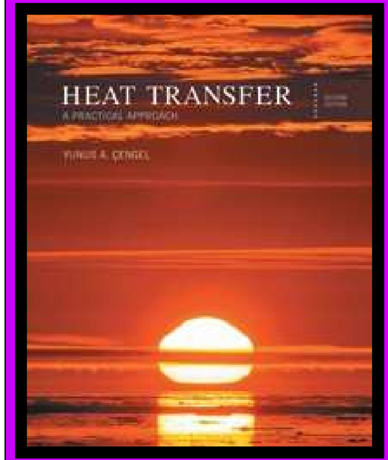

SME 4463

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CHAPTER 1

Introduction

Basic of Heat Transfer

Introduction

Thermodynamics:

- Energy can be transferred between a system and its surroundings.
- A system interacts with its surroundings by exchanging work and heat
- Deals with equilibrium states
- Does not give information about:
  - *Rates at which energy is transferred*
  - *Mechanisms through with energy is transferred*

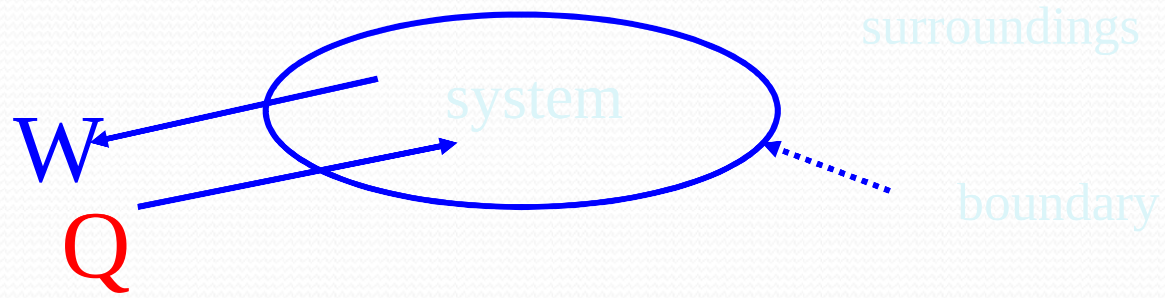
In this chapter we will learn

- What is heat transfer
- How is heat transferred
- Relevance and importance

Thermodynamics

Thermodynamics is about:

Interaction of energy with system and surroundings.



Energy can move in and out of a system in two forms

Work (W) and **Heat (Q)**

- There are three principle laws upon which Engineering studies are derived
  - Conservation of Mass (Continuity, Mass Transfer)
  - Conservation of Momentum (Fluid Mechanics, Mass Transfer)
  - Conservation of Energy (Thermodynamics, Heat Transfer)

- We are primarily interested in the Conservation of Energy in Heat Transfer

Conservation of Energy

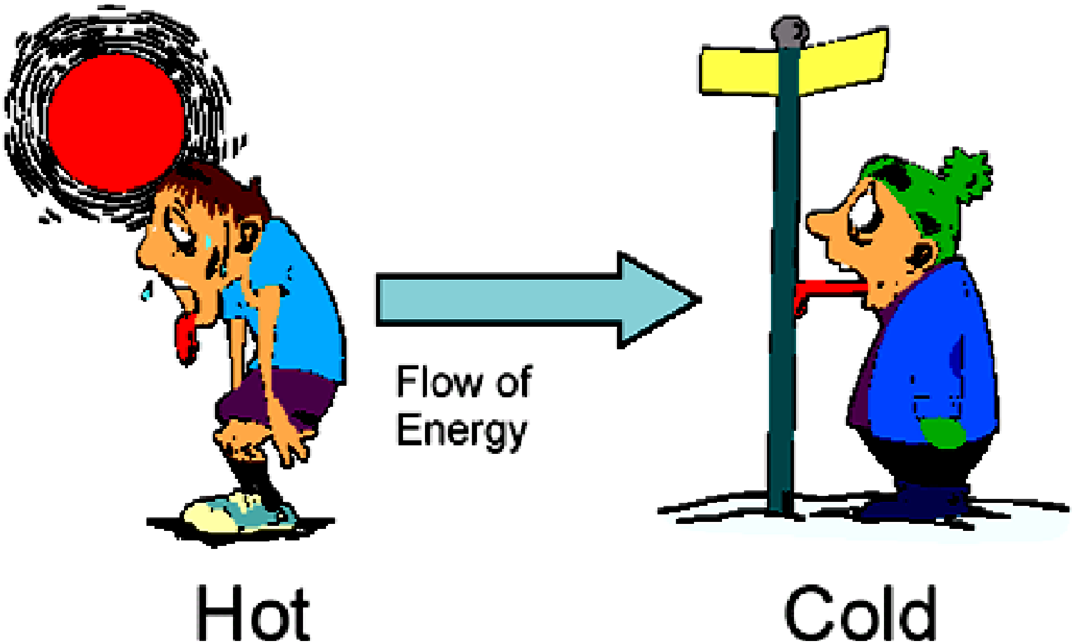
- Thermodynamics – study of the transfer of work and energy between a system and its surroundings – ***in equilibrium***

- How we achieved equilibrium is not of concern in thermodynamics, but to Engineers it is….so…

- Heat Transfer – determination of the rate of energy (mostly internal energy) transferred from one system to another resulting in a temperature change.

HEAT TRANSFER

- Occurs when there is an energy difference in a medium or between mediums
- All of nature "seeks a lower energy state" – in the case of heat transfer:



EXAMPLE

Consider a can of drinks which you want to cool down – you would put it in a refrigerator.

We know from experience that if we leave it in the fridge – ultimately – it will reach equilibrium with its surroundings

BUT HOW LONG? Thermodynamics can not answer that.

Where is heat transfer falls at?

There are three principle laws upon which Engineering studies are derived

- **Conservation of Momentum (Fluid Mechanics, Mass Transfer)**
- **Conservation of Energy (Thermodynamics, Heat Transfer)**
- **Conservation of Mass (Continuity, Mass Transfer)**

In this course we are primarily interested in the

Conservation of Energy in Heat Transfer

The topic of *Heat Transfer* is about…

understanding, determining and predicting flows of heat

All of Heat Transfer study is about answering the question:

What is the heat flow rate from A to B?

Heat Transfer Problems

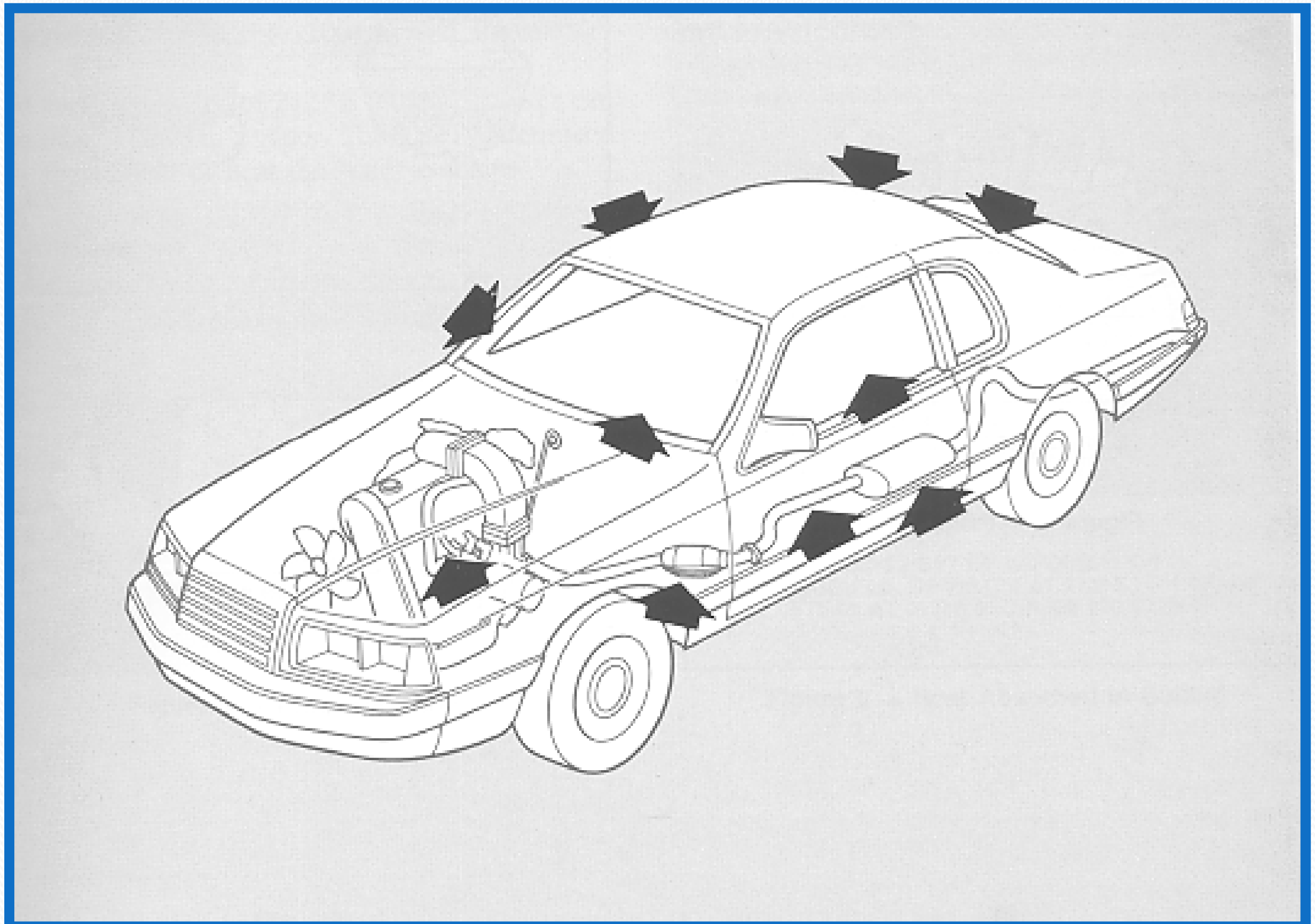
Two types

1. Rating problems
2. Sizing problems

What is temperature ?

- Thermal energy: atomic/molecular/electronic kinetic energy
- Measure to determine how hot/cold a material is (intensity of thermal energy)
- Criterion to determine the direction of thermal-energy transport

From a microscopic view, temperature represents atomic or molecular kinetic energy (translation / vibration / rotation)



Importance of heat transfer in engineering

Power

• High turbine inlet temperatures desired for efficiency.

• Heat transfer from gas or steam to turbine blades (convection, radiation) – blades may fail.

