Thermodynamics
Heat & Work
The First Law of Thermodynamics

Lana Sheridan

De Anza College

April 26, 2018

Last time

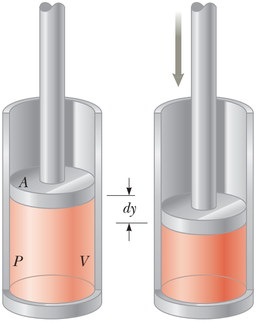
- more about phase changes
- work, heat, and the first law of thermodynamics

Overview

- P-V diagrams
- applying the first law in various cases

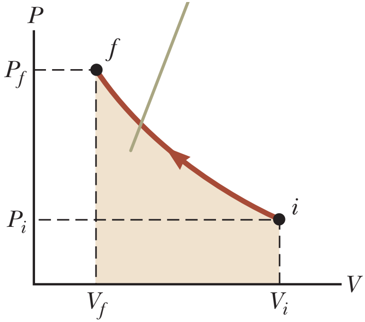
Work done on a gas

Here, the volume decreases, so the work done on the gas is positive.



$$W = -\int_{V_i}^{V_f} P \, \mathrm{dV}$$

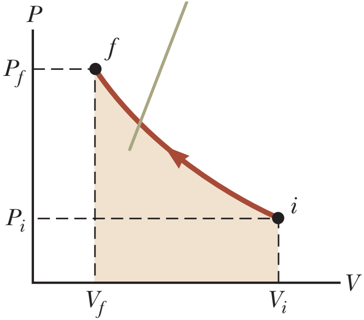
The work done is the area under the P-V curve (with the appropriate sign).



Aside: P-V Diagrams

P-V diagrams are *very* useful in thermodynamics.

Example of a P-V diagram:



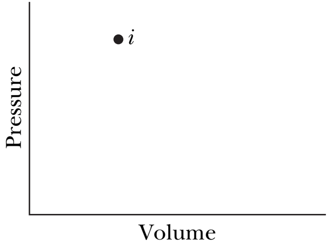
They are graphs of pressure vs volume for a fixed quantity (n moles) of an ideal gas.

They contain a lot of information.

[1]Figure form Serway & Jewett, 9th ed, page 602.

Aside: P-V Diagrams

Example of a P-V diagram:



These diagrams

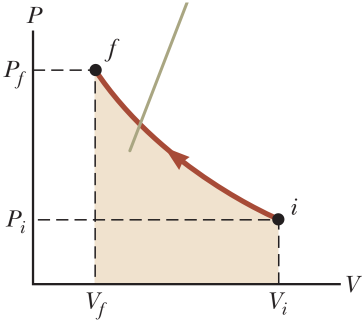
- represent the (thermodynamic) **equilibrium states** of the ideal gas sample,
- each point is a state,
- imply the temperature of a known sample, and
- show the internal energy of the gas. ($E_{\text{int}} \propto T$)

$$PV = nRT$$

[1] Figure (modified) from Halliday, Resnick, and Walker, page 537.

Aside: P-V Diagrams

Example of a P-V diagram:



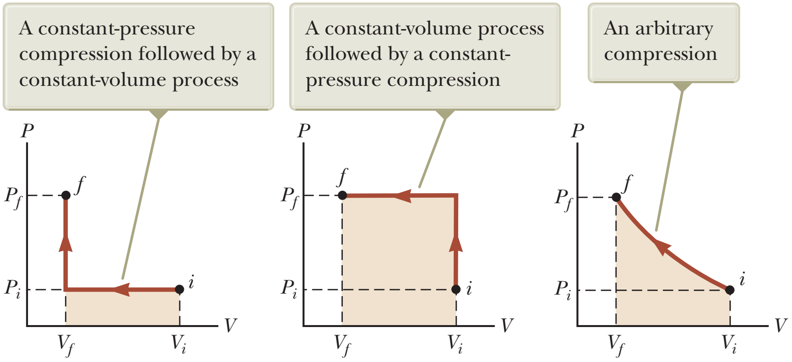
When these diagrams include a path, they

- show reversible processes, eg. compression of gas,
- show all the intermediate thermal states passed through,
- show the work done on the gas,
- indicate the heat transferred to the gas.

$$\Delta E_{\text{int}} = W + Q$$

Work done depends on the process

Different paths or processes to go from (V_i, P_i) to (V_f, P_f) require different amounts of work.

