Physical Chemistry
for Energy Engineering
(3rd: 2018/09/10)

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*The class follows the text book: D.A. McQuarrie, J.D. Simon, “Physical Chemistry: A Molecular Approach", University Science Books (1997).

Course schedule (tentative)

Lecture #	Date	Contents
1	3-Sep	Introduction
2	5-Sep	1. Thermodynamics: Basic concepts of thermodynamics
3	10-Sep	1. Thermodynamics: The first law of thermodynamics
4	12-Sep	1. Thermodynamics: Thermodynamic process and cycle
5	17-Sep	1. Thermodynamics: The second and third laws of thermodynamics-1
6	19-Sep	1. Thermodynamics: The second and third laws of thermodynamics-2
	24-Sep	No lecture (holiday)
	26-Sep	No lecture (holiday)
7	1-Oct	1. Equation of state of gas
	3-Oct	No lecture (holiday)
8	8-Oct	Answer of homework-1
9	10-Oct	Exam-01 (2 hour)
10	15-Oct	2. Introduction to equilibrium theory
11	17-Oct	2. Free energy-1
12	22-Oct	2. Free energy-2
13	24-Oct	2. Calculation of thermodynamic quantities
	29-Oct	No lecture
	31-Oct	

Contents of today

<Last class>

1.1.1. Basics of thermodynamics

1.1.2. The first law of thermodynamics

<Today's class>

1.1.2. The first law of thermodynamics

1.2.1. Thermodynamic process

1.2.2. Thermodynamic cycle

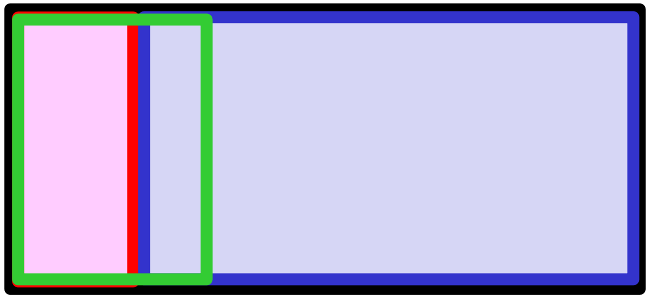
Review of the last class
-quasi-static/reversible/irreversible process>

< Definition of quasi-static process (in this course, we use definition (1)!) >

1) Very (infinitesimally) slow process so that we consider the system is always at some equilibrium state.
2) Very (infinitesimally) slow process and the process takes place with adhering the system to some equilibrium state and keeping concerned thermodynamic quantities of the system and the surroundings equal.
   >> for this definition, “quasi-static” is equivalent with “reversible”
   >> In this course, this is the definition of reversible process.

[Definition-1]

All processes



Reversible
Irreversible
Quasi-static

[Definition-2]

All processes

- ✓ Any process is rev. or irrev.
- ✓ Any rev. process is quasi-static.
- ✓ Some irrev. process is quasi-static.

- ✓ Any process is rev. or irrev.
- ✓ Rev. process = quasi-static process.
- ✓ No irrev. process is quasi-static.

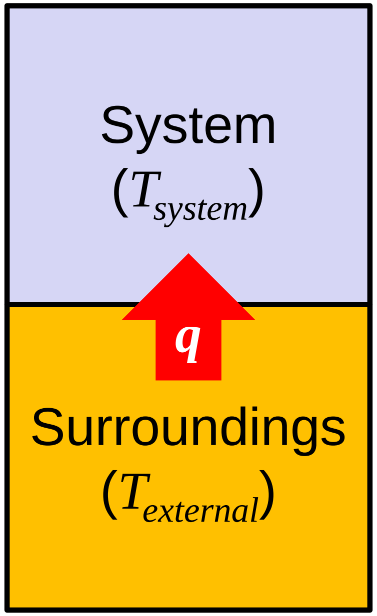
Review

- two energy transfer ways: heat & work -

- ✓ Heat (q) is a way of energy transfer that occurs due to a difference in temperature b/w two systems (or b/w the system and the surroundings).
- ✓ Work (w) is a way of energy transfer that occurs due to an un-balance in force/pressure b/w two systems (or b/w the system and the surroundings).

*The unit of q and w is the same with the unit of energy (e.g. [J]).

<How energy transfer as "heat" occurs ?>



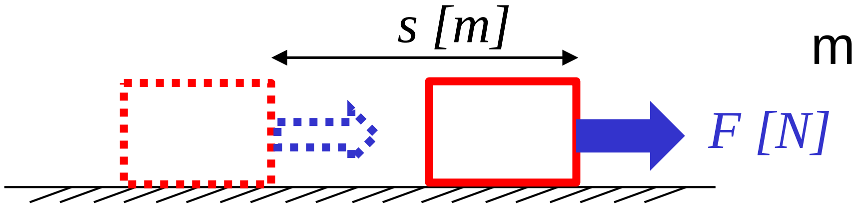
- ✓ If the temperature of a system is different from that of the surroundings, some energy can be transferred b/w the system and the surroundings.
- ✓ Energy is always transferred from a higher-temperature side to a lower-temperature side.
  - ➢ If $T_{external} > T_{system}$, $q > 0$. It means system energy is increased.
  - ➢ If $T_{system} > T_{external}$, $q < 0$. It means system energy is decreased.
  - ➢ If $T_{system} = T_{external}$, $q = 0$. It means no energy transfer as heat.

1.1.2. The First Law of Thermodynamics ($19.1)

- A typical work in thermodynamics: Pressure-Volume work-

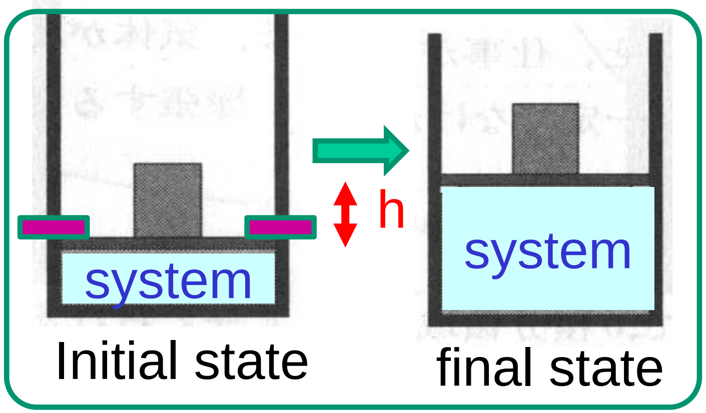
<How energy transfer as “work” occurs?>

(c.f.) Work in classical mechanics



The work (W $[J]$) needed to move the object (over s) is:

$$W = Fs$$



M: the mass of the weight [kg]
g: the gravitational acceleration (9.8 $[m/s^s]$)
h: the change in the height [m]
A: the area of the bottom plane of piston $[m^2]$
$P_{external}$: the pressure of the surroundings
*the surroundings is “piston + weight”

$$w = -Fs = -(Mg)h$$

as in classical mechanics (s is displacement)