• Predict/control temperature of blades. Cooling strategies – internal cool air passages,

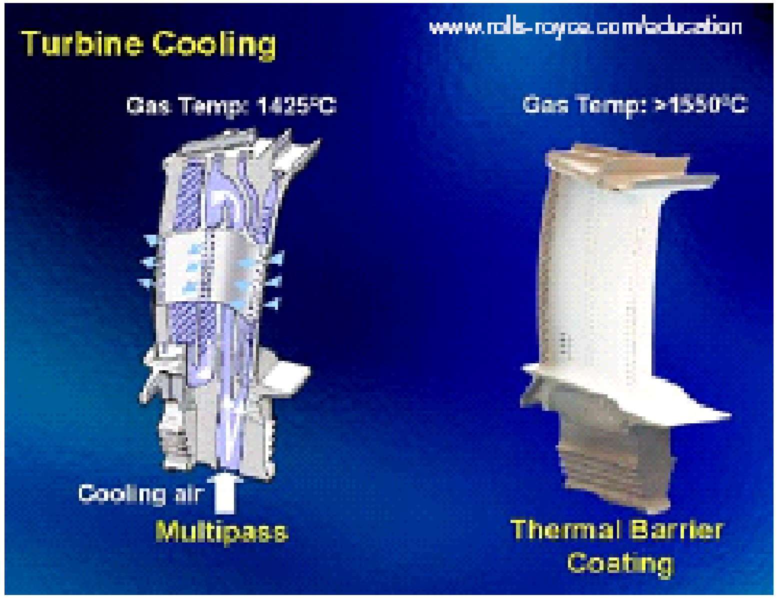
cool air bleed through perforated blade surface.

Turbine blade cooling

Gas turbines (aero engines)

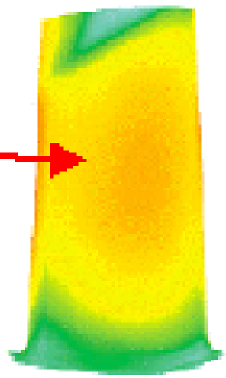
Turbine gas (direct from the combustion chamber) is at 1500°C or higher. Blade metal must be protected.

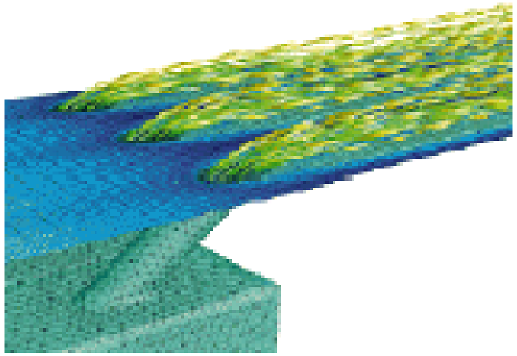
- "cool" air (~500 °C) circulates inside blade
- some air injected via holes in blade to give cool layer on outer surface – *film cooling*
- ceramic *thermal barrier coating*



Design / R&D processes:

- aerodynamics (wind tunnel testing, computation) → basic blade shape
- aerodynamics + heat transfer → blade temperature
- wind tunnel studies and computation assess effects of film cooling and other techniques





Biomedical

• Thermal cancer treatments – electromagnetic radiation (laser, radio), ultrasonic waves, etc used to heat tumor.

• Necessary to predict tumor temperature and understand heat transfer to surrounding

tissue (conduction, convection).

• Sometimes whole body temperature needs to be raised, lowered, maintained – water

and air blanket devices (convection and conduction), IR lamps (radiation).

Building

• Heat is transferred through walls (conduction) to outside air (convection), through

windows (radiation, convection, conduction), open doors/windows (convection)…

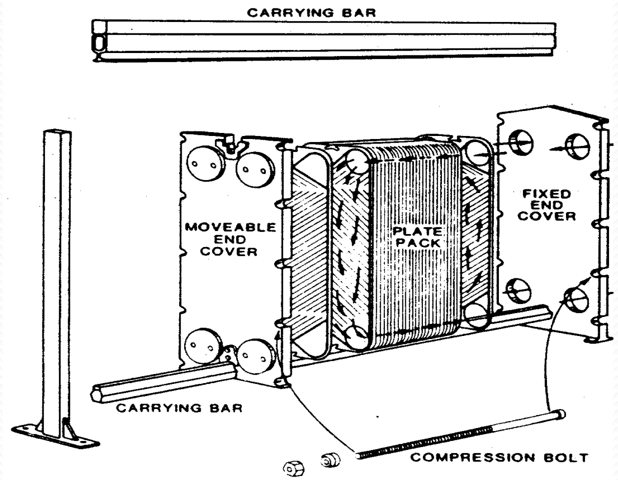
• Heat loss (or gain) determines heating (air-conditioning) requirements.

Heat exchangers

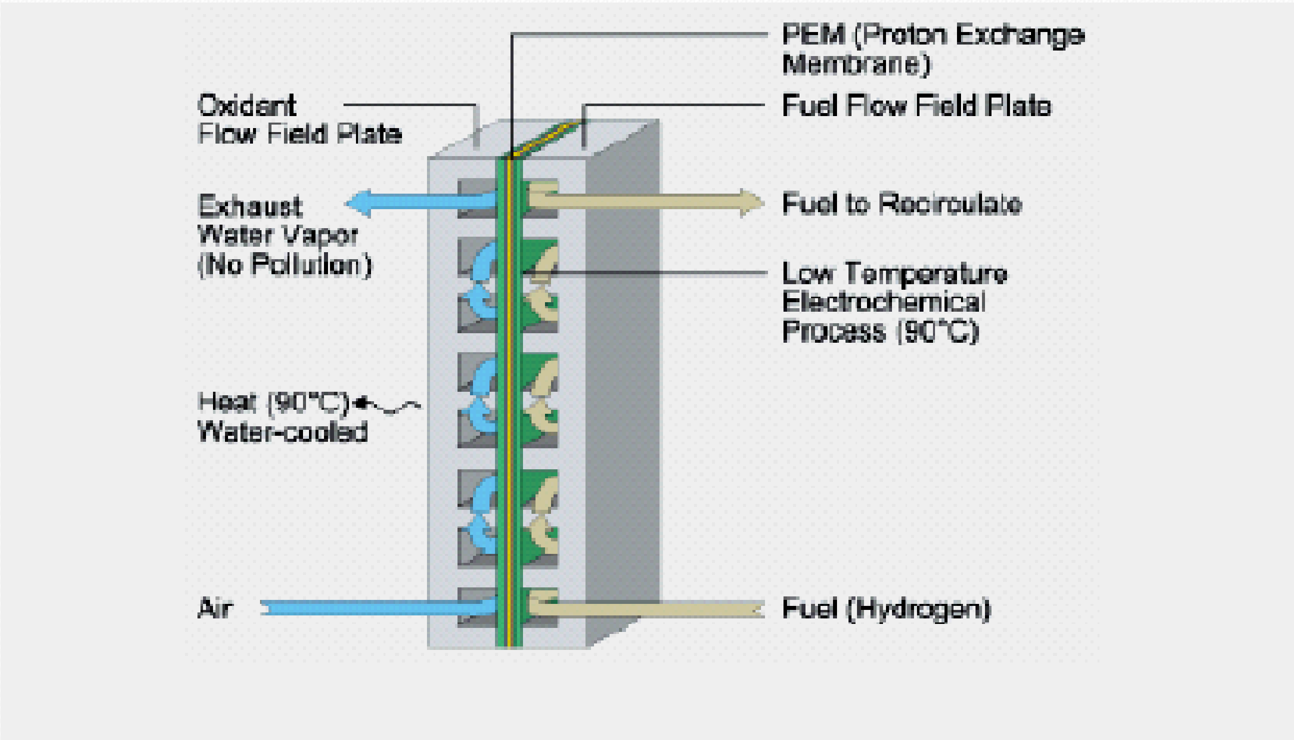
• devices designed specifically to promote heat transfer between two fluids

• car radiators, boilers, condensers, chip cooling, equipment cooling …

and so on…



Fuel cells

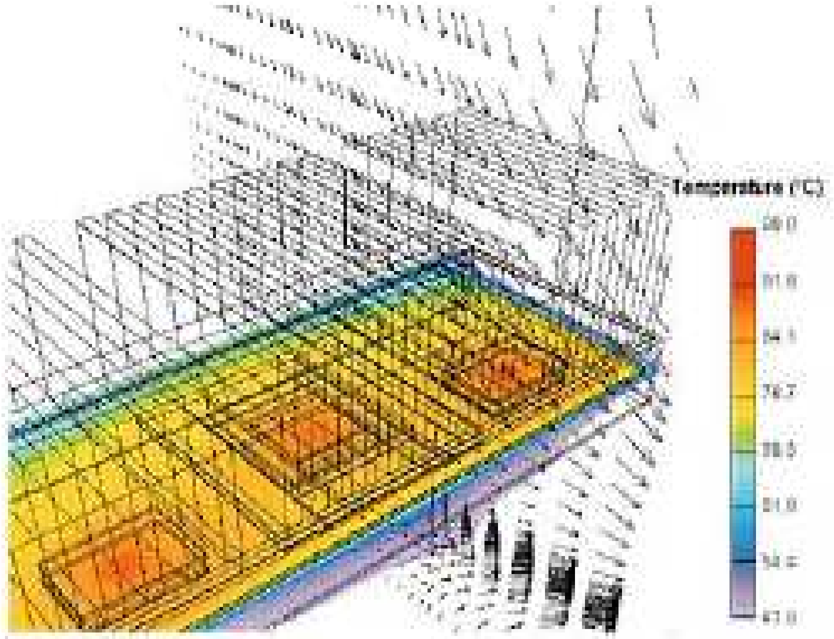

PEM (Proton Exchange Membrane)
Oxidant Flow Field Plate
Fuel Flow Field Plate
Exhaust Water Vapor (No Pollution)
Fuel to Recirculate
Low Temperature Electrochemical Process (90°C)
Heat (90°C) Water-cooled
Air
Fuel (Hydrogen)

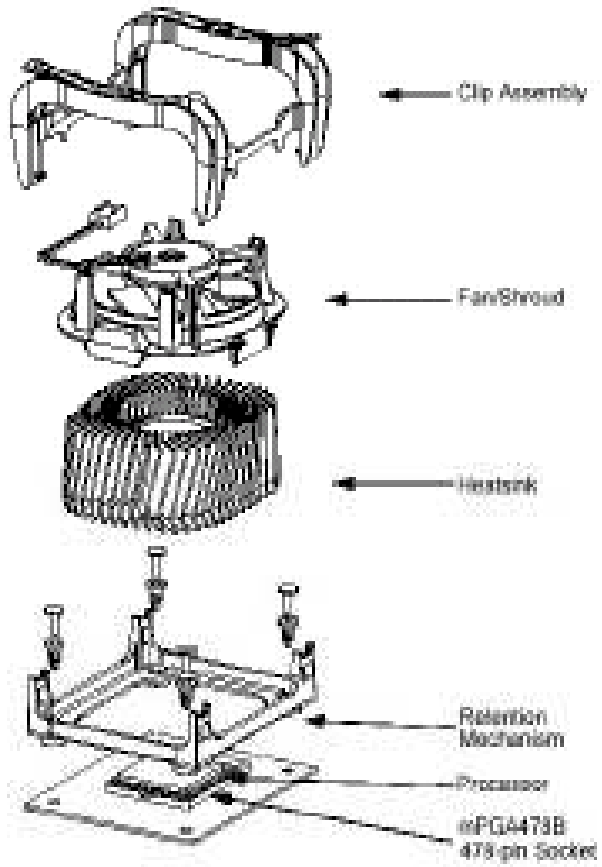
Electronics Cooling

Cooling is a major issue in electronics design.

- Components must not overheat. Cooling systems take up space, cost money, increase power consumption. Critical for mobile electronics.
- Some systems are refigerated to improve performace (reduced "noise" at low T).

