EPFL

Nanoscale Heat Transfer (and Energy Conversion) ME469

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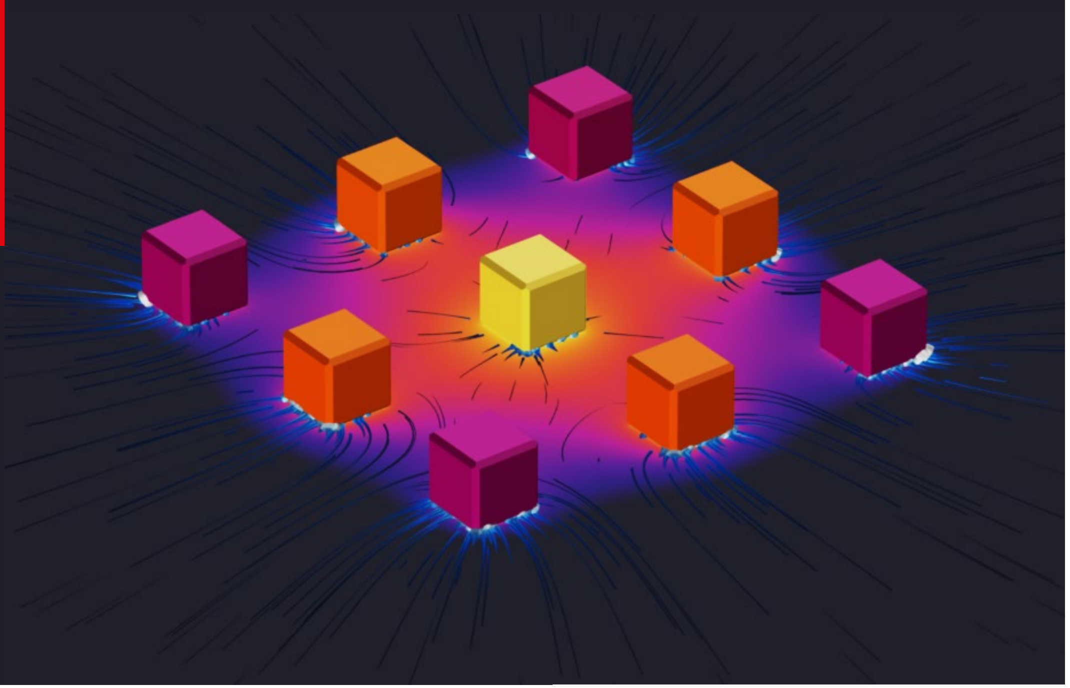


École polytechnique fédérale de Lausanne

Spring Semester

EPFL

Heat transfer is the **energy flow** across the **boundaries** of a system* under a **temperature difference**

Heat transfer is a **non-equilibrium boundary phenomenon**

1st Law of Thermodynamics (Closed System) $\dot{U} = Q - W + \dot{E}_{gen}$

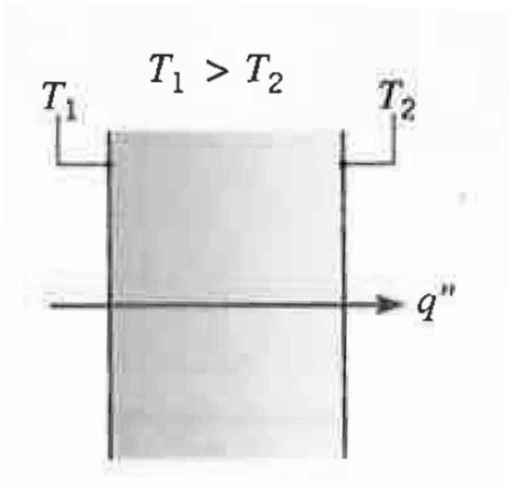
2nd Law of Thermodynamics $Q_{rev} = TdS \neq Q$

