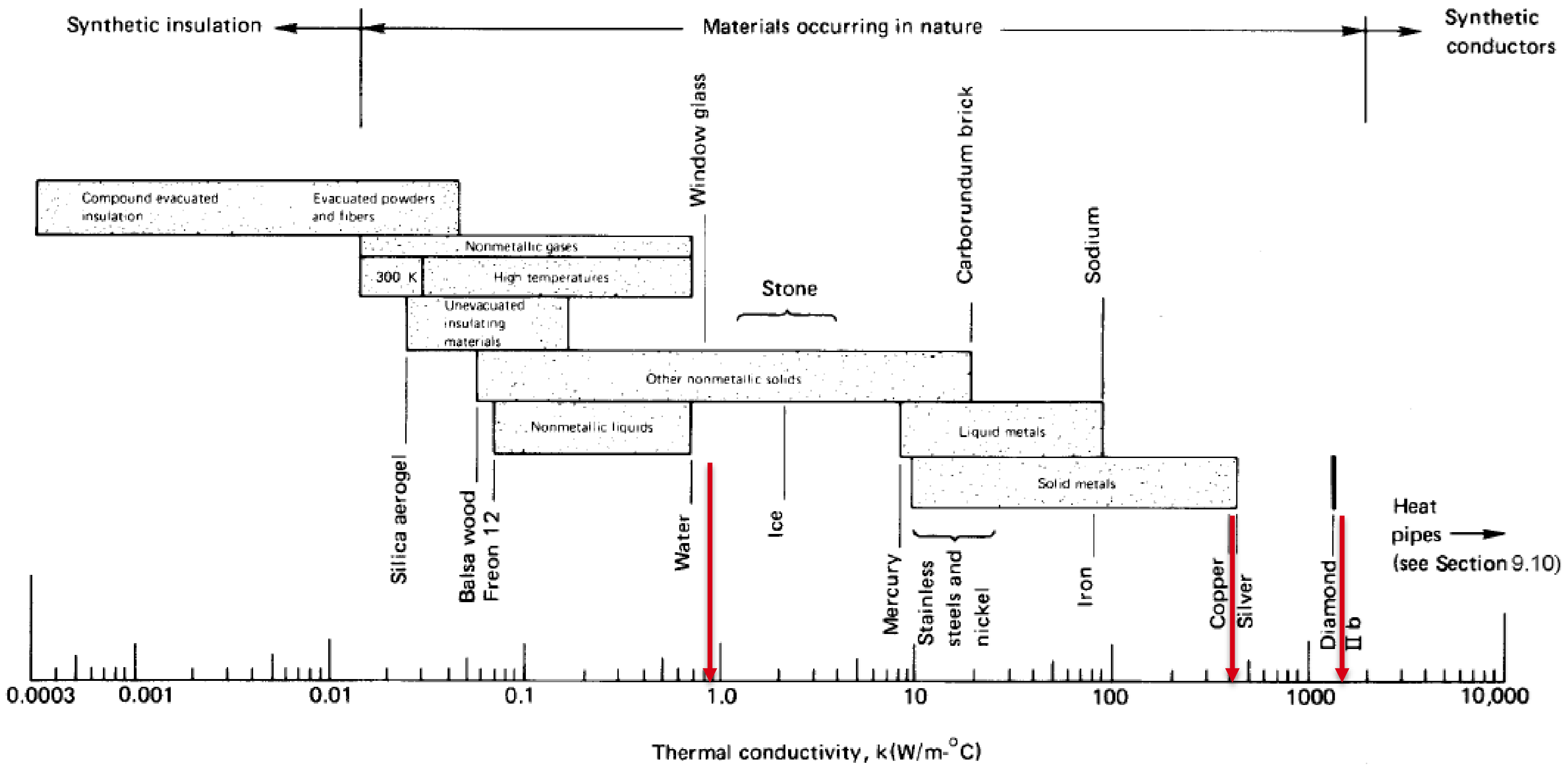
In the limit of an infinitesimal thickness *dx* :

