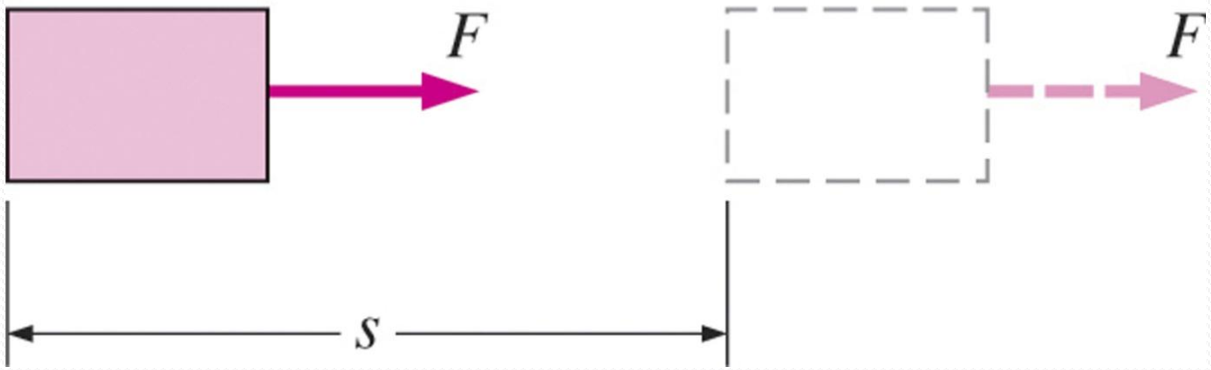
Chapter 4 Work and Heat



Work is usually defined as a force F acting through a displacement x, where the displacement is in the direction of the force.

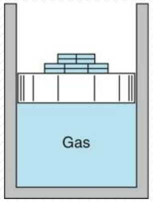
Work = Force × Distance

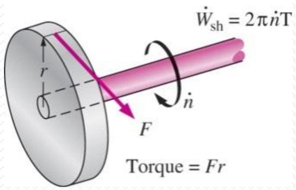
$$W = Fs \qquad \text{(kJ)}$$

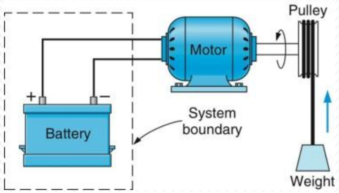
When force is not constant

$$W = \int_1^2 F\,ds \qquad \text{(kJ)}$$

A rising piston, a rotating shaft, and **an electric wire crossing the system boundaries** are all associated with work interactions.







The product of a unit force (one newton) acting through a unit distance (one meter). This unit for work in SI units is called the joule (J).

$$1 \text{ J} = 1 \text{ N m}$$

Power is the time rate of doing work and is designated by the symbol $\dot{W}$:

$$\dot{W} = \frac{\delta W}{dt}$$

The unit for power is a rate of work of one joule per second, which is a watt (W):

$$1 \text{ W} = 1 \text{ J/s}$$

A familiar unit for power in English units is the horsepower (hp), where

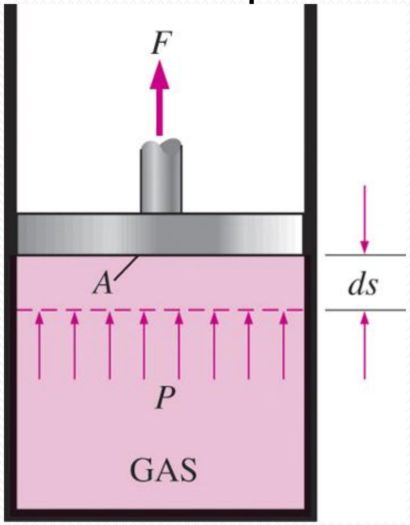
$$1 \text{ hp} = 550 \text{ ft Ibf/s} = 0.7457 \text{ kW}$$

MECHANICAL FORMS OF WORK

- **Formal sign convention**: Work done *by* a system is considered positive and work done *on* a system is considered negative.

- There are two requirements for a work interaction between a system and its surroundings to exist:
  - there must be a ***force*** acting on the boundary.
  - the boundary must ***move***.