Computational fluid dynamics prediction of chip temperature and airflow (Flomerics)





Pentium 4 – dissipates 52.4 W – max safe temperature 68°C

Notation

Notation used in this course

Q - a quantity of heat transfer (same as in thermo)

$\dot{Q}$ - heat transfer rate (per unit time), [J/s = W]

$\dot{q} = \dot{Q}/A$ - heat flux (per unit time, per unit area), [W/m^2]

$\dot{G}$ - heat generation, [W]

$\dot{g} = \dot{G} / V$ - heat generation per unit volume, [W/m^3]

ALWAYS PAY CLOSE ATTENTION TO YOUR UNITS

Symbols and units

Thermal energy: E=[J] (thermal energy or heat has the same unit as work (=force×displacement)

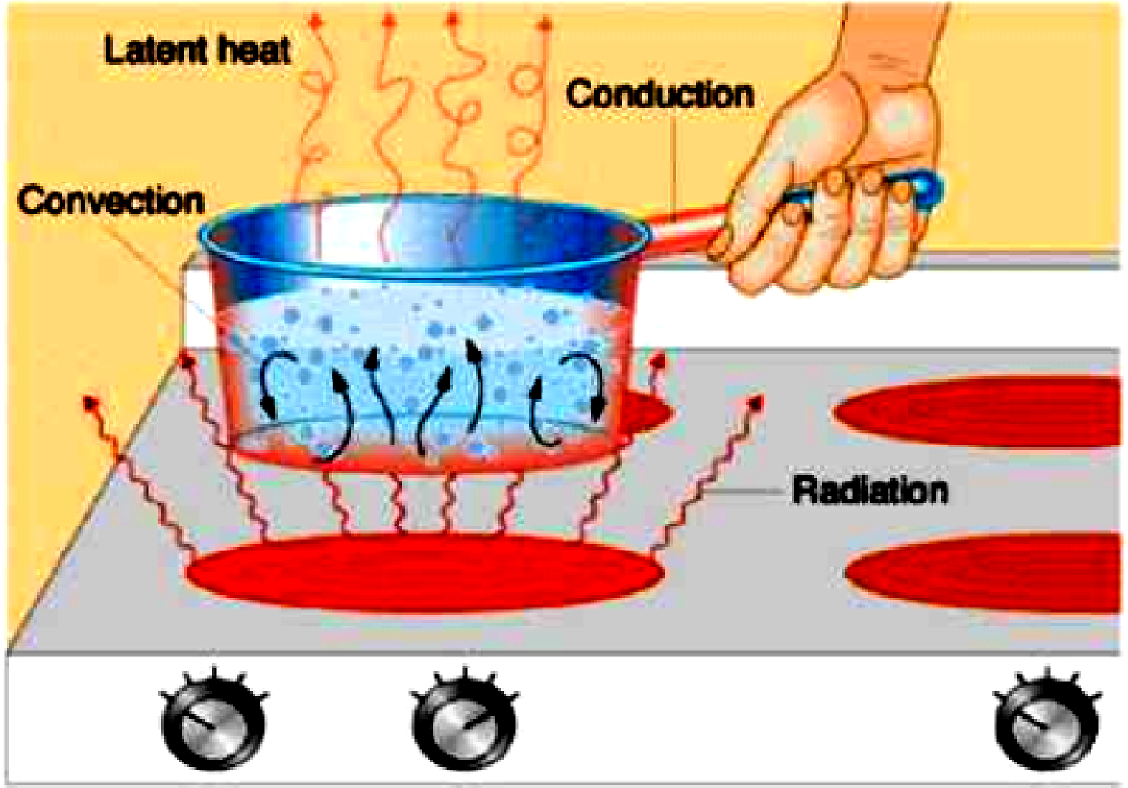
- Temperature: T=[^oC] or [K] T(^oC)=T(K)+273.15

Note: When ^oC or K unit is in the denominator, unit change doesn't affect the numerical value, e.g., specific heat C_p 1 J/kg·^oC=1 J/kg·K, thermal conductivity 1 W/m·^oC=1 W/m·K

Methods of Heat Transfer

Objectives are to:

- describe the three methods of heat transfer
- give practical/environmental examples of each

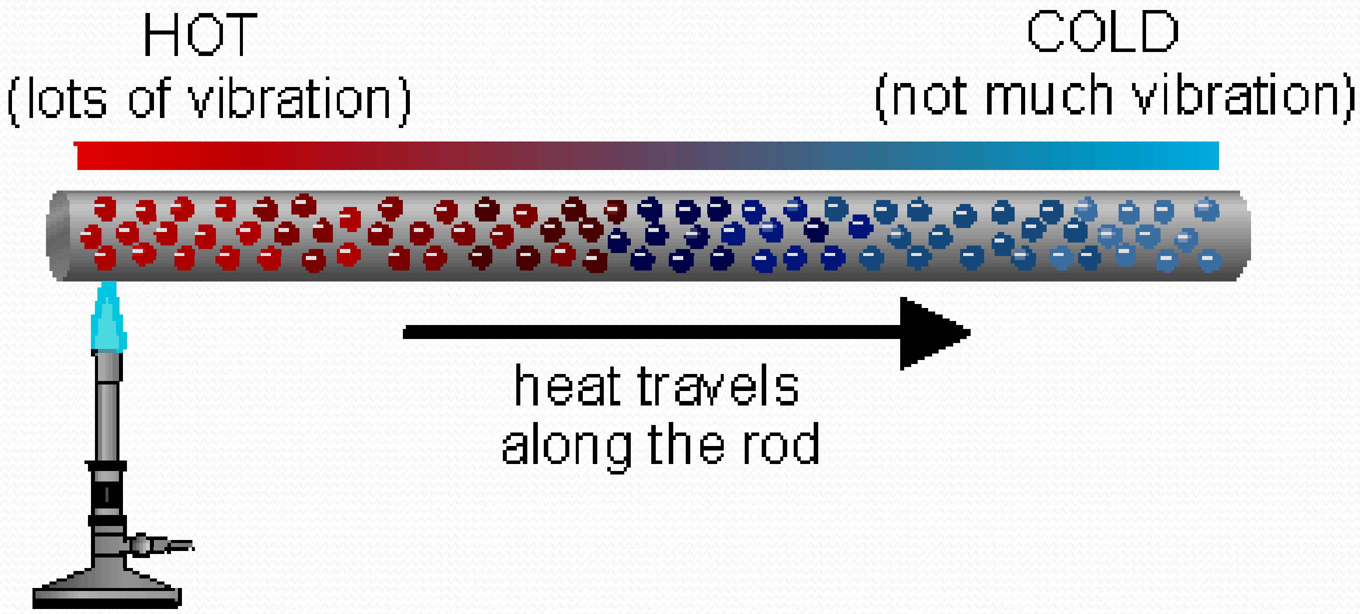


Modes of Heat Transfer

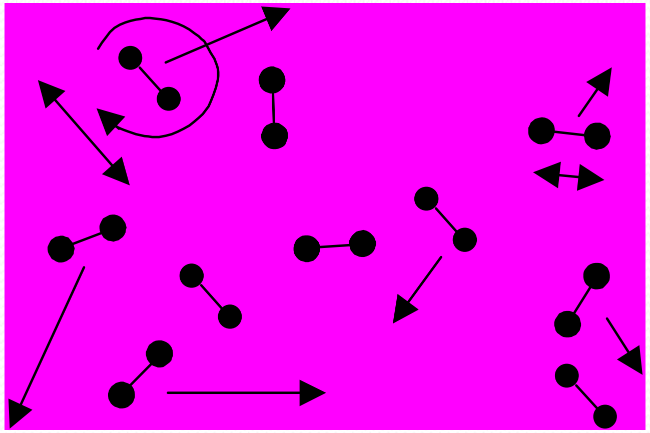
There are three principle mode of heat transfer

- **Conduction**
- **Convection (forced or free)**
- **Radiation**

CONDUCTION


HOT
(lots of vibration)
COLD
(not much vibration)
heat travels
along the rod

CONDUCTION

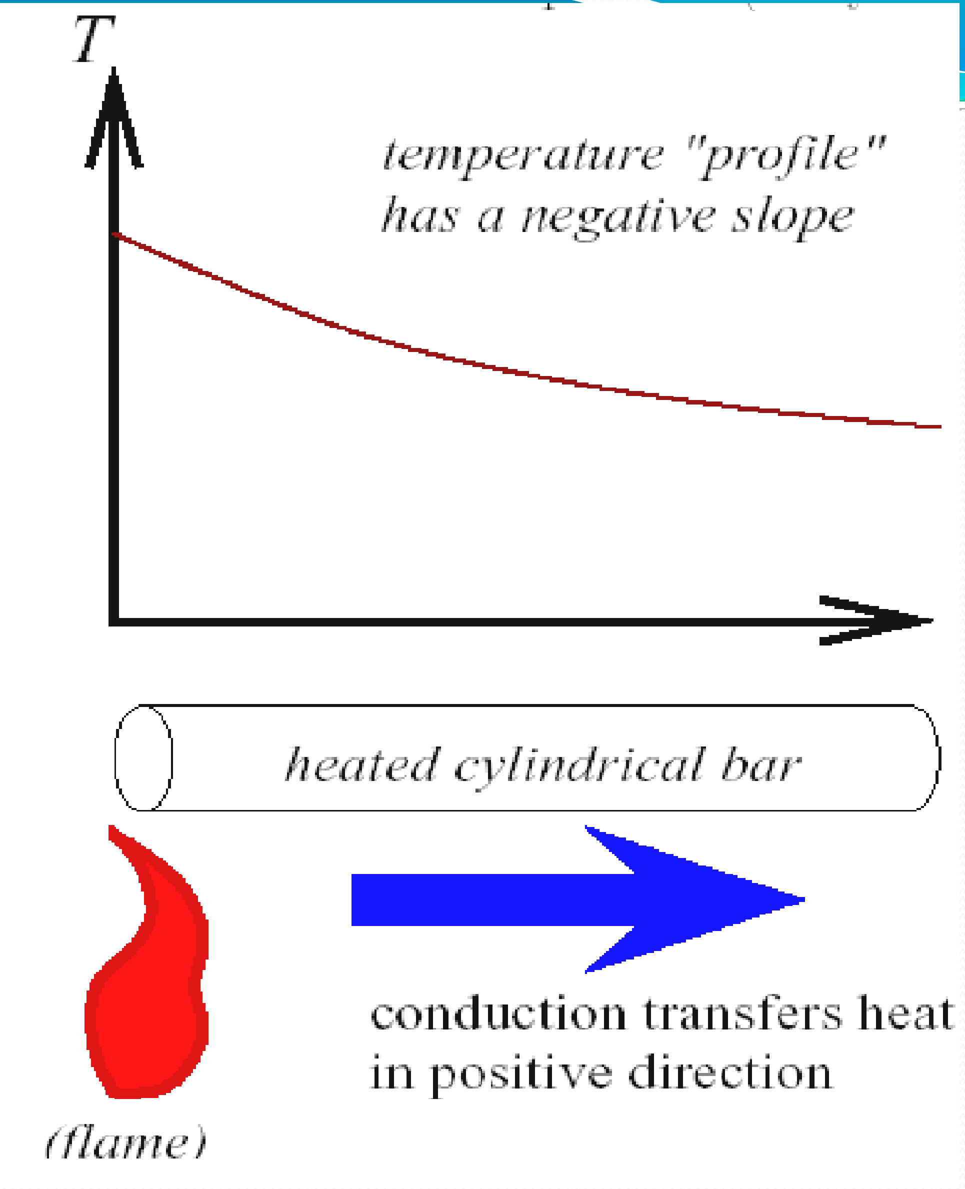


- Straightforward transmission of heat within a stationary medium
- Solid, liquid, or gas (usually most important in solids)

