General Physics (PHY 2130)

Lecture X

- Laws of Thermodynamics
  - Heat and internal energy
  - Work and heat
  - Heat Engines
    - The Carnot Engine
  - Entropy

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http://www.physics.wayne.edu/~apetrov/PHY2130/

If you want to know your progress so far, please send me an email request at

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Note: scores are available from the course's website.

Lightning Review

Last lecture:

1. Heat
   - ✓ Specific heat, phase transitions
   - ✓ Heat transfer (conduction, convection, radiation)

<u>Review Problem:</u> Water at the top of Niagara Falls has a temperature of 10.0°C. Would the temperature of water at the bottom of the falls be

1. higher
2. the same as
3. lower

than the temperature at the top? If you want to estimate the effect numerically, consider 1.00 kg of water and assume that it falls a distance of 50.0 m.

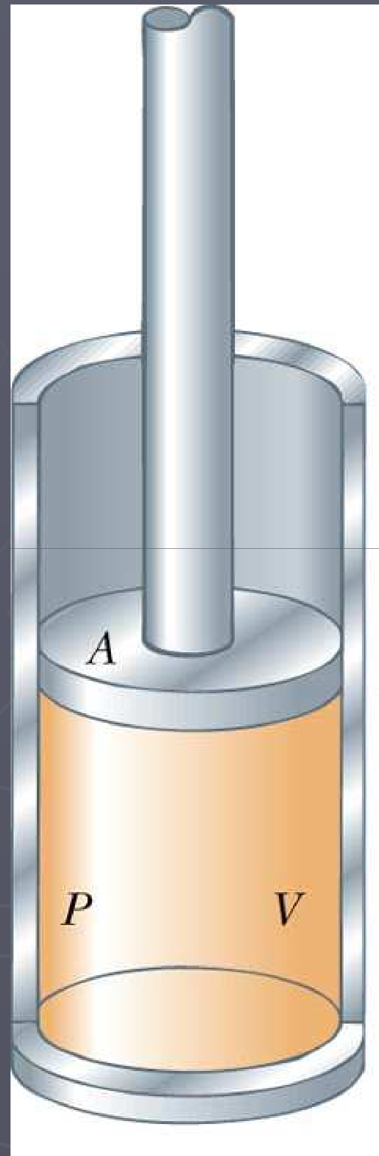
The Laws of Thermodynamics

Work in Thermodynamic Processes – State Variables

- State of a system
  - Description of the system in terms of *state variables*
    - Pressure
    - Volume
    - Temperature
    - Internal Energy
  - A *macroscopic state* of an isolated system can be specified only if the system is in internal thermal equilibrium

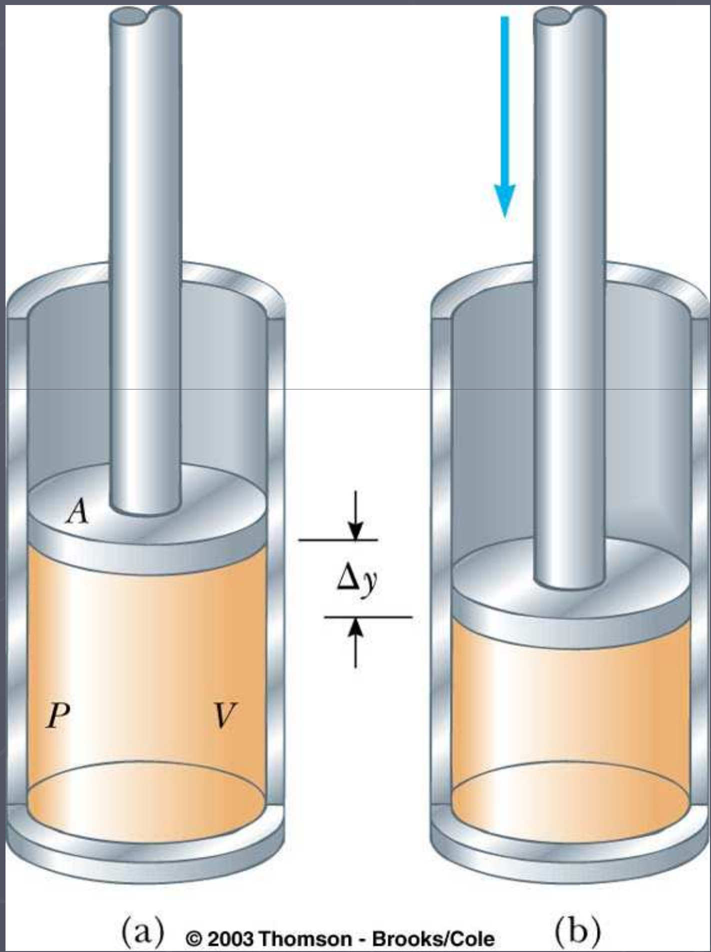
Work

- Work is an important energy transfer mechanism in thermodynamic systems
- Heat is another energy transfer mechanism
- Example: gas cylinder with piston
  - The gas is contained in a cylinder with a moveable piston
  - The gas occupies a volume V and exerts pressure P on the walls of the cylinder and on the piston



Work in a Gas Cylinder

- A force is applied to slowly compress the gas
  - The compression is slow enough for all the system to remain essentially in thermal equilibrium
- $W = - P \Delta V$
  - This is the work done *on* the gas



Work on a Gas Cylinder

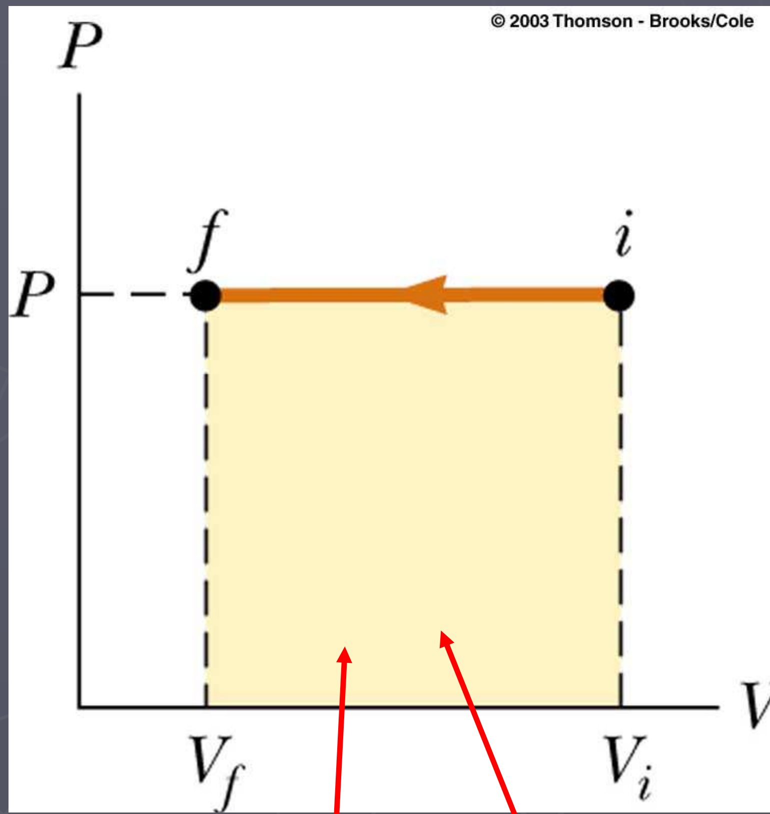
$$W = -P\,\Delta V$$

- When the gas is compressed
  - ΔV is negative
  - The work done on the gas is positive
- When the gas is allowed to expand
  - ΔV is positive
  - The work done on the gas is negative
- When the volume remains constant
  - No work is done on the gas