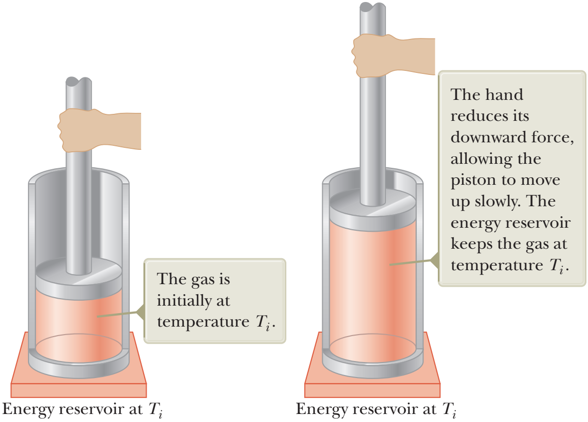


In all of the processes shown above, there are temperature changes during the process.

[1]Figure form Serway & Jewett.

Heat transfer also depends on the process

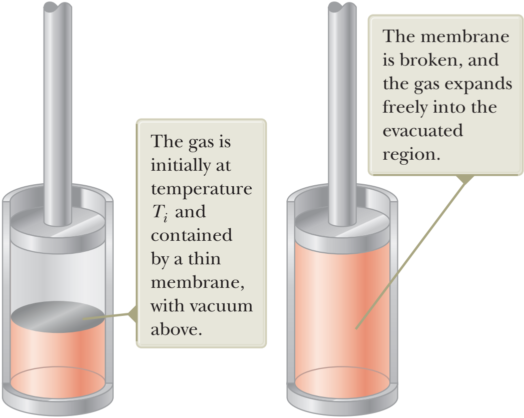
This process (shown) happens at constant temperature:



Heat Q is transferred to the gas, and the gas does positive work on its surroundings. (Equivalently, negative work is done on the gas.)

Heat transfer also depends on the process

This process also happens at constant temperature, and has the same start and end points, (V_i, P_i) to (V_f, P_f):



No heat is transferred to the gas, and the gas does no work.

(We cannot represent the path for this process on a P-V diagram.)

First Law of Thermodynamics

Reminder:

Internal energy, E_{int} or U

The energy that a system has as a result of its temperature and all other molecular motions, effects, and configurations, when viewed from a reference frame at rest with respect to the center of mass of the system.

1st Law

The change in the internal energy of a system is equal to the sum of the heat added to the system and the work done on the system.

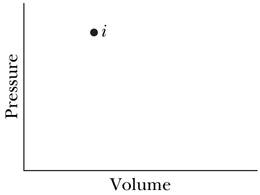
$$\Delta E_{\text{int}} = W + Q$$

This is just the conservation of energy assuming only the internal energy changes.

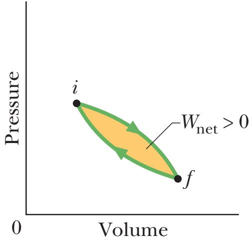
Applying the 1st Law

Some special cases of interest:

- for an isolated system,
  $W = Q = 0 \Rightarrow \Delta E_{\text{int}} = 0$

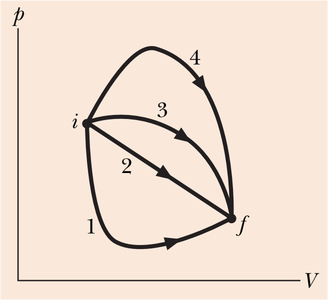


- for a process (V_i, P_i) to (V_i, P_i),
  a **cycle**, $\Delta E_{\text{int}} = 0 \Rightarrow Q = -W$



