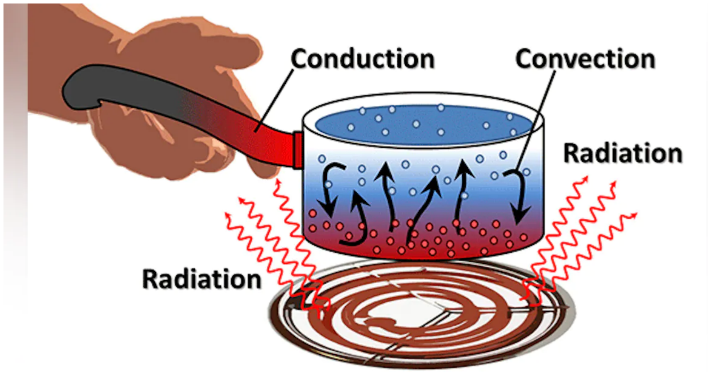
General Physics II: Thermodynamics

Prof. M. Hirschmann



Spring semester 2024

Recap… Chapter 10 — TD potentials

- What are basic relations in thermodynamics connecting internal energy with state variables T, S, P, V, mu and n?

Recap… Chapter 10 — TD potentials

- What are thermodynamic potentials?

- Until when does a TD process continue?

- What are the natural variables of a TD system?

Recap… Chapter 10 — TD potentials

- What are the natural variables of the internal energy?

- How can you express the change in internal energy by its natural extensive variables?

- How can you derive the remaining intensive state variables of a TD system (T, P, mu) from the internal energy and its natural variables?

Recap… Chapter 10 — TD potentials

- Which thermodynamic potentials do you know other than the internal energy? How can they be computed from internal energy?

- Under which conditions (in reversible experiments) are these TD potentials useful?

Recap… Chapter 10 — TD potentials

- How are equilibrium states of a thermodynamic system and thermodynamic potentials H, F, & G connected?

Content of this course — today's lecture

Lecture 1: —Chapter 1. Introduction
—Chapter 2. Temperature and zeroth law of thermodynamics

Lecture 2: —Chapter 3. Gas laws

Lecture 3: —Chapter 4. Statistical thermodynamics I: Kinetic theory of gas (slides in previous file)
—Mathematical Excursion — Preparation for Chapter 5.

Lecture 4: —Chapter 5. Statistical thermodynamics II (Boltzmann factor, Maxwell-Boltzmann distribution)

Lecture 5: —Chapter 6. Energy, heat and heat capacity

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Lecture 7: — Mock exam I *with Dr. Robin Tress*

Lecture 8: —Chapter 8. Entropy and the second and third law of thermodynamics

Lecture 9/10: —Chapter 9. Thermal machines

Lecture 11: —Chapter 10. Thermodynamic potentials and equilibria

Lecture 12: —Mock Exam II *with Dr. Robin Tress*
Lecture 13: —Chapter 11. Heat transfer (Conduction, Convection, Radiation)