Notes about the Work Equation

$W = - P \Delta V$

- If the pressure remains constant during the expansion or compression, the process is called an *isobaric* process
- If the pressure changes, the average pressure may be used to estimate the work done

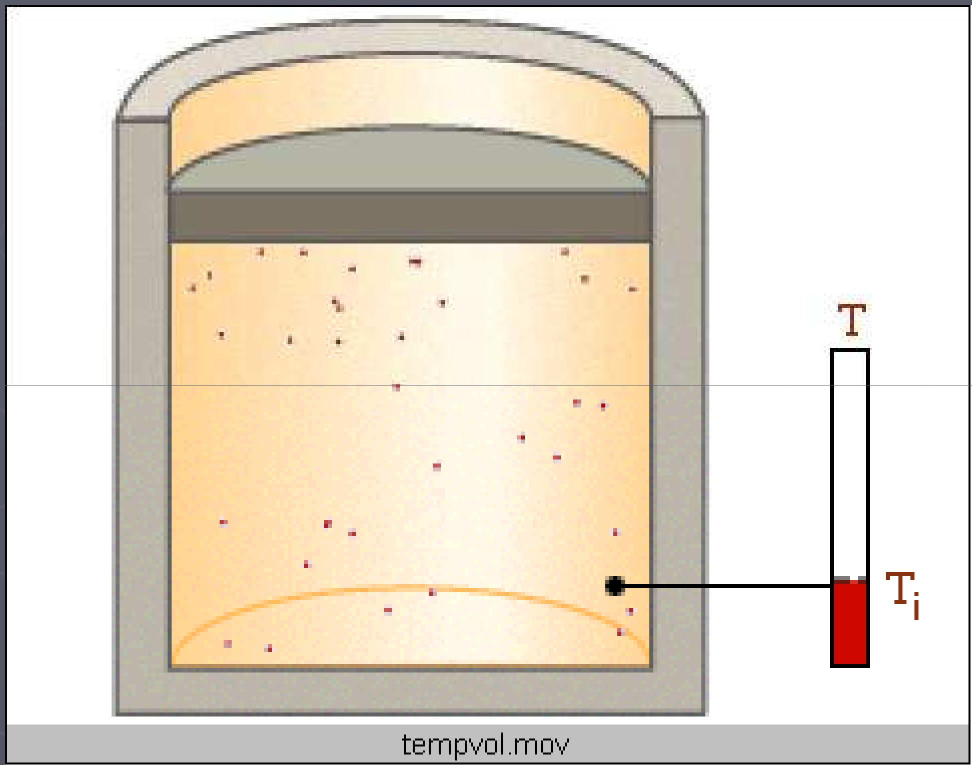


$W = - P \Delta V$

Work=Area under the curve

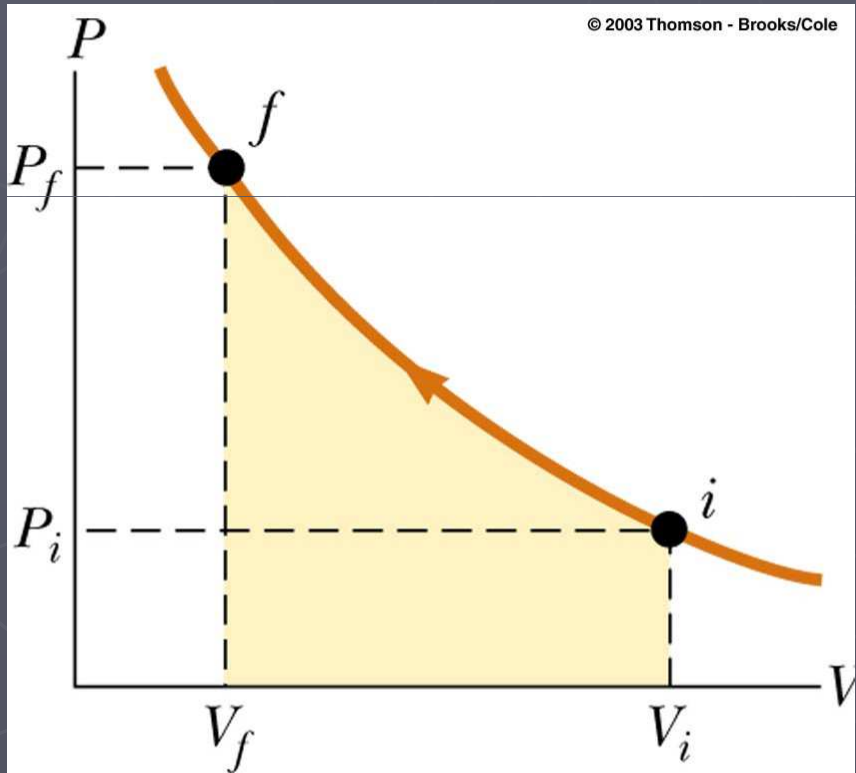
Work done on the gas

Let’s watch the movie!



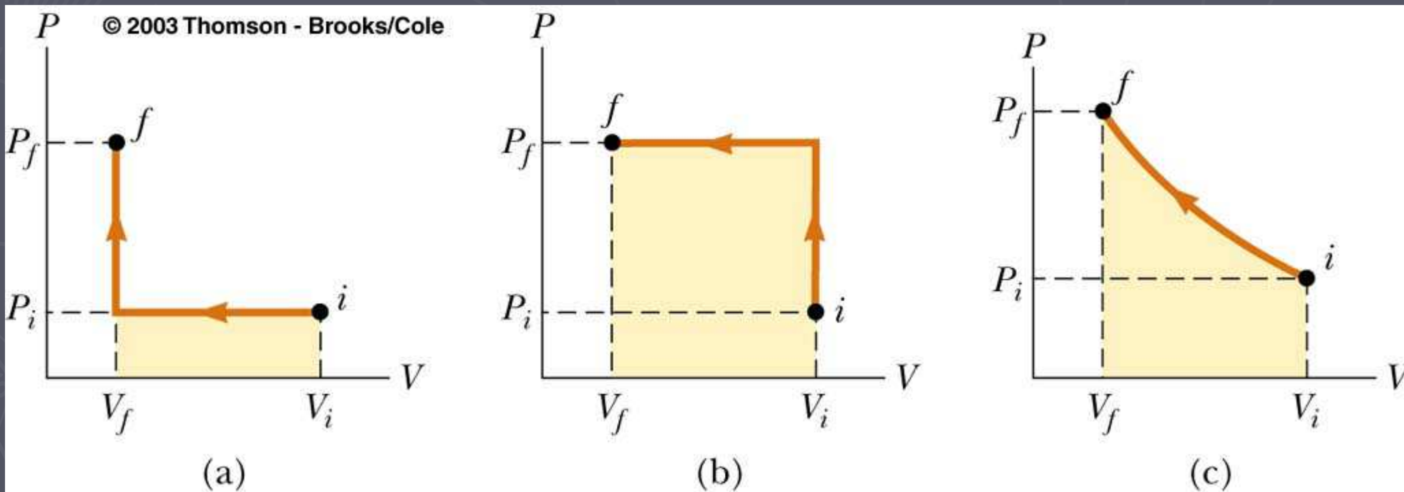
PV Diagrams

- Used when the pressure and volume are known at each step of the process
- The work done on a gas that takes it from some initial state to some final state is the negative of the area under the curve on the PV diagram
  - This is true whether or not the pressure stays constant