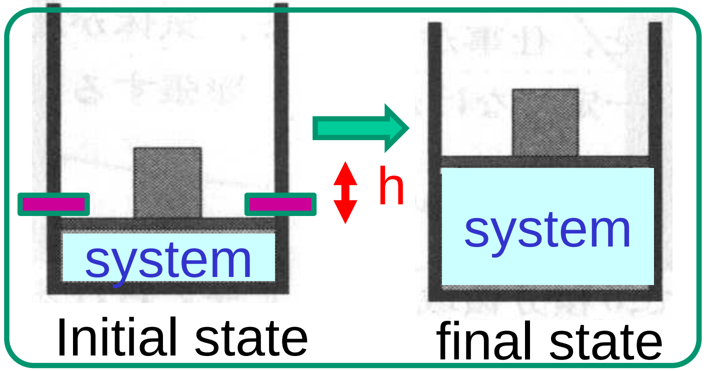
$$= -\frac{Mg}{A} \times Ah$$

$$= -P_{external}\Delta V$$

as "Ah" corresponds to volume change (ΔV)

*Regarding the unit: $[N/m^2]$ $[m^2\ m]$ = [Pa] $[m^3]$

(exercise)



M: the mass of the weight [kg]
g: the gravitational acceleration (9.8 $[\mathrm{m/s^s}]$)
h: the change in the height [m]
A: the area of the bottom plane of piston $[\mathrm{m^2}]$
$P_{external}$: the pressure of the surroundings

Let's apply : $M = 10$ kg, $h = 0.10$ m, $A = 1.0\ \mathrm{m^2}$

---

(1) How much work did the system make to the surroundings?

$$-w = -(-P_{external}\Delta V)$$

$$P_{external} = \frac{Mg}{A} = \frac{10\times 9.8}{1.0} = 98\ [\mathrm{Pa}]$$

$$\Delta V = Ah = 1.0 \times 0.10 = 0.10\ [\mathrm{m^3}]$$

$$-w = -(-P_{external}\Delta V) = 98 \times 0.10 = 9.8\ [\mathrm{J}]$$

(2) How much energy did the surroundings obtain by lifting up the weigh?

- ✓ By this, the potential energy of surroundings (piston + weight) is increased as: $\Delta U_{surroundings} = Mgh = 10 \times 9.8 \times 0.10 = 9.8\ [\mathrm{J}]$

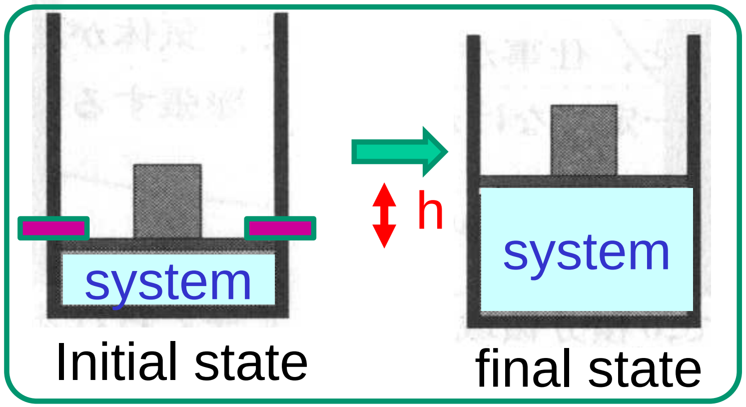
So, in this process, the energy loss of the system is equal to the energy gain of the surroundings, as energy conservation in classical mechanics.

1.1.2. The First Law of Thermodynamics

- (Appendix) kinds of "work"-

- ✓ In thermodynamics, the most common work is "pressure-volume work".

$$w = -P_{external}\Delta V$$



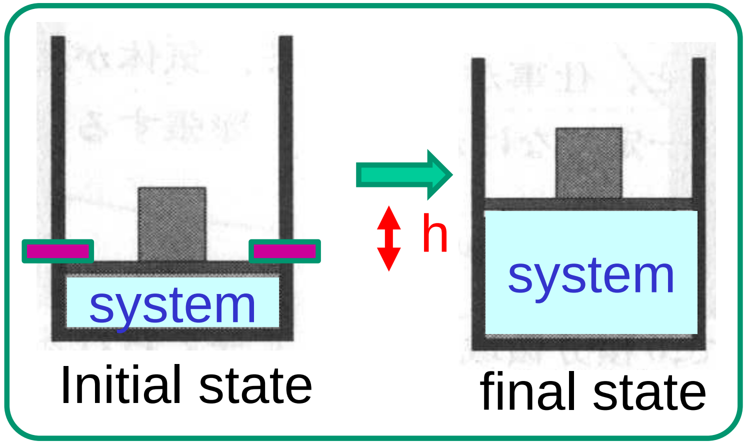
- ✓ In addition to it, we have several other forms of work.
  - ✓ Mechanical forms
    - ➢ P-V work: $w = -Fs = -(Mg)h = -\frac{Mg}{A} \times Ah = -P_{external}\Delta V$
    - ➢ Shaft work: $w = -Fs = 2\pi nT$

      * T is the torque and n is the number of revolutions.
    - ➢ Spring work: $w = -Fs = \frac{1}{2}kx^2 - \frac{1}{2}kx_0^2$

      * k is the spring constant.
  - ✓ Non-mechanical forms
    - ➢ Electrical work: e.g. $w = \frac{q_1 q_2}{4\pi\varepsilon_0}\frac{1}{r}$
    - ➢ Magnetic work
    - ➢ Gravitational work