Applying the 1st Law & P-V diagrams questions

The figure shows four paths on a p-V diagram along which a gas can be taken from state i to state f. Rank the paths, greatest to least, according to
(a) the change ΔE_{int} in the internal energy of the gas,



A 1, 2, 3, 4

B 4, 3, 2, 1

C 1, 4, 3, 2

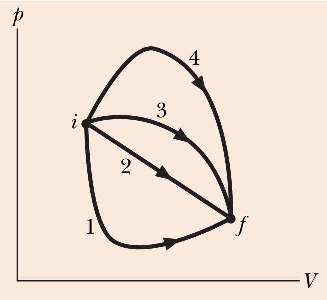
D all the same

[1] Based on question from Halliday, Resnick, and Walker, page 491.

Applying the 1st Law & P-V diagrams questions

The figure shows four paths on a p-V diagram along which a gas can be taken from state i to state f. Rank the paths, greatest to least, according to

(a) the change ΔE_{int} in the internal energy of the gas,



A 1, 2, 3, 4

B 4, 3, 2, 1

C 1, 4, 3, 2

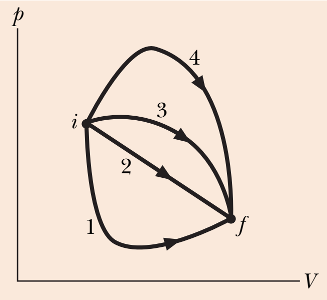
D all the same ←

[1] Based on question from Halliday, Resnick, and Walker, page 491.

Applying the 1st Law & P-V diagrams questions

The figure shows four paths on a p-V diagram along which a gas can be taken from state i to state f. Rank the paths, greatest to least, according to

(b) the work W done **on** the gas,



A 1, 2, 3, 4

B 4, 3, 2, 1

C 1, 4, 3, 2

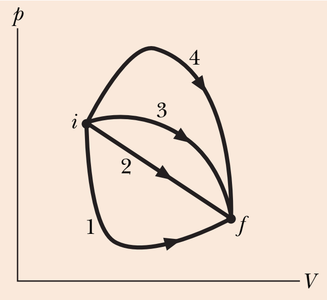
D all the same

[1] Based on question from Halliday, Resnick, and Walker, page 491.

Applying the 1st Law & P-V diagrams questions

The figure shows four paths on a p-V diagram along which a gas can be taken from state i to state f. Rank the paths, greatest to least, according to

(b) the work W done **on** the gas, W is negative for them all.



A 1, 2, 3, 4 ←

B 4, 3, 2, 1

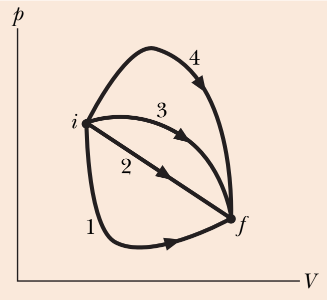
C 1, 4, 3, 2

D all the same

[1] Based on question from Halliday, Resnick, and Walker, page 491.

Applying the 1st Law & P-V diagrams questions

The figure shows four paths on a p-V diagram along which a gas can be taken from state i to state f. Rank the paths, greatest to least, according to
(c) the energy transferred **to** the gas as heat Q.



A 1, 2, 3, 4

B 4, 3, 2, 1

C 1, 4, 3, 2

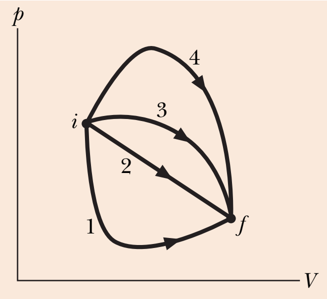
D all the same

[1] Based on question from Halliday, Resnick, and Walker, page 491.

Applying the 1st Law & P-V diagrams questions

The figure shows four paths on a p-V diagram along which a gas can be taken from state i to state f. Rank the paths, greatest to least, according to

(c) the energy transferred **to** the gas as heat Q.