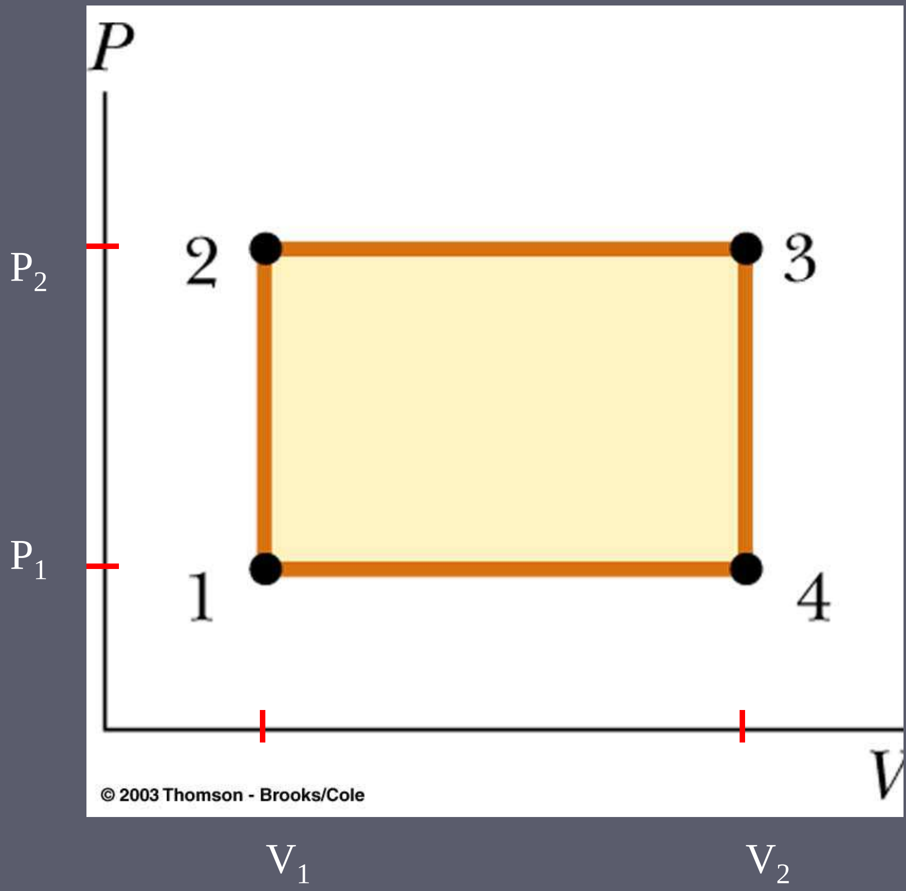
PV Diagrams

- The curve on the diagram is called the *path* taken between the initial and final states
- The work done depends on the particular path
  - Same initial and final states, but different amounts of work are done



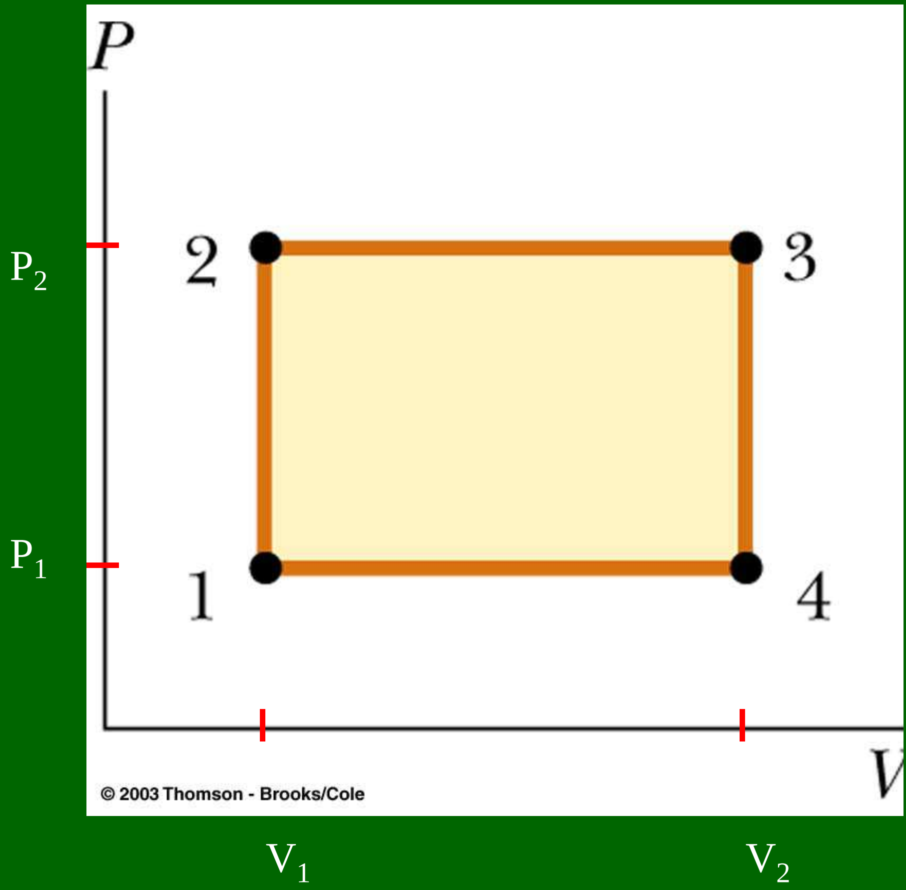
Question

Find work done by the gas in this cycle.



Question

Find work done by the gas in this cycle.



Note: work is equal to the area:

$$W = (p_2 - p_1)(V_2 - V_1)$$

Other Processes

- *Isovolumetric*
  - Volume stays constant
  - Vertical line on the PV diagram
- *Isothermal*
  - Temperature stays the same
- *Adiabatic*
  - No heat is exchanged with the surroundings

Example:

Calculate work done by expanding gas of 1 mole if initial pressure is 4000 Pa, initial volume is 0.2 m^3, and initial temperature is 96.2 K. Assume a two processes: (1) *isobaric* expansion to 0.3 m^3, T_f=144.3 K (2) *isothermal* expansion to 0.3 m^3.

<u>Given:</u>

$n = 1$ *mole*
$T_i = 96.2\ K$
$T_f = 144.3\ K$
$V_i = 0.2$ m^3
$V_f = 0.3$ m^3
$P = const$

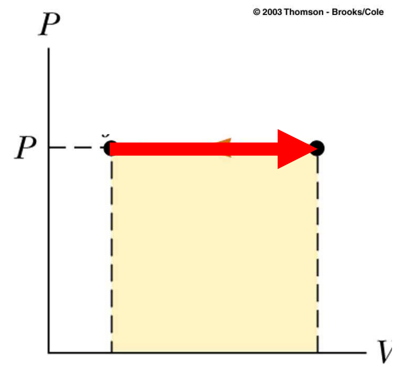
<u>Find:</u>

$W = ?$

1. <u>Isobaric</u> expansion:

$$W = P\Delta V = P\left(V_f - V_i\right) = 4000\ \text{Pa}\left(0.3\text{m}^3 - 0.2m^3\right)$$
$$= 400\ J$$

✓



Also:

$$\frac{T_f}{T_i} = \frac{P_f V_f / nR}{P_i V_i / nR} = \frac{V_f}{V_i} = \frac{0.3m^3}{0.2m^3} = \underline{1.5}$$

A 50% increase in temperature!

Example:

Calculate work done by expanding gas of 1 mole if initial pressure is 4000 Pa, initial volume is 0.2 m^3, and initial temperature is 96.2 K. Assume a two processes: (1) *isobaric* expansion to 0.3 m^3, T_f=144.3 K (2) *isothermal* expansion to 0.3 m^3.

Given:

n = *1 mole*
$T_i = 96.2\ K$
V_i = 0.2 m^3
V_f = 0.3 m^3
$T = const$

Find:

$W = ?$

2. Isothermal expansion:

Example:

Calculate work done by expanding gas of 1 mole if initial pressure is 4000 Pa, initial volume is 0.2 m^3, and initial temperature is 96.2 K. Assume a two processes: (1) *isobaric* expansion to 0.3 m^3, T_f=144.3 K (2) *isothermal* expansion to 0.3 m^3.