Heat transfer requires **transport laws** and **boundary conditions**

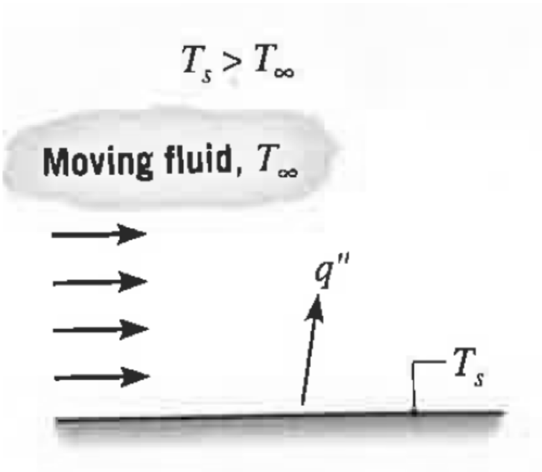
**** A system can be defined in the most general form as a control volume. Do you remember the difference between closed and open systems?***

Heat Transfer Mechanisms

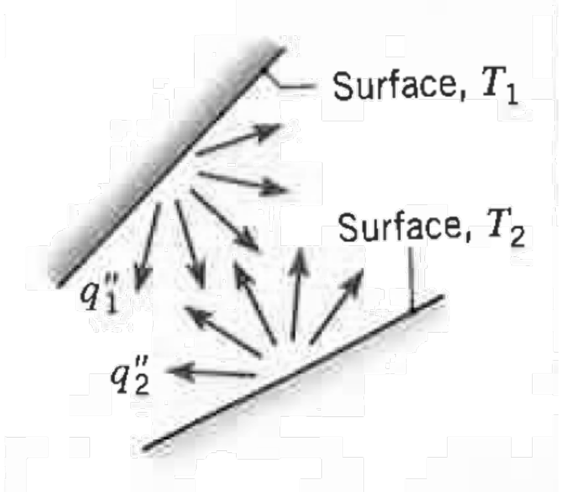
Conduction



Convection



Radiation



No mass transport

Involves mass transport

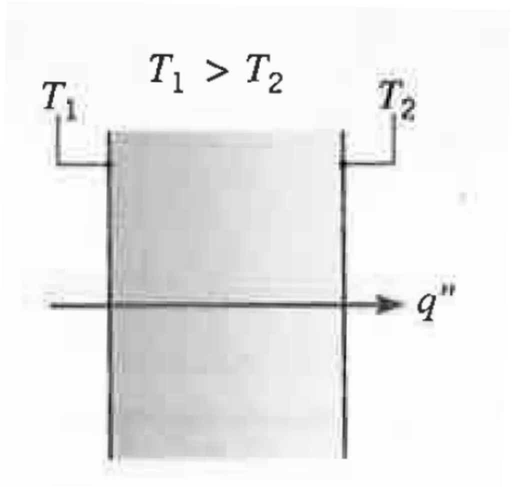
Involve physical contact

No physical contact

Source: Incropera et al. Fundamentals of Heat and Mass Transfer, 6th Ed.