    -Usually in solid(s) , maybe liquids
    -Rarely gases (negligible to convection)

- Mechanisms are on molecular/atomic level: molecular vibrations, motion of free electrons
- Can often come up with exact mathematical solutions

    Need a temperature gradient


T
temperature "profile"
has a negative slope
heated cylindrical bar
conduction transfers heat
in positive direction
(flame)

Conduction is simply:

Transfer of energy from more energetic to less energetic particles of a substance due to interactions between particles

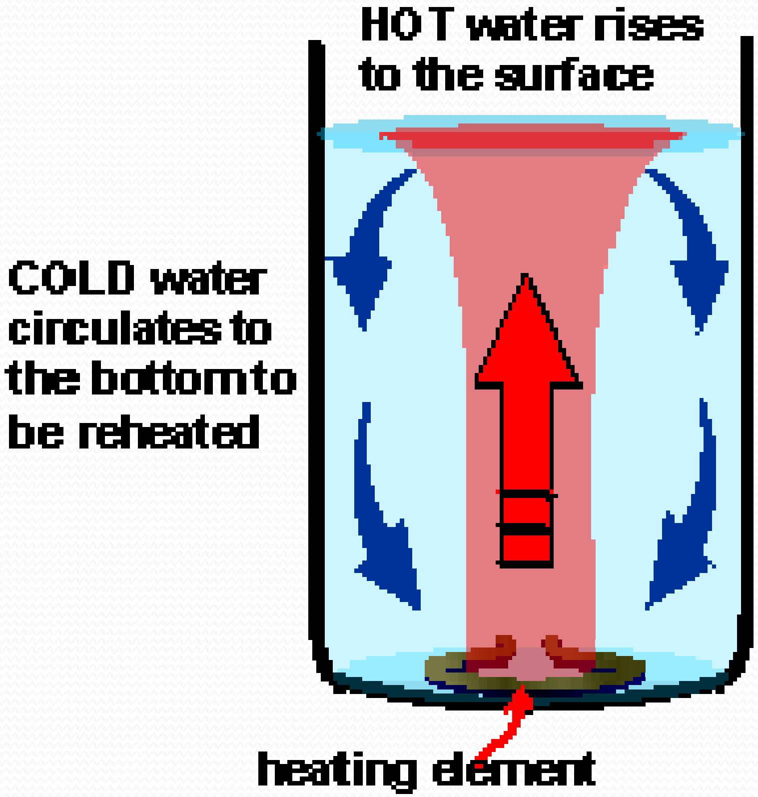
From empirical observations (experiments)

Fourier's Law

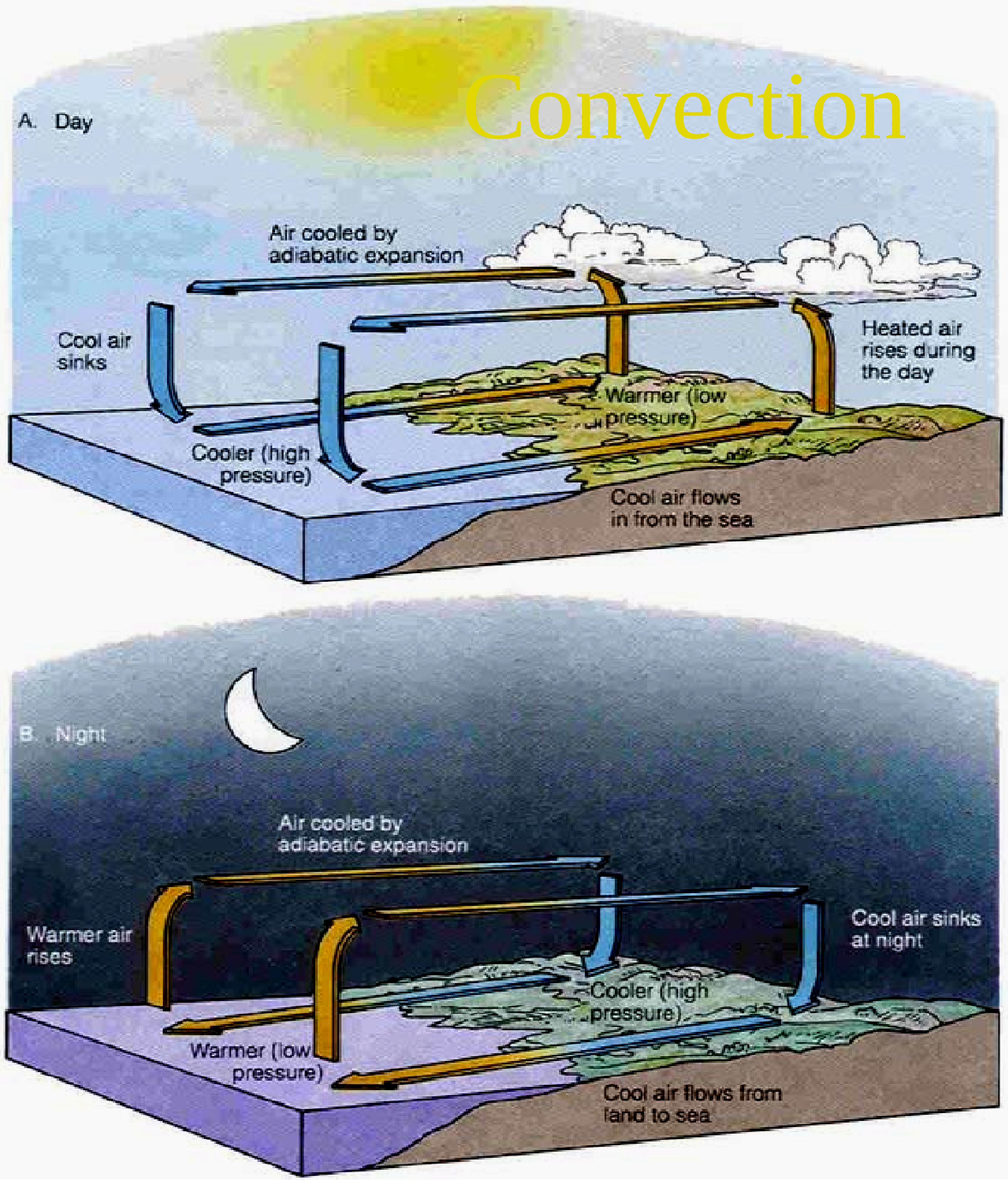
$$\dot{Q} = -k\nabla T$$

- Q: heat transfer rate
- A: cross-sectional area
- L: length
- k: thermal conductivity
- ΔT: temperature difference across conductor

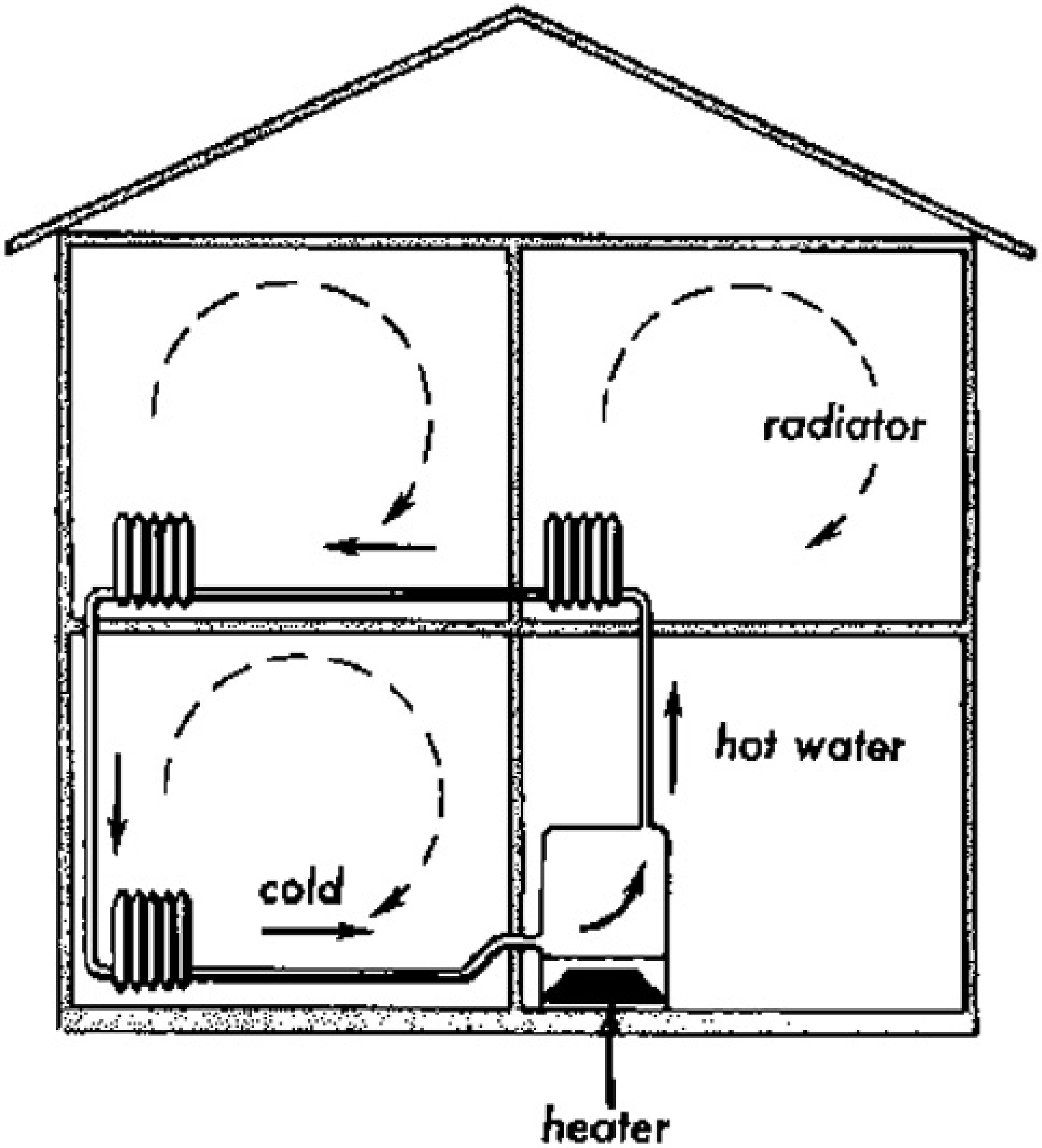
Convection


HOT water rises
to the surface
COLD water
circulates to
the bottom to
be reheated
heating element

