PHYSICS 2: FLUID MECHANICS AND THERMODYNAMICS

Phan Hiền Vũ

Department of Physics - IU VNU-HCM

Office: A1.503

Email: phvu@hcmiu.edu.vn

Chapter 2 Heat, Temperature, and the First Law of Thermodynamics

2.1. Temperature and the Zeroth Law of Thermodynamics

2.2. Thermal Expansion

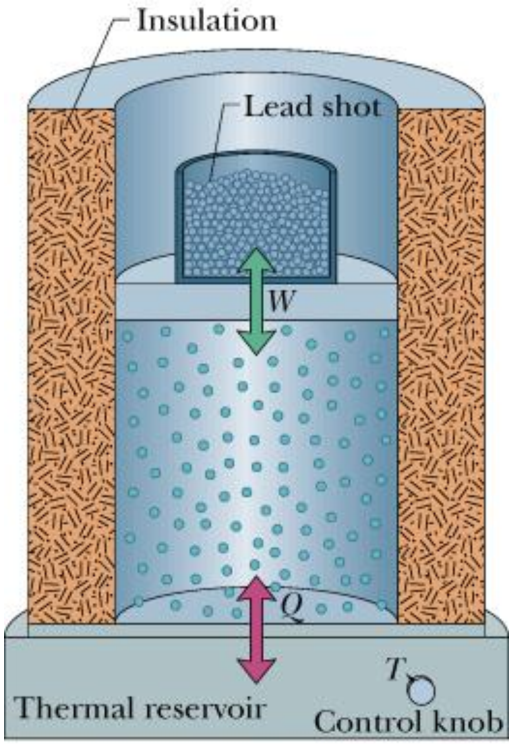
2.3. Heat and the Absorption of Heat by Solids and Liquids

2.4. Work and Heat in Thermodynamic Processes

2.5. The First Law of Thermodynamics and Some Special Cases

2.6. Heat Transfer Mechanisms

2.4. Work and Heat in Thermodynamic Processes



We change a system, which is a gas confined to a cylinder with a movable piston, from an initial state p_i, V_i, T_i to a final state p_f, V_f, T_f:

- The procedure for changing the system from its initial state to its final one is called a thermodynamic process.
- During a thermodynamic process, energy as heat may be transferred into the system from a thermal reservoir (positive heat) or vice versa (negative heat). Work can also be done by the system by raising (positive work) or lowering the piston (negative work).
- The differential work dW done by the system for a differential displacement $d\vec{s}$:

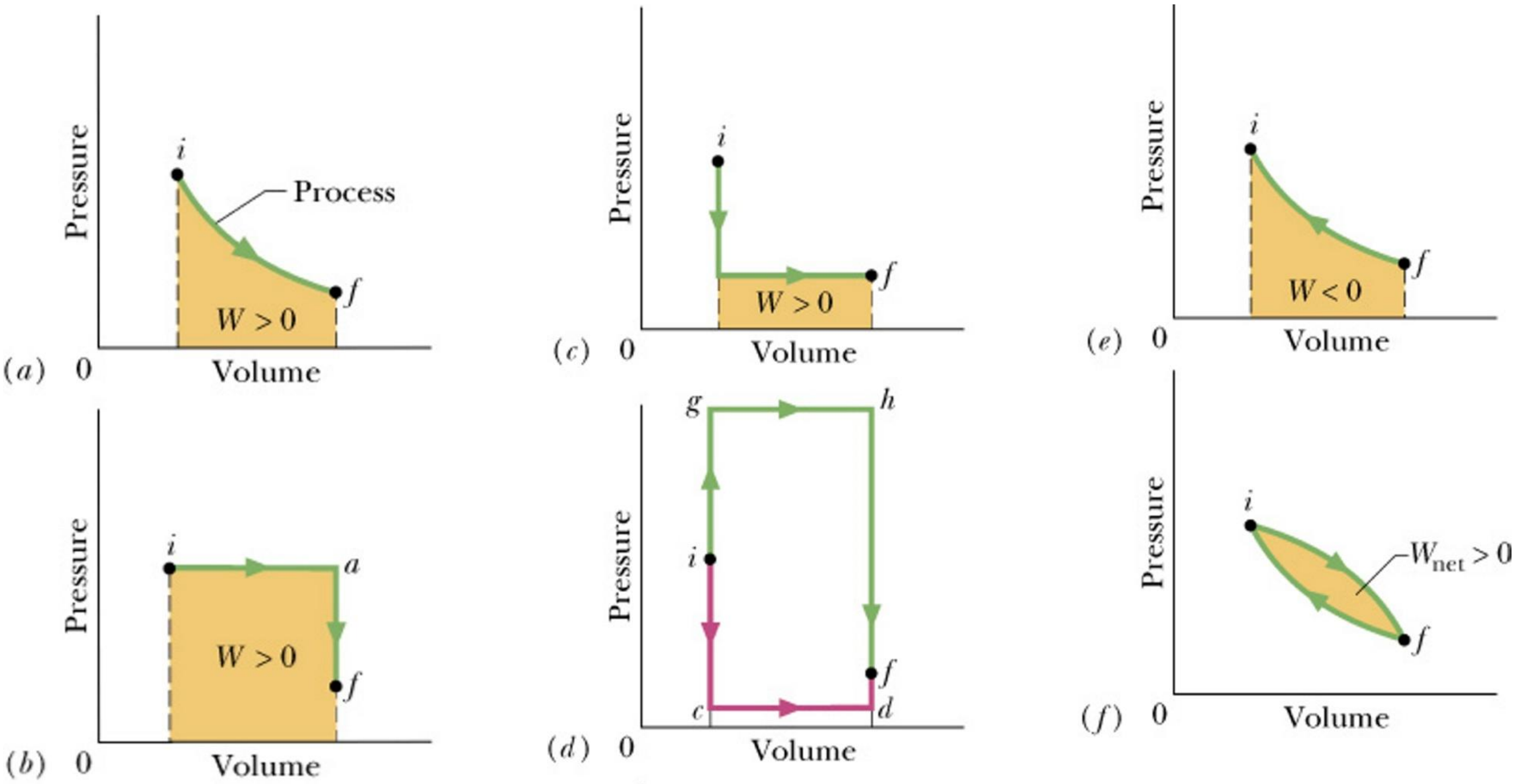
$$dW = \vec{F}d\vec{s} = (pA)(ds) = p(Ads) = pdV$$

$\vec{F}$: the force exerted by the gas on the piston;

A: the cross-sectional area of the piston;