1.1.2. The First Law of Thermodynamics ($19.1)

- how to calculate Pressure-Volume work-

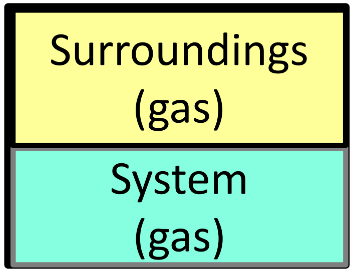


$$w = -P_{external}\Delta V$$

M: the mass of the weight [kg]
g: the gravitational acceleration (9.8 $[\mathrm{m/s^s}]$)
h: the change in the height [m]
A: the area of the bottom plane of piston $[\mathrm{m^2}]$
$P_{external}$: the pressure of the surroundings

- ✓ If we only consider “a piston with a weight”, the pressure ($P_{external} = \frac{Mg}{A}$) is always constant.
- ✓ If we consider some gasses or mechanical devices as the surroundings, the pressure can be changed ($P_{external}(V)$). Then, we need an integral as:

$$w = -\int_{V_{system-initial}}^{V_{system-final}} P_{external}\, dV = -\int_{V_{ini}}^{V_{fin}} P_{ext}\, dV$$



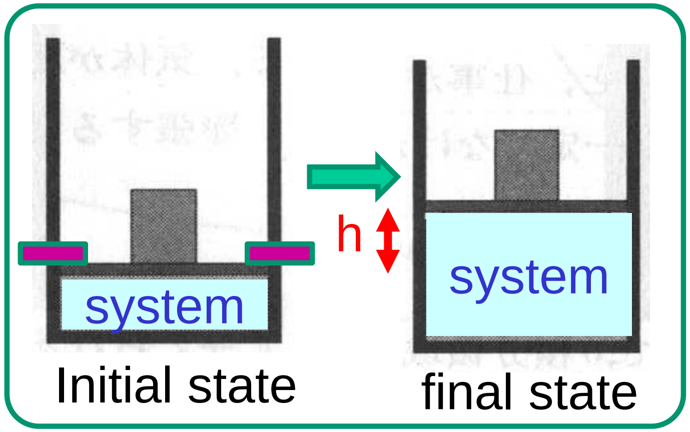
Surroundings
(gas)

System
(gas)

* This integral form is more general because if $P_{ext} = const.$, this equation gives: $\mathrm{w} = -\int P_{ext} dV = -P_{ext}\int dV = -P_{ext}\Delta V.$

1.1.2. The First Law of Thermodynamics ($19.1)

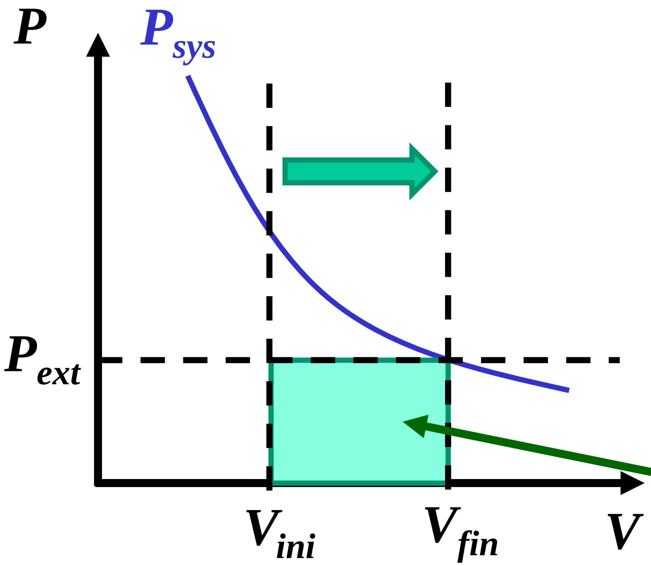
- how to calculate P-V work-



$$w = -\int_{V_{ini}}^{V_{fin}} P_{ext}\, dV$$

✓ To make this integral, P_{ext} should be expressed as a function of V, like $P_{ext} = P_{ext}(V)$.

*Note this V is the system volume, not the volume of the surroundings.



$V_{ini} = 1.0\ \mathrm{m}^3$, $V_{fin} = 2.0\ \mathrm{m}^3$
$P_{ext} = 10$ Pa (= const.)
$P_{sys} = 20/V$ Pa, thus $P_{ini} = 20$ Pa, $P_{fin} = 10$ Pa.

$$w = -\int_{V_{ini}}^{V_{fin}} P_{ext}\, dV = -10\int_{1.0}^{2.0} dV = -10\ [\mathrm{J}]$$

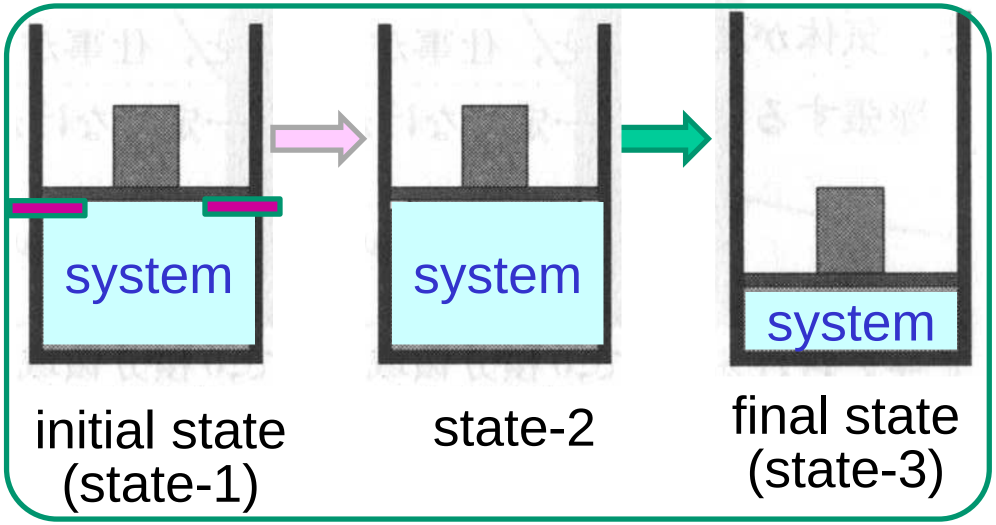
* *This area corresponds to the work.*

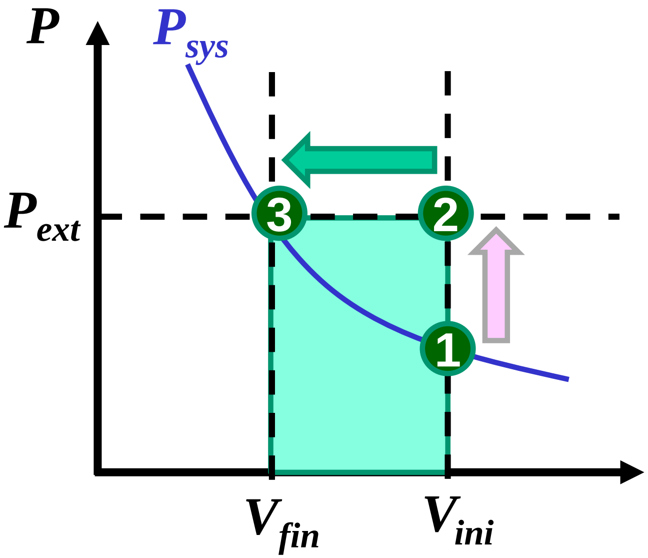
We use external pressure (not system pressure) for work calculation !