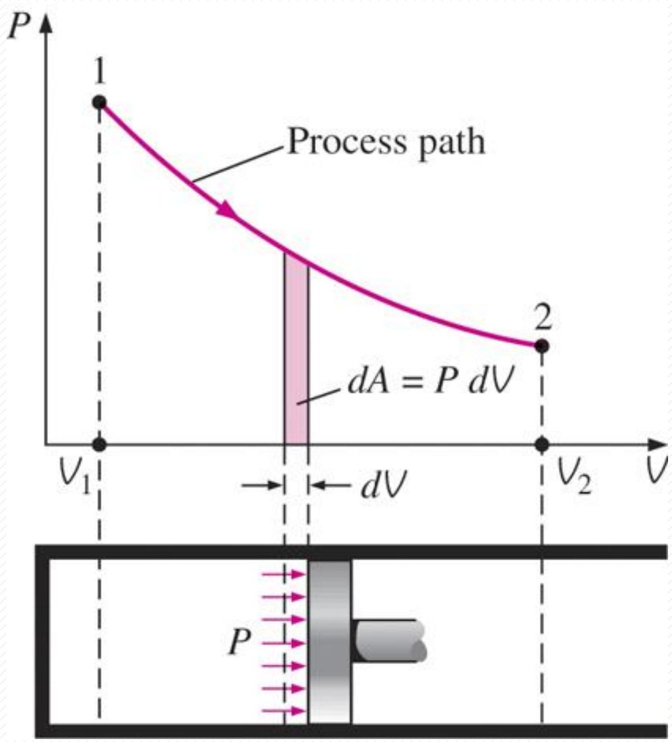
Moving boundary work (*P dV* work): The expansion and compression work in a piston-cylinder device.



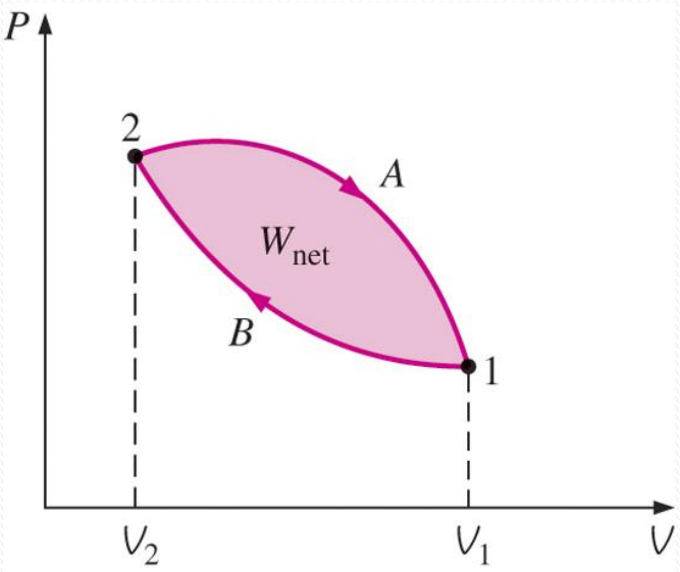
$$\delta W_b = F\,ds = PA\,ds = P\,dV$$

$$W_b = \int_1^2 P\,dV \qquad (\text{kJ})$$

A gas does a differential amount of work δW_b as it forces the piston to move by a differential amount *ds*.



The net work done during a cycle is the difference between the work done by the system and the work done on the system.



The area under the process curve on a *P-V* diagram represents the boundary work.

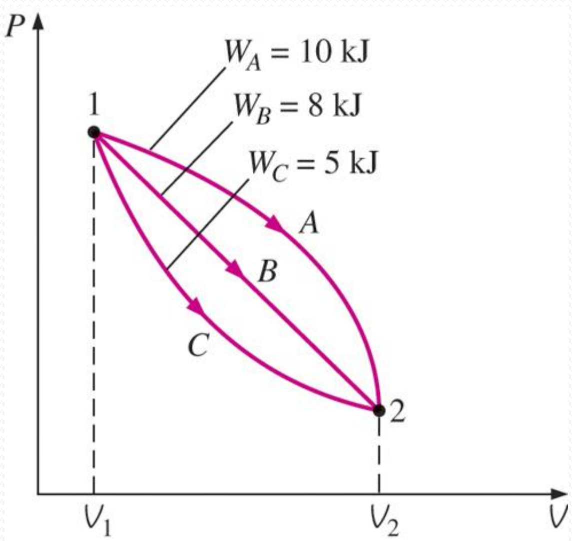
$$\text{Area} = A = \int_1^2 dA = \int_1^2 P\, dV$$

Thermodynamic properties are <u>point functions</u>. The differentials of point functions are <u>exact differentials</u>, and the integration is simply

$$\int_1^2 dV = V_2 - V_1 \quad = \Delta V$$ **Properties are point functions have exact differentials (d).**

Thus, the volume in state 2 and the volume in state 1, and the change in volume depends only on the initial and final states.

The boundary work done during a process depends on the path followed as well as the end states.