Transport Laws

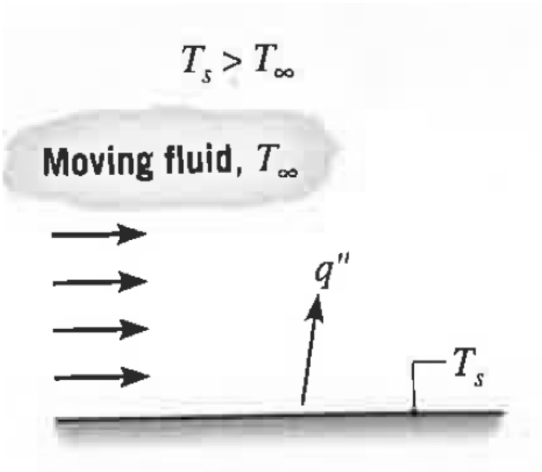
Conduction



$$q'' = -k\nabla T$$

Fourier's Law

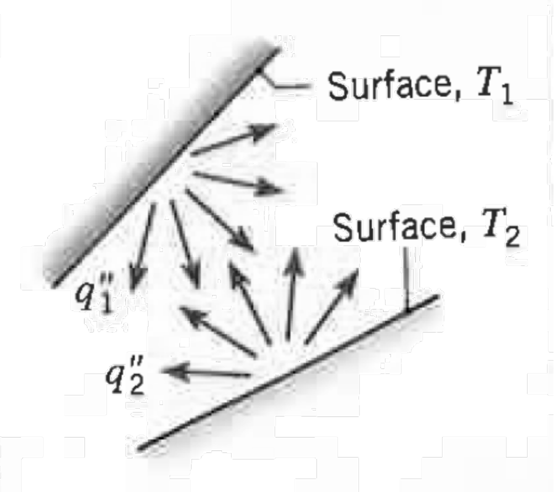
Convection



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

Newton's Law

Radiation



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

Stefan-Boltzmann's Law

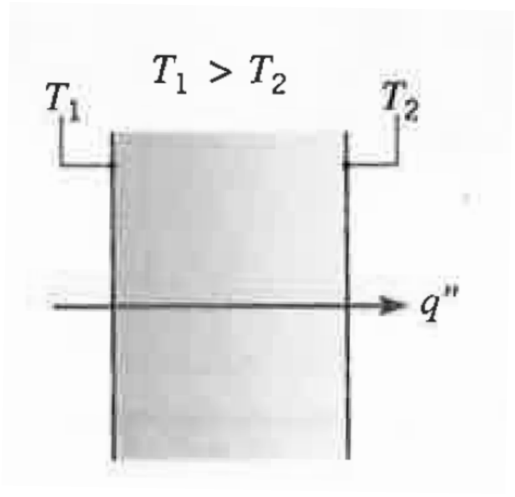
Source: Incropera et al. Fundamentals of Heat and Mass Transfer, 6th Ed.

Why Nanoscale Heat Transfer and Energy Conversion ?

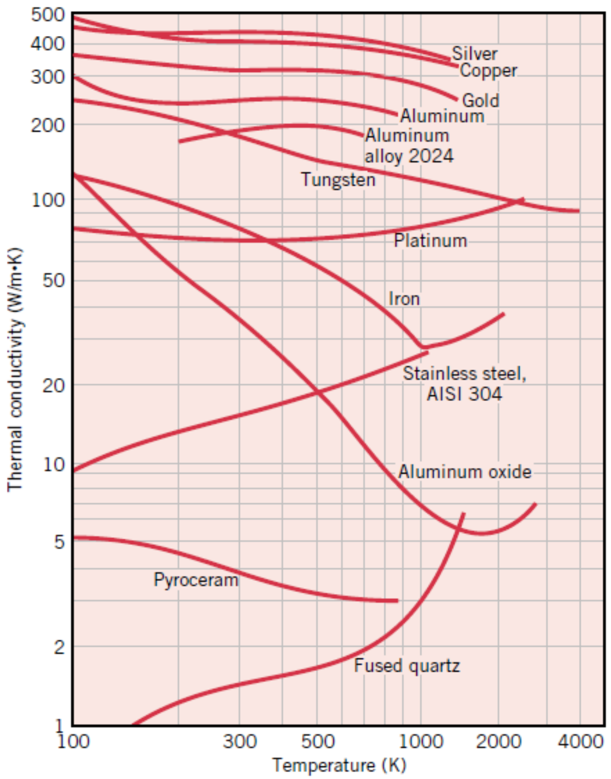
- Where do transport laws come from ?
- Are these transport laws always valid ?
- How is energy transported at the nanoscale?
- Why materials have different physical properties ?
- Can we predict the physical properties ?
- How do we define temperature at the microscopic level ?
- …

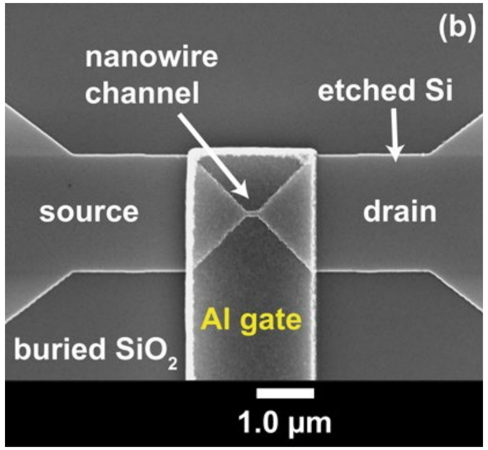
Why Nanoscale Heat Transfer and Energy Conversion ?