1.1.2. The First Law of Thermodynamics ($19.1)

- how to calculate P-V work: compression case -

Here, we consider compression case.



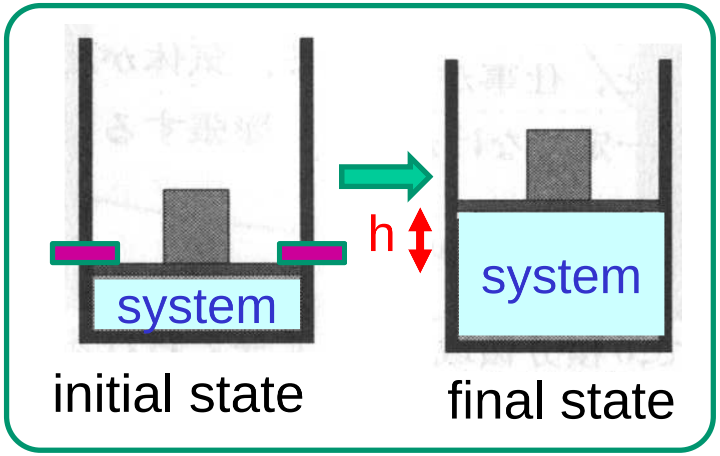


- ✓ At state-1, due to the pin, $P_{sys} = P_{ext}(< \frac{Mg}{A})$.
  - ✓ [Process 1→2] Taking out the pin. Because no change in system volume, no work is brought.
- ✓ At state-2, because the pin is out, $P_{sys} < P_{ext}\ (= \frac{Mg}{A})$.
  - ✓ [Process 2 → 3] Compressing the system.
- ✓ At state-3, $P_{sys} = P_{ext}(= \frac{Mg}{A})$.

1.1.2. The First Law of Thermodynamics

- how to calculate P-V work: comp. b/w expansion & compression-

<*Expansion*>



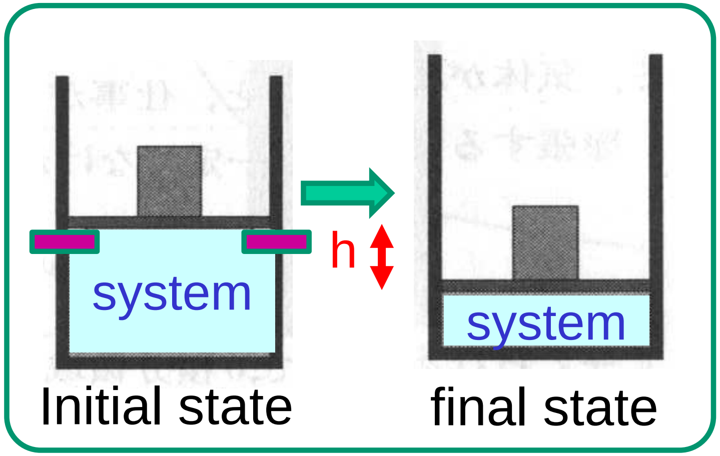
P-V work is defined as:

$$w = -\int_{V_{ini}}^{V_{fin}} P_{ext}\, dV$$

If $P_{ext} = const.$ like the left figures,

$$w = -P_{ext}\, \Delta V$$

<*Compression*>



Because pressure cannot take a negative value ($P_{ext} \geq 0$)

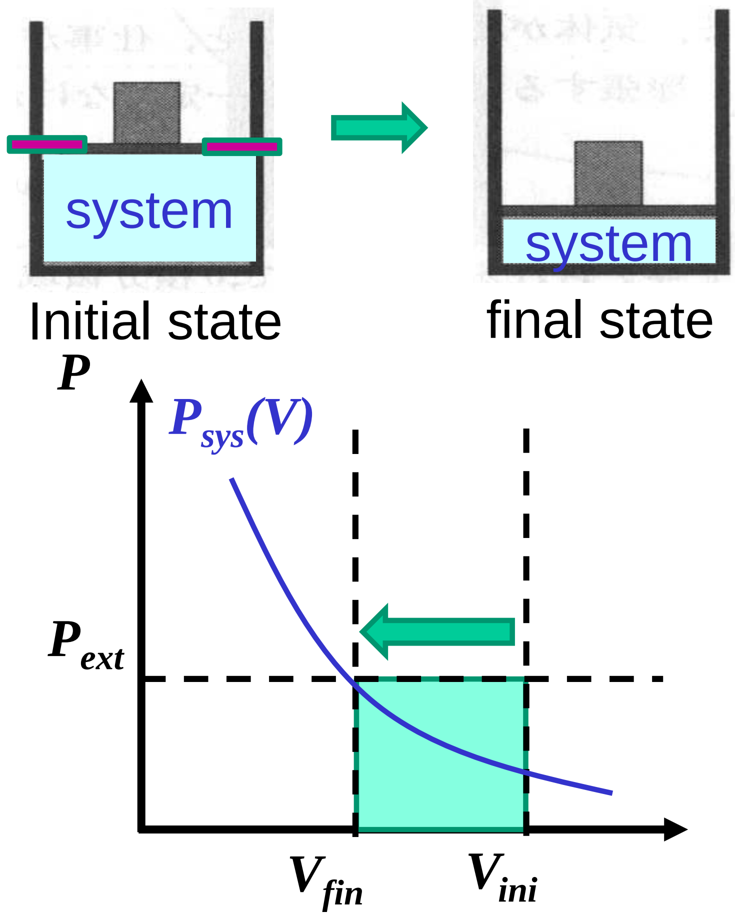
- ✓ for expansion ($\Delta V > 0$), "$w \leq 0$" is always achieved, which mean the system energy is decreased.
- ✓ for compression ($\Delta V < 0$), "$w \geq 0$" is always achieved, which mean the system energy is increased.

