Rutgers University
Department of Physics & Astronomy

01:750:271 Honors Physics I
Fall 2015

Lecture 23

Final Exam

- Wednesday, December 21st, 8-11:00am, PHL
- Chapters 10,11,12,13,15,18,19,20
  (Lecture 15 → end)
- Also need to know the basic concepts and laws introduced before: Newton's laws, energy, momentum, conservation laws.
- Will **not** be on the test:
  - Elasticity (Ch. 12.3 in the 10th edition or 12.7 in the 9th edition.)
  - Damped and forced oscillations (Ch. 15.5, 15.6 in the 10th edition or 15.8, 15.9 in the 9th edition.)

- Will **not** be on the test:
  - Heat transfer mechanisms (Ch. 18.6 in the 10th edition or Ch. 18.12 in the 9th edition.)
  - Engines.

- **Temperature:** **Intrinsic macroscopic** quantity which measures the kinetic energy of the **average** microscopic constituent (atom, molecule . . .) of a physical system.

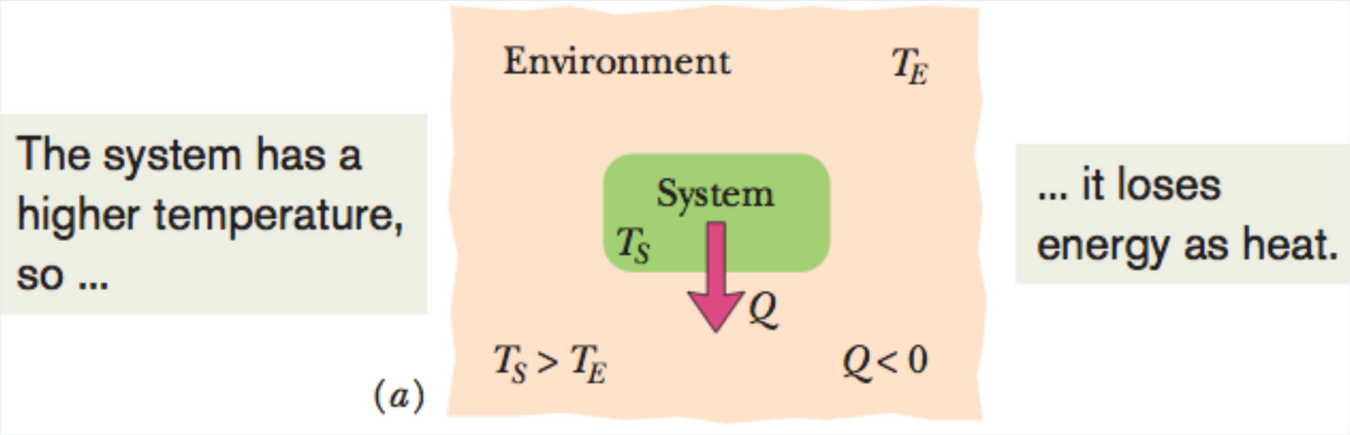
The Zeroth Law of Thermodynamics

If bodies A and B are each in thermal equilibrium with a third body T, then A and B are in thermal equilibrium with each other.

Thermal equilibrium: two bodies are in thermal equilibrium if no energy transfer occurs when the two bodies are in contact.

- **Temperature and heat**

Heat (Q): the **energy transferred** between a system and its environment because of a temperature difference that exists between them.


The system has a higher temperature, so ...

... it loses energy as heat.

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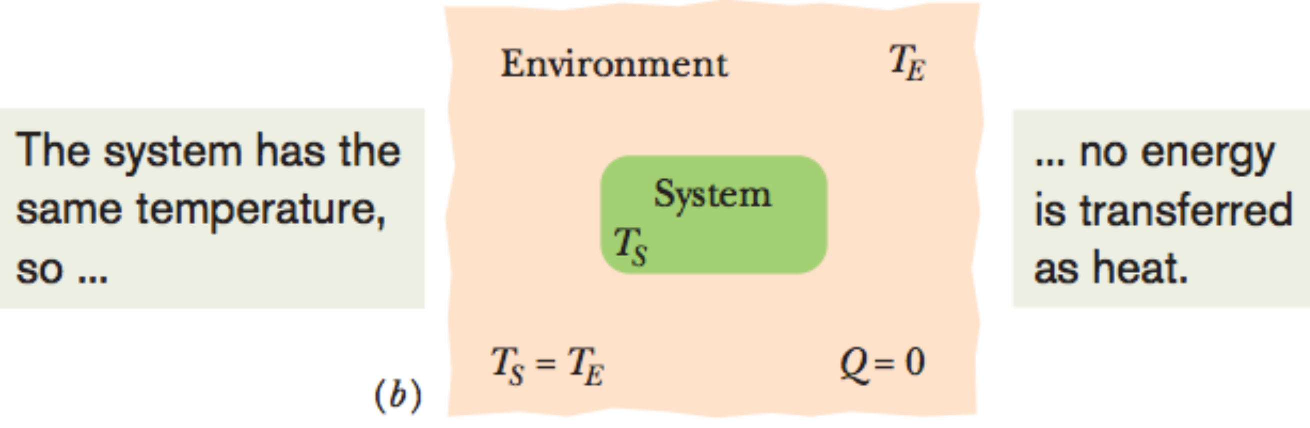
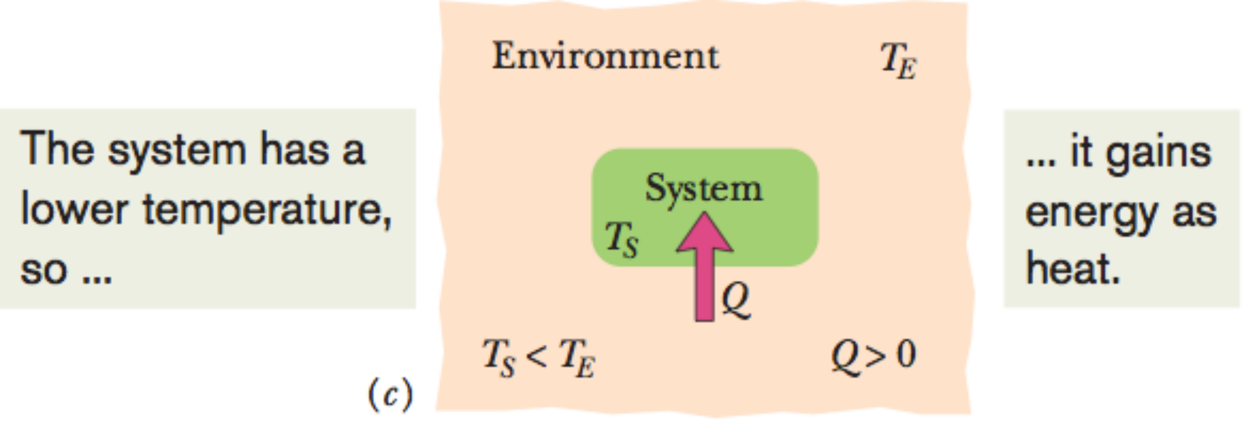