A 1, 2, 3, 4

B 4, 3, 2, 1 ←

C 1, 4, 3, 2

D all the same

[1] Based on question from Halliday, Resnick, and Walker, page 491.

Applying the 1st Law: new Vocabulary

There are infinitely many paths (V_i, P_i) to (V_f, P_f) that we might consider.

Ones that are of particular interest for modeling systems in engines, *etc.* are processes that keep one of the variables constant.

There is a technical name for each kind of process that keeps a variable constant.

Applying the 1st Law: new Vocabulary

Adiabatic process

is a process where no heat is transferred into or out of the system.

$$Q = 0$$

This type of transformation occurs when the gas is in a thermally insulated container, or the process is very rapid, so there is no time for heat transfer.

Since $Q = 0$:

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

Applying the 1st Law: new Vocabulary

Isobaric process

is a process that occurs at constant pressure.

$$P_i = P = P_f$$

This type of transformation occurs when the gas is free to expand or contract by coming into force equilibrium with a constant external environmental pressure.

In this case, the expression for work simplifies:

$$W = -\int_{V_i}^{V_f} P\,\mathrm{dV} = -P(V_f - V_i)$$

Applying the 1st Law: new Vocabulary

Isovolumetric process

is a process that occurs at constant volume.

$$V_i = V = V_f$$

In an isovolumetric process the work done is zero, since the volume never changes.

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

(An isovolumetric process can also be called an "isochoric process".)

Applying the 1st Law: new Vocabulary

Isothermal process

is a process that occurs at constant temperature.

$$T_i = T = T_f$$

This kind of transformation is achieved by putting the system in thermal contact with a large constant-temperature reservoir.

In an isothermal process, assuming no change of phase (staying an ideal gas!):

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

Isothermal Expansion of an Ideal Gas

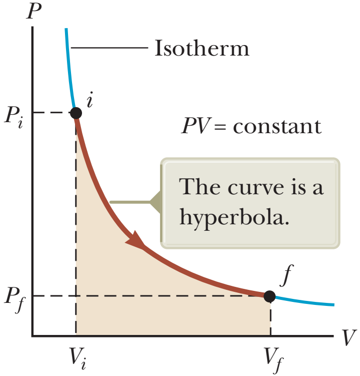
Since $\Delta T = 0$, $PV = nRT$ reduces to:

$$PV = a$$

where a is a constant. We could also write this as:

$$P = \frac{a}{V}$$

Plotting this function:



Isothermal Expansion of an Ideal Gas

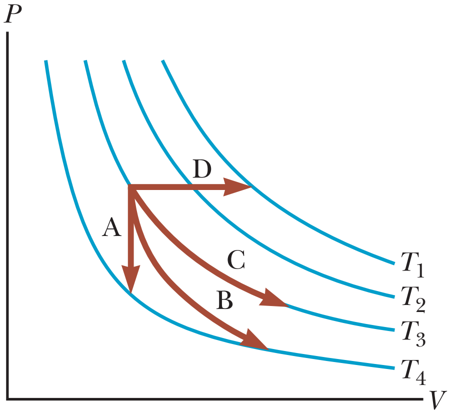
Since nRT is constant, the work done on the gas in an isothermal expansion is:

$$\begin{aligned} W &= -\int_{V_i}^{V_f} P \, \mathrm{dV} \\ &= -\int_{V_i}^{V_f} \frac{nRT}{V} \, \mathrm{dV} \\ &= -nRT \ln\left(\frac{V_f}{V_i}\right) \end{aligned}$$

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

Questions

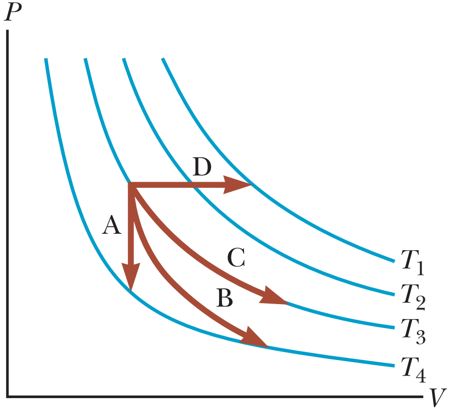
Which path is isobaric?