Work is a path function since the work done in a quasi–equilibrium process between two given states depends on the path followed. The differentials of path functions are inexact differentials

$$\int_1^2 \delta W = {}_1W_2 \quad \neq W_2 - W_1 \text{ or not } \Delta W$$

Path functions have inexact differentials (δ)

We must know the relationship between P and V during a process to calculate the work.

$$P = f(V)$$

Polytropic, Isothermal, and Isobaric processes (Relationship between P and V)

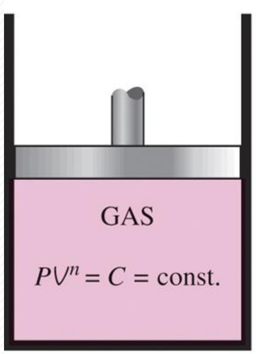
$P = CV^{-n}$ Polytropic process: *C* and *n* (polytropic exponent) are constants

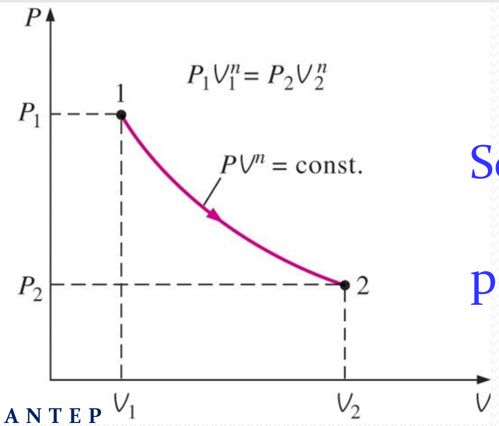
$$W_b = \int_1^2 P\,dV = \int_1^2 CV^{-n}\,dV = C\frac{V_2^{-n+1} - V_1^{-n+1}}{-n+1} = \frac{P_2V_2 - P_1V_1}{1-n}$$ Polytropic process

$$W_b = \frac{mR(T_2 - T_1)}{1-n}$$ Polytropic and for ideal gas

$$W_b = \int_1^2 P\,dV = \int_1^2 CV^{-1}\,dV = PV\ln\left(\frac{V_2}{V_1}\right)$$ When ***n* = 1** (isothermal process)

$$W_b = \int_1^2 P\,dV = P_0\int_1^2 dV = P_0(V_2 - V_1)$$ Constant pressure process (**isobaric process**) **n=0**





Schematic and *P-V* diagram for a polytropic process.

What is the boundary work for a constant-volume process?

Shaft Work

A force F acting through a moment arm r generates a torque T

$$\mathrm{T} = Fr \quad \rightarrow \quad F = \frac{\mathrm{T}}{r}$$

This force acts through a distance s

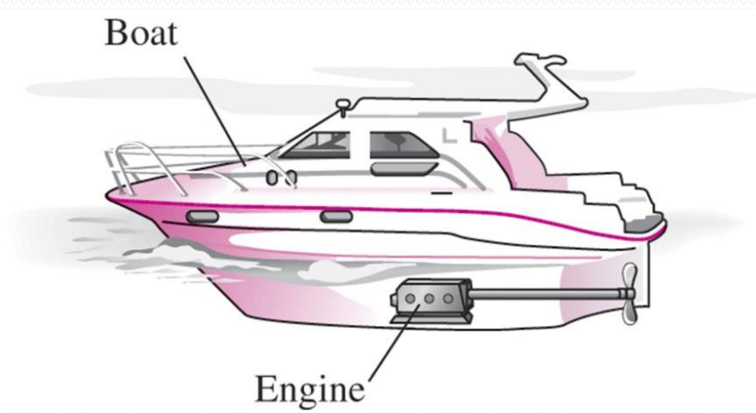
$$s = (2\pi r)n$$

Shaft work

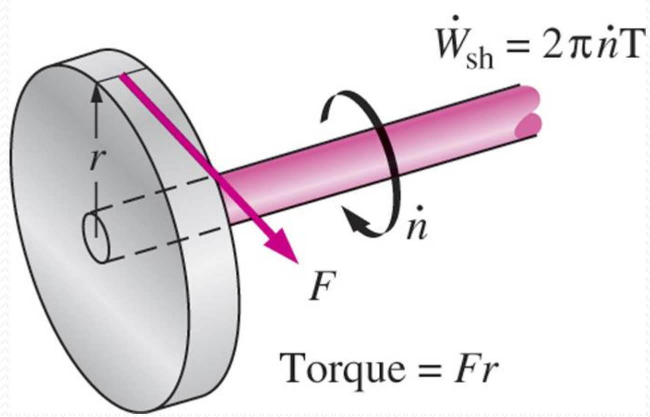
$$W_{sh} = Fs = \left(\frac{\mathrm{T}}{r}\right)(2\pi rn) = 2\pi n\mathrm{T} \qquad \text{(kJ)}$$

The power transmitted through the shaft is the shaft work done per unit time

$$\dot{W}_{sh} = 2\pi\dot{n}\mathrm{T} \qquad \text{(kW)}$$



Energy transmission through rotating shafts is commonly encountered in practice.



Shaft work is proportional to the torque applied and the number of revolutions of the shaft.