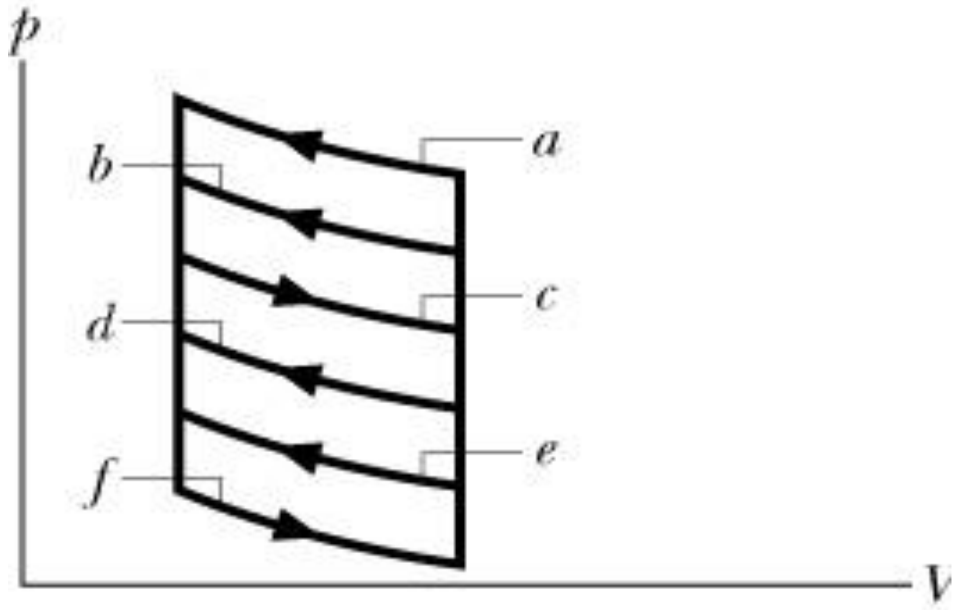
- The total work done by the gas is: $W = \int dW = \int_{V_i}^{V_f} p\,dV$

- Many ways to change the gas from state i to f:



- (f): The net work done by the gas for a complete cycle W_{net}>0.

Checkpoint: The p-V diagram here shows 6 curved paths (connected by vertical paths) that can be followed by a gas. Which two of the curved paths should be part of a closed cycle (those curved paths plus connecting vertical paths) if the net work done by the gas during the cycle is to be at its maximum positive value?



2.5. The First Law of Thermodynamics and Some Special Cases

The first law of thermodynamics:

When a system changes from state i to state f:

- The work W done by the system depends on the path taken.
- The heat Q transferred by the system depends on the path taken.

However, the difference Q-W does NOT depend on the path taken. It depends only on the initial and final states.

The quantity Q-W therefore represents a change in some intrinsic property of the system and this property is called the internal energy E_{int}.

$$\boxed{\Delta E_{int} = E_{int,f} - E_{int,i} = Q - W}$$

For a differential change: $dE_{int} = dQ - dW$

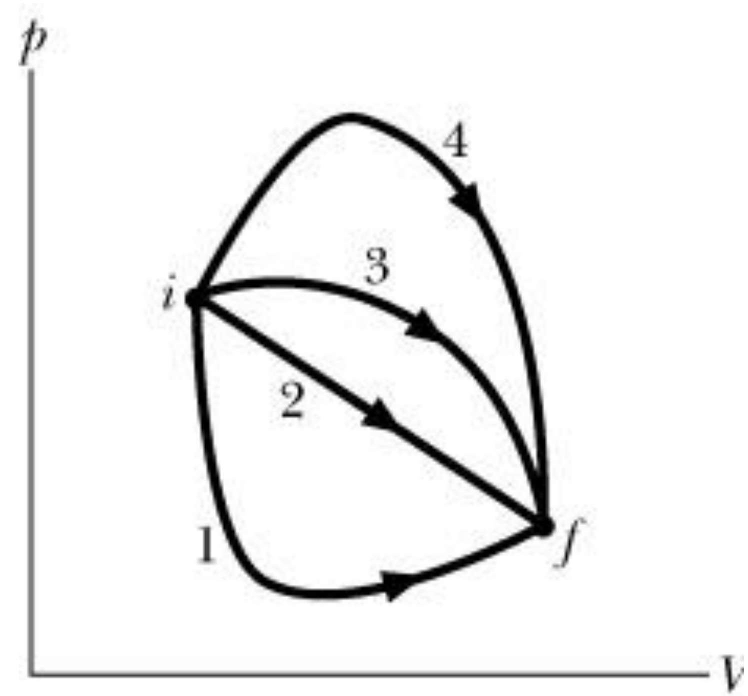
The internal energy E_{int} of a system tends to increase if energy is added as heat Q and tends to decrease if energy is lost as work done by the system.

Let W_{on} be the work done on the system:

$$W_{on} = - W$$

$$\Delta E_{int} = Q + W_{on}$$

Checkpoint: In the figure below, rank the paths according to (a) ΔE_{int}, (b) W done by the gas, (c) Q; greatest first.

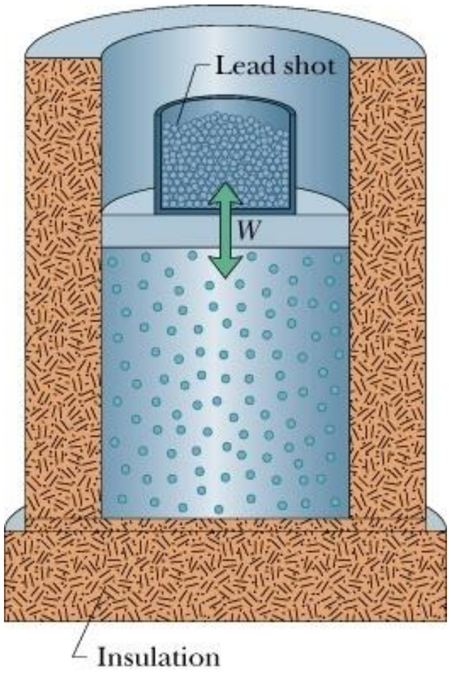


Some special cases:

$$\Delta E_{int} = Q - W$$

1. Adiabatic processes: Q=0
(no transfer of energy as heat)
 - A well-insulated system.
 - Or a process occurs very rapidly.