Lecture 14: —Final review, conceptual and open questions

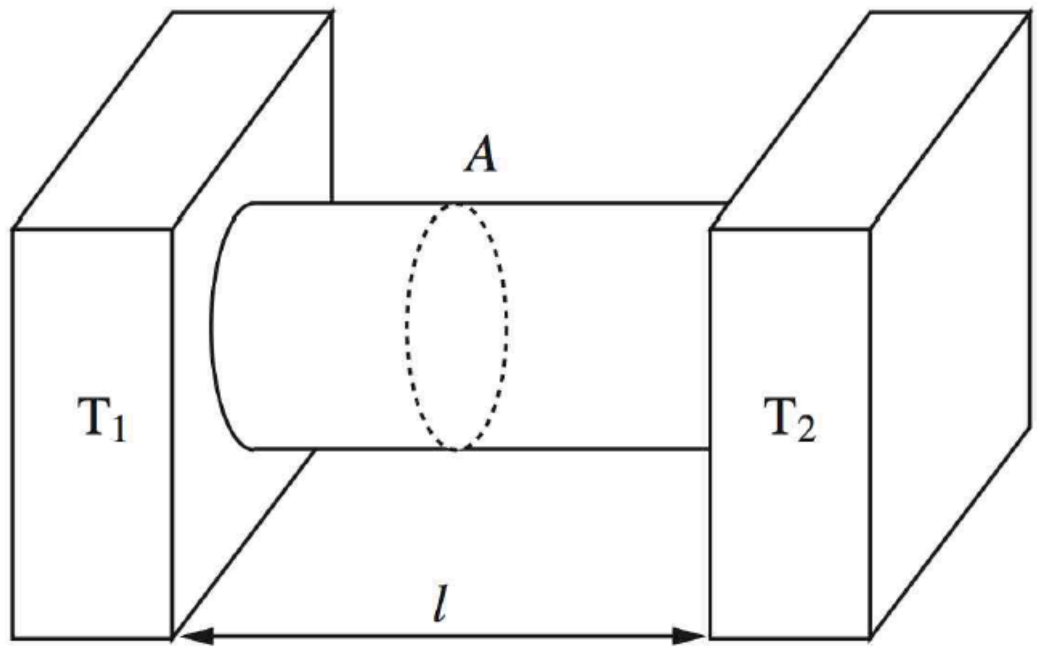
11. Heat transfer

- 11.1 Heat conduction and Fourier's law
- 11.2 Heat convection
- 11.3 Radiation of heat

11.1 Heat conduction and Fourier's law

Thermal energy transferred through direct contact of materials with different T.

Heat bath1

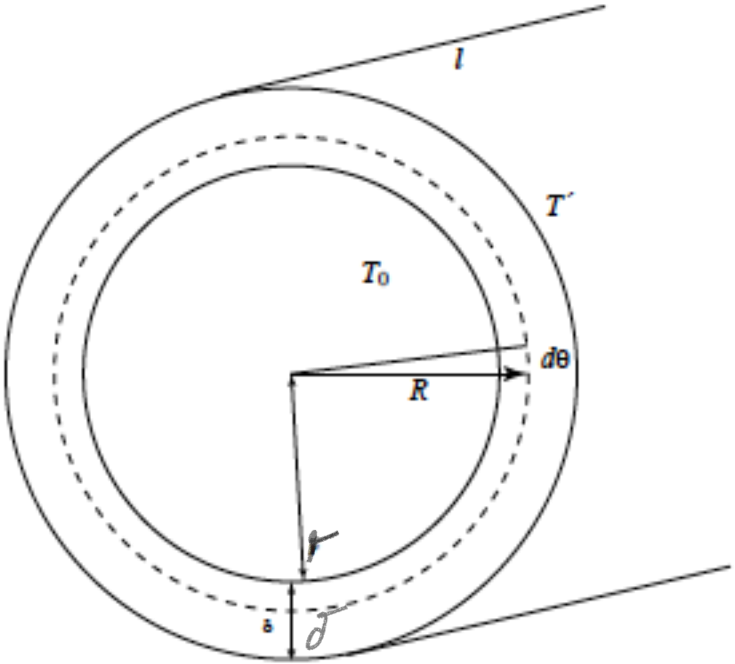


Heat bath2 connected by a beam with A, l

$T_1 > T_2$

Application 1: heat loss through windows

Application 2: Cylindrical pipes filled with hot water



Radius r; wall thickness δ;
Length l of pipe
hot water inside with T_0
T' outside
Assume T_0 & T' const (steady-state case)

heat proceeds through cylindrical layers outwards R = r to r+δ

Q1: What is the T profile in the cylinder wall?
Q2: How much energy / heat is lost per unit time?