*D.A. McQuarrie, J.D. Simon, "Physical Chemistry: A Molecular Approach", University Science Books (1997).

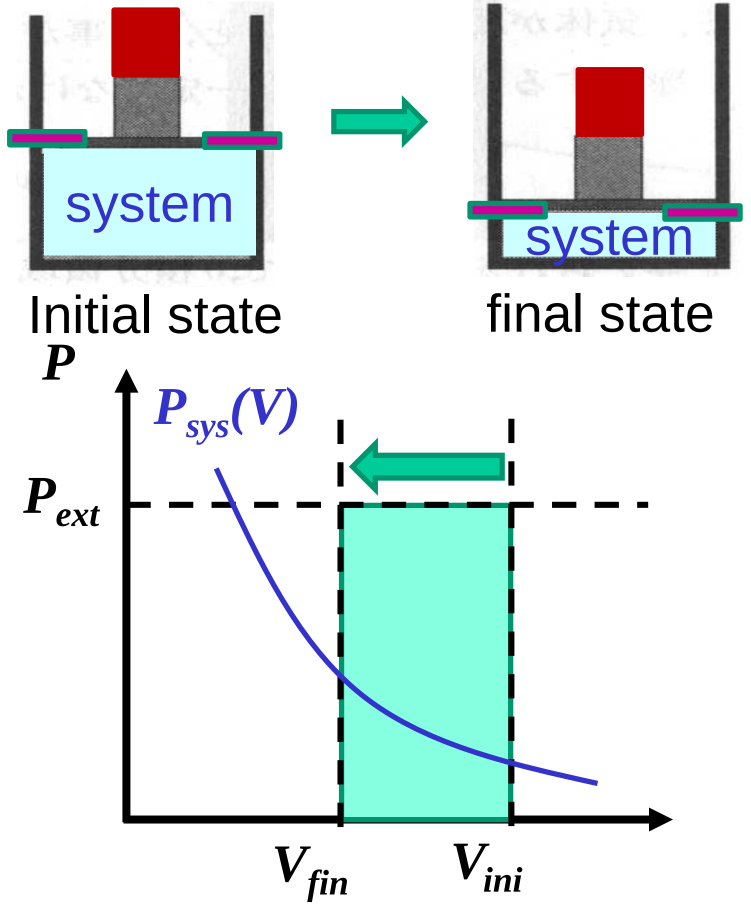
1.1.2. The First Law of Thermodynamics ($19.1)

- compression with different external pressures-

<case-A>



<case-B>



- ✓ $w_A < w_B$, as the work depends on P_{ext}, not on P_{sys}. (P_{ext-A} < P_{ext-B})
- ✓ To induce compression, $P_{ext} > P_{sys}$ is needed. However, if $\Delta P = P_{ext} - P_{sys}$ is too large, more energy (as work) is needed for the compression. Case-A is more effective.

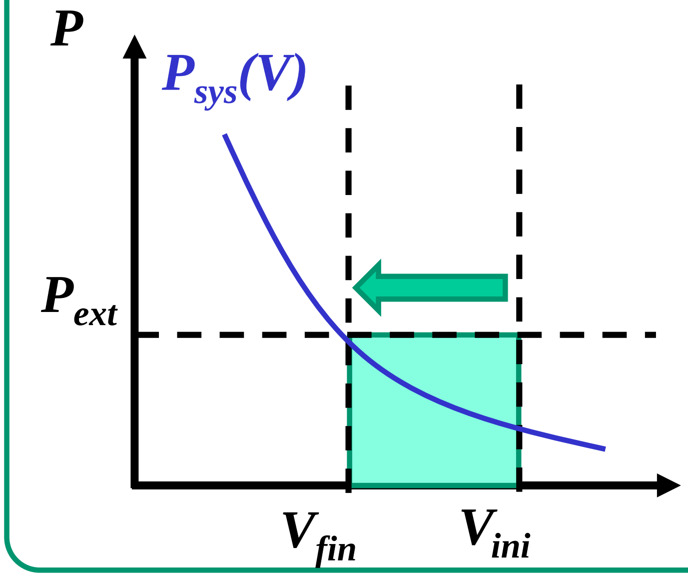
1.1.2. The First Law of Thermodynamics ($19.1)

- how to make expansion in an effective way?-

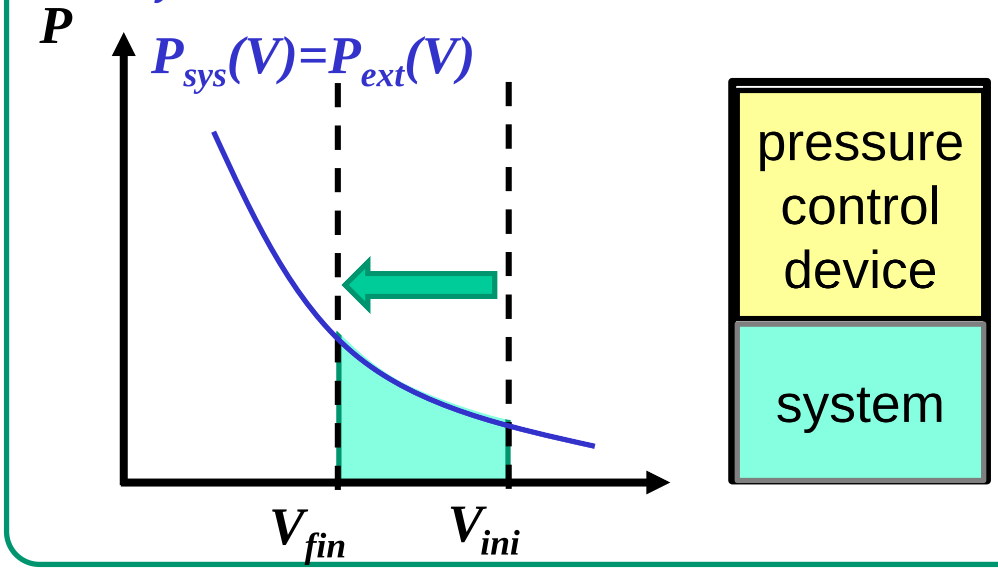
<How to make compression effectively?>

- ✓ To make a compression process, it is needed to keep the external pressure larger than the system pressure ($P_{ext} > P_{sys}$).
- ✓ If P_{ext} is decreased close to P_{sys}, we can imaginarily consider "compression with keeping $P_{ext} = P_{sys}$".
  - ✓ In this condition, this process is quasi-static and reversible.
  - ✓ In this condition, the work needed to give to the system for compression is minimized, thus most effective.