$$\Delta E_{int} = -W$$

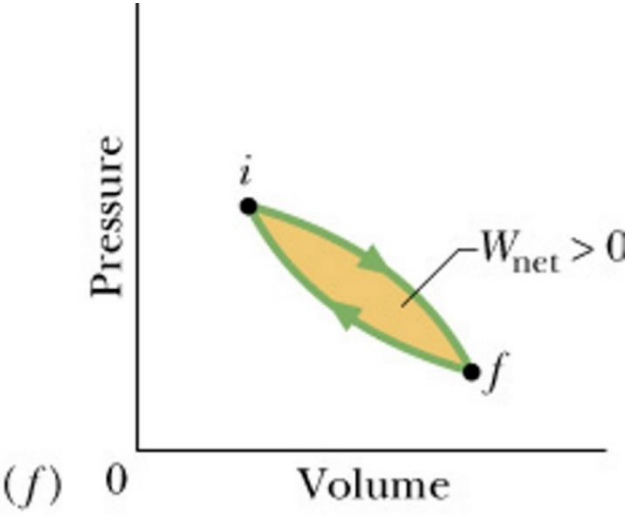


2. Constant-volume (isochoric) processes:
W=0 (no work done by the system)

$$\Delta E_{int} = Q$$

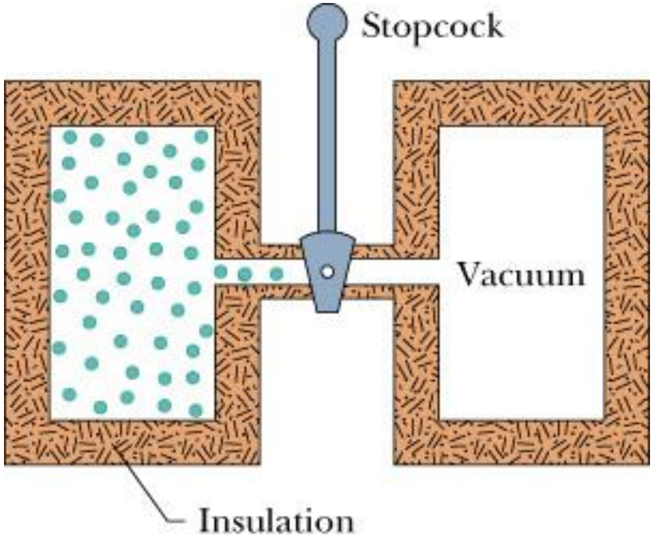
3. Cyclical processes: $\Delta E_{int}=0$
In these processes, after some interchanges of heat and work, the system is restored to its initial state.

$$Q = W$$



4. Free expansion: Q=W=0

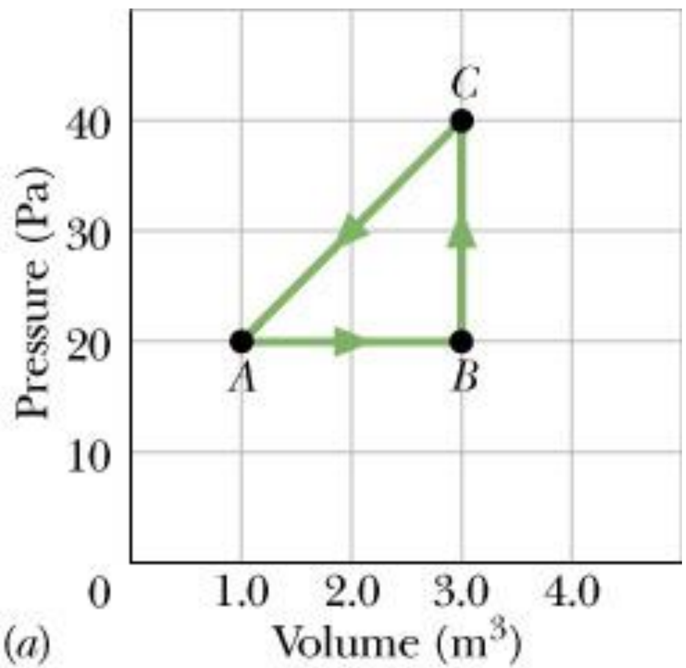
$$\Delta E_{int} = 0$$



https://www.youtube.com/watch?v=T2Nuxralkj8

Checkpoint: One complete cycle is shown (see figure). Are (a) ΔE_{int} for the gas and (b) the net energy transferred as heat Q positive, negative, or zero?

Problem 44. A thermodynamic system is taken from state A to state B to state C, and then back to A, as shown in the p-V diagram of Fig.a. (a)-(g) Complete the table in Fig.b by inserting a plus sign, a minus sign, or a zero in each indicated cell. (h) What is the net work done by the system as it moves once through the cycle ABCA?



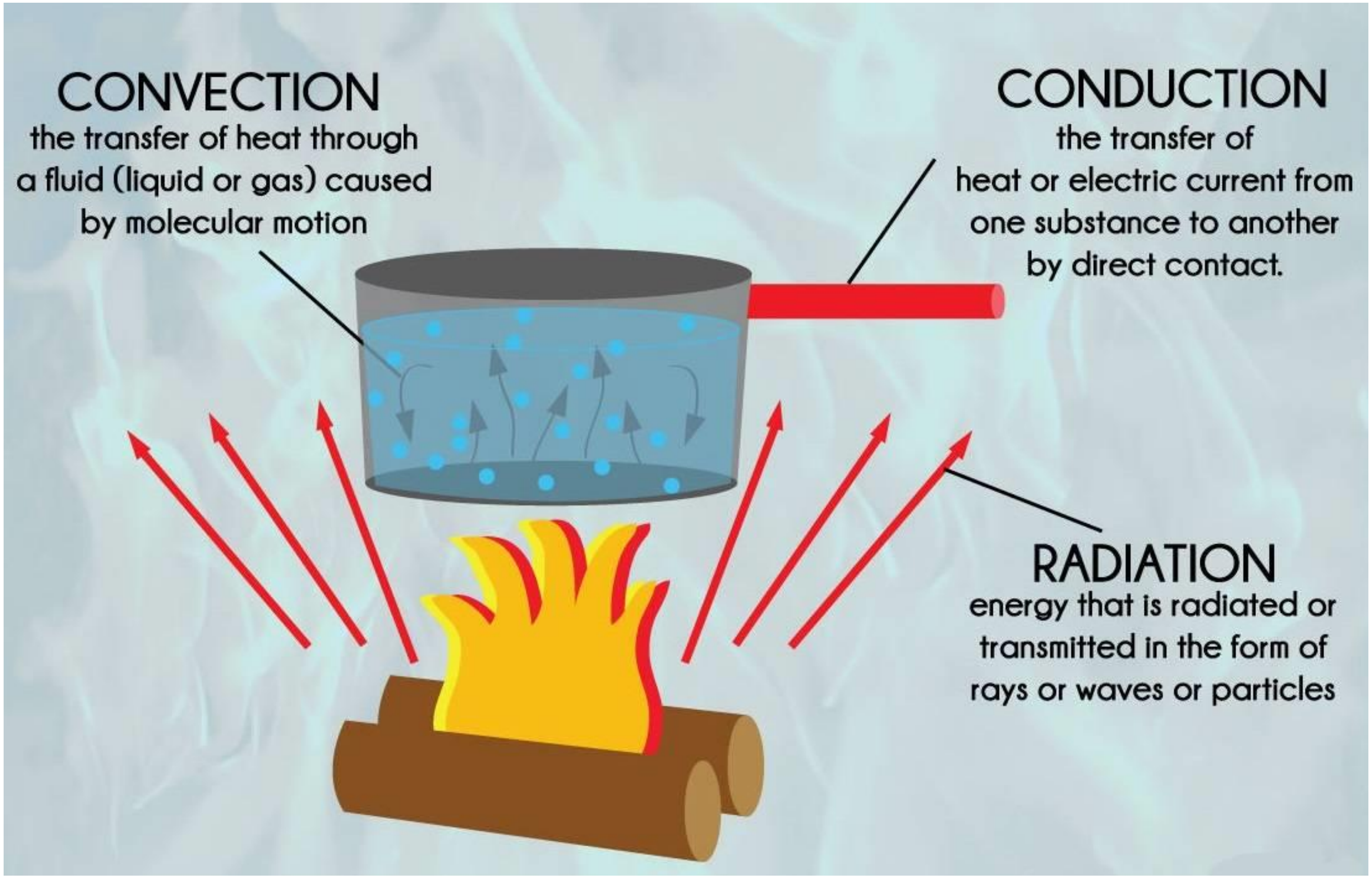
(a)