$$q'' = -k\frac{dT}{dx} \quad [\,W/m^2]$$

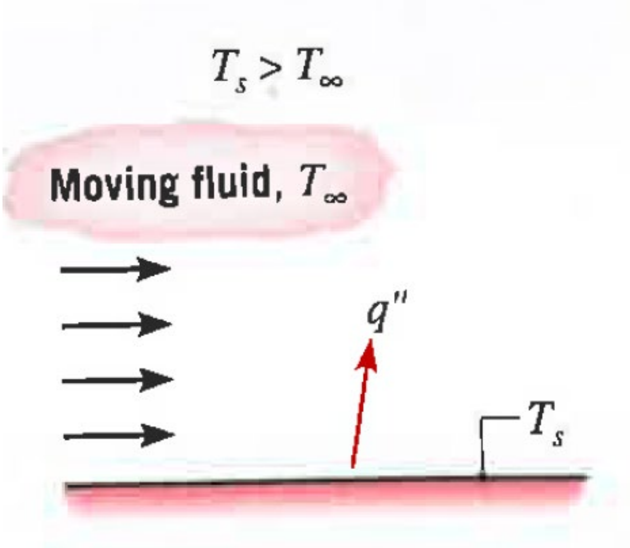
k = thermal conductivity, [W/mK]