[1]Based on Quick Quiz 20.4, Serway & Jewett, page 606.

Questions

Which path is isobaric?[1]

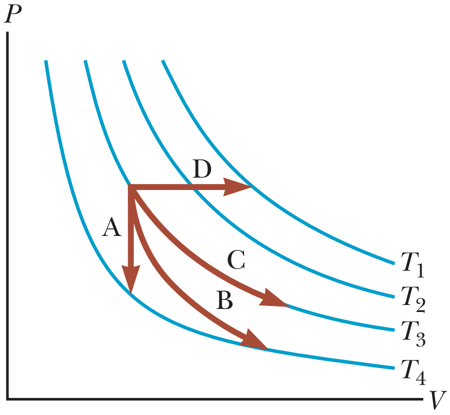


Path D.

[1]Based on Quick Quiz 20.4, Serway & Jewett, page 606.

Questions

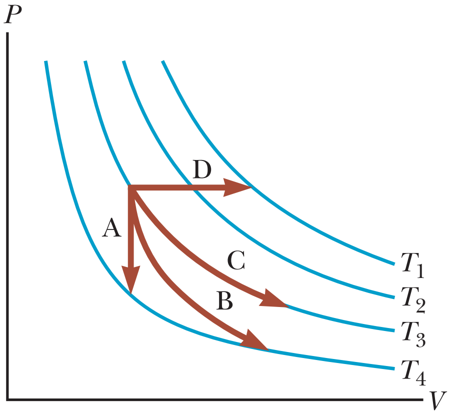
Which path is isothermal?



[1]Based on Quick Quiz 20.4, Serway & Jewett, page 606.

Questions

Which path is isothermal?[1]

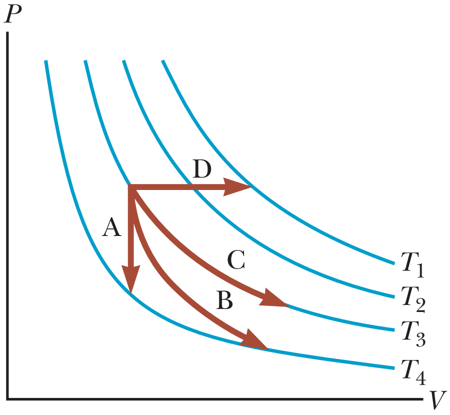


Path C.

[1]Based on Quick Quiz 20.4, Serway & Jewett, page 606.

Questions

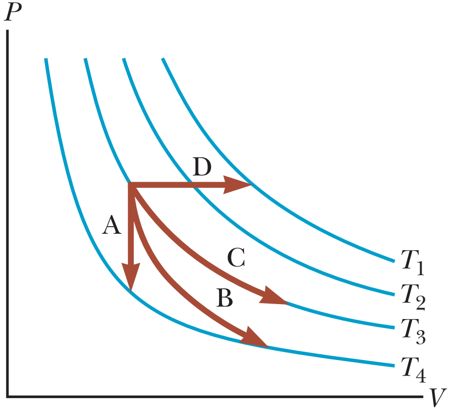
Which path is isovolumetric?



[1]Based on Quick Quiz 20.4, Serway & Jewett, page 606.

Questions

Which path is isovolumetric?[1]

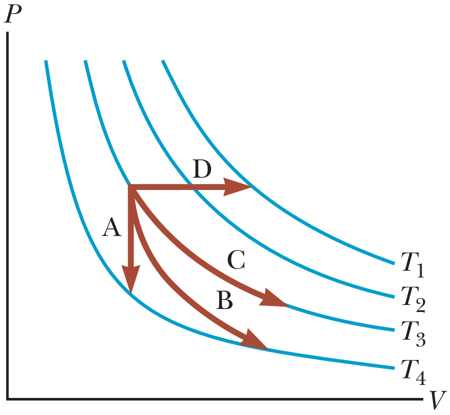


Path A.