The system has the same temperature, so ...

... no energy is transferred as heat.



The system has a lower temperature, so ...

... it gains energy as heat.

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- **Heat Absorbtion by solids and liquids**

Heat capacity (C): the proportionality constant between the heat Q that the object absorbs or loses and the resulting temperature change ΔT of the object:

$$Q = C\Delta T$$

Specific heat (c): heat capacity per unit mass:

$$C = cm \quad \Rightarrow \quad Q = cm\Delta T$$

Units for C: J/K. Also **British thermal units (Btu)** and **Calories (cal)**

$$1\,\mathrm{cal} = 3.968 \times 10^{-3}\,\mathrm{Btu} = 4.1868\,\mathrm{J}$$

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Phase change: transition from **solid** to **liquid** or form **liquid** to **vapors**.

Heat of transformation (L): the amount of energy per unit mass that must be transferred as heat when a sample completely undergoes a phase change.

$$Q = Lm$$

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Solid → liquid

Heat of fusion:

$$Q = L_F m$$

Liquid → vapors

Heat of vaporization:

$$Q = L_V m$$

Example:

A copper slug of mass $m_c = 75\,\mathrm{g}$ is heated to a temperature $T = 312^\circ\,\mathrm{C}$. The slug is then dropped into a glass beaker containing $m_w = 220\,\mathrm{g}$ of water. The heat capacity C_b of the beaker is $45\,\mathrm{cal/K}$. The initial temperature T_i of the water and the beaker is $12^\circ\,\mathrm{C}$. Assuming that the slug, beaker, and water are an isolated system and the water does not vaporize, find the final temperature T_f of the system at thermal equilibrium.

$$\boxed{\text{Heated slug}} \xrightarrow{\text{heat}} \boxed{\text{Water} + \text{beaker}}$$

- Heat absorbed by the water:

$$Q_w = m_w c_w (T_f - T_i) > 0$$

- Heat absorbed by the beaker:

$$Q_b = C_b (T_f - T_i) > 0$$

- Heat lost by the copper slug:

$$Q_c = m_c c_c (T_f - T) < 0$$

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- Isolated system:

$$Q_w + Q_b + Q_c = 0$$

$$m_w c_w (T_f - T_i) + C_b (T_f - T_i) + m_c c_c (T_f - T) = 0$$

$$T_f = \frac{m_w c_w T_i + C_b T_i + m_c c_c T}{m_w c_w + C_b + m_c c_c}$$

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Example:

How much heat must be absorbed by ice of mass $m = 720\,\mathrm{g}$ at $-10^\circ\,\mathrm{C}$ to take it to the liquid state at $15^\circ\,\mathrm{C}$?

Three step process:

Step1 : heat the ice from $T_i = -10^\circ\,\mathrm{C}$ to the melting temperature $T_m = 0^\circ\,\mathrm{C}$

$$Q_1 = mc_{ice}(T_m - T_i)$$

Step1 : melt the ice at constant temperature $T_m = 0^\circ\,\mathrm{C}$

$$Q_2 = mL_F = mL_{ice\to water}$$

Step3 : warm the liquid water from $T_m = 0^\circ\,\mathrm{C}$ to the final temperature $T_f = 15^\circ\,\mathrm{C}$

$$Q_3 = mc_w(T_f - T_m)$$

Total heat:

$$Q_1 + Q_2 + Q_3 = mc_{ice}(T_m - T_i) + mL_F + mc_w(T_f - T_m)$$

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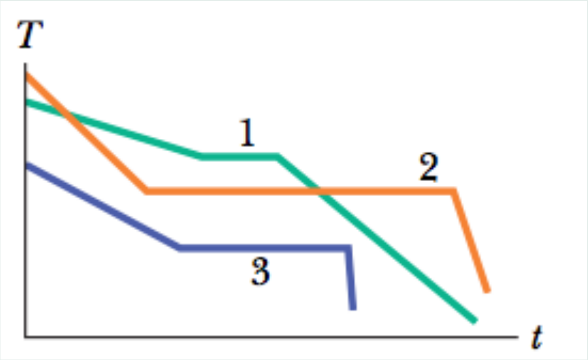

A) $c_1 > c_2 > c_3$

B) $c_1 > c_3 > c_2$

C) $c_2 > c_3 > c_1$

D) $c_2 > c_1 > c_3$

Three different materials of identical mass are placed one at a time in a freezer that can extract energy from a material at a certain constant rate. During the cooling process, each material begins in the liquid state and ends in the solid state. The figure shows the temperature T versus time t.

Rank the materials according to specific heat in liquid state.