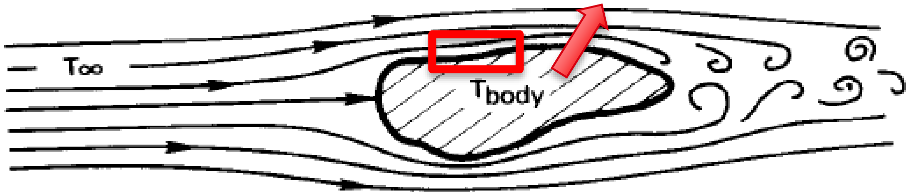
LINEAR TEMPERATURE PROFILE

Transport Laws 1: Fourier's Law of Heat Conduction



Transport Laws 2: Newton's Law of Heat Convection





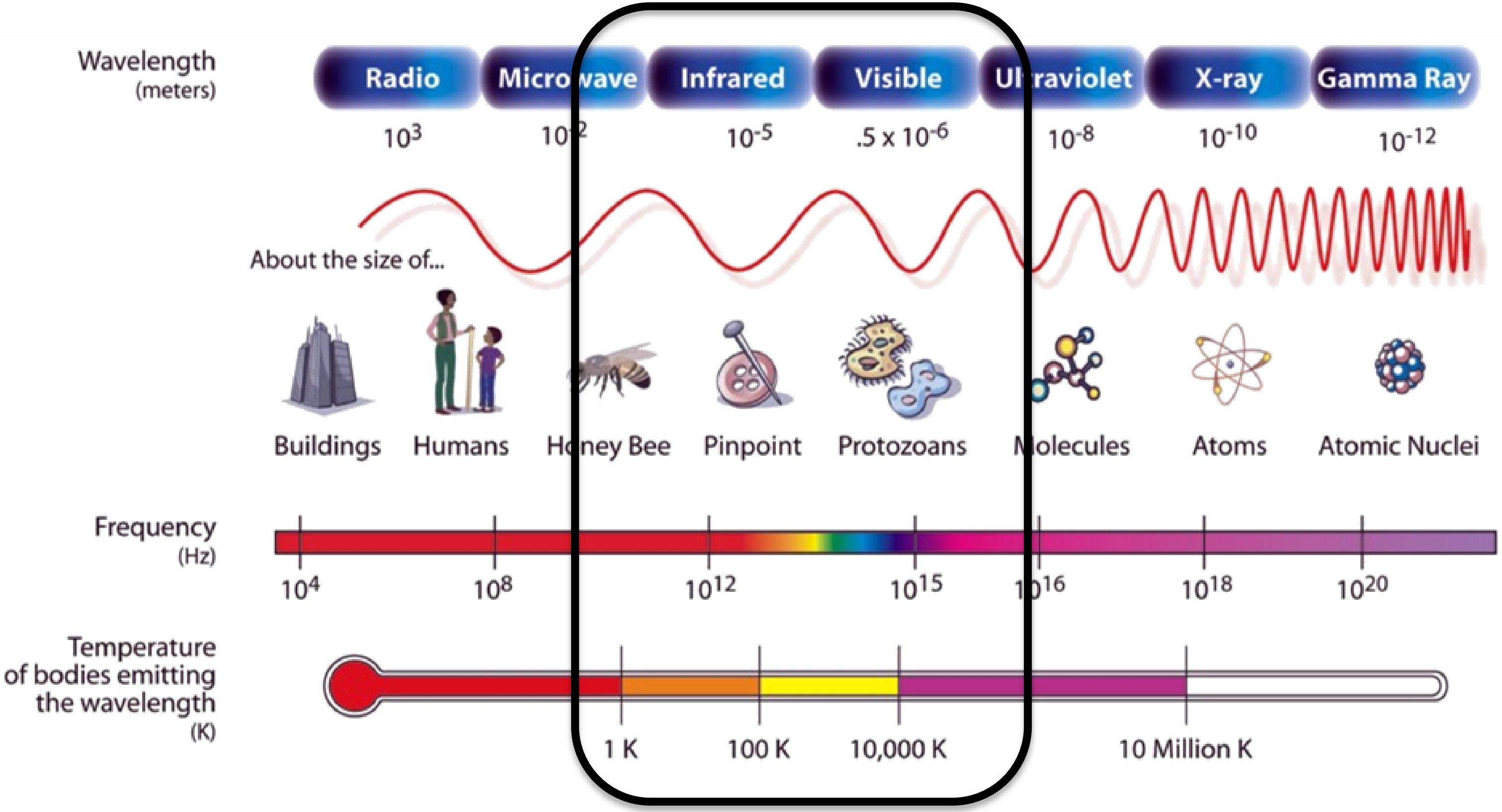
$$q'' = \bar{h}\,(T_s - T_\infty)$$

h = convective heat transfer coefficient, [W/**m²**K]

Transport Laws 2: Newton's Law of Heat Convection

Situation	$\overline{h}$, W/m²K
Natural convection in gases	
• 0.3 m vertical wall in air, $\Delta T = 30°C$	4.33
Natural convection in liquids	
• 40 mm O.D. horizontal pipe in water, $\Delta T = 30°C$	570
• 0.25 mm diameter wire in methanol, $\Delta T = 50°C$	4,000
Forced convection of gases	
• Air at 30 m/s over a 1 m flat plate, $\Delta T = 70°C$	80
Forced convection of liquids	
• Water at 2 m/s over a 60 mm plate, $\Delta T = 15°C$	590
• Aniline-alcohol mixture at 3 m/s in a 25 mm I.D. tube, $\Delta T = 80°C$	2,600
• Liquid sodium at 5 m/s in a 13 mm I.D. tube at 370°C	75,000
Boiling water	
• During film boiling at 1 atm	300
• In a tea kettle	4,000
• At a peak pool-boiling heat flux, 1 atm	40,000
• At a peak flow-boiling heat flux, 1 atm	100,000
• At approximate maximum convective-boiling heat flux, under optimal conditions	10^6
Condensation	
• In a typical horizontal cold-water-tube steam condenser	15,000
• Same, but condensing benzene	1,700
• Dropwise condensation of water at 1 atm	160,000

Transport Laws 3: Stefan-Boltzmann's Law of Radiation

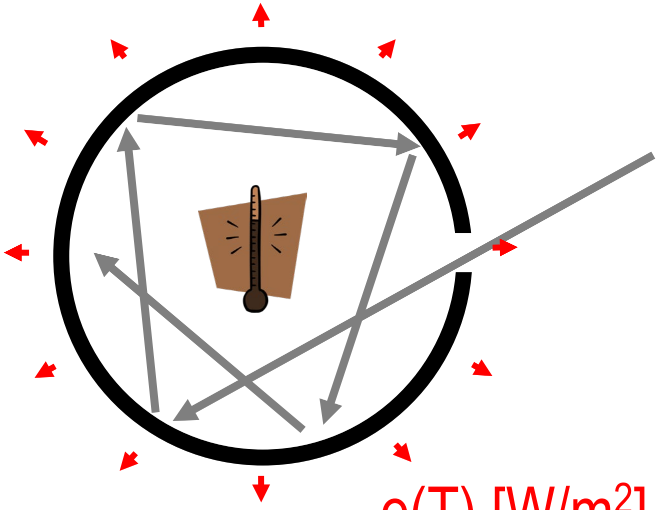


$$E = h\nu = \frac{hc}{\lambda}$$

Transport Laws 3: Stefan-Boltzmann's Law of Radiation

Gray Body

$\alpha_\lambda \neq 1$ $\alpha_\lambda = \varepsilon_\lambda$



$$\boldsymbol{e(T) = \varepsilon\sigma T^4}$$

T = **absolute** temperature [K]