Conduction



$$q'' = -k\nabla T \qquad k = thermal\ conductivity$$





Fundamental & Engineering Questions

- Why Fourier law?
- Why different materials have different k values?
- What happens in nanostructures ?
- Can we engineer the thermal conductivity?

Why Nanoscale Heat Transfer and Energy Conversion ?

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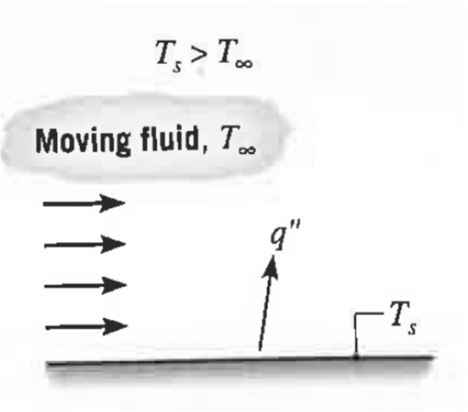
Convection



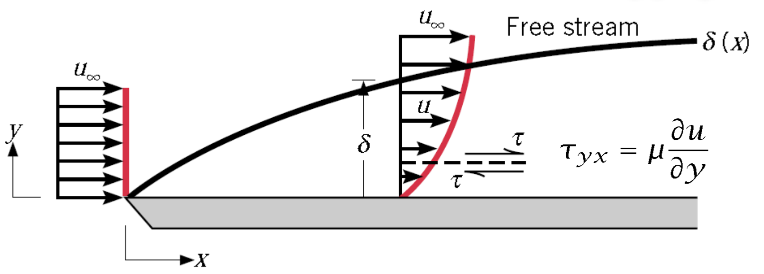
No-slip condition

$$h = \frac{\left(-k_f \frac{\partial T}{\partial y}\Big|_{y=0}\right)}{((T_s - T_\infty))}$$

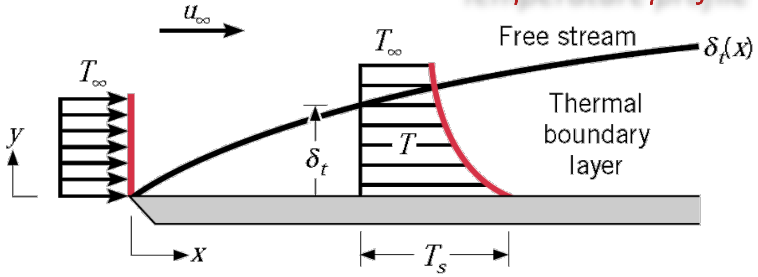
$$q'' = \bar{h}\,(T_s - T_\infty)$$

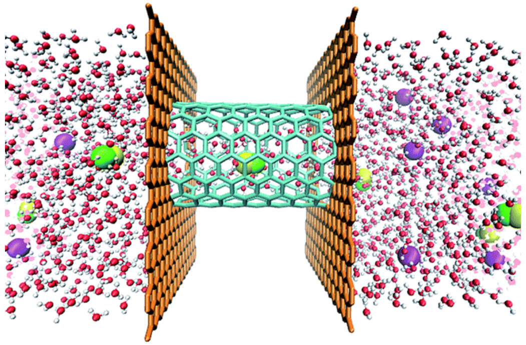
$$h = convection\ coefficient$$

Velocity profile



Temperature profile





Fundamental & Engineering Questions

- Where do Newton's stresses come from?
- Is the no-slip condition always valid ?
- What happens when the fluid is confined to nanoscales?

Why Nanoscale Heat Transfer and Energy Conversion ?