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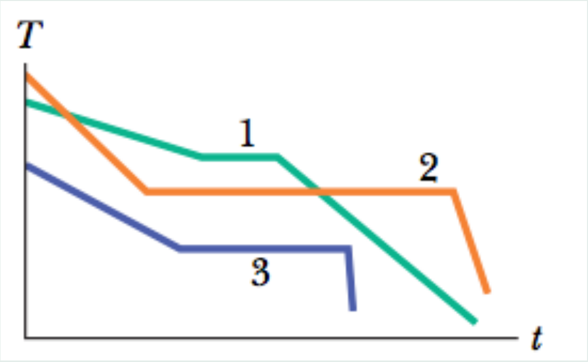

A) $c_1 > c_2 > c_3$

B) $c_1 > c_3 > c_2$

C) $c_2 > c_3 > c_1$

D) $c_2 > c_1 > c_3$

$mc\Delta T = Q = -H\Delta t$, $H =$ constant rate of heat absorbtion. $c = -(H/m)(\Delta t/\Delta T) = (H/m)|\Delta t/\Delta T|$

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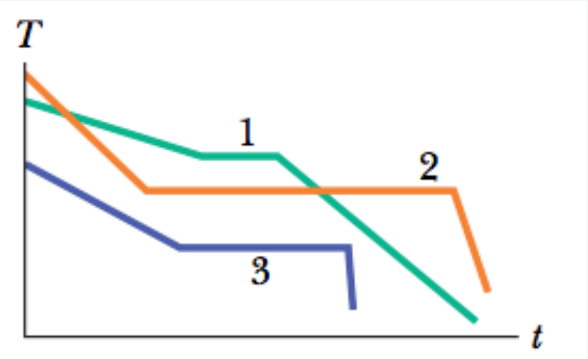

Same situation. Rank the materials according to heat of fusion.

A) $(L_F)_1 > (L_F)_2 > (L_F)_3$

B) $(L_F)_3 > (L_F)_2 > (L_F)_1$

C) $(L_F)_2 > (L_F)_1 > (L_F)_3$

D) $(L_F)_2 > (L_F)_3 > (L_F)_1$

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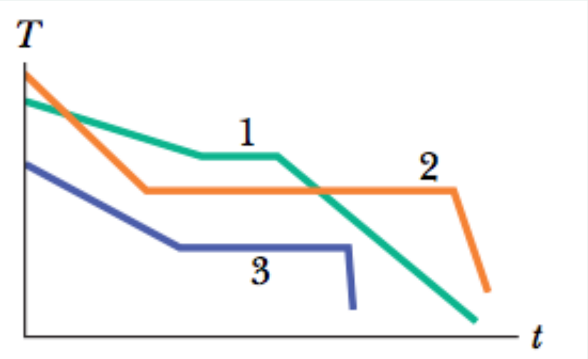
Same situation. Rank the materials according to heat of fusion.



$A)\ (L_F)_1 > (L_F)_2 > (L_F)_3$

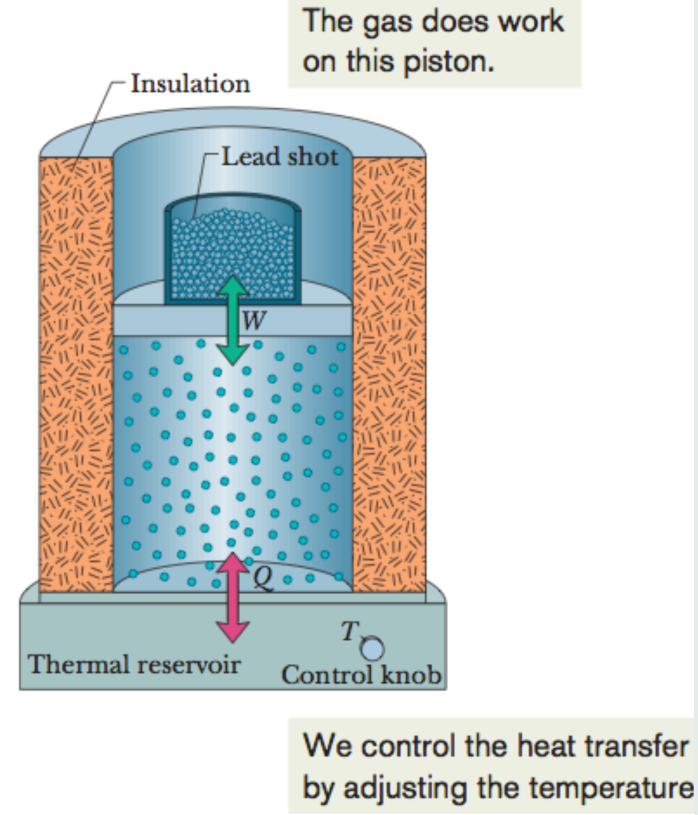
$B)\ (L_F)_3 > (L_F)_2 > (L_F)_1$

$C)\ (L_F)_2 > (L_F)_1 > (L_F)_3$

$D)\ (L_F)_2 > (L_F)_3 > (L_F)_1$

$$H\Delta t = mL_F$$

A closer look at heat and work



The gas does work on this piston.

We control the heat transfer by adjusting the temperature

- gas confined to an **isolated** cylinder
- bottom is in contact to a **thermostat** which can heat the system to a controllable temperature T
- top closed by a **piston** carrying a lead shot.