$\sigma = 5.670367\ 10^{-8}\ W/m^2K^4$

ε = emittance $0 < \varepsilon < 1$

$$\boldsymbol{Q_{rad} = \varepsilon\sigma A_s(T^4 - T_{sur}^4)}$$

Methodology to Solve Heat Transfer Problems

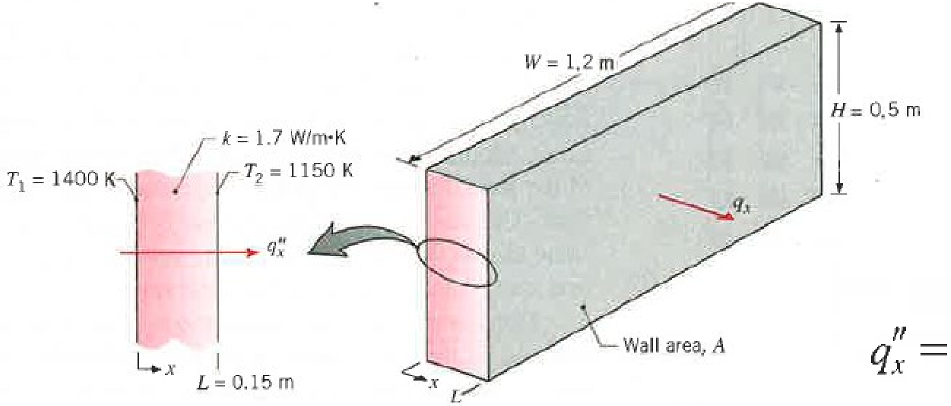
1. ***Find***: Imagine the physical situation and define what needs to be found
2. ***Schematic***: Draw a schematic of the system
   - Identify the boundaries of the system
   - Identify the heat transfer mechanisms at the boundaries
   - Define the arrows for heat transfer so to have consistent signs
   - Identify heat sources within the control volume
   - Add all known information about the system (dimensions, physical properties, temperatures, heat sources etc.)
3. ***Assumptions***: List all pertinent simplifying assumptions (e.g. steady-state)
4. ***Solution***: Write the appropriate conservation laws and transport laws
5. ***Verify***: Verify the physical consistency of your results
   - Are temperature across bodies consistent with their physical properties? If the direction of heat flow consistent with the temperature gradients etc.

Example 1: Fourier's Law of Heat Conduction

The wall of an industrial furnace is constructed from 0.15-m-thick fireclay brick having a thermal conductivity of 1.7 W/m · K. Measurements made during steady-state operation reveal temperatures of 1400 and 1150 K at the inner and outer surfaces, respectively. What is the rate of heat loss through a wall that is 0.5 m by 1.2 m on a side?

Assumptions:

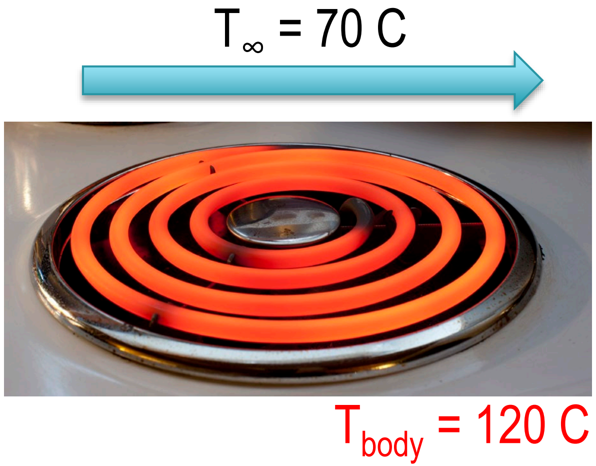
1. Steady-state conditions.
2. One-dimensional conduction through the wall.
3. Constant thermal conductivity.



$$q''_x = k\frac{\Delta T}{L} = 1.7\ \text{W/m}\cdot\text{K} \times \frac{250\ \text{K}}{0.15\ \text{m}} = 2833\ \text{W/m}^2$$

$$q_x = (HW)\,q''_x = (0.5\ \text{m} \times 1.2\ \text{m})\ 2833\ \text{W/m}^2 = 1700\ \text{W}$$

Example 2: Newton's Law of Heat Convection



The heat flux, q, is 6000 W/m^2 at the surface of an electrical heater. The heater temperature is 120°C when it is cooled by air at 70°C. What is the average convective heat transfer coefficient, $\overline{h}$? What will the heater temperature be if the power is reduced so that q is 2000 W/m^2?

$$\overline{h} = \frac{q}{\Delta T} = \frac{6000}{120 - 70} = 120\ \mathrm{W/m^2K}$$

If the heat flux is reduced, $\overline{h}$ should remain unchanged during forced convection. Thus

$$\Delta T = T_{\text{heater}} - 70°\mathrm{C} = \frac{q}{\overline{h}} = \frac{2000\ \mathrm{W/m^2}}{120\ \mathrm{W/m^2K}} = 16.67\ \mathrm{K}$$

so $T_{\text{heater}} = 70 + 16.67 = 86.67°\mathrm{C}$ ■