$P_{sys} < P_{ext}$ ***(irreversible)***



$P_{sys} = P_{ext}$ ***(reversible)***

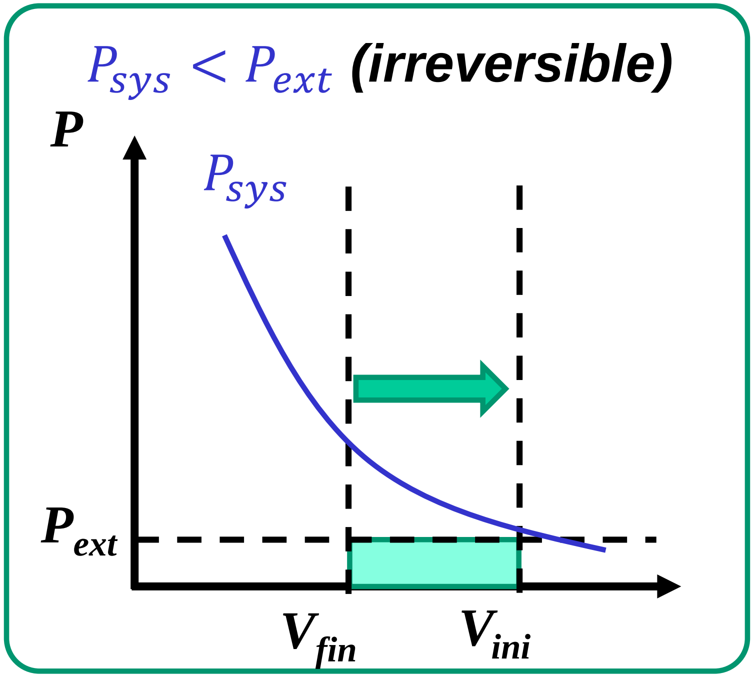


1.1.2. The First Law of Thermodynamics ($19.1)

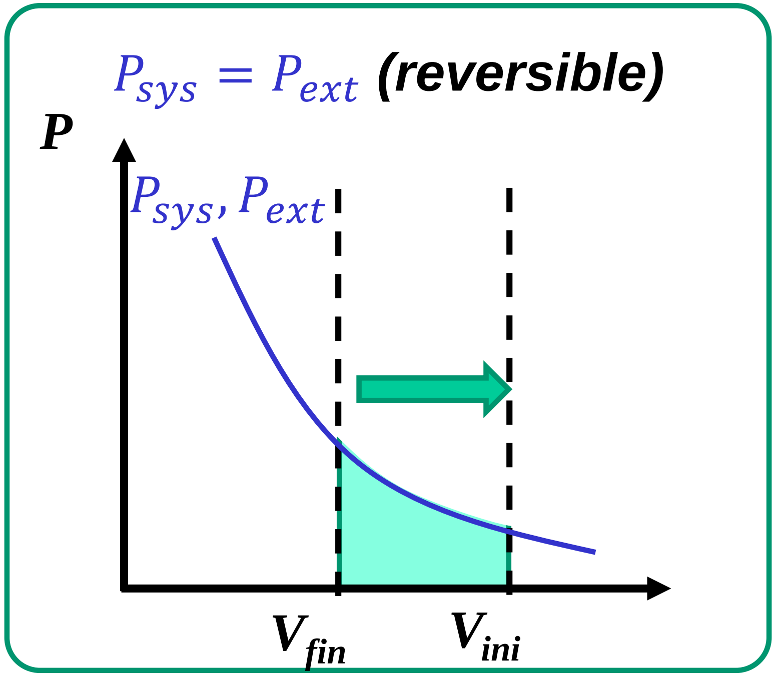
- how to make expansion in an effective way?-

<How to make expansion effectively?>

- ✓ To make an expansion process, it is needed to keep the external pressure smaller than the system pressure ($P_{ext} < P_{sys}$).
- ✓ If P_{ext} is increased close to P_{sys}, we can imaginarily consider "expression with keeping $P_{ext} = P_{sys}$".
  - ✓ In this condition, this process is quasi-static and reversible.
  - ✓ In this condition, the work extracted from the system by expansion is maximized, thus most effective.



$P_{sys} < P_{ext}$ **(irreversible)**

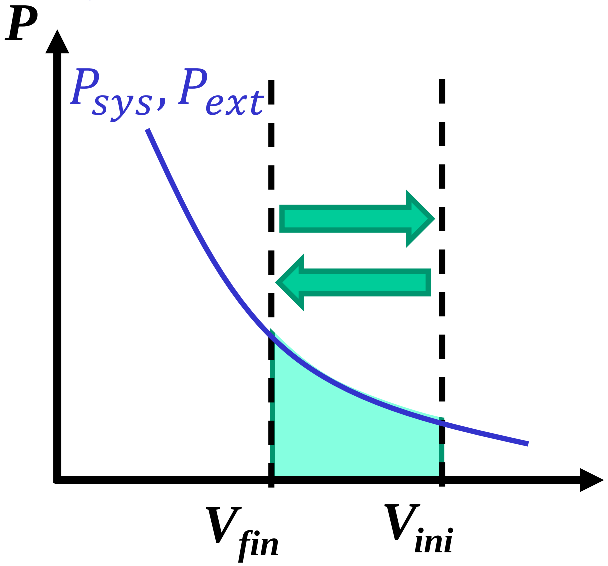


$P_{sys} = P_{ext}$ **(reversible)**

1.1.2. The First Law of Thermodynamics ($19.1)

- how to calculate P-V work in reversible process (quasi-static) -

$P_{sys} = P_{ext}$ ***(reversible)***



- ✓ P-V work is determined as:

$$w = -\int_{V_{ini}}^{V_{fin}} P_{ext}\, dV$$

- ✓ If the process is reversible, $P_{ext} = P_{sys}$. Then,

$$w = -\int_{V_{ini}}^{V_{fin}} P_{ext}\, dV = -\int_{V_{ini}}^{V_{fin}} P dV$$

*we usually write P to mean P_{sys}.