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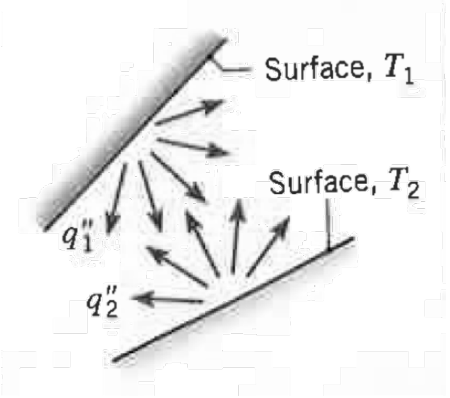
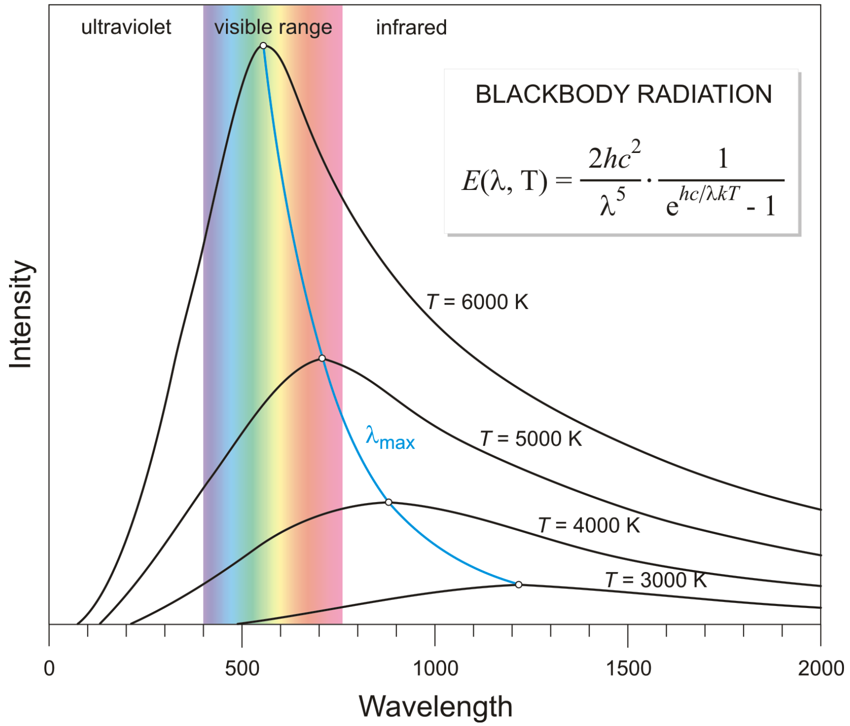
Radiation

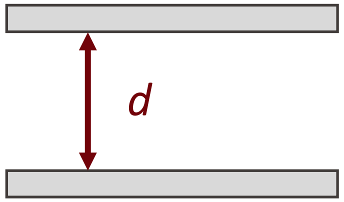


$$Q_{rad} = \varepsilon\sigma A_s(T^4 - T_{sur}^4) \qquad \varepsilon = emissivity$$



Fundamental & Engineering Questions

- Where does the blackbody spectrum come from?
- Can we engineer the emissivity ?
- What happens when the separation between two surfaces becomes nanoscopic?



$$F_{12} = F_{21} = 1$$

Why Nanoscale Heat Transfer and Energy Conversion ?

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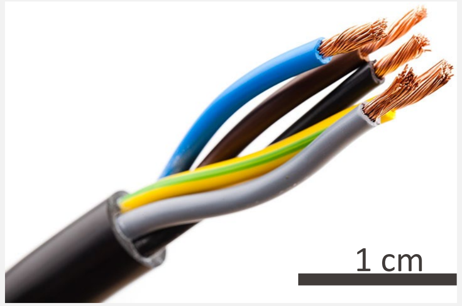
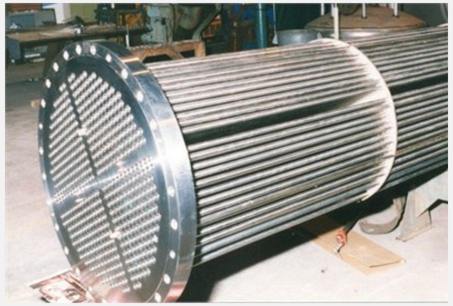
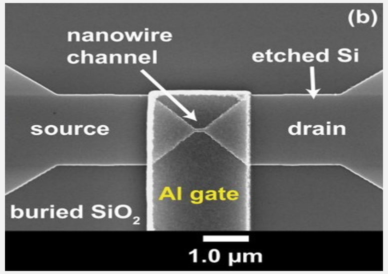
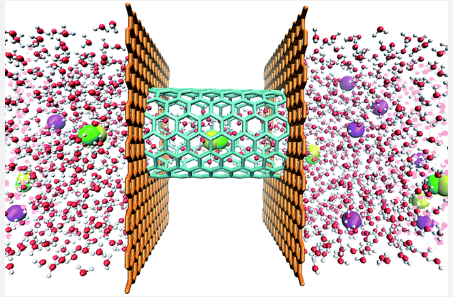
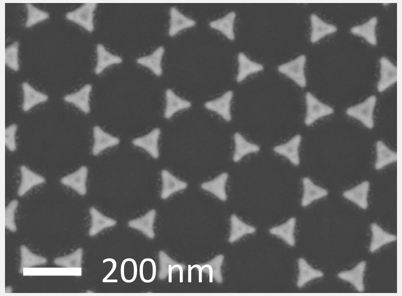
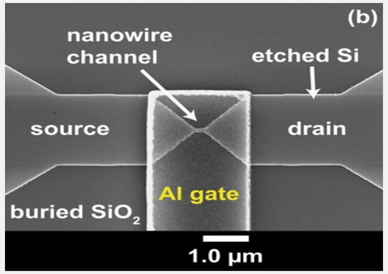
	Conduction	Convection	Radiation
Macro-scale			
Nano-scale			