Spring Work

When the length of the spring changes by a differential amount *dx* under the influence of a force *F*, the work done is

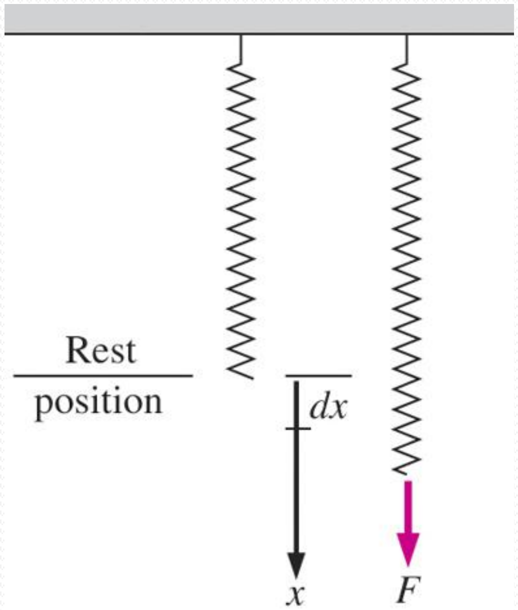
$$\delta W_{\text{spring}} = F\,dx$$

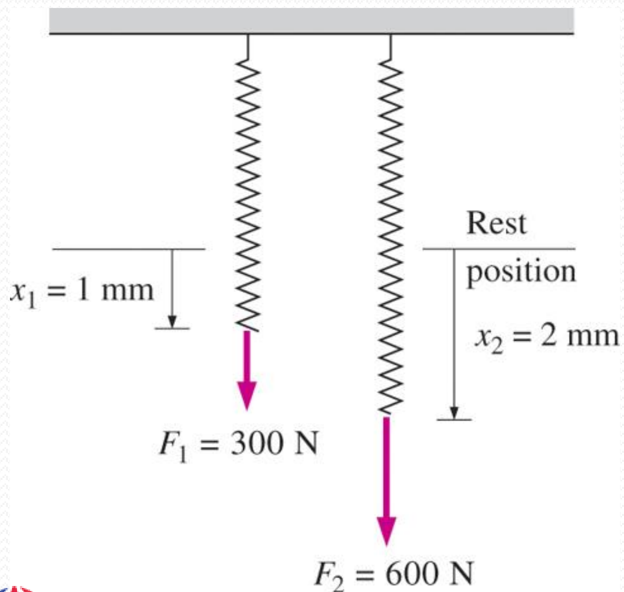
For linear elastic springs, the displacement *x* is proportional to the force applied

$$F = kx \qquad (\text{kN})$$

k: spring constant (kN/m)

Elongation of a spring under the influence of a force.





The displacement of a linear spring doubles when the force is doubled.

Substituting and integrating yield

$$W_{\text{spring}} = \tfrac{1}{2}k\left(x_2^2 - x_1^2\right) \qquad (\text{kJ})$$

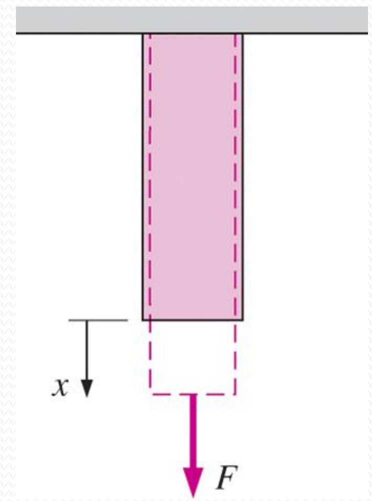
x_1 and x_2: the initial and the final displacements

Work Done on Elastic Solid Bars

$$ {}_1W_2 = -\int_1^2 \mathfrak{I}\, dL \quad \text{where } \mathfrak{I} \text{ tension} $$

dL amount of the length change of the wire

Solid bars behave as springs under the influence of a force.



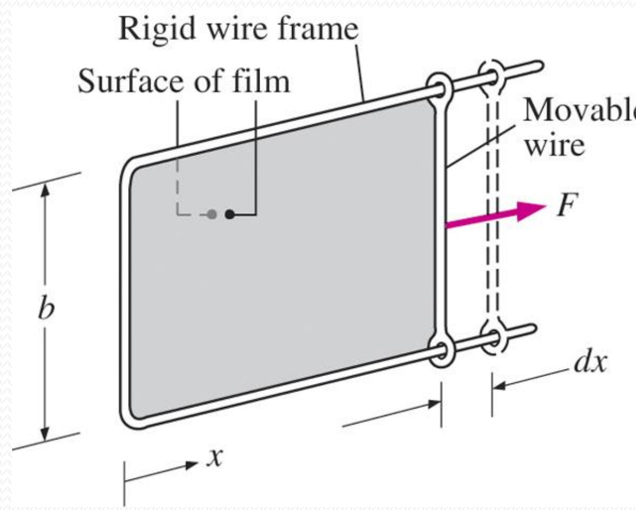
Work Associated with the Stretching of a Liquid Film

$$ \delta W = -\mathcal{S}\, dA $$

$$ {}_1W_2 = -\int_1^2 \mathcal{S}\, dA $$

surface tension $\mathcal{S}$

Stretching a liquid film with a movable wire.