	Q	W	ΔE_{int}
$A \longrightarrow B$	(a)	(b)	+
$B \longrightarrow C$	+	(c)	(d)
$C \longrightarrow A$	(e)	(f)	(g)

(b)

2.6. Heat Transfer Mechanisms

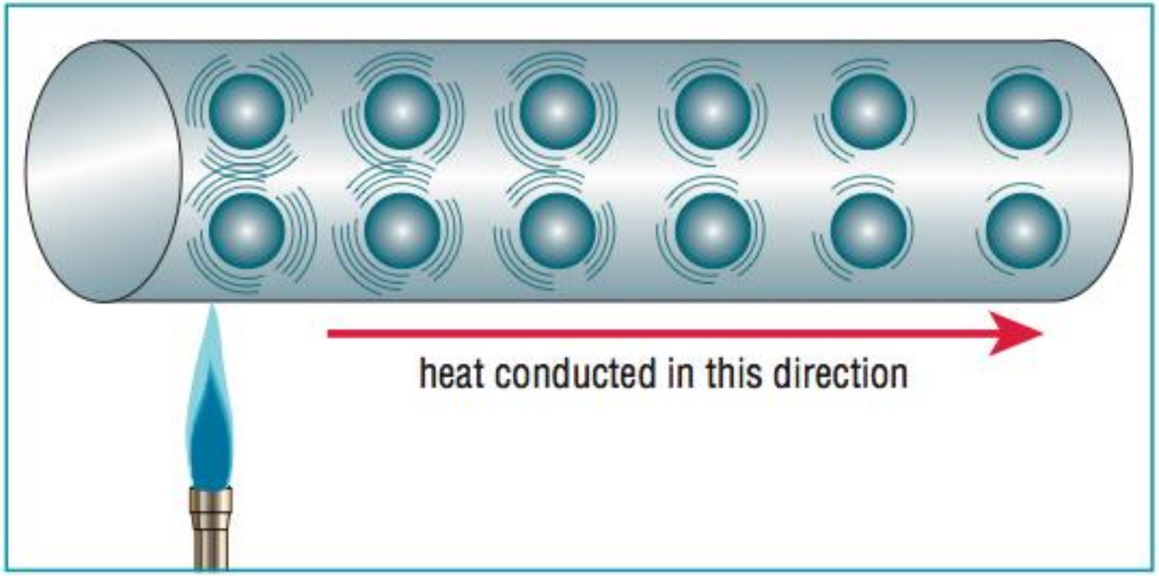
There are three types of transfer of energy as heat between a system and its environment: conduction, convection, and radiation.



2.6.1. Conduction

Example: Leaving the end of a metal poker in a fire → its handle gets hot because energy is transferred from the fire to the handle by conduction.

Physical mechanism: Due to the high temperature of the poker's environment, the vibration amplitudes of the atoms and electrons of the metal are relatively large, and thus the associated energy are passed along the poker, from atom to atom during collisions between adjacent atoms.

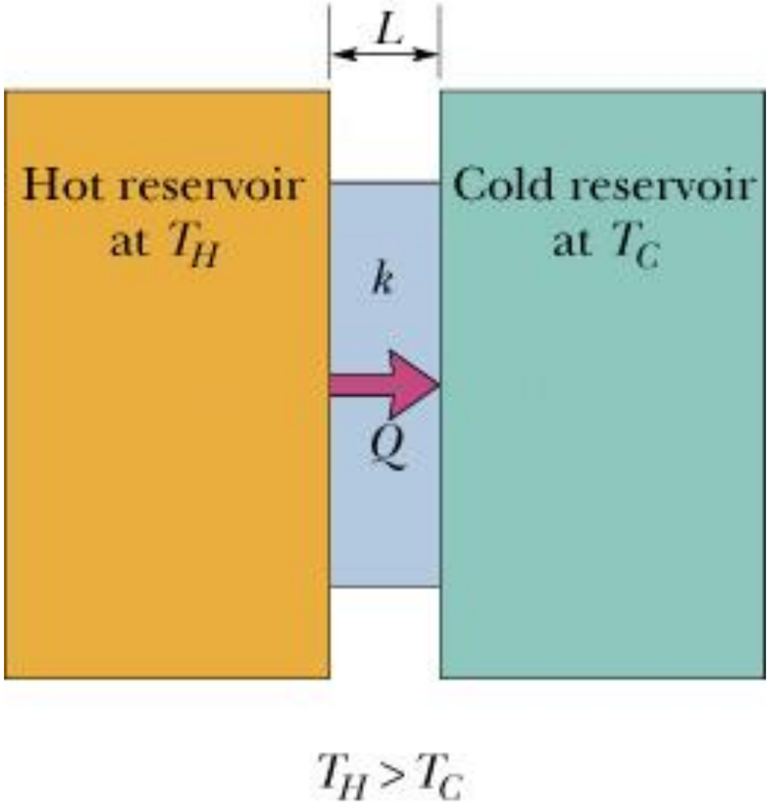


We consider a slab of face area A, thickness L, in thermal contact with a hot reservoir T_H and a cold reservoir T_C:

- Let Q be the energy transferred as heat through the slab in time t.
- Based on experiment, the conduction rate P_{cond}, which is the amount of energy transferred per unit time, is calculated by:

$$P_{cond} = \frac{Q}{t} = kA\frac{T_H - T_C}{L}$$

(Unit: W = J/s)



k is called the thermal conductivity; good thermal conductors (or poor thermal insulator) have high k-values.

Material	Thermal conductivity ($Wm^{-1}K^{-1}$)
Diamond	1000
Metals	
Silver	428
Copper	401
Gold	314
Aluminum	235
Brass	109
Iron	67
Steel	50
Lead	35
Stainless steel	14

Material	Thermal conductivity ($Wm^{-1}K^{-1}$)
Gases	
Hydrogen	0.18
Helium	0.15
Air (dry)	0.026
Building Materials	
Window glass	1.0
White pine	0.11
Fiberglass	0.048
Rock wool	0.043
Polyurethane form	0.024

Thermal Resistance to Conduction:

A measure of a body's ability to prevent heat from flowing through it.