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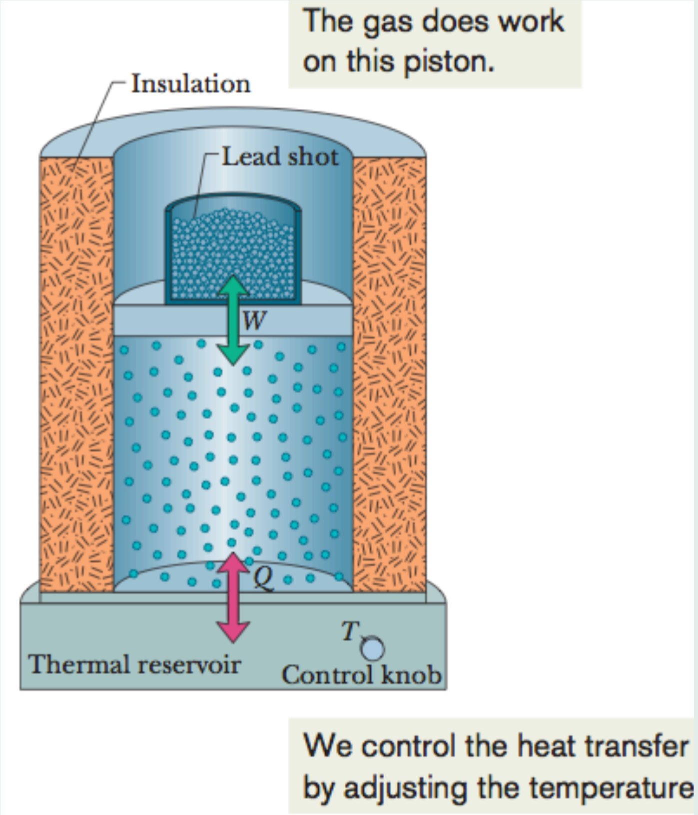


The gas does work on this piston.

We control the heat transfer by adjusting the temperature

The state of the system is specified by three physical quantities:

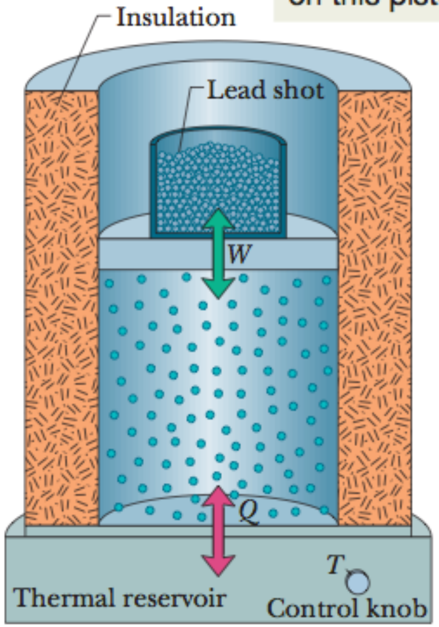
- **The volume** V of the gas
- **The temperature** T of the gas
- **The pressure** p exerted on the walls of the cylinder

$$p = \frac{F}{A}$$

For system in equilibrium:

$$pA = \text{weight of piston and lead shot}$$

The gas does work on this piston.



We control the heat transfer by adjusting the temperature

Thermodynamic process

Change in the system from an **initial state**

$$(V_i, T_i, p_i)$$

to a **final state**

$$(V_f, T_f, p_f)$$

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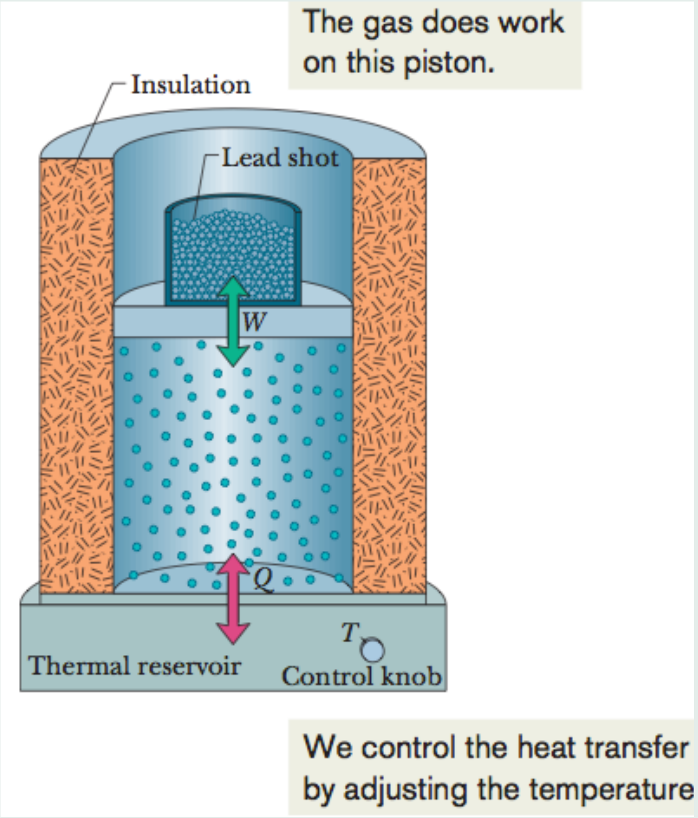

The gas does work on this piston.

We control the heat transfer by adjusting the temperature

- Suppose we remove the lead shot such that the gas will push the piston upward.

- For an infinitesimal displacement $d\vec{s}$ of the cylinder the **differential work** done by the gas is

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

dV = differential change in volume

- For a finite displacement:

$$W = \int dW = \int pdV$$

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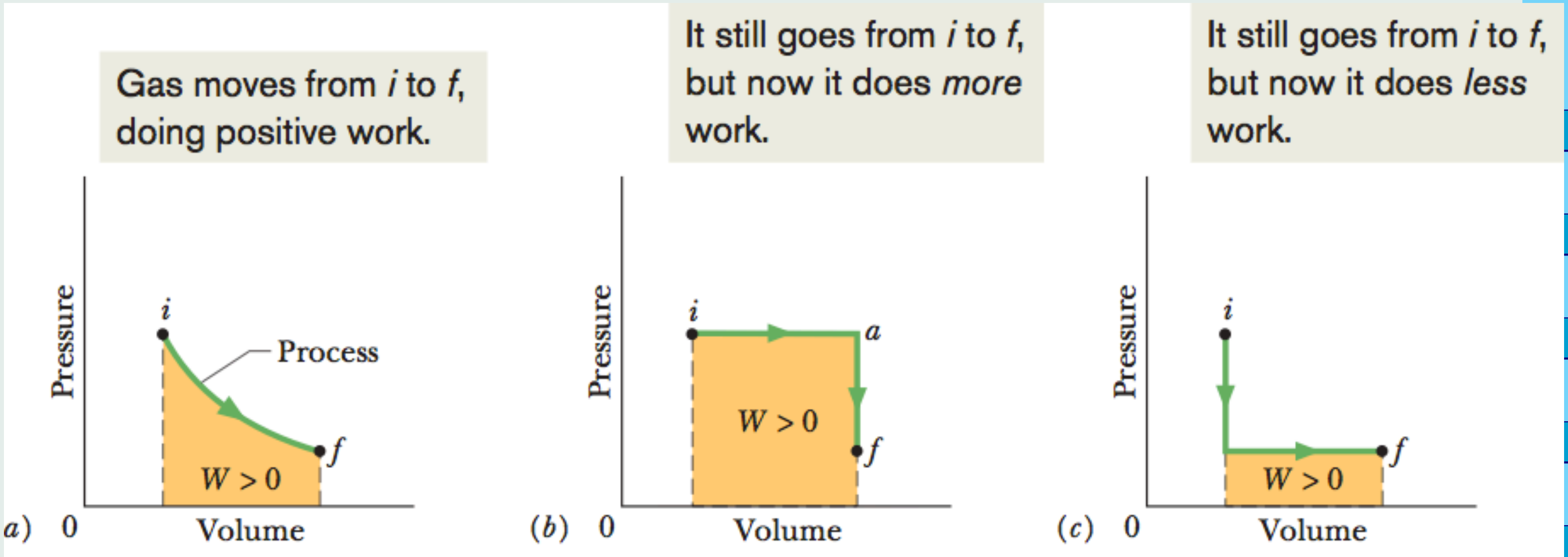
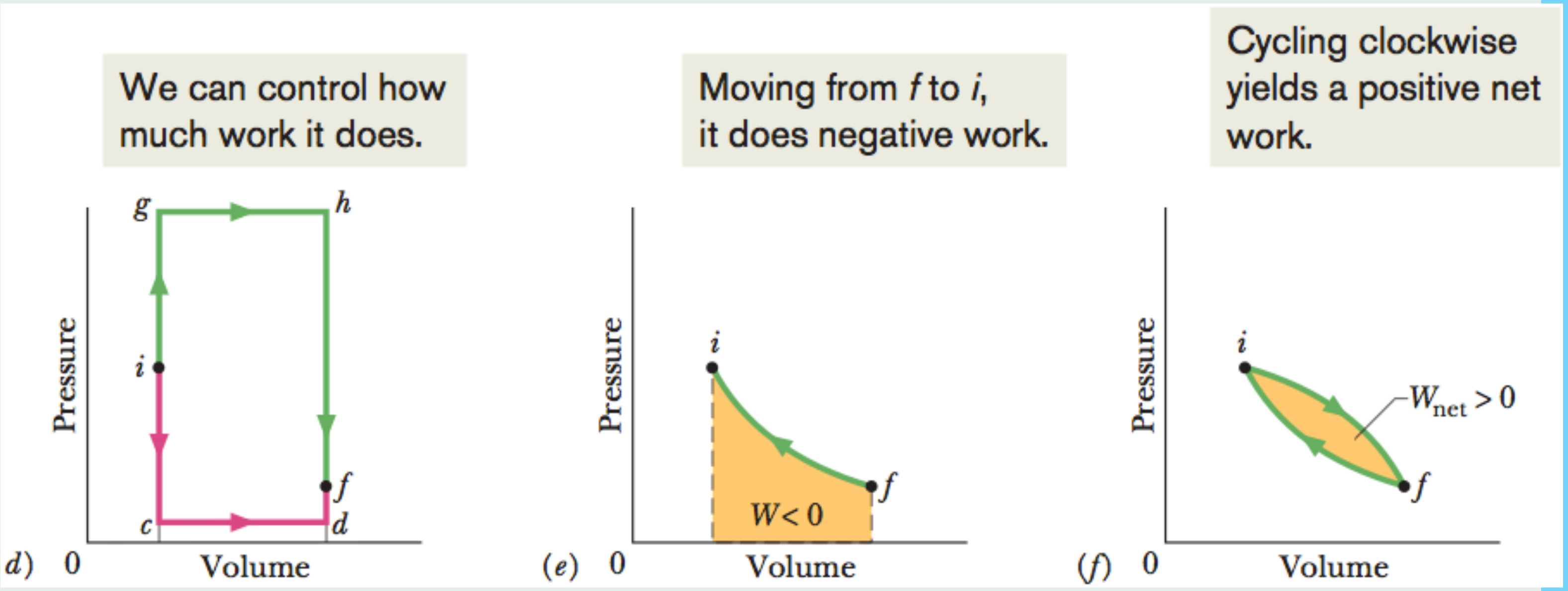


- $|W|$ = area below the graph $p = p(V)$ in the (p, V) plane
- W depends on the path in (p, V) plane

$$0 < W_c < W_a < W_b$$

- $W > 0$ during expansion (work done by the gas)



We can control how much work it does.

Moving from *f* to *i*, it does negative work.

Cycling clockwise yields a positive net work.

- $W < 0$ during contraction (work done on the gas)
- reversing the process changes the sign of W.
- cyclic process: $|W| =$ enclosed area; $W > 0$ clockwise; $W < 0$ counterclockwise.