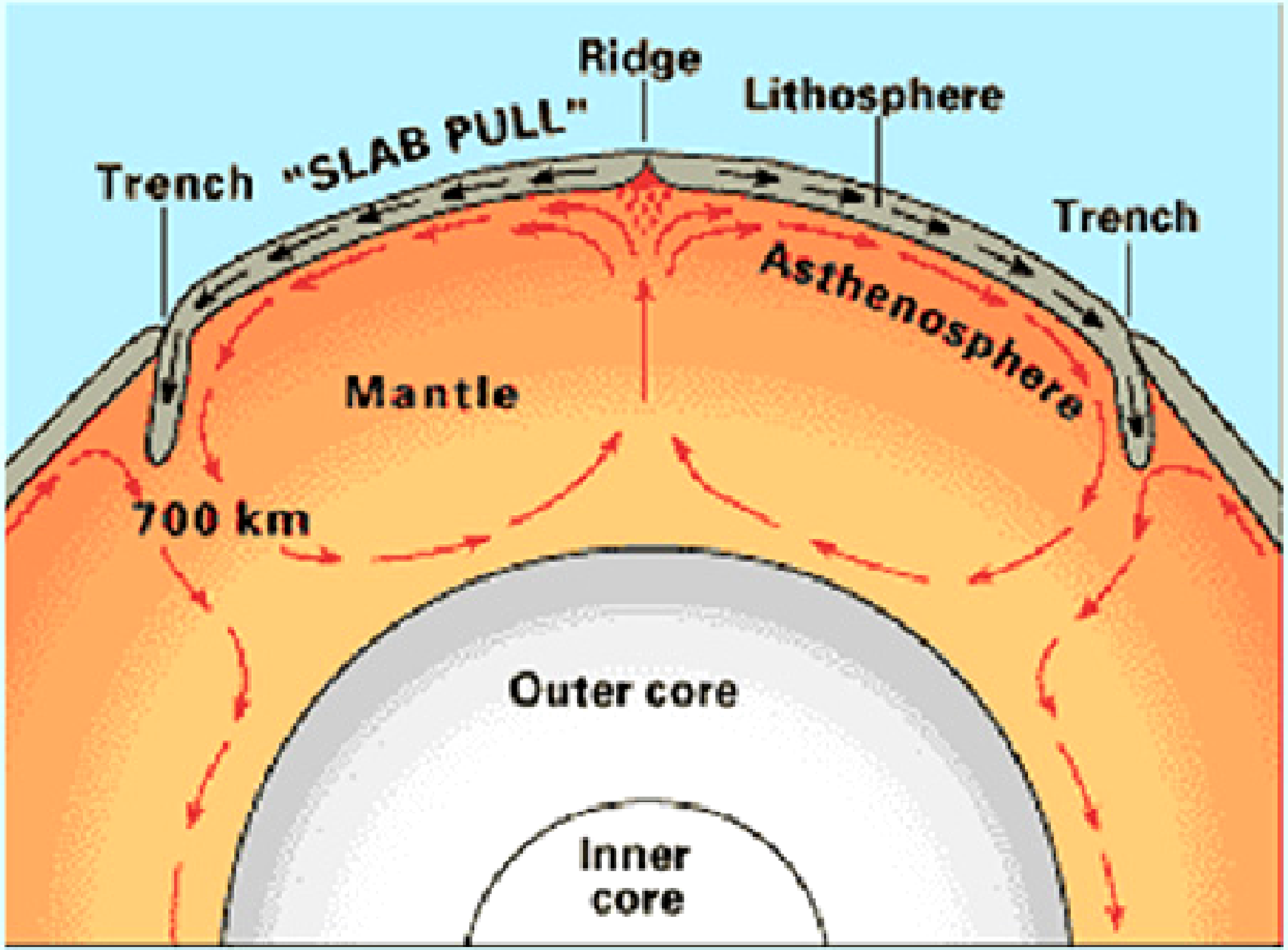
Convection


A. Day
Air cooled by adiabatic expansion
Cool air sinks
Heated air rises during the day
Warmer (low pressure)
Cooler (high pressure)
Cool air flows in from the sea
B. Night
Air cooled by adiabatic expansion
Warmer air rises
Cool air sinks at night
Cooler (high pressure)
Warmer (low pressure)
Cool air flows from land to sea

Convection at Home

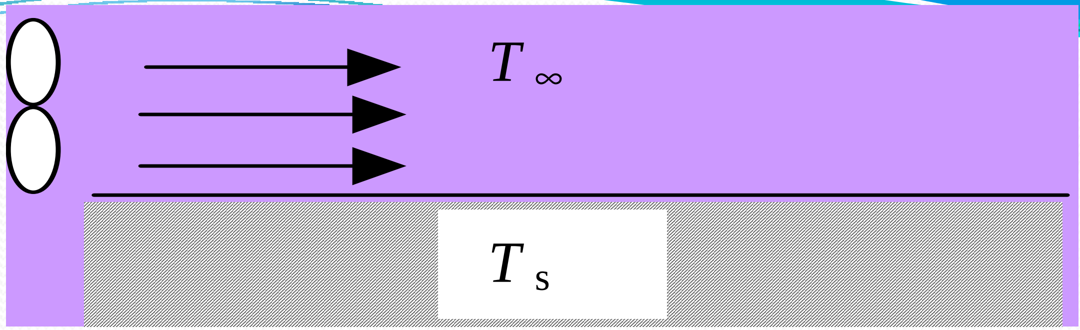


Convection in the Earth



Convection currents move the earth's continents.

Convection



The convection heat transfer mode is comprised two mechanisms:

1. Energy transfer due to random molecular motion (diffusion)

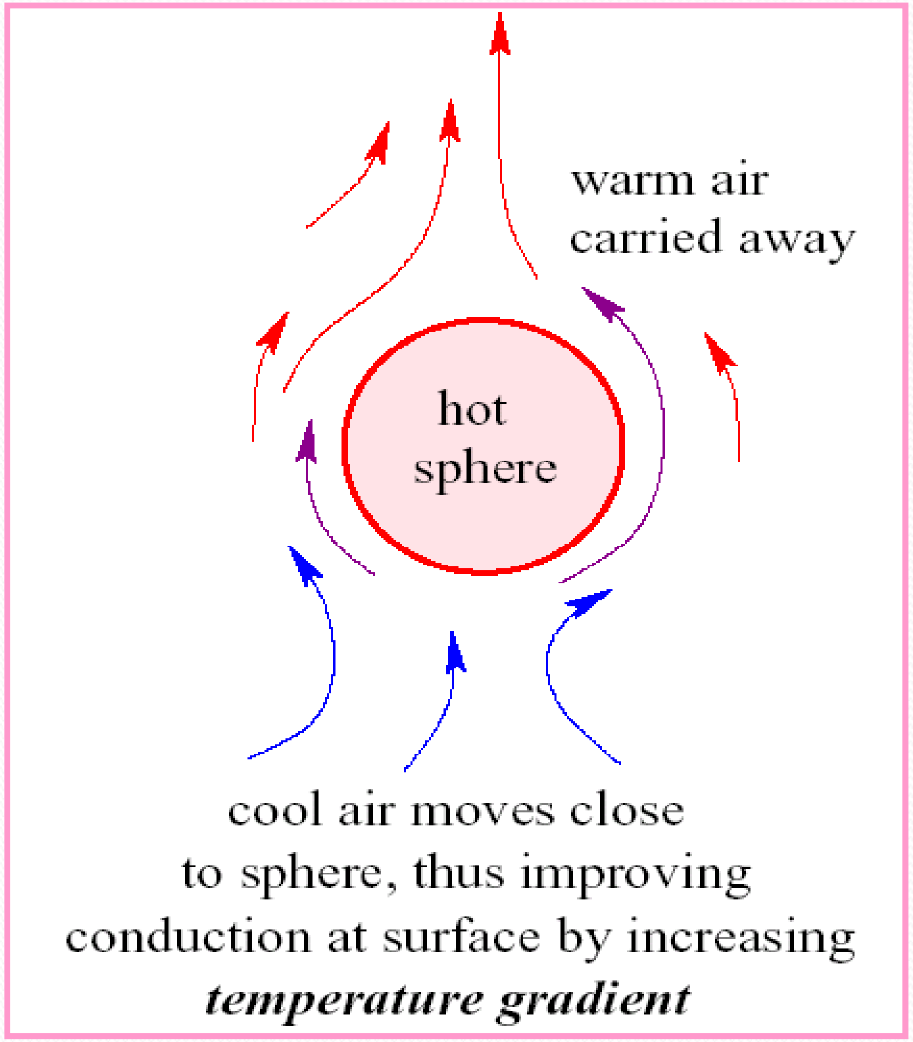
2. Energy transfer due to bulk (or macroscopic) motion of the fluid (called advection)

- If both transport of energy is present, the term **CONVECTION** is generally used.
- If transport of energy due only to bulk motion of the fluid, the term **ADVECTION** is used.

Convection

Convection is what happens when the motion of a heat conducting fluid increases the rate of heat transfer.

In other words, the *convective* air currents increase the rate of heat transfer by improving the conduction at the surface.



•Convection heat transfer normally takes place in a moving liquid or gas

• Conduction still takes place

• Usually interested in cooling or heating of a solid object by a fluid stream – e.g. pipes in a boiler, cooling fin on an engine…

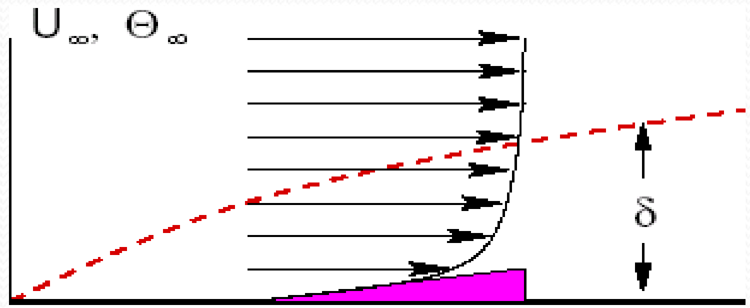
• Exact mathematical analysis usually impossible – usually rely on empirical correlations

Convection

We are interested mainly in cases where there is heat transfer between a fluid in motion and a bounding surface.

a. **Velocity boundary layer**

b. **Thermal boundary layer**



There are two types of convection:

Forced convection - flow caused by external means

Free convection - caused by buoyancy forces

Newton's Law of Cooling:

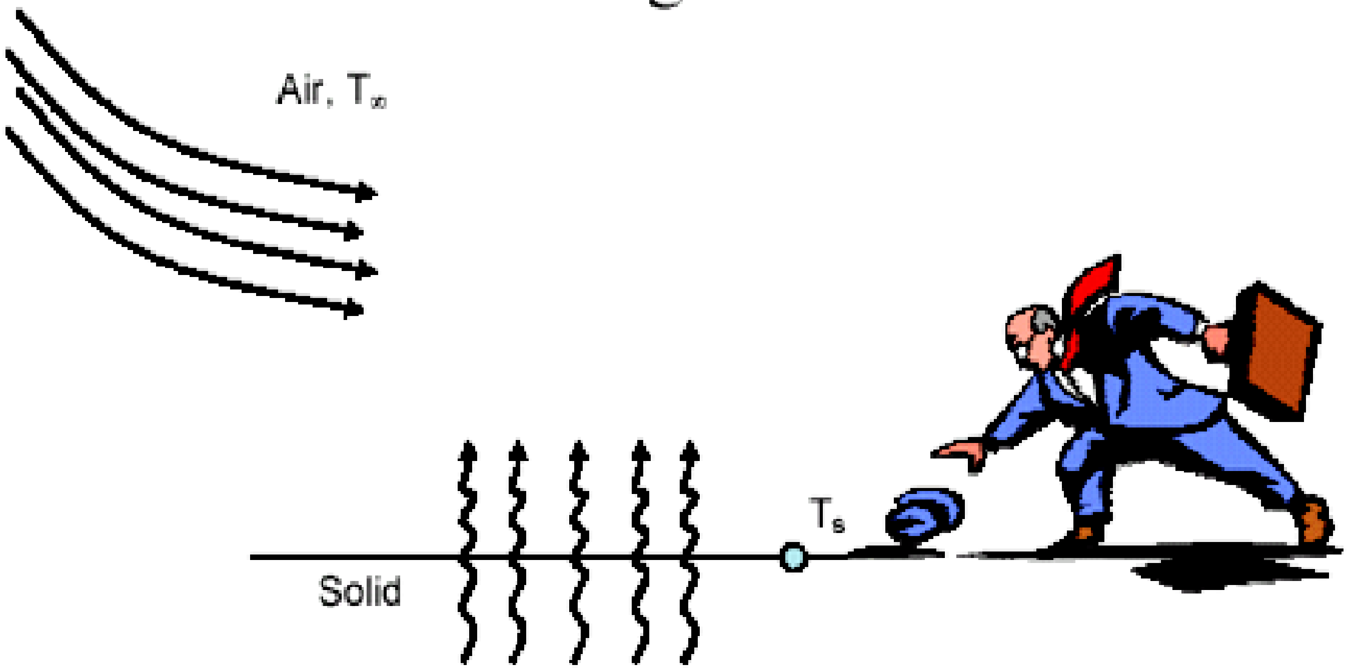
$$Q_{conv} = hA_s(T_s - T)$$

Q is the **convective heat transfer rate** (W), and is proportional to the difference between surface and fluid temps.

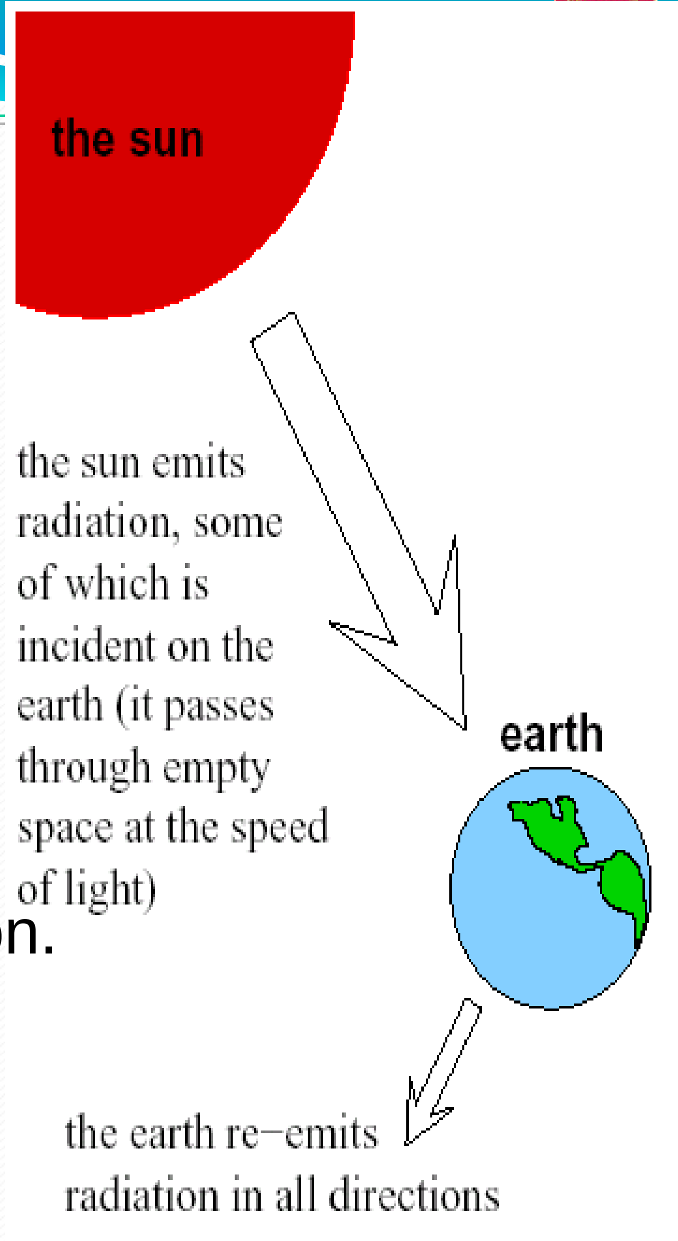
h (W/m^2 K) is **convective heat transfer coefficient** - depends on conditions in boundary layer, surface geometry, nature of fluid motion, and fluid thermo and transport properties.

Convection

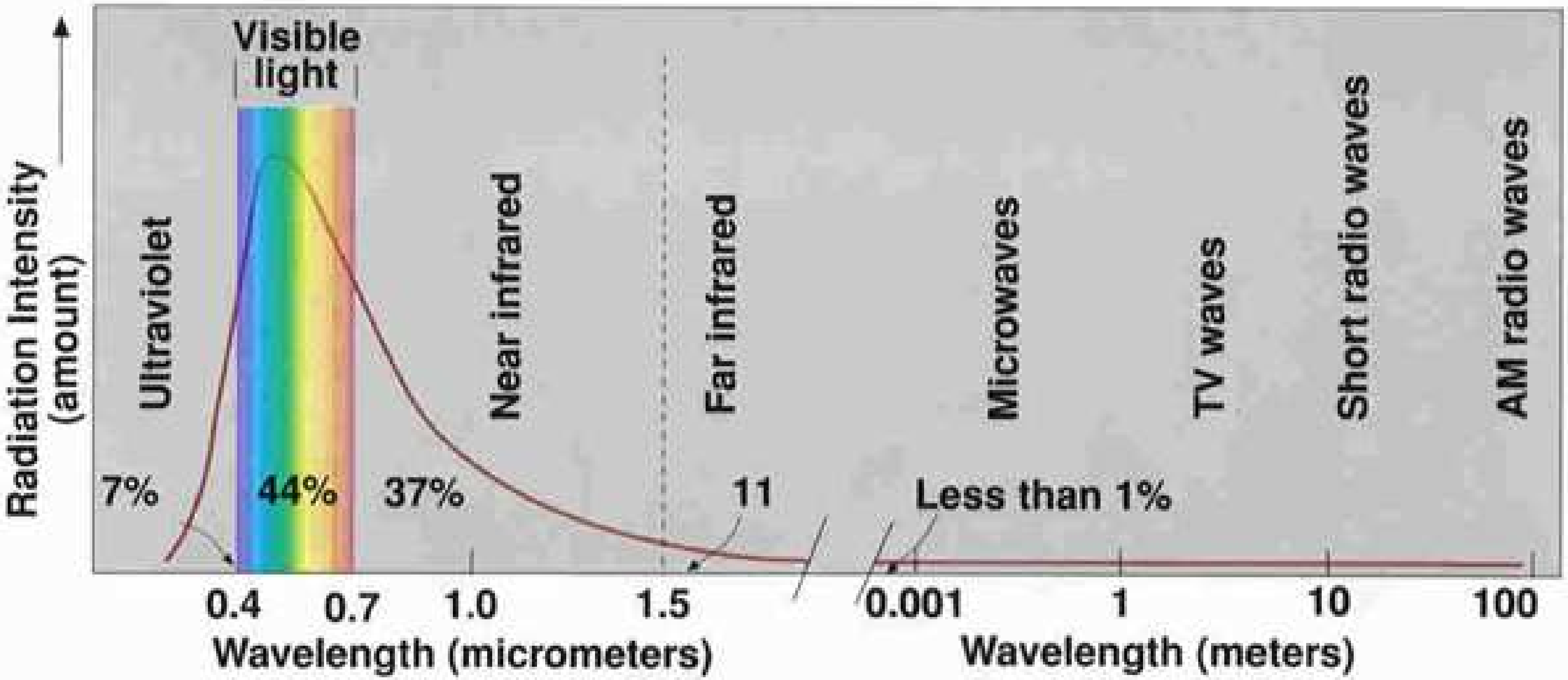
We feel colder on a windy day, summer or winter. And we get colder faster, as the wind blows stronger.

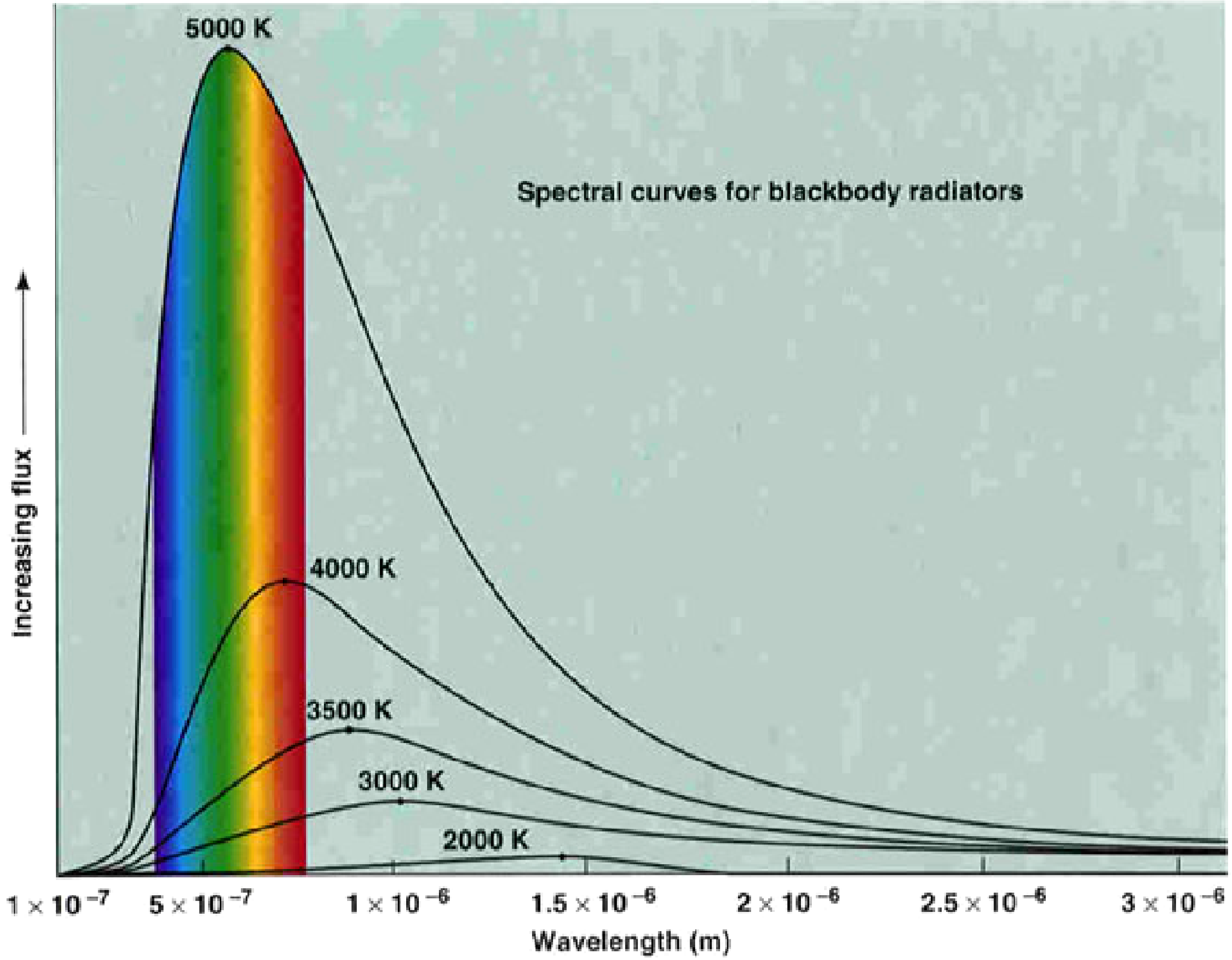


RADIATION



- **Radiation** is energy emitted by matter that is at a finite temperature.
- The emission is **due to changes in electron configurations** of constituent atoms or molecules.
- Transported by electromagnetic radiation.
- **Does not require a material medium**, occurs most efficiently in vacuum.