[1] Based on Quick Quiz 20.4, Serway & Jewett, page 606.

Questions

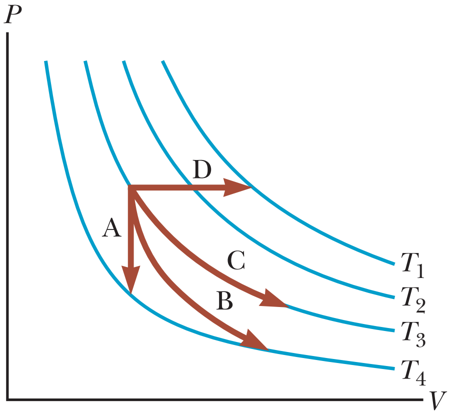
Which path is adiabatic?



[1]Based on Quick Quiz 20.4, Serway & Jewett, page 606.

Questions

Which path is adiabatic?[1]



Path B.

[1] Based on Quick Quiz 20.4, Serway & Jewett, page 606.

Example 20.6: Boiling water

This example illustrates how we can apply these ideas to liquids and solids also, and even around phase changes, as long as we are careful.

Suppose 1.00 g of water vaporizes isobarically at atmospheric pressure (1.013×10^5 Pa).

Its volume in the liquid state is $V_i = V_{\text{liq}} = 1.00 \text{ cm}^3$, and its volume in the vapor state is $V_f = V_{\text{vap}} = 1671 \text{ cm}^3$.

Find the work done in the expansion and the change in internal energy of the system. Ignore any mixing of the steam and the surrounding air; imagine that the steam simply pushes the surrounding air out of the way.

Example 20.6: Boiling water

$V_i = V_{\text{liq}} = 1.00 \text{ cm}^3$
$V_f = V_{\text{vap}} = 1671 \text{ cm}^3$
$L_v = 2.26 \times 10^6 \text{ J/kg}$

Work done,

Example 20.6: Boiling water

$V_i = V_{\text{liq}} = 1.00\ \text{cm}^3$
$V_f = V_{\text{vap}} = 1671\ \text{cm}^3$
$L_v = 2.26 \times 10^6\ \text{J/kg}$

Work done,

$$\begin{aligned} W &= -P(V_f - V_i) \\ &= -(1.013 \times 10^5\ \text{Pa})(1671 - 1.00) \times 10^{-6}\ \text{m}^3 \\ &= -169\ \text{J} \end{aligned}$$

Internal energy, ΔE_{int}?

Example 20.6: Boiling water

$V_i = V_{\text{liq}} = 1.00\ \text{cm}^3$
$V_f = V_{\text{vap}} = 1671\ \text{cm}^3$
$L_v = 2.26 \times 10^6\ \text{J/kg}$

Work done,

$$\begin{aligned} W &= -P(V_f - V_i) \\ &= -(1.013 \times 10^5\ \text{Pa})(1671 - 1.00) \times 10^{-6}\ \text{m}^3 \\ &= -169\ \text{J} \end{aligned}$$

Internal energy, ΔE_{int}? Know W, must find Q:

$$\begin{aligned} Q &= L_v m \\ &= (2.26 \times 10^6\ \text{J/kg})(1^{-3}\ \text{kg}) \\ &= 2260\ \text{J} \end{aligned}$$

So,

$$\Delta E_{\text{int}} = W + Q = 2.09\ \text{kJ}$$

Summary

- P-V diagrams
- applying the first law in various cases

Quiz in class Monday, April 30.

Homework Serway & Jewett:

- Read chapter 20 and look at the examples.
- prev: Ch 20, OQs: 1, 13; Probs: 25, 27, 29, 31, 35, 39, 41, 59