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The first law of thermodynamics

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

- $E_{\text{int}} =$ **internal** energy of the system
- Q heat exchanged by the system
- W work done by the system

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 W done by the system

Special processes

- **Adiabatic processes**

$$Q = 0 \;\Rightarrow \Delta E_{\text{int}} = -W$$

- **Constant volume processes**

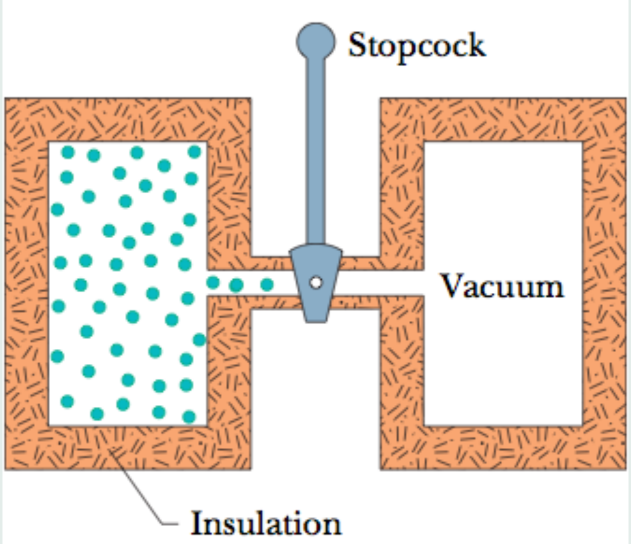
$$W = 0 \;\Rightarrow\; \Delta E_{\text{int}} = Q$$

- **Cyclical processes**

$$\Delta E_{\text{int}} = 0 \;\Rightarrow\; Q = W$$

- **Free expansions:**

$$Q = W = 0 \;\Rightarrow\; \Delta E_{\text{int}} = 0$$

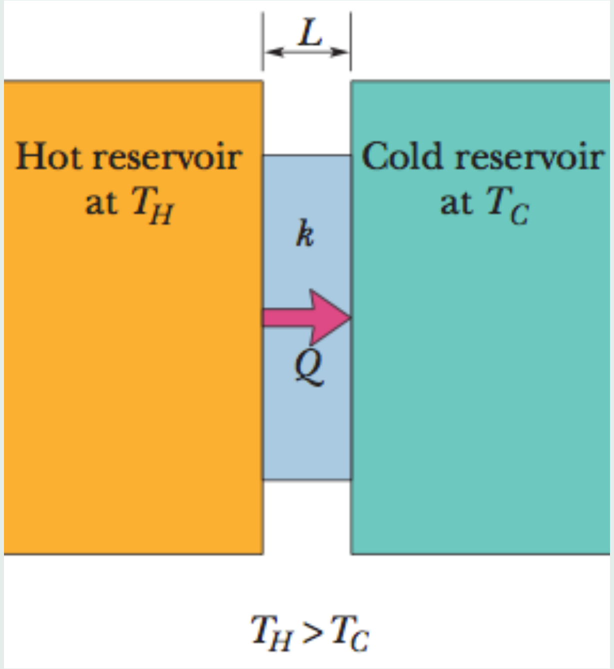


Free expansion

Heat conduction mechanisms

- **Conduction**
- **Convection**
- **Radiation**

- **Conduction**



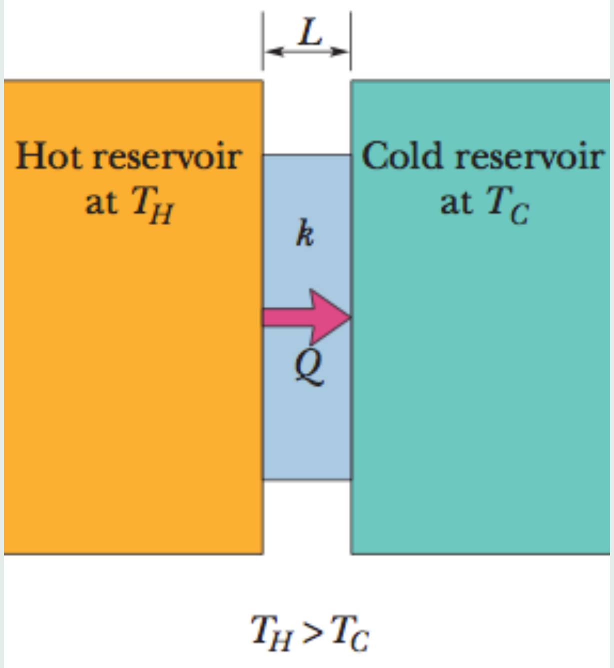
- Energy is transferred as heat from a reservoir at temperature T_H to a reservoir at temperature $T_C < T_H$ through a conducting slab of thickness L.

- Conduction rate:

$$P_{\text{cond}} = \frac{Q}{t}$$

where Q is the energy transferred in time t.

- **Conduction**



- Experimental formula

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

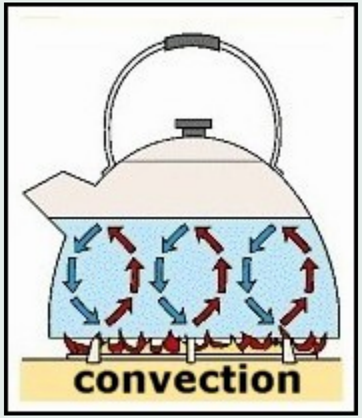
where A is the area of the slab's cross section and