So far: heat conduction in material / solids

basic principle: coupling of neighbouring atoms
(solid state physics) so that oscillation energy can be transferred from x to $x + dx$

Metals: special case due to free movable e^-
↳ collisions among e^- & atoms contribute to heat conduction
↳ typically thermal conductors

also possible in liquids and gases:

Liquids: coupling between neighbouring atoms weaker → smaller thermal conduction

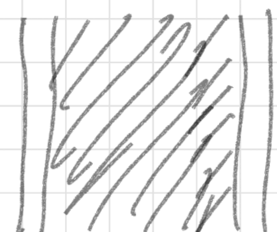
(But see melted metals, ...)

Water has small conduction capability

Gases: Energy transfer via collisions between atoms/molecules

Even smaller conductivity than liquids/solids (lower density)

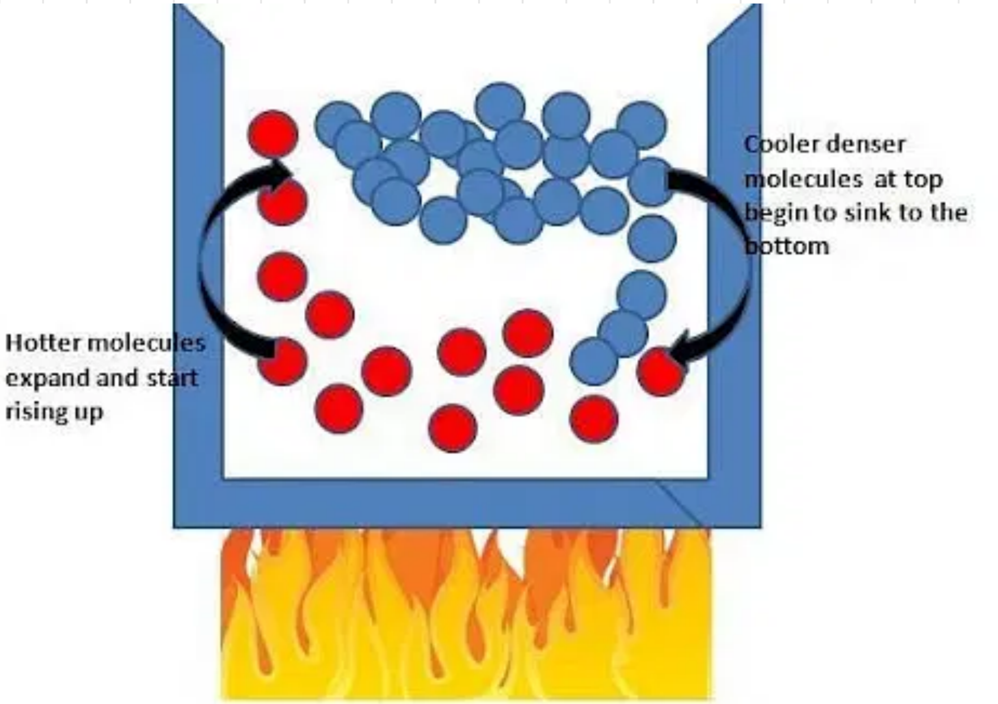
Air or other gas good for insulation, e.g. double glazed window



↳ • significantly reduced heat losses

11.2 Convection

Matter transport / flow in gases and liquids with different T due to change of density & gravitational forces