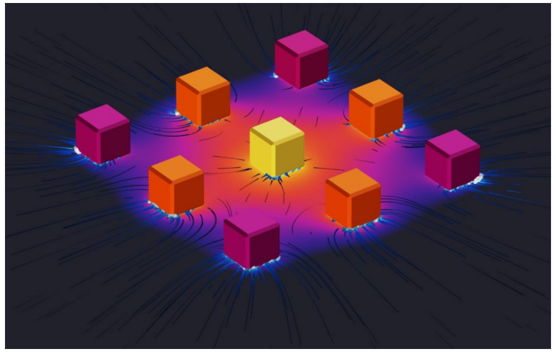
What emerging energy conversion devices can we realize by leveraging nano-scale phenomena ?

Why Nanoscale Heat Transfer and Energy Conversion ?

Nano-scale

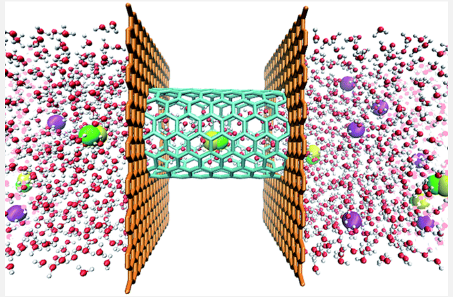
Conduction





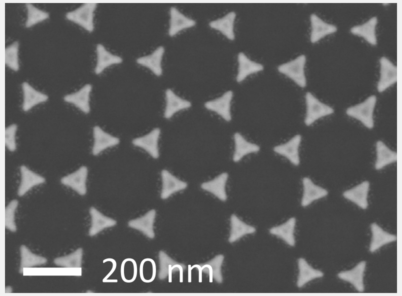
Thermo-electric Devices
Phononic Crystals
Thermoplasmonic Catalysis

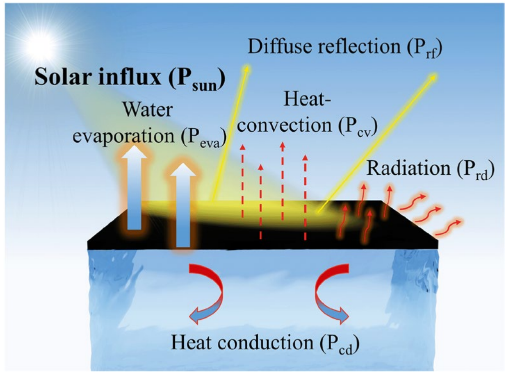
Convection



Hydrovoltaic Devices
Hydrophilic/phobic Coatings
Ion pumps

Radiation





Solar Evaporation
Radiative Cooling
Photovoltaic at Night

Why Nanoscale Heat Transfer and Energy Conversion ?