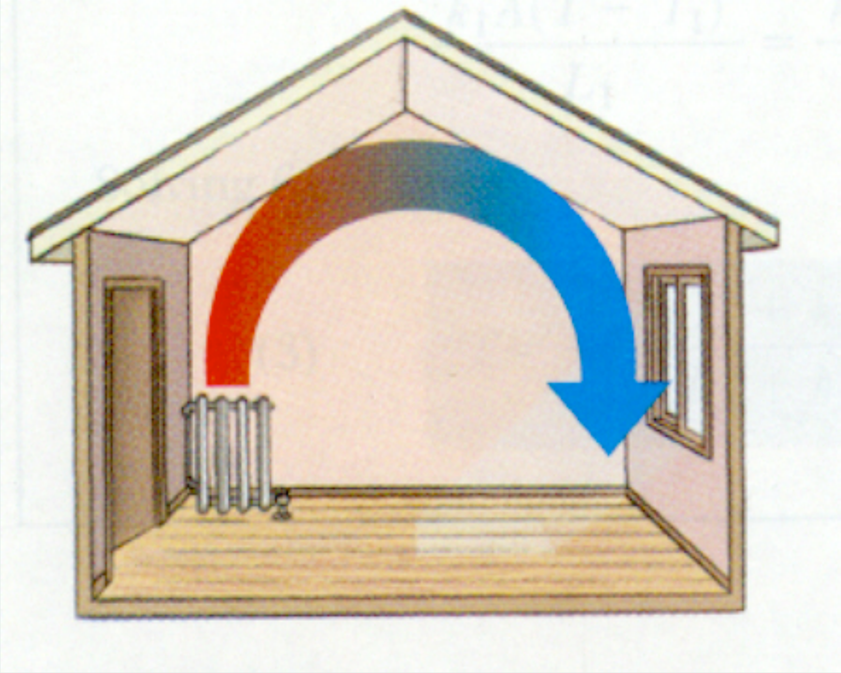
- $k =$ **thermal conductivity**

- **Thermal resistance**

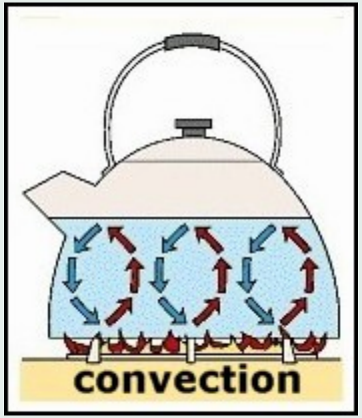
$$R = \frac{L}{k}$$

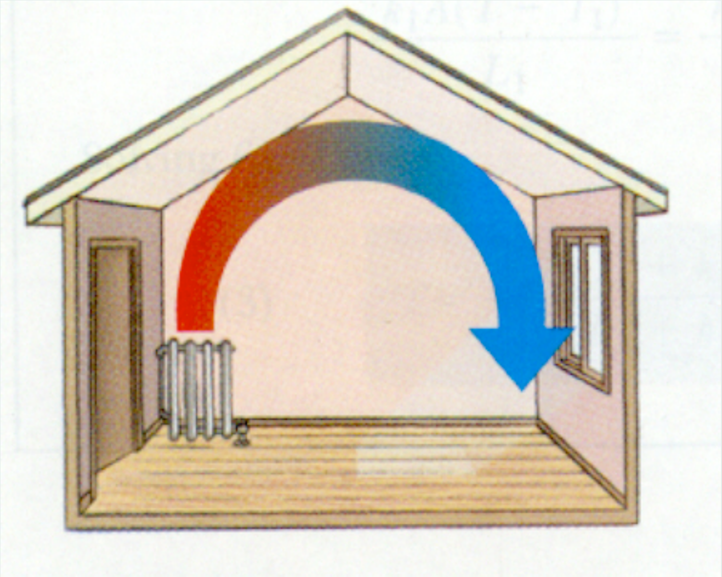
- **Convection**



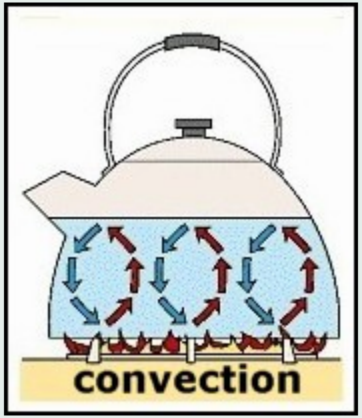


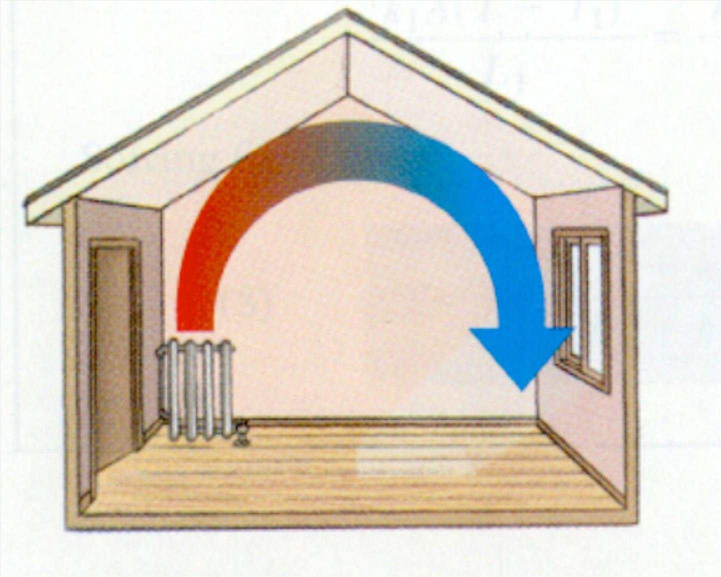
- Energy transfer occurs when a fluid, such as air or water, comes in contact with an object whose temperature is higher than that of the fluid.