Nonmechanical Forms of Work

Electrical work: The generalized force is the *voltage* (the electrical potential) and the generalized displacement is the *electrical charge.*

Magnetic work: The generalized force is the *magnetic field strength* and the generalized displacement is the total *magnetic dipole moment*.

Electrical polarization work: The generalized force is the *electric field strength* and the generalized displacement is the *polarization of the medium*.

Electrical Work

Electrical work

$$W_e = \mathbf{V}N$$

Electrical power

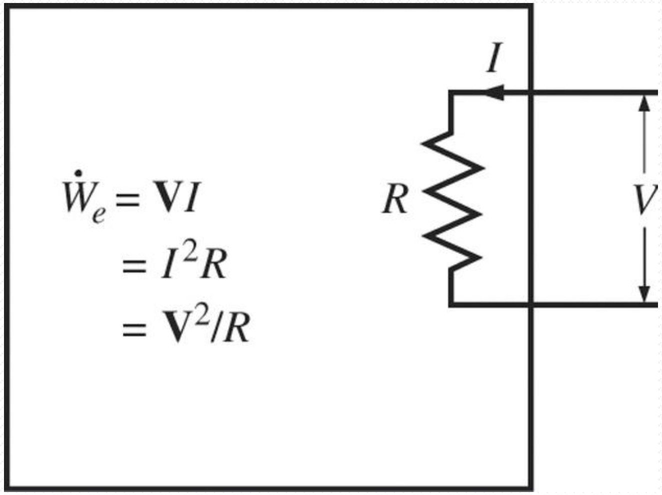
$$\dot{W}_e = \mathbf{V}I \qquad \text{(W)}$$

When potential difference and current change with time

$$W_e = \int_1^2 \mathbf{V}I\,dt \qquad \text{(kJ)}$$

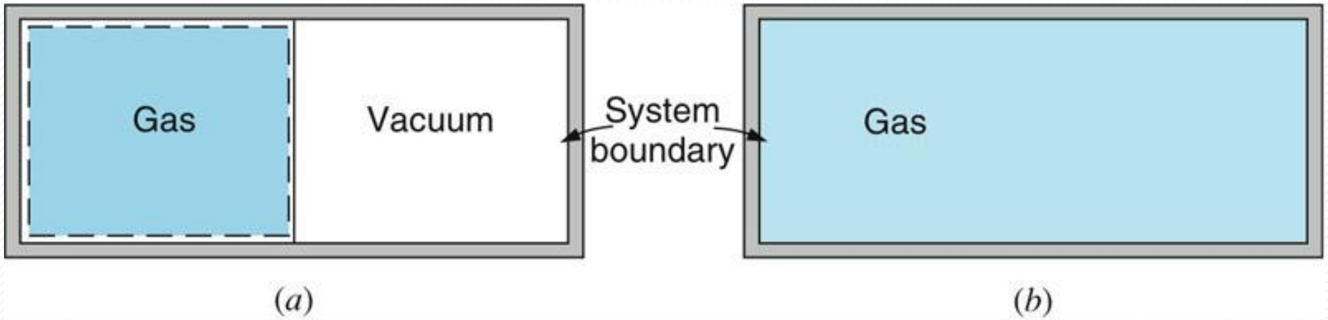
When potential difference and current remain constant

$$W_e = \mathbf{V}I\,\Delta t \qquad \text{(kJ)}$$



Electrical power in terms of resistance *R*, current *I*, and potential difference **V**.

Figure shows a gas separated from the vacuum by a membrane. Let the membrane rupture and the gas fill the entire volume. Neglecting any work associated with the rupturing of the membrane, we can ask whether work is done in the process.



If we take as our system the gas and the vacuum space, we readily conclude that no work is done because no work can be identified at the system boundary.

If we take the gas as a system, we conclude that for this system no work is done in this process of filling the vacuum because there is no resistance at the system boundary as the volume increases.