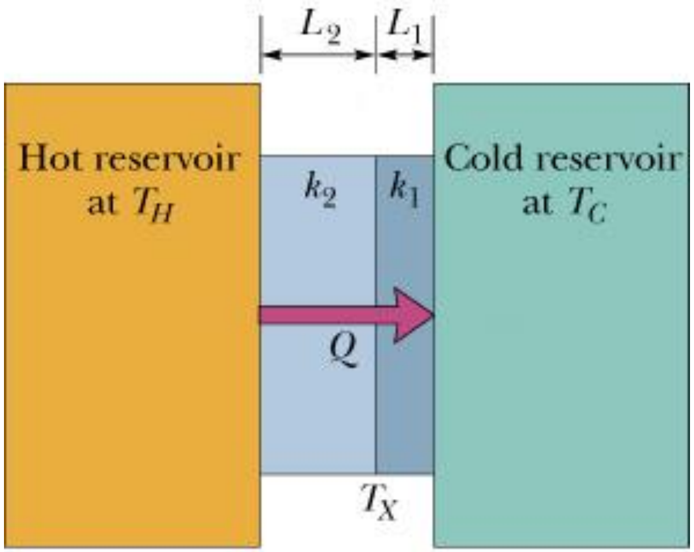
$$R = \frac{L}{k}; L: \text{the thickness of the slab}$$

Good thermal insulators (poor thermal conductors) have high R-values.

Conduction Through a Composite Slab:

A composite slab consisting of two materials having thicknesses L_1 and L_2, and thermal conductivities k_1 and k_2.

If the transfer is a steady-state process that is the temperature everywhere in the slab and the rate of energy transfer do not change with time.

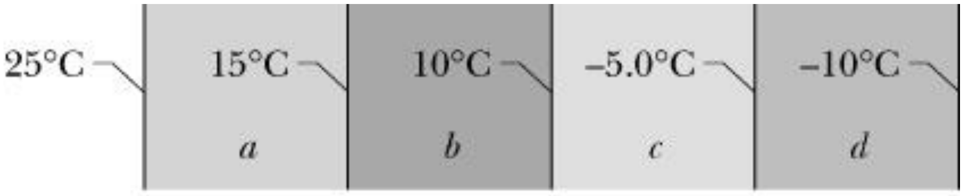


$$P_{cond} = \frac{k_2 A(T_H - T_X)}{L_2} = \frac{k_1 A(T_X - T_C)}{L_1} \rightarrow P_{cond} = \frac{A(T_H - T_C)}{L_1/k_1 + L_2/k_2}$$

If the slab consists of n materials:

$$P_{cond} = \frac{A(T_H - T_C)}{\sum_{i=1}^{n} (L_i / k_i)}$$

Checkpoint: The figure shows the face and interface temperature of a composite slab consisting of four materials, of identical thickness, through which the heat transfer is steady. Rank the materials according to their thermal conductivities, greatest first.



Sample Problem:

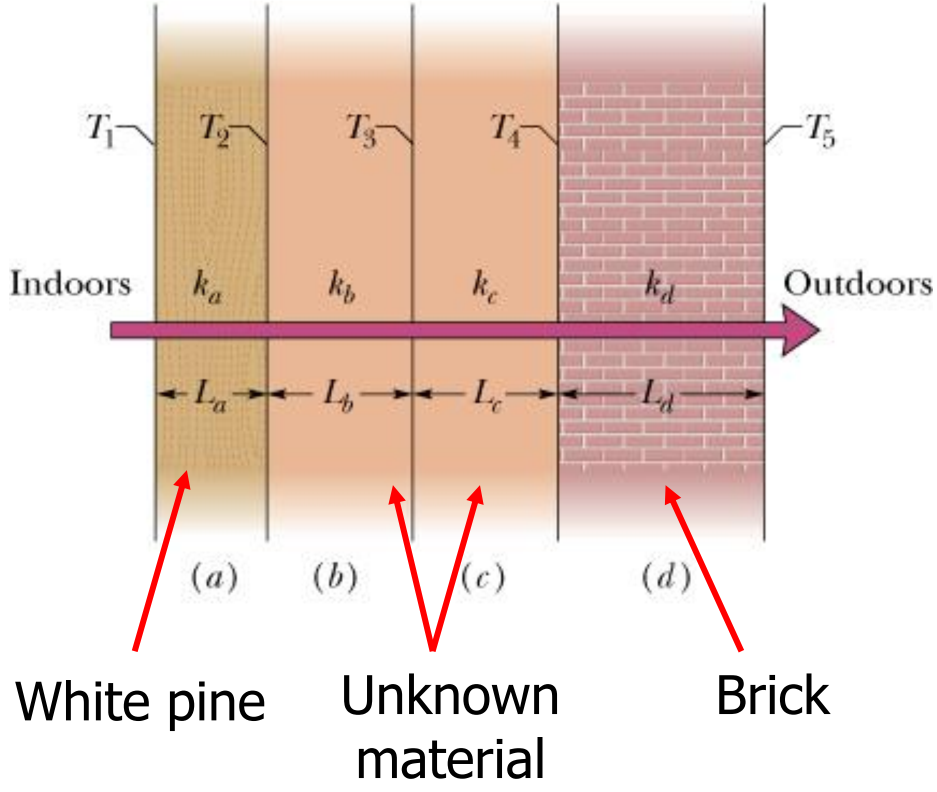
$L_d = 2\,L_a$ (thickness)

$k_d = 5\,k_a$ (conductivity)

The heat transfer is steady

$T_1=25^0C$; $T_2=20^0C$; $T_5=-10^0C$

T_4?



$$k_a A \frac{T_1 - T_2}{L_a} = k_d A \frac{T_4 - T_5}{L_d}$$

$$T_4 = \frac{k_a L_d}{k_d L_a}(T_1 - T_2) + T_5$$

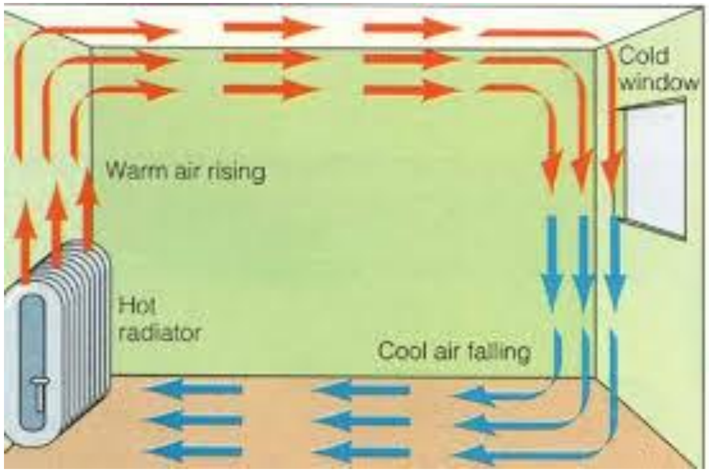
$$L_d = 2L_a \text{ and } k_d = 5k_a \rightarrow T_4 = \frac{k_a(2L_a)}{(5k_a)L_a}(25-20) - 10 = -8(^0C)$$

2.6.2. Convection

Energy is transferred through fluid motion (gases, liquids).