Visible light
Radiation Intensity (amount)
Ultraviolet
Near infrared
Far infrared
Microwaves
TV waves
Short radio waves
AM radio waves
7%
44%
37%
11
Less than 1%
0.4
0.7
1.0
1.5
0.001
1
10
100
Wavelength (micrometers)
Wavelength (meters)



5000 K
Spectral curves for blackbody radiators
4000 K
3500 K
3000 K
2000 K
Increasing flux
1 × 10⁻⁷
5 × 10⁻⁷
1 × 10⁻⁶
1.5 × 10⁻⁶
2 × 10⁻⁶
2.5 × 10⁻⁶
3 × 10⁻⁶
Wavelength (m)

Radiation

Solids emit radiant energy – depends on T_{abs}

Stefan-Boltzmann Law:

$$q'' = \sigma T_s^4$$

- Ever wondered why a room at 70°F in the summer feels too hot and in the winter feels too cold?

Ideal Radiator

Stefan-Boltzmann Law for Blackbody (Ideal Radiator):

$$\frac{\dot{Q}_{rad}}{A} = q'' = \sigma T_s^4$$

Ideal radiator

or *Blackbody*

Maximum flux at which radiation may be emitted from a surface, where,

T_s is the *absolute temp (K)* of the surface

σ is the Stefan Boltzmann constant (5.67×10^{-8} W/m^2K^4)

Heat flux emitted by a **real object** (less than that of a blackbody)

$$Q_{rad} \; q'' = \varepsilon \sigma A_s T_s^4 \quad \text{or} \quad q'' = \varepsilon \sigma T_s^4$$

ε: emissivity, a radiative property of surface, how efficient

radiation emission is compared to blackbody

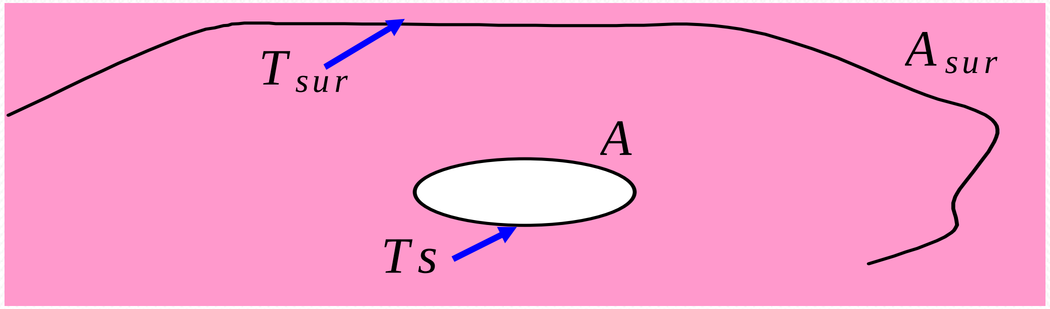
$$0 \leq \varepsilon \leq 1$$

Determination of the net rate at which radiation is exchanged between surfaces is **complicated**

Most often, we only need to know the net exchange between a **small surface and the surroundings.**

Small surface and large surroundings

The net rate of radiation heat exchange between a **small surface and a large surroundings** per a unit area of the small surface



$$Q_{rad}\, q = \varepsilon\sigma A\left(T_S^{\ 4} - T_{SUR}^{\ 4}\right)$$

- ε: emissivity

  Maximum ε = 1.00, black charcoal surface, $0 \leq \varepsilon \leq 1$

  Minimum ε = 0.01, shiny gold surface
- σ: Stefan-Boltzmann constant, **5.67 x 10^{-8} W/m^2K^4**

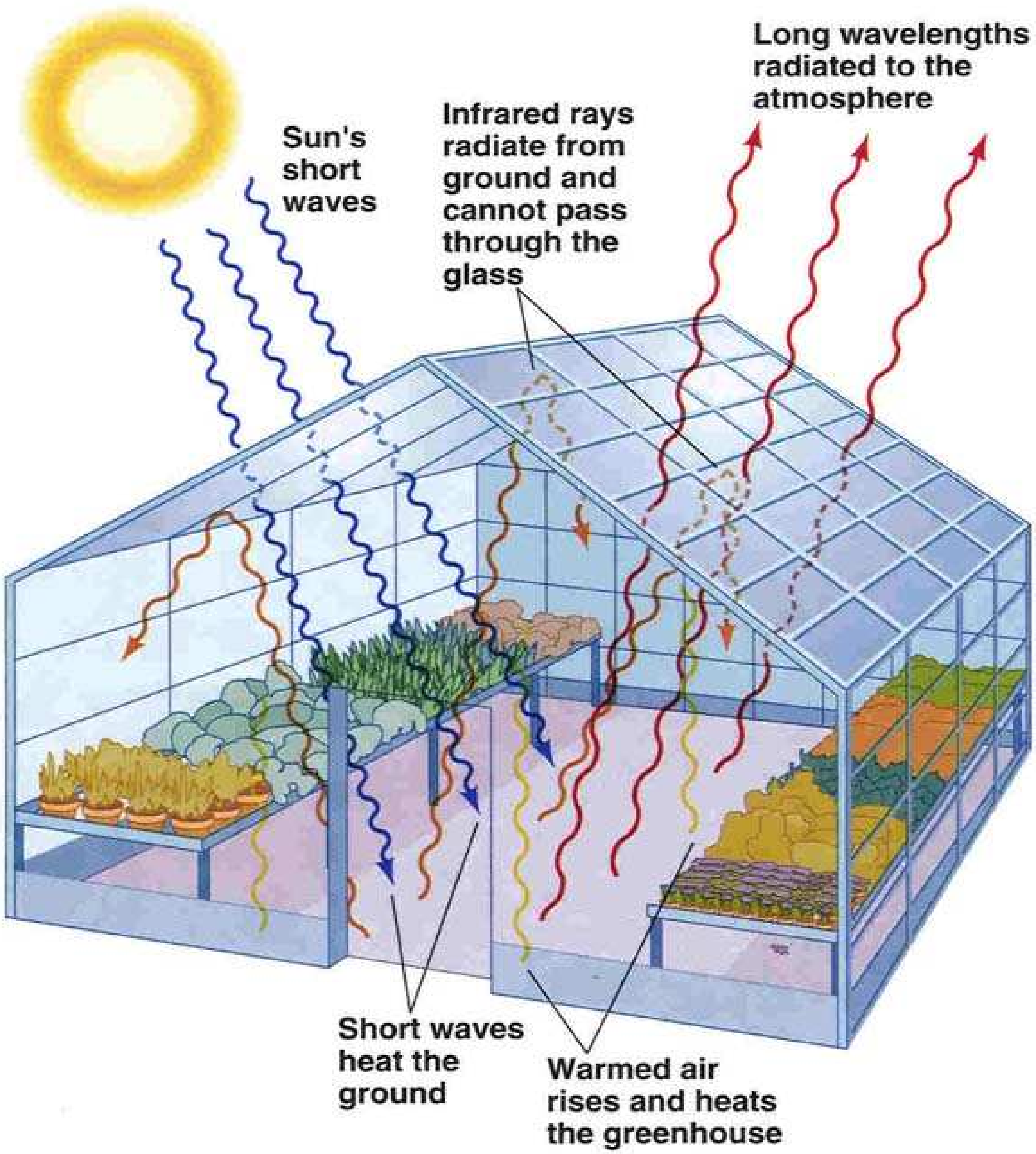
Previous equation can also be written in the following form,

$$\dot{Q} = h_r A(T_s - T_{sur})$$

Where h_r is the radiation heat transfer coefficient

$$h_r = \varepsilon\sigma(T_s + T_{sur})(T_s^2 + T_{sur}^2)$$

where we have linearized the equation shown earlier.