Moving boundary work

$$\int_1^2 P\,dV$$

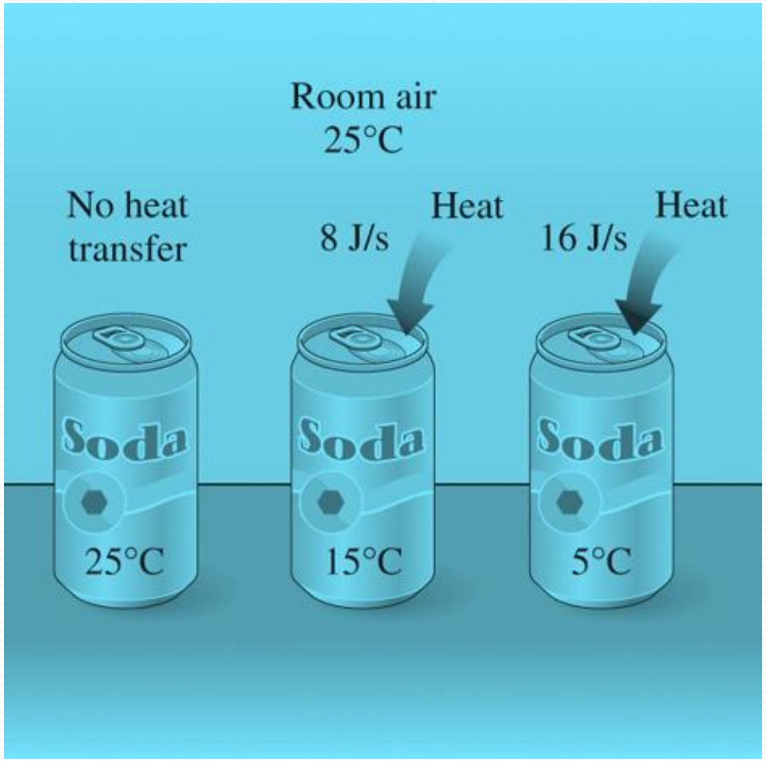
Work can be calculated for a quasi-equilibrium process
However, this process is not a quasi-equilibrium process

ENERGY TRANSFER BY HEAT

Heat: The form of energy that is transferred between two systems (or a system and its surroundings) by virtue of a temperature difference.

In the International System the unit for heat (energy) is the joule.

In English Units, the unit for heat is British thermal unit (Btu) = 1.055 kJ.

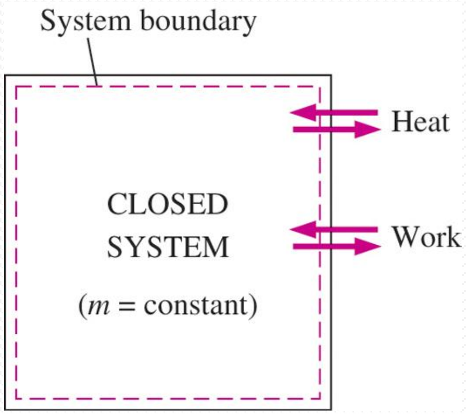


Temperature difference is the driving force for heat transfer. The larger the temperature difference, the higher is the rate of heat transfer.

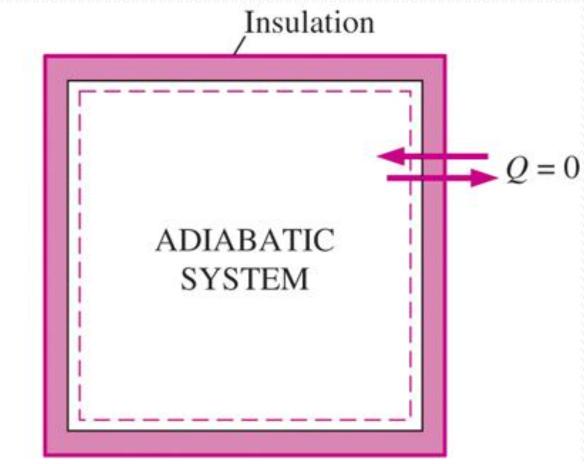
Heat transferred *to* a system is considered positive, and heat transferred *from* a system is negative.

Thus, positive heat represents energy transferred to a system, and negative heat represents energy transferred from a system. The symbol Q represents heat. A process in which there is no heat transfer ($Q = 0$) is called an adiabatic process.

Work done by a system is considered positive and work done on a system is considered negative.



Energy can cross the boundaries of a closed system in the form of heat and work.



During an adiabatic process, a system exchanges no heat with its surroundings.