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- **“Size” effects and Surface Effects**
  Short length scales and short time scales require new understanding and enable new mechanisms
  Interfacial effects and surface forces become dominant at the nanoscale

- **Atomic perspective**
  Today we can routinely observe atoms and engineer nanoscale phenomena
  Predominant role of non-equilibrium transport on device behavior as well as energy conversion processes.

- **Unified view**
  A microscopic picture highlights similarity of phenomena and behaviors across different physics
  (e.g. Fourier law and drift-diffusion equation for electrical current flow)

Learning Objectives of the Course

- Become familiar with fundamental concepts from quantum mechanics, solid state physics and statistical thermodynamics
- Know how the classical transport laws emerge from a microscopic picture
- Know the assumptions of the classical transport laws and understand the limits of their applicability
- Understand energy transport from nanoscale up to macroscale
- Learn about emerging opportunities in energy device engineering (materials and physical mechanisms)

Content of the Course

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Nanoscale Heat Transfer (and Energy Conversion)

Energy States
- Introduction to Quantum Mechanics (Ch. 2)
- Introduction to Solid State Physics (Ch. 3)

Thermal Energy Storage
- Introduction to Statistical Thermodynamics (Ch. 4)

Thermal Energy Transport
- Energy Transport by Waves (Ch. 5)
- Energy Transport by Particles (Ch. 6 -7)
  - Classical Laws
  - Classical Size Effects
- Energy Transport in Liquids (Ch. 9)

Energy Conversion
- Energy Conversion Mechanisms (Ch. 8) [only recorded lectures]
- Emerging Energy Devices
  - Thermoelectric
  - Plasmonic Catalysis
  - Radiative Heat Transfer
  - Hydrovoltaic Devices

Course Organization

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Course Schedule	
Thu. 8-9	Exercises (HW)
Thu. 9-10	Project
Thu. 10-12	Lectures

Course Evaluation	
Mid-term Exam	30%
Project Report	30%
Final Assignment (Report)	40%

- **Exercises:**
  - New set of problems is assigned every Thursday, the solution becomes available on Friday, TAs are available for questions next Thursday 8-9.
  - Not part of the grade

- **Project Assignment (group):**
  - Set of problems requiring a combination of analytical derivations, reading&analysis, simple coding and numerical modelling
  - To be **solved in groups** (**4/5 students**).
  - The Project is assigned at the beginning of the course and **a concise report must be handed in before 23:59h of 30.03.2025** (one per group)
  - **The report is evaluated and contributes to the final grade (30%).**

- **Mid-Term Exam (individual):**
  - Written Exam on the **lecture content of Week 1-7 (L1-L16)**.
  - The Exam will last ~2h and **take place on 17.04.25, 09:15-11:15.**

- **Final Assignment (group):**
  - We will assign 2 papers to read on the topics of nanophotonics for energy and hydrovoltaics
  - **There will be two lab experiences on Week 10 (Nanophotonics) and Week 13 (Hydrovoltaics)**
  - **Each group must submit a report** including: (i) a critical analysis of each paper, including a discussion of the underlying physics; (ii) a small literature review on the topic of the paper; (iii) a description/report of the lab experience (iv) a critical discussion on each paper and the results of the lab experience.
  - **Hand-in before 23:59h of 09.06.25**