Given:

n = *1 mole*
$T_i = 96.2\ K$
V_i = 0.2 m^3
V_f = 0.3 m^3
$T = const$

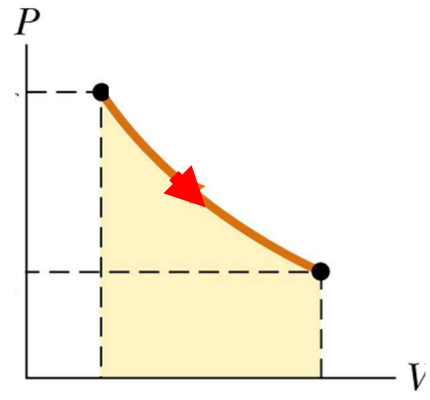
Find:

$W = ?$

2. Isothermal expansion:

$$W = nRT\ln\left(\frac{V_f}{V_i}\right) = P_i V_i \ln\left(\frac{V_f}{V_i}\right)$$

$$= (4000\text{ Pa})(0.2m^3)\ln\frac{0.3m^3}{0.2m^3} = 324\ J$$ ✓



Also:

$$P_f = P_i\frac{V_i}{V_f} = 4000\ Pa\frac{0.2m^3}{0.3m^3} = 2667\ Pa$$

A ~67% decrease in pressure!

Processes for Transferring Energy

- By doing work
  - Requires a macroscopic displacement of the point of application of a force
- By heat
  - Occurs by random molecular collisions
- Results of both
  - Change in internal energy of the system
  - Generally accompanied by measurable macroscopic variables
    - Pressure
    - Temperature
    - Volume

First Law of Thermodynamics

- Consider energy conservation in thermal processes. Must include:
  - Q
    - Heat
    - Positive if energy is transferred *to* the system
  - W
    - Work
    - Positive if done *on* the system
  - U
    - Internal energy
    - Positive if the temperature increases

First Law of Thermodynamics

- The relationship among U, W, and Q can be expressed as

$$\Delta U = U_f - U_i = Q + W$$

- This means that the change in internal energy of a system is equal to the sum of the energy transferred across the system boundary by heat and the energy transferred by work

Applications of the First Law – 1. Isolated System

- An *isolated system* does not interact with its surroundings
- No energy transfer takes place and no work is done
- Therefore, the internal energy of the isolated system remains constant

Example:

If 500 J of heat added to ideal gas that is expanding from 0.2 m^3 to 0.3 m^3 at a constant pressure of 4000 Pa, what is the change in its internal energy?

Given:

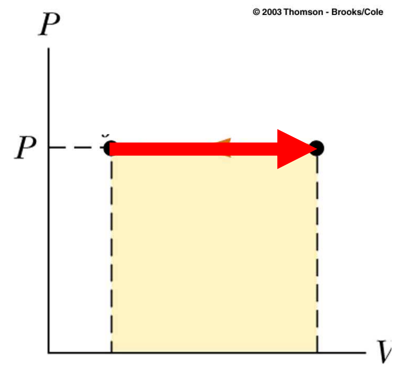
n = *1 mole*
V_i = 0.2 m^3
V_f = 0.3 m^3
P = const
Q=500 J

Find:

$\Delta U = ?$

1. Isobaric expansion:

$$W = P\Delta V = P\left(V_f - V_i\right) = 4000\ \text{Pa}\left(0.3\text{m}^3 - 0.2m^3\right)$$
$$= 400\ J$$



Use 1st law of thermodynamics:

$$Q = \Delta U + W$$
$$\Delta U = Q - W = 500\ J - 400\ J = \underline{100\ J}$$

✓

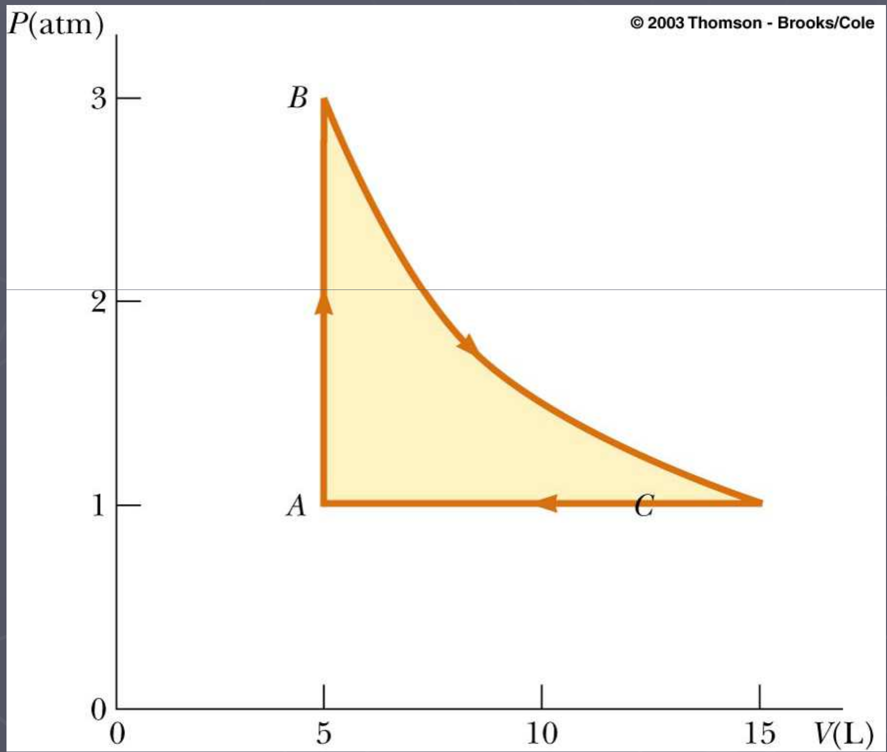
What if volume is kept constant?

Applications of the First Law – 2. Cyclic Processes

- A cyclic process is one in which the process originates and ends at the same state
  - $U_f = U_i$ and $Q = -W$
- The net work done per cycle by the gas is equal to the area enclosed by the path representing the process on a PV diagram

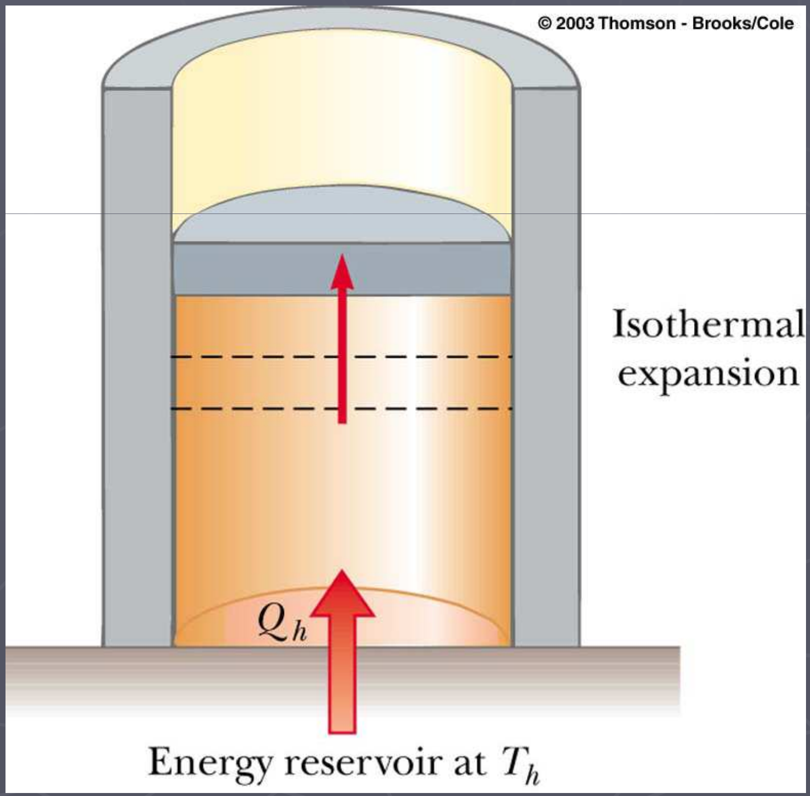
Cyclic Process in a PV Diagram

- This is an ideal monatomic gas confined in a cylinder by a moveable piston
- A to B is an isovolumetric process which increases the pressure
- B to C is an isothermal expansion and lowers the pressure
- C to A is an isobaric compression
- The gas returns to its original state at point A