Physical mechanism: When a fluid comes in contact with an object whose temperature is higher than that of the fluid. The part of the fluid in contact with the hot object has a temperature higher than that of the surrounding cooler fluid, hence that fluid becomes less dense; buoyant forces cause it rise. The cooler fluid flows to take the place of the rising warmer fluid, producing fluid motion.

Convection of Air Through the Walls of a House



Convection in the Earth's atmosphere; in the oceans, in the Sun.

Hurricane Felix (NASA)

Example: Most houses are not airtight: air goes in and out around doors and windows, through cracks and crevices, following wiring to switches and outlets, and so on. The air in a typical house is completely replaced in less than an hour. Suppose that a moderately-sized house has inside dimensions $12.0\text{m} \times 18.0\text{m} \times 3.00\text{m}$ high, and that all air is replaced in 30.0 min. Calculate the heat transfer per unit time in watts needed to warm the incoming cold air by 10.0 C° thus replacing the heat transferred by convection alone.

The specific heat and the density of air are $c = c_p \cong 1000$ J/kg·C° and $\rho = 1.29$ kg/m^3

The rate of heat transfer is then Q/t, where $Q = mc\Delta T$

$$m = \rho V = (1.29)(12.0 \times 18.0 \times 3.00) = 836 \text{ kg}$$

$$Q = (836)(1000)(10.0) = 8.36 \times 10^6 \text{ J}$$

$$Q/t = 8.36 \times 10^6/1800 = 4.64 \text{ kW}$$

2.6.3. Radiation

Thermal energy is transferred via electromagnetic waves.

Physical mechanism: Thermal radiation is generated when heat from the movement of charged particles within atoms and molecules is converted to electromagnetic radiation.

Properties:

- Every object whose temperature above 0 K emits thermal radiation via electromagnetic waves.
- No medium is required for heat transfer via radiation.
- The rate of emitting energy of an object is given by:

$$P_{rad} = \frac{Q}{t} = \sigma \varepsilon A T^4$$

$\sigma = 5.6703 \times 10^{-8}\ \mathrm{W\ m^{-2}\ K^{-4}}$: the Stefan - Boltzmann constant

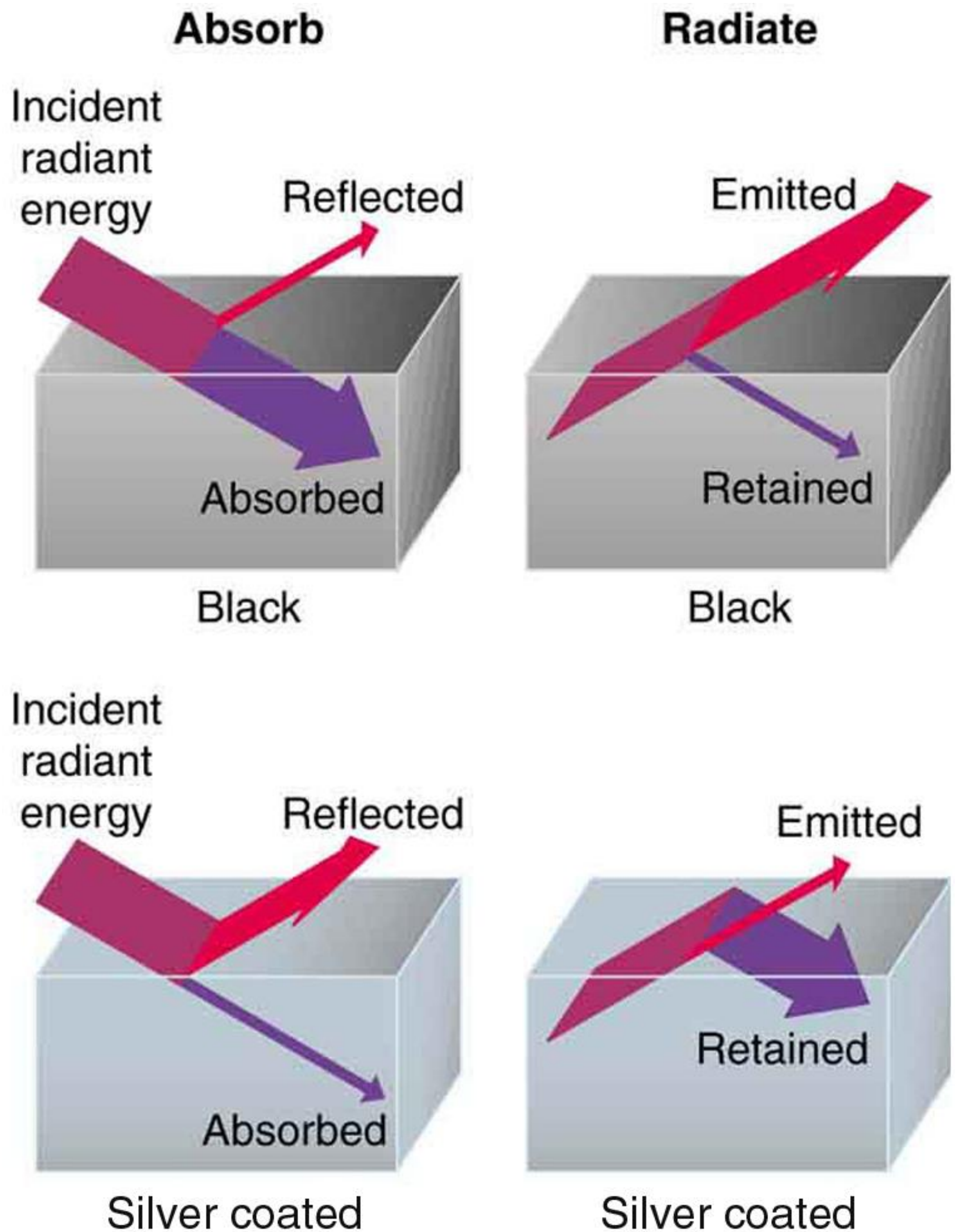
ε is the emissivity of the object's surface (values from 0 to 1)

$\varepsilon = 1$: an idealized blackbody radiator will absorp all the radiated energy it intercepts