Greenhouse Effect

Greenhouse Effect

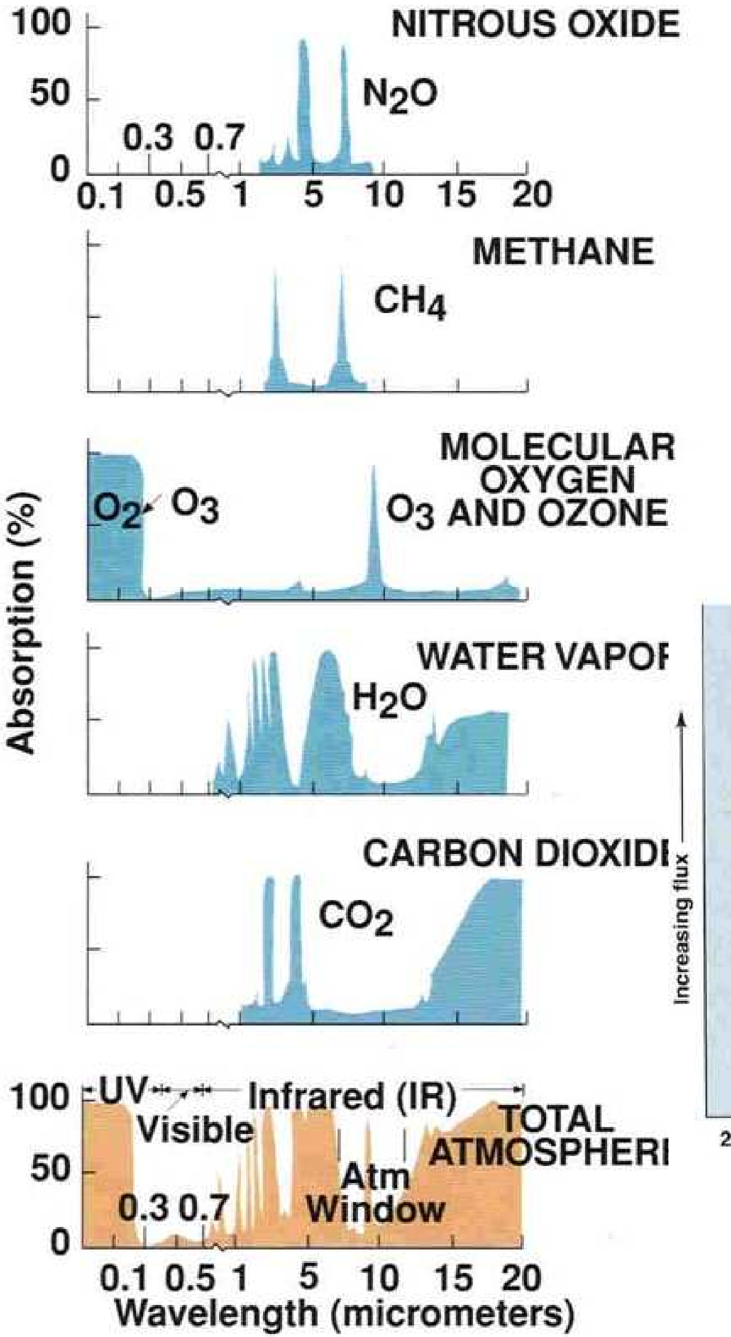
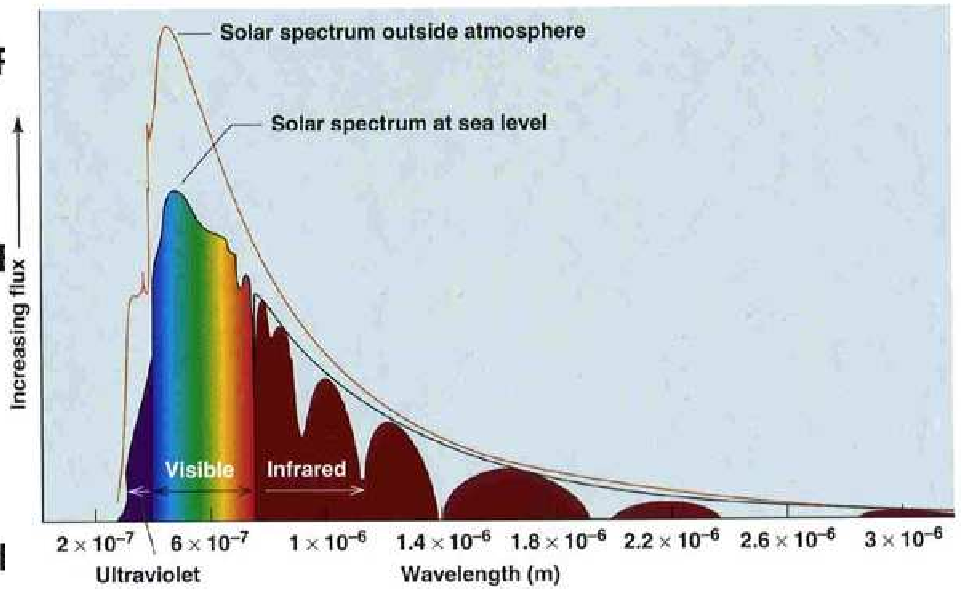
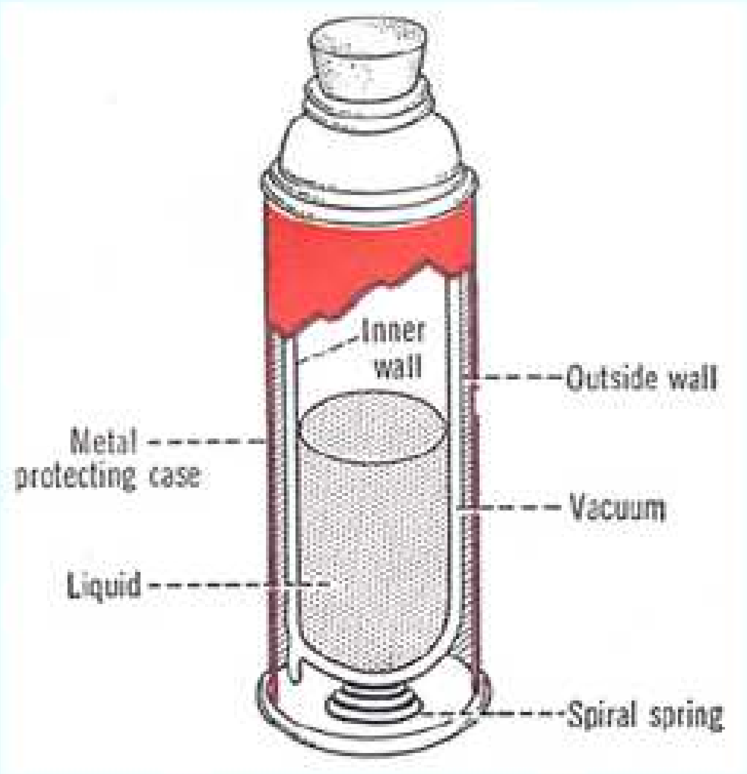
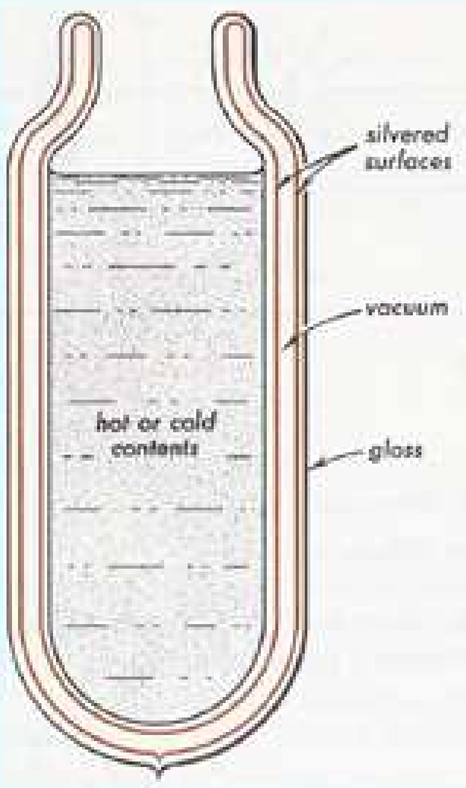


Fig. 2.9 Absorption of radiation by gases in the atmosphere.



Thermos Bottle





Silvered surface reflects radiated heat.
Vacuum prevents convection and conduction.
Insulated stopper reduces conduction.

Conservation of energy

A. Define control volume

B. *The rate at which thermal and mechanical energy enters a control volume minus the rate at which this energy leaves the control volume must equal the rate at which this energy is stored (or accumulated) in the control volume*

C. $$\dot{E}_{in} + \dot{E}_{gen} - \dot{E}_{out} = \dot{E}_{accum}$$ Applies at any instant in time.

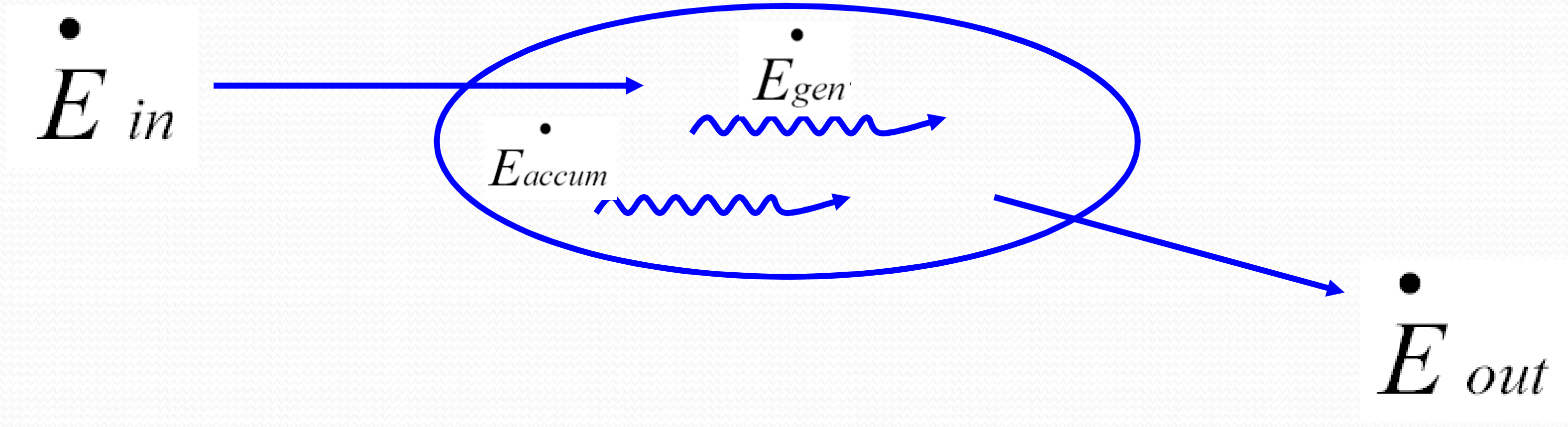
D. E_{in} and E_{out} are surface phenomena, associated only with control surfaces

1. often involve transfer via conduction, convection, or radiation, also by bulk flow into and out of control volume.

E. E_{gen} is a volumetric phenomenon, proportional to the volume

1. Remember we are discussing thermal energy (heat), and so thermal energy can be generated. Back in thermodynamics, we wrote E-balance for total energy. Total energy (heat, work, U, KE, PE) is not generated.

F. E_{accum} is also volumetric phenomenon.



$$\dot{E}_{in} + \dot{E}_{gen} - \dot{E}_{out} = dE_{st}/dt = \dot{E}_{accum}$$

The surface energy balance

A. Control surface includes no mass or volume, so E_{gen} and E_{accum} do not apply

B. Thus, Conservation of Energy becomes: $\dot{E}_{in} - \dot{E}_{out} = 0$

1. Even though generation and accumulation may be occurring in the control volume, it will not affect the energy balance at the control surface. This holds true for both steady state and transient conditions.

C. Methodology - for finite or differential control volumes

1. Define control volume, with control surface represented by dashed line
2. Identify relevant energy transfer processes. Each process should be shown on the control volume by an appropriately labeled arrow
3. Write the conservation equations, and then substitute appropriate rate expressions for the terms in the equations.

Surface energy balance

$$\dot{E}_{in} - \dot{E}_{out} = 0$$

Analysis of h.t problem – Mesti buat seperti ini !!!

MUST USE THIS FORMAT WHEN WORKING PROBLEMS FOR HW, EXAMS AND QUIZZES

A. KNOWN: after reading the problem, state briefly and concisely what is known about the problem. Do not repeat the problem statement.

B. FIND: State briefly and concisely what must be found

C. SCHEMATIC: Draw a schematic of the physical system. Represent required control surfaces. Identify relevant heat transfer processes by labeled arrows.

D. ASSUMPTIONS: List all pertinent simplifying assumptions.

E. PROPERTIES: Compile property values needed for the calculations

F. ANALYSIS:

1. Begin by applying appropriate conservation laws, and introduce rate equations as needed.
2. Develop analysis as completely as possible before substituting numerical values.
3. Perform calculations to obtain result.
4. CIRCLE OR BOX YOUR ANSWER

Mode	Mechanism	Rate Equations	Transport Property or Coefficient
Conduction	Diffusion of energy due to random molecular motion	$q_x = -k\frac{dT}{dx}$	k (W/m K)
Convection	Diffusion of energy due to random molecular motion plus energy transfer due to bulk motion (advection)	$q = h(T_s - T_\infty)$ **IMPORTANT !!!**	h (W/m² K)
Radiation	Energy transfer by electromagnetic waves	$q = \frac{\dot{Q}}{A} = \varepsilon\sigma(T_s^4 - T_{sur}^4)$ [redacted]	ε [redacted]