Applications of the First Law – 3. Isothermal Processes

- Isothermal means constant temperature
- The cylinder and gas are in thermal contact with a large source of energy
- Allow the energy to transfer into the gas (by heat)
- The gas expands and pressure falls to maintain a constant temperature
- The work done is the negative of the heat added



Applications of the First Law – 4. Adiabatic Process

- Energy transferred by heat is zero
- The work done is equal to the change in the internal energy of the system
- One way to accomplish a process with no heat exchange is to have it happen very quickly
- In an adiabatic expansion, the work done is negative and the internal energy decreases

Applications of the First Law – 5. Isovolumetric Process

- No change in volume, therefore no work is done
- The energy added to the system goes into increasing the internal energy of the system
  - Temperature will increase

Additional Notes About the First Law

- The First Law is a general equation of Conservation of Energy
- There is no practical, macroscopic, distinction between the results of energy transfer by heat and by work
- Q and W are related to the properties of state for a system

The First Law and Human Metabolism

- The First Law can be applied to living organisms
- The internal energy stored in humans goes into other forms needed by the organs and into work and heat
- The *metabolic rate* (ΔU / ΔT) is directly proportional to the rate of oxygen consumption by volume
  - Basal metabolic rate (to maintain and run organs, etc.) is about 80 W

Various Metabolic Rates

TABLE 12.1 **Oxygen Consumption and Metabolic Rates for Various Activities for a 65-kg Male**[a]

Activity	O_2 use rate (mL/min · kg)	Metabolic rate (kcal/h)	Metabolic rate (W)
Sleeping	3.5	70	80
Light activity (dressing, slow walking, desk work)	10	200	230
Moderate activity (walking briskly)	20	400	465
Heavy activity (basketball, (fast breast stroke)	30	600	700
Extreme activity (bicycle racing)	70	1 400	1 600

[a] Source: *A Companion to Medical Studies*, 2/e, R. Passmore, Philadelphia, F. A. Davis, 1968.

Fig. T12.1, p. 369

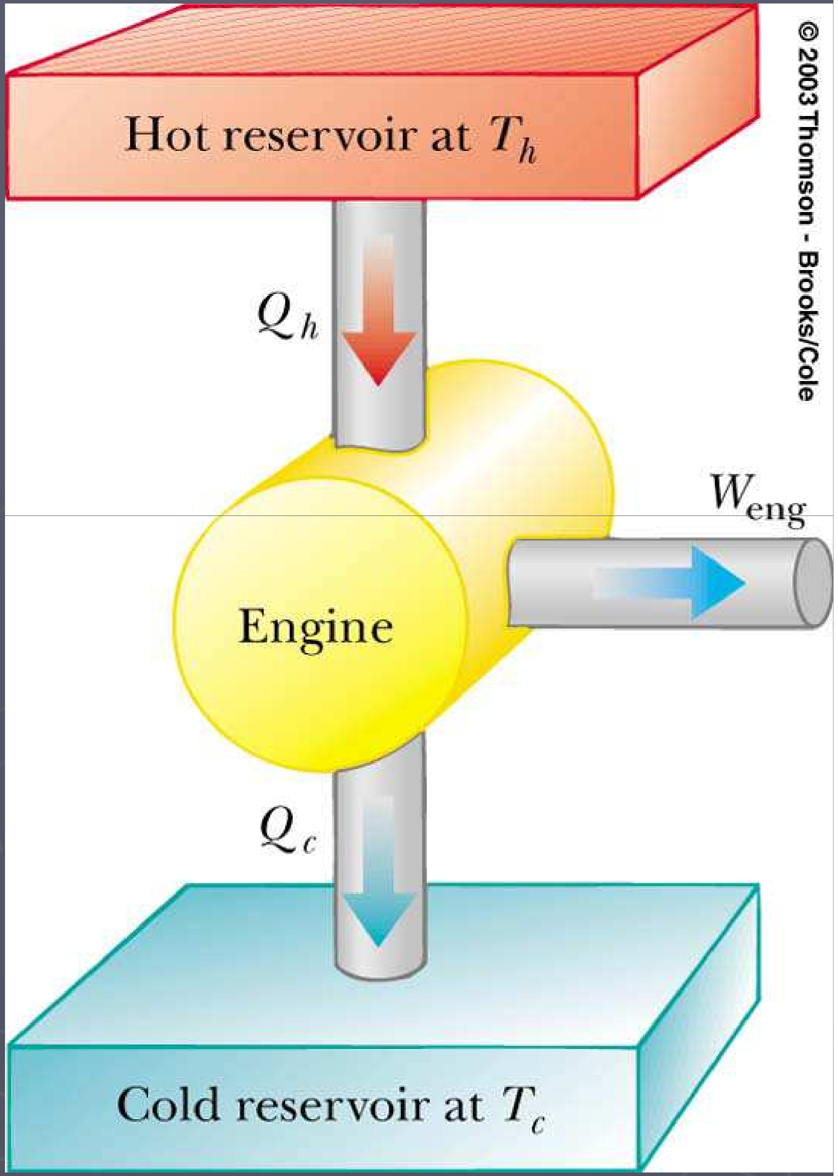
Heat Engine

- A *heat engine* is a device that converts internal energy to other useful forms, such as electrical or mechanical energy
- A heat engine carries some working substance through a cyclical process

Let’s watch the movie!

Heat Engine

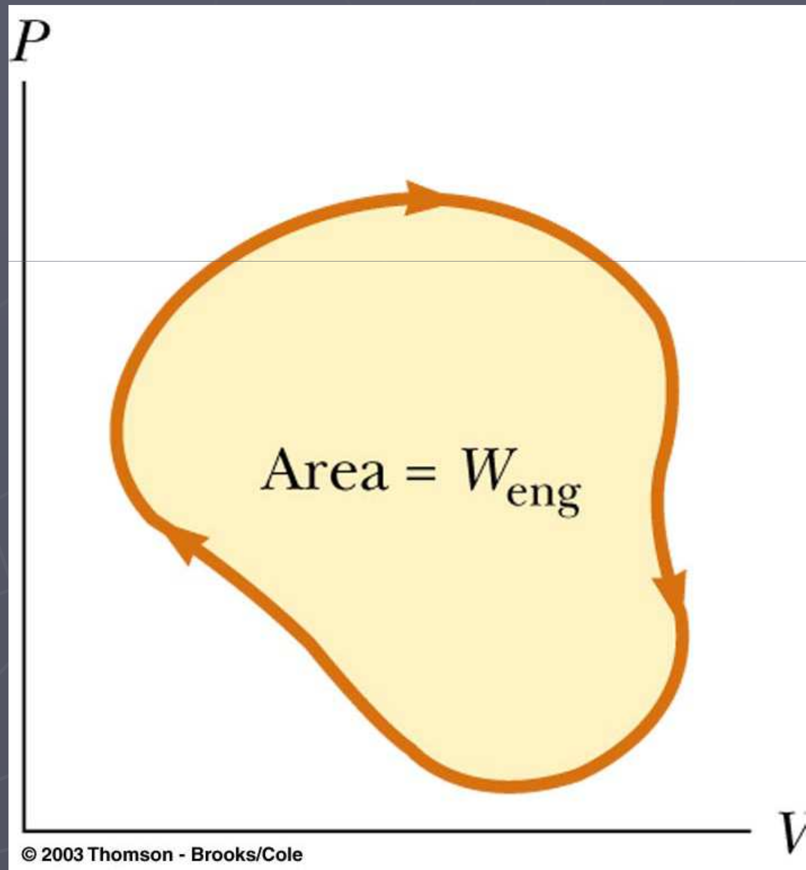
- Energy is transferred from a source at a high temperature (Q_h)
- Work is done by the engine (W_{eng})
- Energy is expelled to a source at a lower temperature (Q_c)



Let’s watch the movie!