Review of the last class
-quasi-static/reversible/irreversible process>

< Definition of quasi-static process (in this course, we use definition (1)!) >

1) Very (infinitesimally) slow process so that we consider the system is always at some equilibrium state.
2) Very (infinitesimally) slow process and the process takes place with adhering the system to some equilibrium state and keeping concerned thermodynamic quantities of the system and the surroundings equal.

>> for this definition, “quasi-static” is equivalent with “reversible”

>> In this course, this is the definition of reversible process.

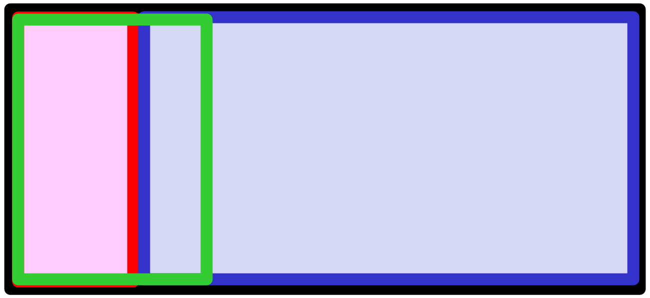
Reversible

Irreversible

Quasi-static

[Definition-1]

All processes



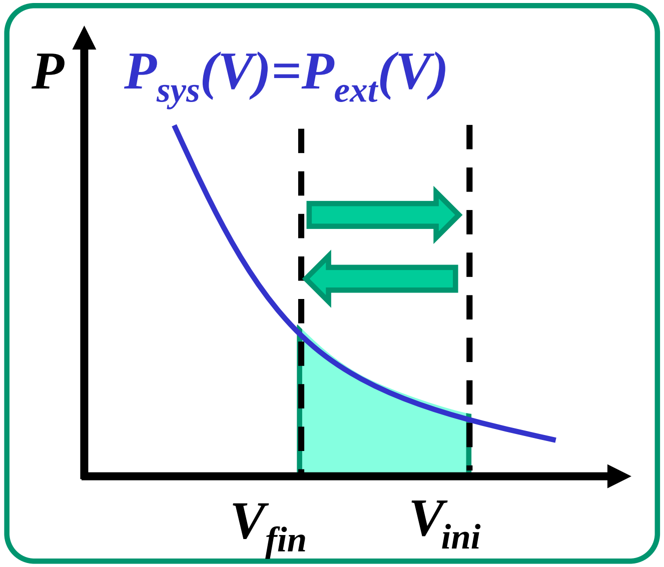
- ✓ Any process is rev. or irrev.
- ✓ Any rev. process is quasi-static.
- ✓ Some irrev. process is quasi-static.

[Definition-2]

All processes

- ✓ Any process is rev. or irrev.
- ✓ Rev. process = quasi-static process.
- ✓ No irrev. process is quasi-static.

Quiz



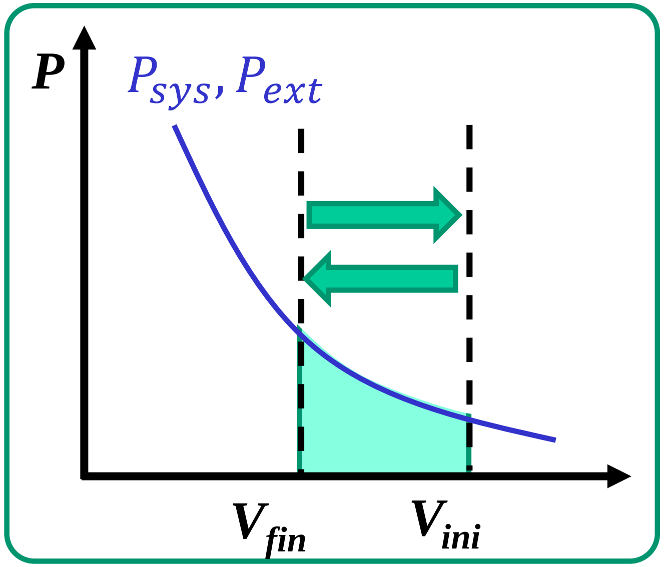
- ✓ If the process is reversible, $P_{ext} = P$ is achieved. (P means P_{sys}). Then, the P-V work is defined as:

$$w = -\int_{V_{ini}}^{V_{fin}} P dV$$

(for reversible processes)

[Q01] If P behaves as $P = 2.0 \times V^{-2}$ in SI units, how much is the minimum work required to compress the system from 3.0 m^3 to 2.0 m^3.

Quiz



- ✓ If the process is reversible, $P_{ext} = P$ is achieved. (P means P_{sys}). Then, the P-V work is defined as:

$$w = -\int_{V_{ini}}^{V_{fin}} P dV$$

(for reversible processes)

[Q01] If P behaves as $P = 2.0 \times V^{-2}$ in SI units, how much is the minimum work required to compress the system from 3.0 m^3 to 2.0 m^3.

The minimum work is achieved for reversible process. Thus $P_{ext} = P$ and then,

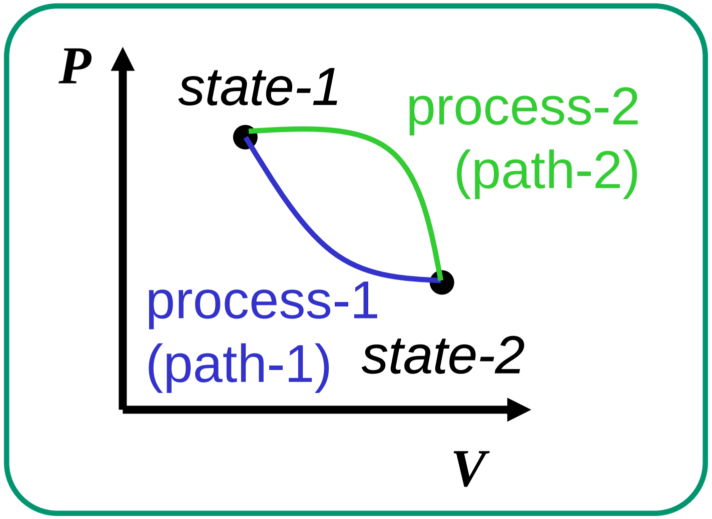
$$w = -\int_{V_{ini}}^{V_{fin}} P dV = -\int_{3.0}^{2.0} (2.0 \times V^{-2}) dV = 2.0[V^{-1}]_{3.0}^{2.0} = 0.33 \text{ [J]}$$

This value corresponds to the energy transferred from the surroundings to the system as work.