A is the object's surface area

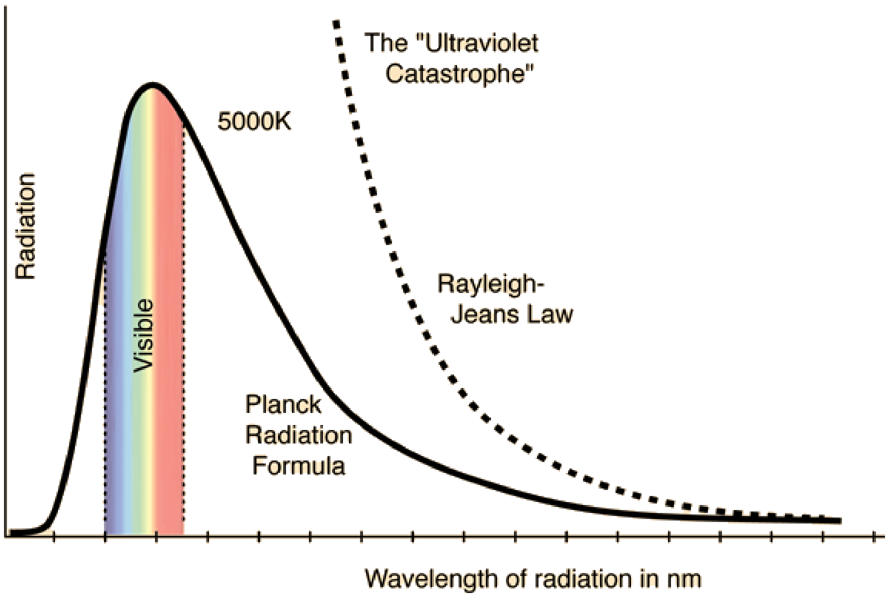
T is the object's surface temperature

A thermograph of part of a building shows temperature variations, indicating where heat transfer to the outside is most severe. Windows are a major region of heat transfer to the outside of homes. (credit: U.S. Army)


Absorb
Radiate
Incident radiant energy
Reflected
Absorbed
Black
Emitted
Retained
Black
Incident radiant energy
Reflected
Absorbed
Silver coated
Emitted
Retained
Silver coated

Blackbody radiation

- **Black-body radiation** is the thermal electromagnetic radiation within or surrounding a body in thermodynamic equilibrium with its environment, or emitted by a black body (an opaque and non-reflective body).
- It has a specific spectrum and intensity that depends only on the body's temperature, which is assumed for the sake of calculations and theory to be uniform and constant.



$$\langle E \rangle = \frac{h\upsilon}{e^{h\upsilon/kT} - 1}$$

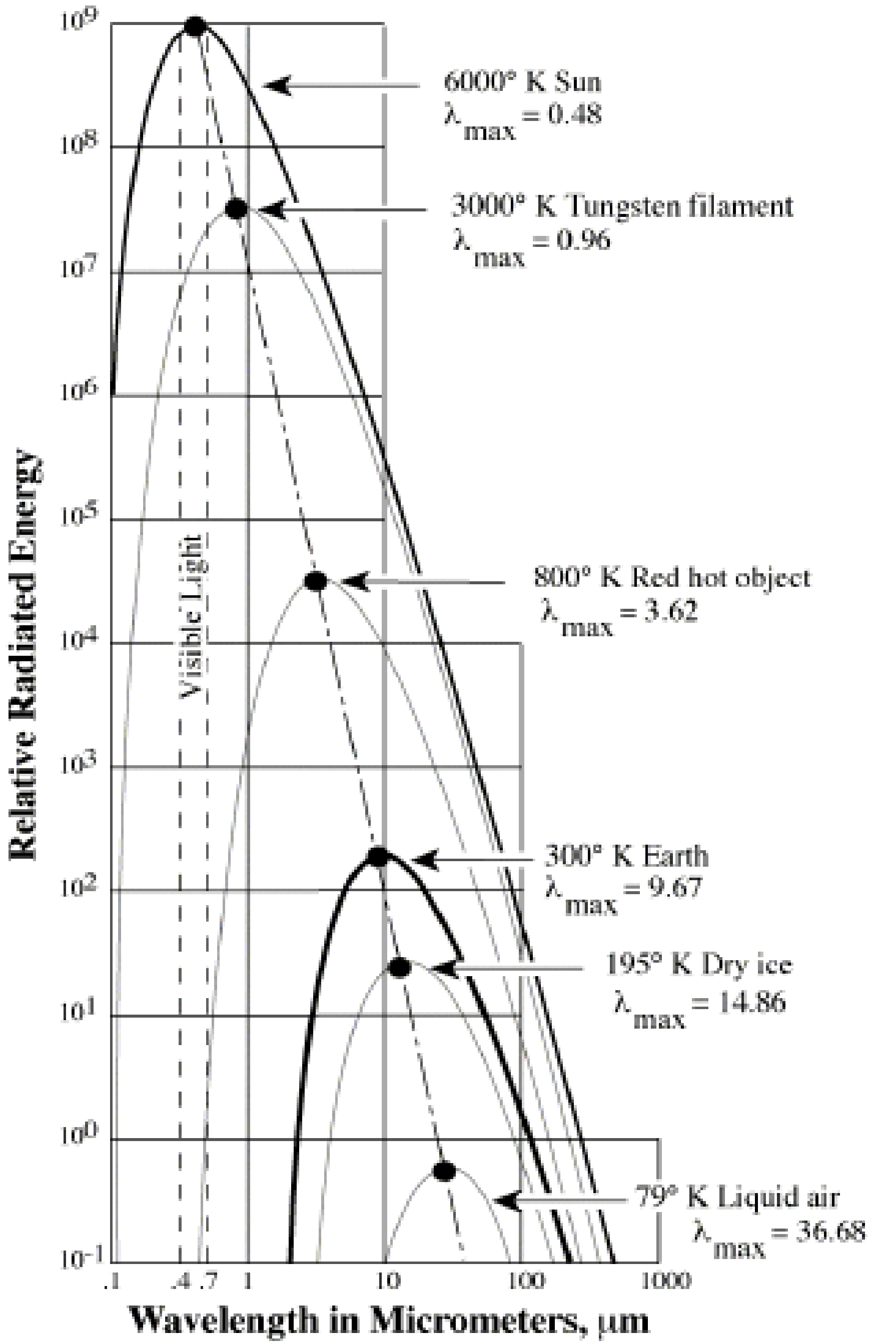
http://hyperphysics.phy-astr.gsu.edu/hbase/mod6.html

Wien’s displacement law

Wien's displacement law states that the black body radiation curve for different temperature peaks at a wavelength that is inversely proportional to the temperature.