Heat Engine

- Since it is a cyclical process, $\Delta U = 0$
  - Its initial and final internal energies are the same
- Therefore, $Q_{net} = W_{eng}$
- The work done by the engine equals the net energy absorbed by the engine
- The work is equal to the area enclosed by the curve of the PV diagram



Thermal Efficiency of a Heat Engine

- Thermal efficiency is defined as the ratio of the work done by the engine to the energy absorbed at the higher temperature

$$e = \frac{W_{eng}}{|Q_h|} = \frac{|Q_h| - |Q_c|}{|Q_h|} = 1 - \frac{|Q_c|}{|Q_h|}$$

- e = 1 (100% efficiency) only if $Q_c = 0$
  - No energy expelled to cold reservoir

Second Law of Thermodynamics

- It is impossible to construct a heat engine that, operating in a cycle, produces no other effect than the absorption of energy from a reservoir and the performance of an equal amount of work
  - Means that Q_c cannot equal 0
    - Some Q_c must be expelled to the environment
  - Means that e cannot equal 100%

Heat Pumps and Refrigerators

- Heat engines can run in reverse
  - Send in energy
  - Energy is extracted from the cold reservoir
  - Energy is transferred to the hot reservoir
- This process means the heat engine is running as a heat pump
  - A refrigerator is a common type of heat pump
  - An air conditioner is another example of a heat pump

Summary of the First and Second Laws

- First Law
  - We cannot get a greater amount of energy out of a cyclic process than we put in
- Second Law
  - We cannot break even

Reversible and Irreversible Processes

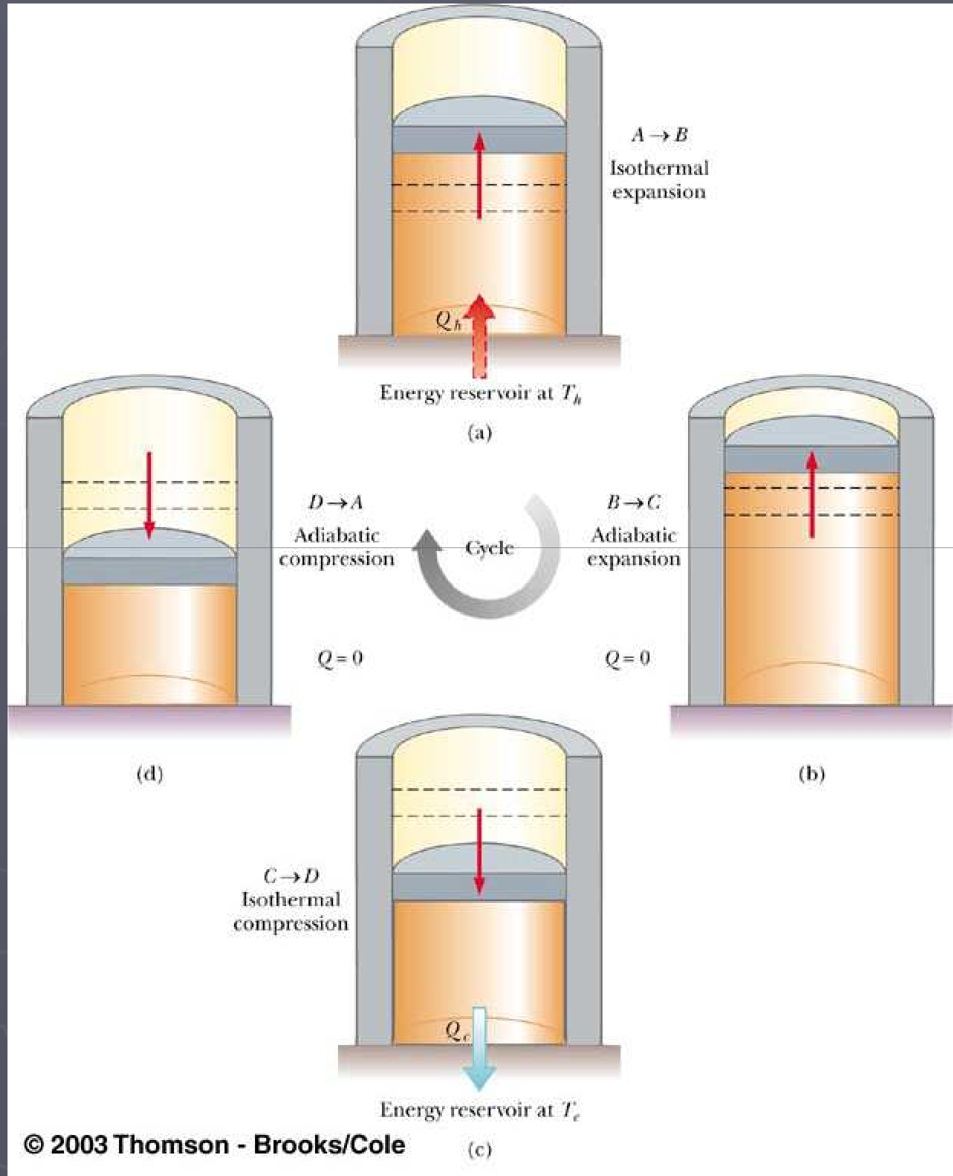
- A *reversible* process is one in which every state along some path is an equilibrium state
  - And one for which the system can be returned to its initial state along the same path
- An *irreversible* process does not meet these requirements
  - Most natural processes are irreversible
  - Reversible process are an idealization, but some real processes are good approximations

Carnot Engine

- A theoretical engine developed by Sadi Carnot
- A heat engine operating in an ideal, reversible cycle (now called a *Carnot Cycle*) between two reservoirs is the most efficient engine possible
- *Carnot's Theorem*: No real engine operating between two energy reservoirs can be more efficient than a Carnot engine operating between the same two reservoirs