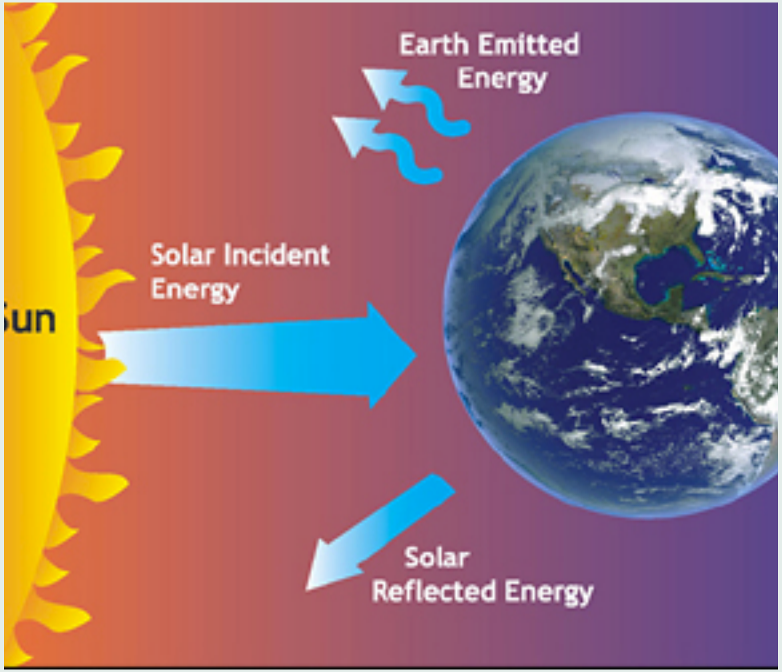
- The temperature of the part of the fluid that is in contact with the hot object increases, and (in most cases) that fluid expands and thus becomes less dense.
- The expanded fluid is now lighter than the surrounding cooler fluid, and the buoyant forces cause it to rise.





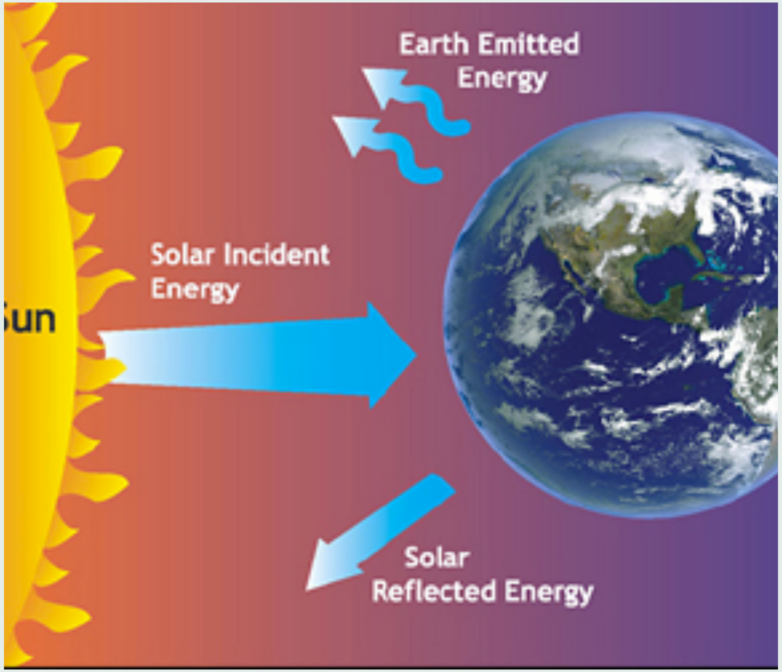
- Some of the surrounding cooler fluid then flows so as to take the place of the rising warmer fluid, and the process can then continue.

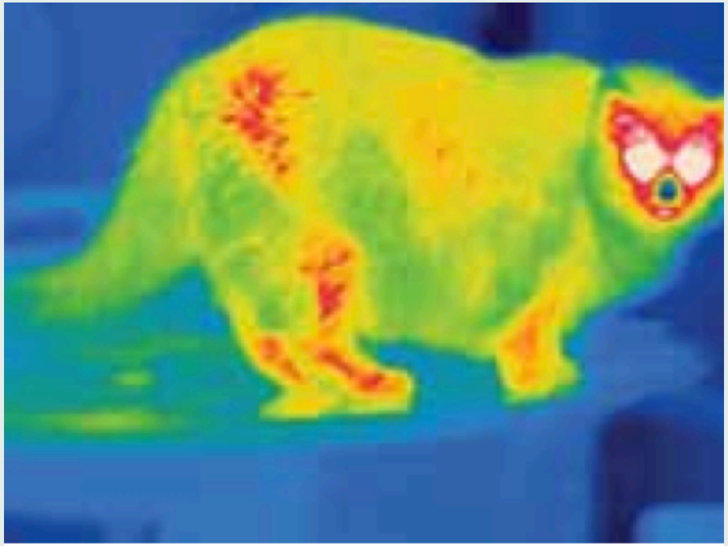
- **Radiation**



Energy transferred through **electromagnetic waves**

No medium required; can occur in vacuum.





All objects above absolute zero emit radiation according to **Boltzmann's law:**

$$P_{\text{rad}} = \frac{Q_{\text{rad}}}{t} = \sigma \epsilon A T^4$$

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$$P_{\mathsf{rad}} = \frac{Q_{\mathsf{rad}}}{t} = \sigma \epsilon A T^4$$

- $A =$ area of the surface
- $T =$ temperature of the object
- $\sigma = 5.6704 \times 10^{-8}\ \mathrm{W/m^2 \cdot K^4}$ **Stefan-Boltzmann** constant
- $\epsilon =$ **emissivity** depends on the material

$$0 \leq \epsilon \leq 1$$

- $\epsilon = 1$ ideal **black body radiator**

- The rate P_{abs} at which an object absorbs energy via thermal radiation from its environment, which we take to be at uniform temperature T_{env} (in kelvins), is

$$P_{\text{abs}} = \sigma \epsilon A T_{\text{env}}^4$$

- $\epsilon = 1 \Rightarrow$ an ideal blackbody will absorb all the radiated energy it intercepts (no reflection or scattering).

- An object will radiate energy to the environment while it absorbs energy from the environment, hence the objects net rate P_{net} of energy exchange due to thermal radiation is

$$P_{\text{net}} = P_{\text{abs}} - P_{\text{rad}} = \sigma \epsilon A (T_{\text{env}}^4 - T^4)$$

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