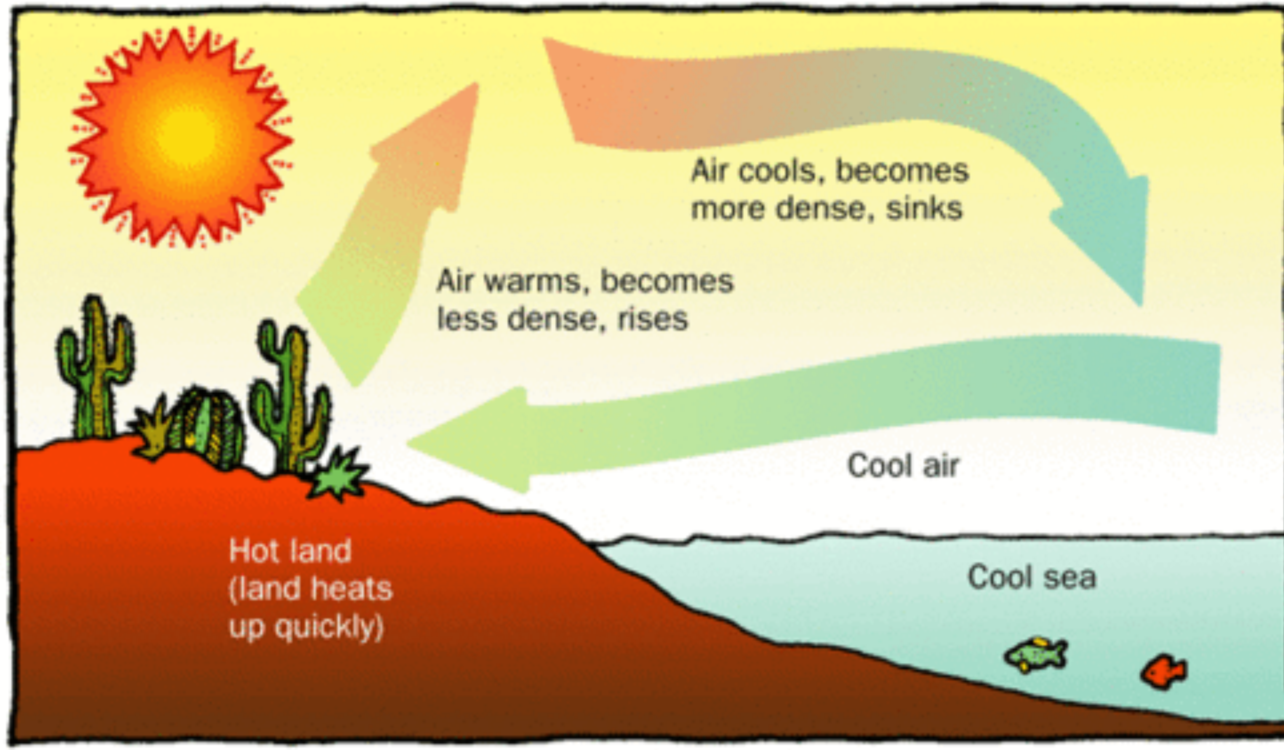


Example:

water in a pot

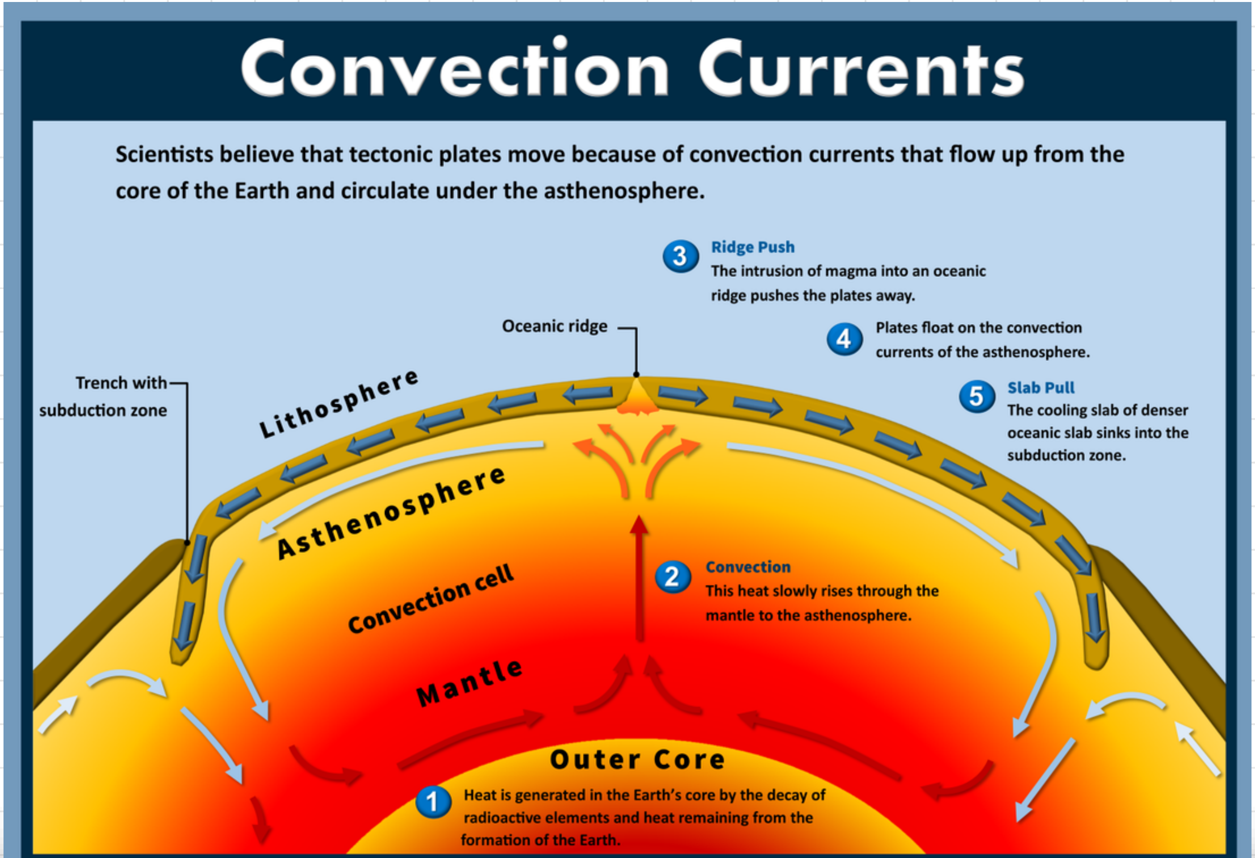
Convection in earth's atmosphere:

Complex to model, highly non-linear, fluid dynamics simulations




I NEED
Blue
Red

Convection inside planets, like earth, responsible for movement of tectonic plates :



https://www.youtube.com/watch?v=MmMX83diwl0

Summary 11.1 and 11.2 — Conduction and Convection

- Conduction is transfer of thermal energy in solids via oscillations of atoms/ molecules.
    - The heat transfer is described by Fourier's law: $\frac{dQ}{dt} = -kA\frac{dT}{dx}$
    - k is the thermal conductivity.
    - Conduction also possible for liquids and gases, but in general, with decreasing conductivity.
- Convection is matter transport in gases liquids with a T gradient due to a related change in density and gravitational forces
    - Examples: heating water in a pot, air flows in earth atmosphere, convection flows inside planets (and stars)
    - Complex treatment via fluid dynamics (hydrodynamic simulations)

Experiment 401: Heating of Copper by Radiation

https://www.youtube.com/watch?v=rdT1H7dZaro

Set-up and observation:

A copper block is covered by a glass bell jar. After evacuating the air from this bell jar, the copper block is illuminated by a beam. A rod thermometer gives us the temperature of the copper block, and a slow increase in temperature is observed. If air is allowed into the bell jar, there is a further slight increase in temperature.

Operating Principle:

Thermal radiation, i.e. electromagnetic radiation, is one of the three ways to transfer heat (along with conduction and convection) not needing any medium.

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The electromagnetic waves to which the material is exposed will be partially absorbed by the material. The electrons in the atoms will absorb some of these waves and will be excited (increasing the kinetic energy and thus, T). They can de-excite and emit photons again ("black-body" radiation).

Adding air to the bell jar allows the processes of convection and conduction to come into play —> T can increases a bit more.