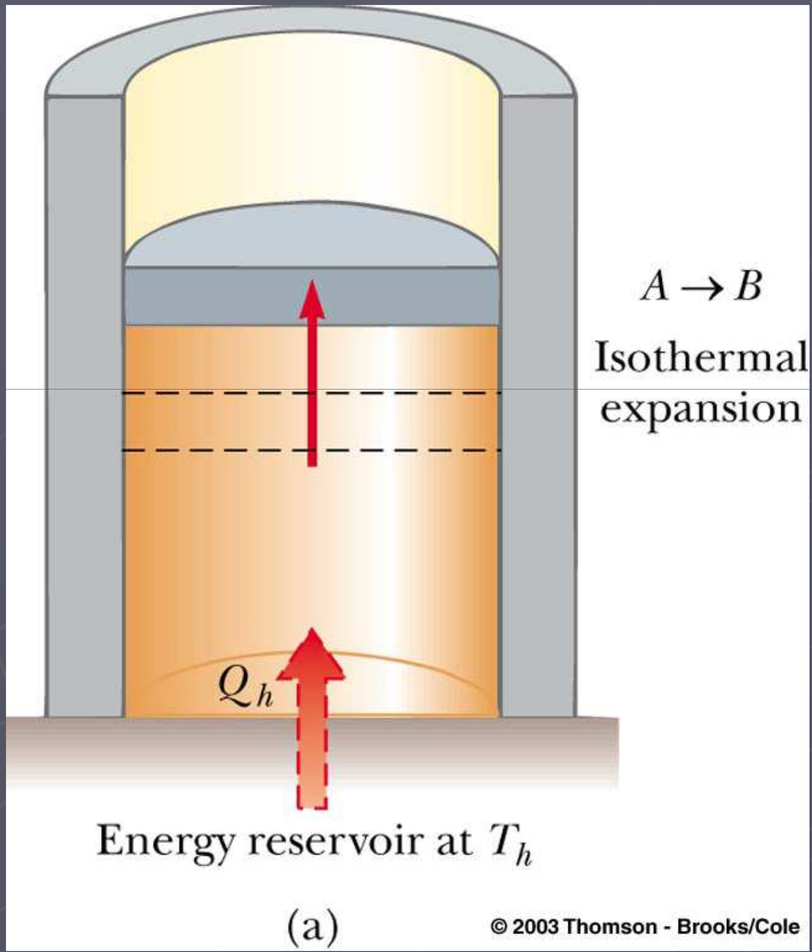
Carnot Cycle

Let's watch the movie!



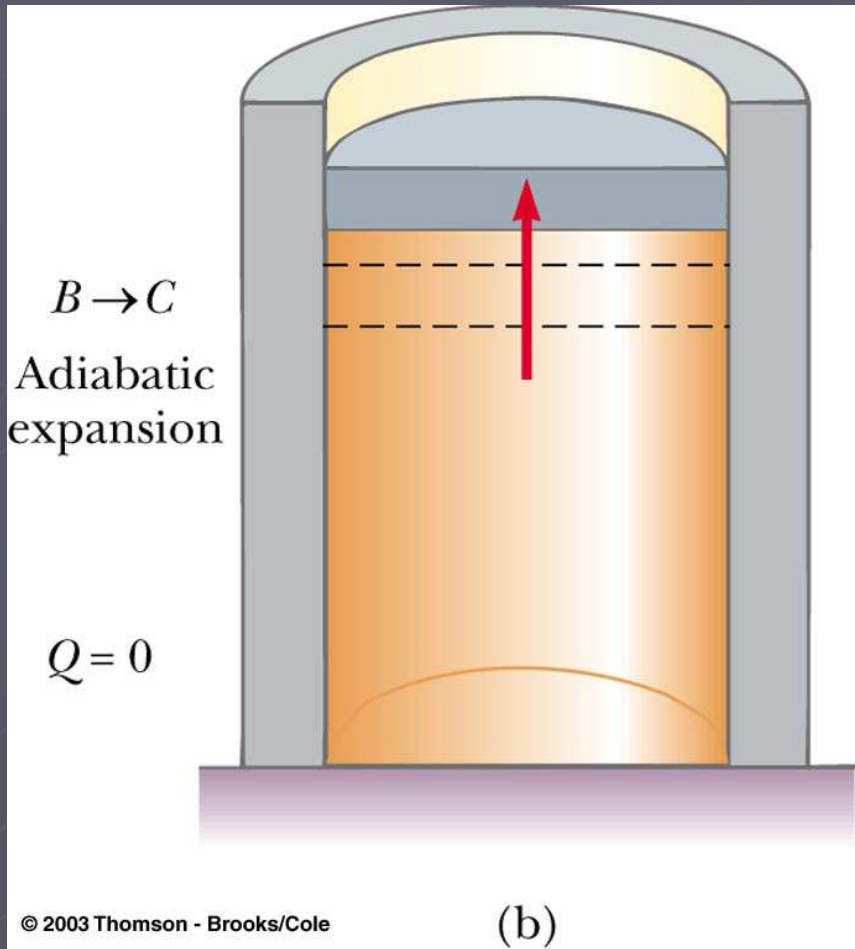
Carnot Cycle, A to B

- A to B is an isothermal expansion
- The gas is placed in contact with the high temperature reservoir
- The gas absorbs heat Q_h
- The gas does work W_{AB} in raising the piston



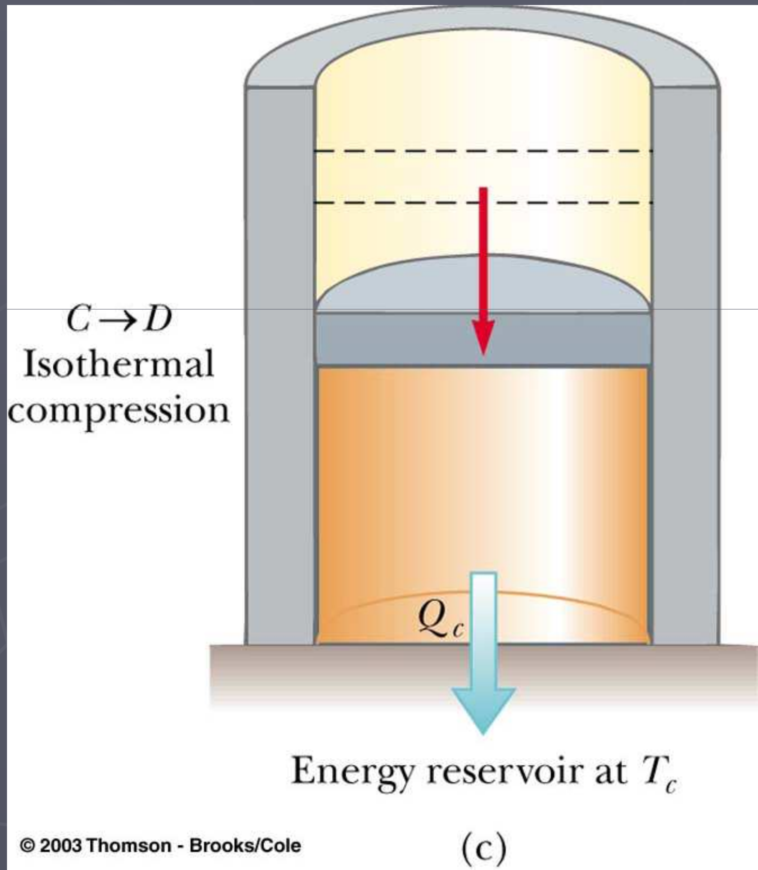
Carnot Cycle, B to C

- B to C is an adiabatic expansion
- The base of the cylinder is replaced by a thermally nonconducting wall
- No heat enters or leaves the system
- The temperature falls from T_h to T_c
- The gas does work W_{BC}