$$q = \frac{Q}{m} \qquad \text{(kJ/kg)}$$

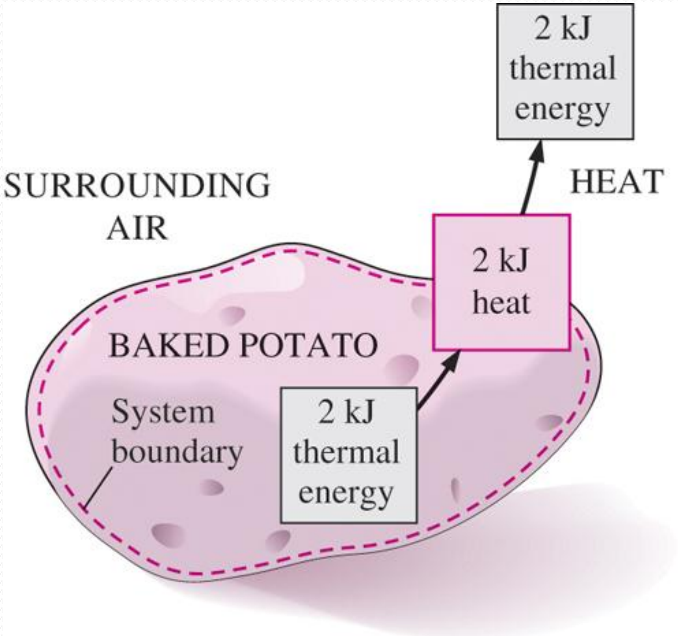
Heat transfer per unit mass

$$Q = \dot{Q}\,\Delta t \qquad \text{(kJ)}$$

Amount of heat transfer when heat transfer rate is constant

$$Q = \int_{t_1}^{t_2} \dot{Q}\,dt \qquad \text{(kJ)}$$

Amount of heat transfer when heat transfer rate changes with time



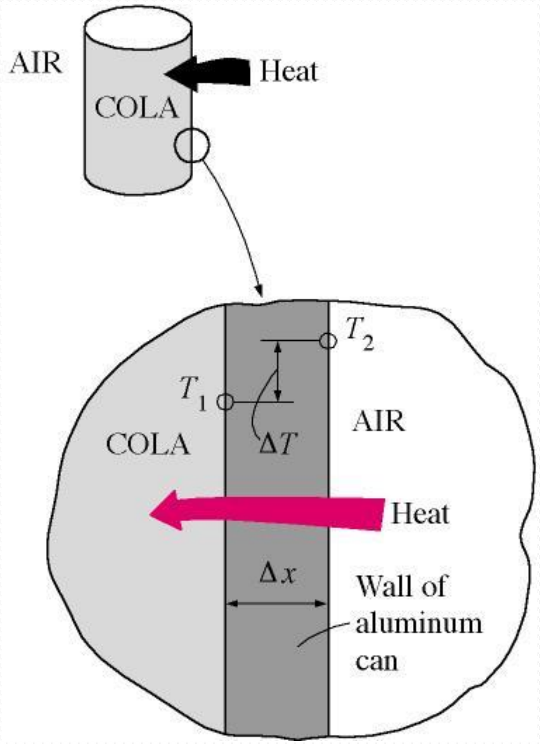
Energy is recognized as heat transfer only as it crosses the system boundary.

Heat transfer mechanisms

Conduction

Conduction heat transfer is a progressive exchange of energy between the molecules of a substance.

Fourier's law of heat conduction is $\dot{Q}_{cond} = -A\,k_t\,\dfrac{dT}{dx}$



where

$\dot{Q}_{cond}$ = heat flow per unit time (W)
k_t = thermal conductivity (W/m·K)
A = area normal to heat flow (m²)

$\dfrac{dT}{dx}$ = temperature gradient in the direction of heat flow (°C/m)

Integrating Fourier's law $\dot{Q}_{cond} = k_t A \dfrac{\Delta T}{\Delta x}$

Since $T_2 > T_1$, the heat flows from right to left in the above figure.

Convection

The transfer of energy between a solid surface and the adjacent fluid that is in motion, and it involves the combined effects of conduction and fluid motion.

The rate of heat transfer by convection is determined from Newton's law of cooling.

Newton's law of cooling is expressed as

$$\dot{Q}_{conv} = h\,A(T_s - T_f)$$

where

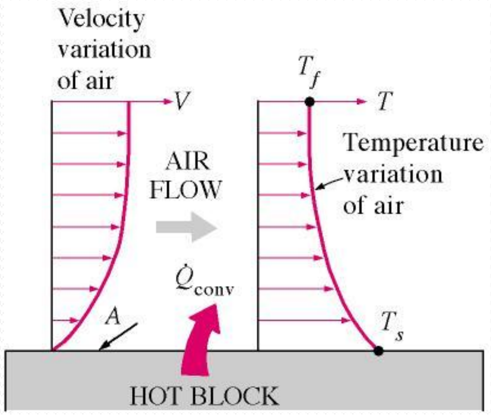
$\dot{Q}_{conv}$ = heat transfer rate (W)

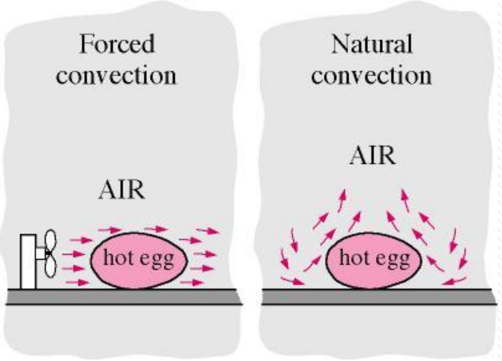
A = heat transfer area (m^2)

h = convective heat transfer coefficient ($W/m^2 \cdot K$)

T_s = surface temperature (K)

T_f = bulk fluid temperature away from the surface (K)