Course Schedule

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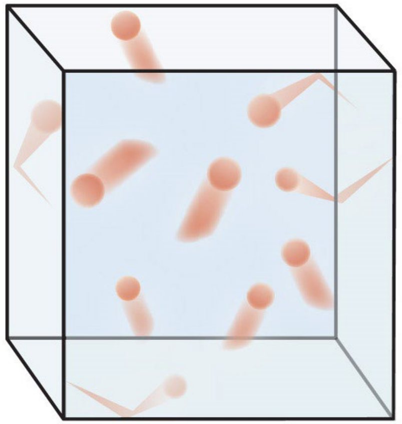
	Date	HOMEWORKS	PROJECT	H1 (8-9)	H2 (9-10)	H3 (10-11)	H4 (11-12)
Week 1	20.02	**HW 1** - Ch1 & 2	**Project Assigment Submit by 23:59h on 30.03**	no class	L1+2 - Intro Course; Particle View & Wave Description	L3+4 - Planck and Einstein relations; Schrodinger Equation & Solutions	Special Lecture on the use of COMSOL by Dr. Narmada Gopal
Week 2	27.02	**HW 2** - Ch 2 & 3		HW1 correction - TAs available for questions	TAs available for questions on Project	**L5** - Crystal Structure; Intro to Periodic Potential;	**L6** - Bloch's Theorem and Electronic Band Structure
Week 3	6.03	**HW 3** - Ch 3 & 4		HW2 correction - TAs available for questions	TAs available for questions on Project	L7 - Density of States; Phonon Band Structure	L8 - Phonon & Photon Density of States; Q&A
Week 4	13.03	**HW 4** - Ch 4 & 5		HW3 correction - TAs available for questions	TAs available for questions on Project	L9 - Partition Functions; Fermi-Dirac and Bose-Einstein Distributions;	L10 - Internal Energy; Specific Heat; Planck's Law
Week 5	20.03	**HW 5** - Ch 5 & 6		HW4 correction - TAs available for questions	TAs available for questions on Project	L11 - EM Wave Propagation (reflection/transmission; evanescent waves; total internal reflection; tunnelling)	L12 - Landauer Formalisms; Quantum Conductance; Interfacial Thermal Resistance; Coherence Lengths
Week 6	27.03	**HW 6** - Ch 6		HW5 correction - TAs available for questions	TAs available for questions on Project	L13 - Intro Boltzmann equation and Carrier Scattering;	L14 - Boltzmann approximation. Fourier Law and Thermal Conductivity;
Week 7	3.04	**HW 7 - Ch 6**		HW6 correction - TAs available for questions	TAs available for questions on Homeworks	L15 - Ohm's & Wiedemann Franz Laws;	L16 - Thermoelectric Effect & Thermoelectric devices
Week 8	10.04			RECAP time for exam & Tas available for questions	L17 - Thermoelectric Devices + Q&A	L18 - State-of-the-art topics - Intro to Plasmonics & nanophotonics	L19 - State-of-the-art topics: Plasmonic Hot Carriers and Photocatalysis
Week 9	17.04				Written Exam on topics from L1 to L16		
	24.04					Easter break	
Week 10	1.05		**Final Assignment Submit by 23:59h on 09.06**	Lab Experience: Nanophotonics			
Week 11	8.05			Reading time for papers	TAs available for questions on Homeworks & Project	L20 - State-of-the-art-topics: Thermoplasmonics, Radiative Cooling, near field heat transfer, interfacial evaporation	L21 - Liquids and Electrokinetic devices
Week 12*	15.05			Reading time for papers	TAs available for questions on Homeworks & Project	L22 - State-of-the-art topics - Hydrovoltaic devices 1 (taught by Tarique Anwar)	L23 - State-of-the-art topics - Hydrovoltaic devices 2 (taught by Tarique Anwar)
Week 13*	22.05			Lab Experience: Hydrovoltaic Devices			
Week 14	29.05	no new HW		ascention day			

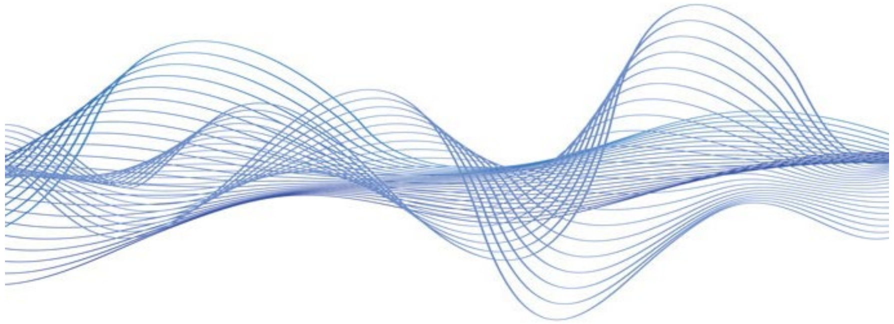
RECAP of Important Dates & contacts

Date	
28.02.2025	Deadline for Defining the Groups
30.03.2025	Submission of Project Report
17.04.2025	Exam
09.06.2025	Submission of Final Report

Next Lecture – Heat (Energy) Transport Mechanisms



Particle View



Wave View