Key Takeaways:

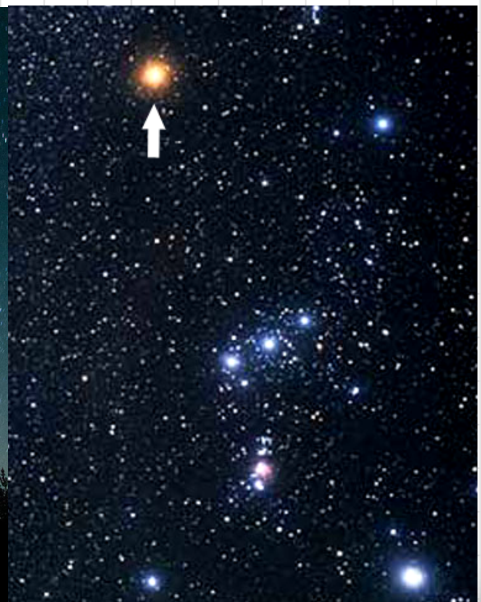
- Heat transfer via electromagnetic radiation, no medium required
- Object at given T emits radiation
- The presence of air allows for the addition of conduction and convection

11.3 Radiation of heat

Importance of Stefan-Boltzmann law in Astrophysics:

Stars ≈ black-body radiators ($\rightarrow \varepsilon \approx 1$)

Giant star Betelgeuse (in Orion, one of the most luminous visible by eye, 640 ly away)



$$\dot{Q}_B = 10^4 \dot{Q}_\odot$$

$$T_B = \tfrac{1}{2} T_\odot \quad \text{(surface T)}$$

$$R_B = \,?$$

$$R_\odot = 7 \cdot 10^8 \, m$$

Note: * Sun in stage of H core burning since 4.6 billion years, total life time ≈ 10 Gyrs

↳ continue for at least 5 Gyrs

red because of lower surface T

* When H fuel exhausted → red giant phase & radius inflation due H shell burning for a few 100 million years (close to or beyond earth orbit)

* Afterwards, gravity takes over, collapse to white dwarf (degenerate e^- gas pressure against gravity)

Summary 11.3 — Radiation

- Energy transfer without any medium, via electromagnetic radiation
- Rate of thermal energy flow from one object follows the Stefan-Boltzmann equation: $\frac{\Delta Q}{\Delta t} = \varepsilon \sigma A T^4$ with $\sigma = 5.67 \times 10^{-8}\ \mathrm{W/(m^2 \cdot K^4)}$
- Epsilon is the emissivity, black-body radiator: epsilon=1
- Object placed into environment with T2, net energy flow rate is

$$\frac{\Delta Q}{\Delta t} = \varepsilon \sigma A \left(T_1^4 - T_2^4\right)$$

  - T1 = T2 —> no energy flow
  - T1 > T2 —> energy flows from object to environment
  - T2 > T1 —> object absorbs energy from environment
- Heating from radiation from sun: sun is a point source, inclination important
- Black-body radiation important for describing the radiation from stars

Conceptual Questions:

- Through which processes can heat loss occur through windows? And what are the exact mechanisms?
- A piece of wood lying in the Sun absorbs more heat than a piece of shiny metal. Yet the metal feels hotter than the wood. Why?
- An emergency blanket is a thin shiny (metal-coated) plastic foil. Explain how it can help to keep an immobile person warm.
- Explain why cities situated by the ocean tend to have less extreme temperatures than inland cities at the same latitude.
- On a cold windy day, a window will feel colder than on an equally cold day with no wind. This is true even if no air leaks near the window. Why?
- A typical thermos bottle has a thin vacuum space between the shiny inner flask and the shiny protective outer flask. Is the vacuum space best in preventing conduction, convection and/or radiation?
- Radiation is emitted a) only by glowing objects like our sun; b) only by objects who's temperature is greater than the temperature of the surrounding; c) by any object not at 0 K; d) only by the objects that have a large specific heat.

Up next: Written exam on ??, ??. June 2025, 9.15am - 12.45pm

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✓

✓ Lecture distribution)

✓ Lecture

✓ Lecture

✓ Lecture

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- Use ED forum to also ask questions
- During exam: One DinA4 paper (front and back), best hand-written, can also be printed, but you should not need magnifier to read the text.

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