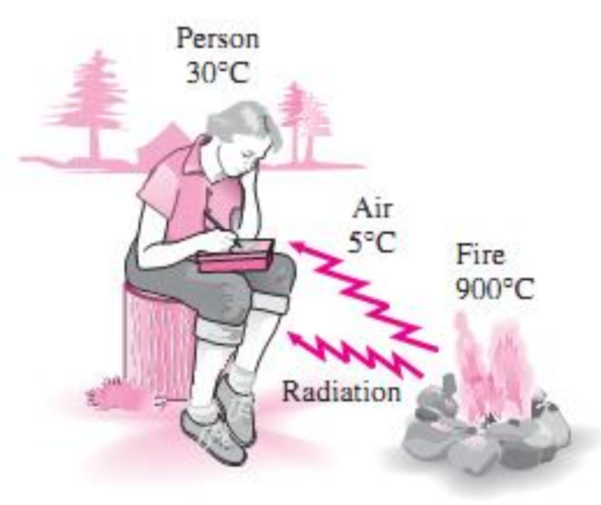




Radiation

The transfer of energy due to the emission of electromagnetic waves (or photons).

$$\dot{Q}_{rad} = \varepsilon\sigma A\left(T_s^4 - T_{surr}^4\right)$$



where

$\dot{Q}_{rad}$ = heat transfer per unit time (W)
A = surface area for heat transfer (m^2)
σ = Stefan-Boltzmann constant, $5.67\text{x}10^{-8}$ W/m^2K^4 and $0.1713\text{x}10^{-8}$ BTU/h ft^2 R^4
ε = emissivity
T_s = absolute temperature of surface (K)
T_{surr} = absolute temperature of surroundings (K)

Comparison of Heat and Work

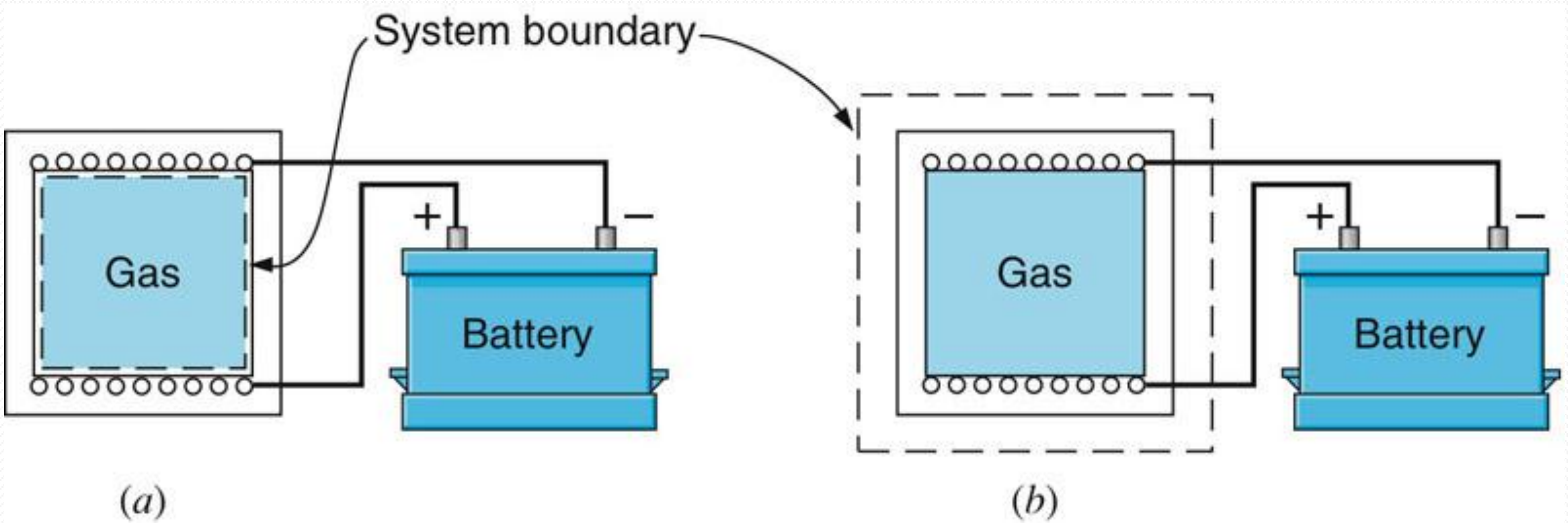
Heat and work are energy transfer mechanisms between a system and its surroundings, and there are many similarities between them:

1. Both are recognized at the boundaries of a system as they cross the boundaries. That is, both heat and work are boundary phenomena.

2. Heat and work are both transient phenomena. Systems possess energy, but not heat or work.

3. Both are associated with a process, not a state. Unlike properties, heat or work has no meaning at a state.

4. Both are path functions (i.e., their magnitudes depend on the path followed during a process as well as the end states).


System boundary
Gas
Battery
+
–
(a)
Gas
Battery
+
–
(b)