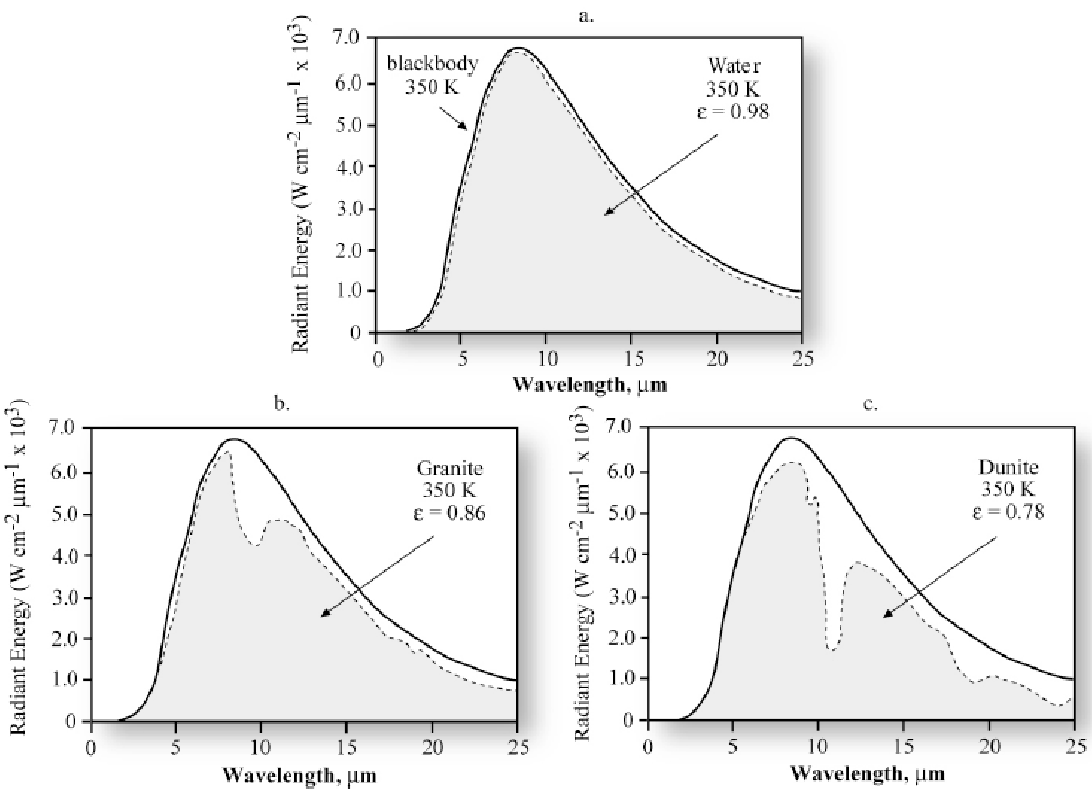
$\lambda_{max} = k / T$

(where k = 2898μmK)



Emissivity

- The emissivity of the surface of a material is its effectiveness in emitting energy as thermal radiation.
- Quantitatively, emissivity is the ratio of the thermal radiation from a surface to the radiation from an ideal black surface at the same temperature as given by the Stefan–Boltzmann law.



$$\varepsilon = M/M_b$$

ε: *emissivity*

M: emittance of a given object

M_b*=that of blackbody*

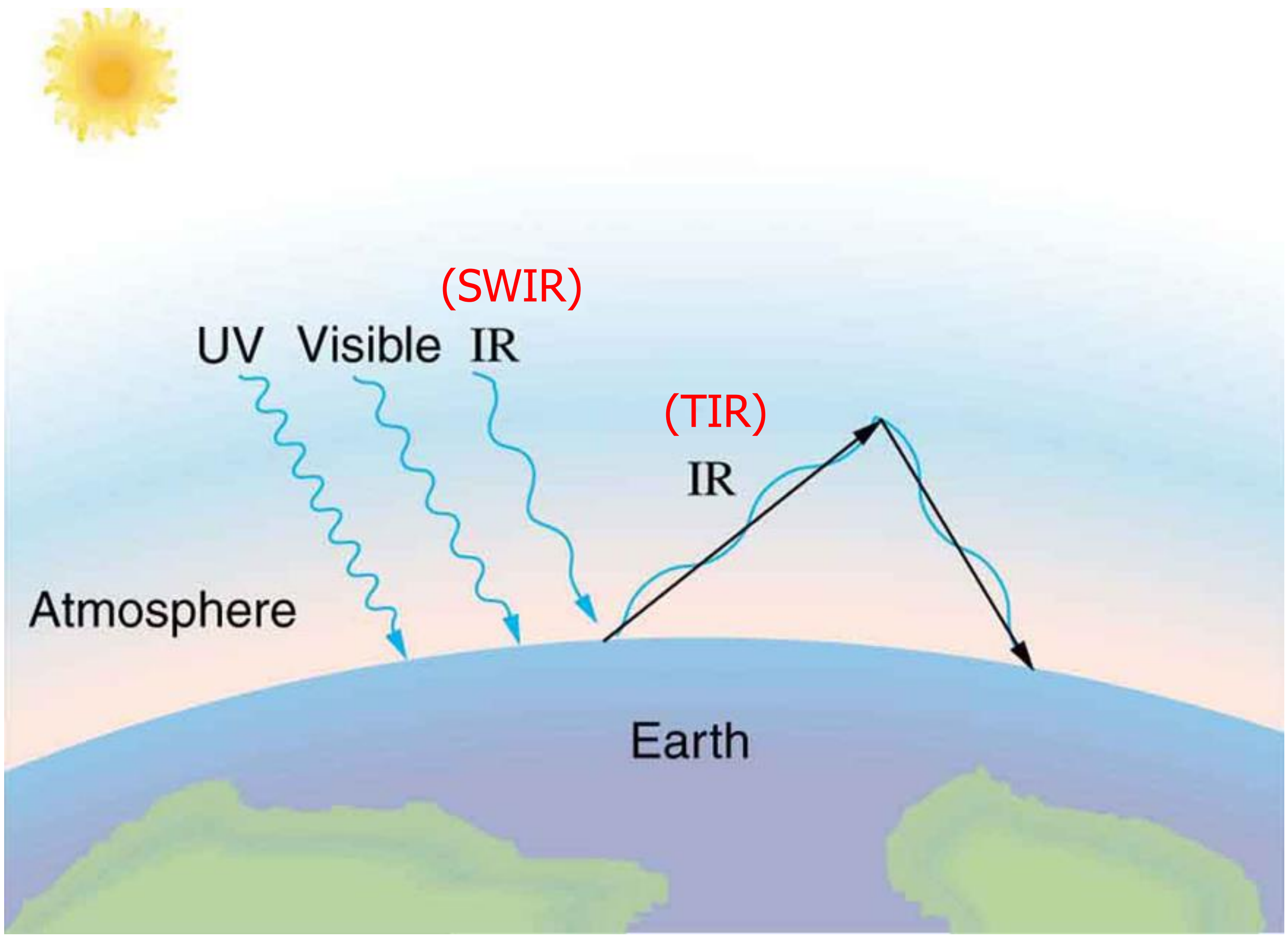
Heat Transfer by Radiation

$$\frac{Q_{net}}{t} = \sigma\varepsilon A\left(T_{env}^{4} - T_{obj}^{4}\right)$$

Example. What is the rate of heat transfer by radiation, with an unclothed person standing in a dark room whose ambient temperature is 22.0ºC. The person has a normal skin temperature of 33.0ºC and a surface area of 1.50m^2. The emissivity of skin is 0.97 in the infrared, where the radiation takes place

T_{obj} = 306 K, and T_{env} = 295 K

$$\frac{Q_{net}}{t} = (5.67\times10^{-8})(0.97)(1.50)[(295)^4-(306)^4 = -99\ \text{J/s} = -99\ \text{W}$$



The greenhouse effect is a name given to the trapping of energy in the Earth's atmosphere by a process similar to that used in greenhouses.

Homework:

Problems 45, 46, 47, 48, 49, 50, 51, 54, 59, 60 in Chapter 18, Textbook