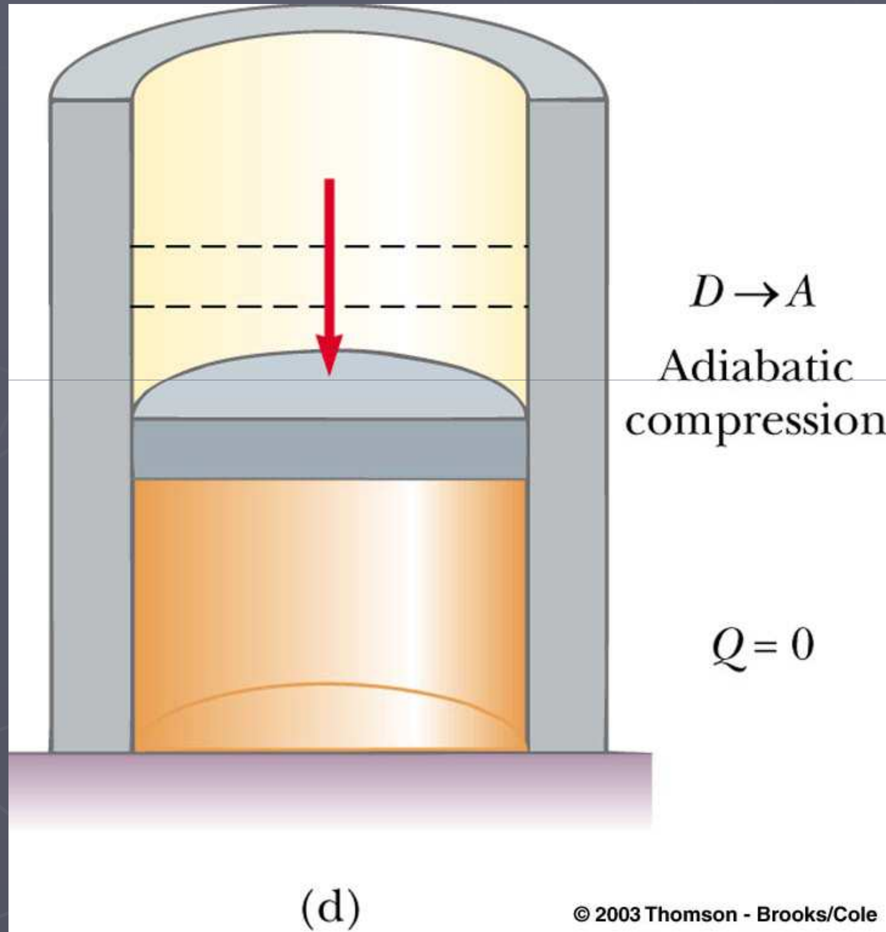
Carnot Cycle, C to D

- The gas is placed in contact with the cold temperature reservoir
- C to D is an isothermal compression
- The gas expels energy Q_C
- Work W_{CD} is done on the gas



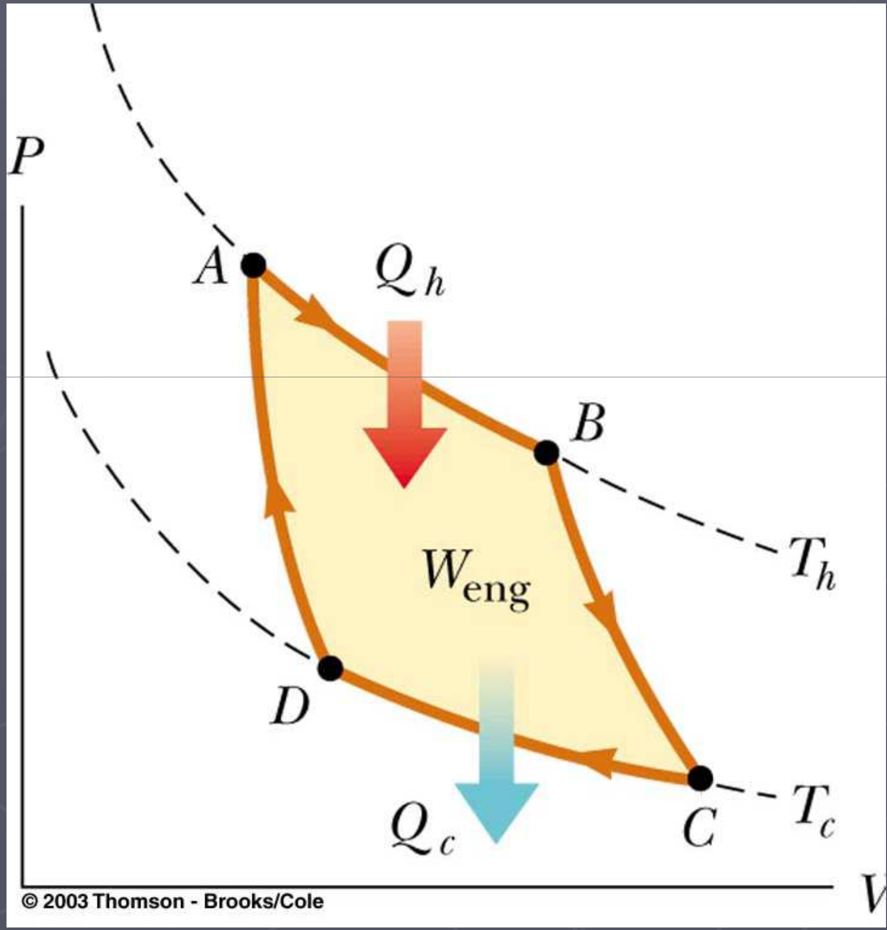
Carnot Cycle, D to A

- D to A is an adiabatic compression
- The gas is again placed against a thermally nonconducting wall
  - So no heat is exchanged with the surroundings
- The temperature of the gas increases from T_C to T_h
- The work done on the gas is W_{CD}



Carnot Cycle, PV Diagram

- The work done by the engine is shown by the area enclosed by the curve
- The net work is equal to $Q_h - Q_c$



Efficiency of a Carnot Engine

- Carnot showed that the efficiency of the engine depends on the temperatures of the reservoirs

$$e_c = 1 - \frac{T_C}{T_h}$$

- Temperatures must be in Kelvins
- All Carnot engines operating between the same two temperatures will have the same efficiency

Notes About Carnot Efficiency

- Efficiency is 0 if $T_h = T_c$
- Efficiency is 100% only if $T_c = 0$ K
  - Such reservoirs are not available
- The efficiency increases at T_c is lowered and as T_h is raised
- In most practical cases, T_c is near room temperature, 300 K
  - So generally T_h is raised to increase efficiency

Real Engines Compared to Carnot Engines

- All real engines are less efficient than the Carnot engine
  - Real engines are irreversible because of friction
  - Real engines are irreversible because they complete cycles in short amounts of time

Entropy

- A state variable related to the Second Law of Thermodynamics, the entropy
- The change in entropy, ΔS, between two equilibrium states is given by the energy, Q_r, transferred along the reversible path divided by the absolute temperature, T, of the system in this interval

Entropy

- Mathematically, $\Delta S = \frac{Q_r}{T}$
- This applies only to the reversible path, even if the system actually follows an irreversible path
  - To calculate the entropy for an irreversible process, model it as a reversible process
- When energy is absorbed, Q is positive and entropy increases
- When energy is expelled, Q is negative and entropy decreases

More About Entropy

- Note, the equation defines the *change in entropy*
- The entropy of the Universe increases in all natural processes
  - This is another way of expressing the Second Law of Thermodynamics
- There are processes in which the entropy of a system decreases
  - If the entropy of one system, A, decreases it will be accompanied by the increase of entropy of another system, B.
  - The change in entropy in system B will be greater than that of system A.

Perpetual Motion Machines

- A perpetual motion machine would operate continuously without input of energy and without any net increase in entropy
- Perpetual motion machines of the first type would violate the First Law, giving out more energy than was put into the machine
- Perpetual motion machines of the second type would violate the Second Law, possibly by no exhaust
- Perpetual motion machines will never be invented

Entropy and Disorder

- Entropy can be described in terms of disorder
- A disorderly arrangement is much more probable than an orderly one if the laws of nature are allowed to act without interference
  - This comes from a statistical mechanics development

Let’s watch the movie!

Entropy and Disorder, cont.

- Isolated systems tend toward greater disorder, and entropy is a measure of that disorder
  - $S = k_B \ln W$
    - k_B is Boltzmann's constant
    - W is a number proportional to the probability that the system has a particular configuration
- This gives the Second Law as a statement of what is most probably rather than what must be
- The Second Law also defines the direction of time of all events as the direction in which the entropy of the universe increases

Heat Death of the Universe

- The entropy of the Universe always increases
- The entropy of the Universe should ultimately reach a maximum
  - At this time, the Universe will be at a state of uniform temperature and density
  - This state of perfect disorder implies no energy will be available for doing work
- This state is called the *heat death* of the Universe