1.1.2. The First Law of Thermodynamics ($19.2)

- energy is a state function, but work is not a state functions -

- ✓ Energy is a state function. Thus, it depends only on the current state, not on the history of the state of the system.
  - ✓ In a process, the energy change depends only on energy difference between the initial state and the final state, not on the path.



$$\Delta U = \int_{state-1}^{state-2} dU = U_2 - U_1$$

$$\Delta U_{path-1} = \Delta U_{path-2}$$

- ✓ On the other hand, work is not a state function. It means the amount of work depends on the path/process, which is called "path function".
  - ✓ For example, if the external pressure is increased, the work is increased, as we learned.
  - ✓ So, even if the initial and the final state are identical between 2 paths, the work may be different each other. ($w_{path-1} \neq w_{path-2}$)

1.1.2. The First Law of Thermodynamics ($19.2)

- energy is a state function, but work is not a state functions -

State function (e.g. U)

$$\Delta U = \int_{state-1}^{state-2} dU = U_2 - U_1$$

$$\int_{state-1}^{state-2\,(along\,path-1)} dU = \int_{state-1}^{state-2\,(along\,path-2)} dU$$

$$\Delta U_{path-1} = \Delta U_{path-2}$$

Path function (e.g. w)

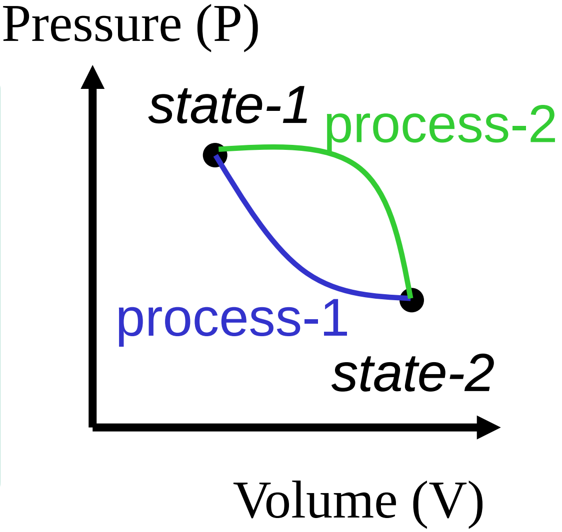
$$\mathrm{w} = \int_{state-1}^{state-2} \delta w$$

$$\int_{state-1}^{state-2\,(along\,path-1)} \delta w \neq \int_{state-1}^{state-2\,(along\,path-2)} \delta w$$

$$w_{path-1} \neq w_{path-2}$$

*In mathematics, d is for an exact differential, and δ is for an inexact differential.

* "along path-1" means "by process-1"



(Appendix)

- ✓ If $dU = 0$ throughout the process, always $\Delta U = \int dU = 0$.
    - ✓ However, $\Delta U = 0$ does not guarantee $dU = 0$.

- ✓ If $\delta w = 0$ throughout the process, always $w = \int \delta w = 0$.
    - ✓ However, $w = 0$ does not guarantee $\delta w = 0$.

1.1.2. The First Law of Thermodynamics ($19.2)

- heat is also a path function, like work -

✓ Heat (q), which is a way of energy transfer that occurs due to a difference in temperature between two systems (or the system and its surroundings), is not a state function but a path function, as the same with work.

State function

$$\Delta U = \int_{state-1}^{state-2} dU = U_2 - U_1$$

Path function

$$w = \int_{state-1}^{state-2} \delta w$$

$$q = \int_{state-1}^{state-2} \delta q$$

Is there any constraint in dU, δw and δq ?? >> YES !!

1.1.2. The First Law of Thermodynamics ($19.3)

- the 1st law as energy conservation law for thermodynamics -

<The first law of thermodynamics (energy conservation)>

$$\mathrm{d}U = \delta q + \delta w \ (+\delta z) \qquad \Delta U = q + w \ (+z)$$

- ✓ The term δz accounts for energy transfer due to matter transfer, which is needed for open system. If the concerned system is isolated or closed, this term is 0 ($\delta z = 0$). (we usually omit this term it in this course).

- ✓ Due to this constraint in heat and work (energy transfers), the energy is conserved, although each can take an arbitrary value.
  - ✓ For example, let's consider three paths having identical initial and final states, and thus $\Delta U = U_{fin} - U_{ini} = 10$ [J]
    - ➢ If $q_{path-1} = 5\ [J]$, it must be $w_{path-1} = 5\ [J]$.
    - ➢ If $q_{path-2} = 10\ [J]$, it must be $w_{path-2} = 0\ [J]$.
    - ➢ If $q_{path-3} = -20\ [J]$, it must be $w_{path-3} = 30\ [J]$.

- ✓ In classical mechanics, the energy conservation is considered only for work. In thermodynamics, heat is additionally involved.

1.1.2. The First Law of Thermodynamics ($19.3)

- description of the 1st law -

"The first law of thermodynamics is a version of the law of conservation of energy, adapted for thermodynamic systems. The law of conservation of energy states that the total energy of an isolated system is constant; energy can be transformed from one form to another, but cannot be created or destroyed."

(*wikipedia)

- ✓ There exists for every system a property called energy (E).
  - ✓ E = internal energy (arising from molecular motion - primarily a function of temperature) + kinetic energy (**macroscopic)+ potential energy (**macroscopic) + chemical energy (**which usually contained in internal energy).
- ✓ The change in energy of a system is equal to the difference between the heat added to the system and the work done by the system. (** "done to the system" in our definition)

(*http://web.mit.edu/16.unified/www/FALL/thermodynamics/thermo_4.htm)

- ➢ $\mathrm{d}U = \delta q + \delta w$ (in this course)
- ➢ $\mathrm{d}U = \delta q - \delta w$ (in some textbooks)

Quiz

- ✓ [Q02] "δq *and* δw does not depend on a pathway of the process, but just depend on the initial and the final states of the process." Is this statement correct?

- ✓ [Q03] "$\mathrm{d}U$ does not depend on a pathway of the process, but just depend on the initial and the final states of the process." Is this statement correct?

Quiz

- ✓ [Q02] δq *and* δw does not depend on a pathway of the process, but just depend on the initial and the final states of the process.

  >> No.

- ✓ [Q03] $\mathrm{d}U$ does not depend on a pathway of the process, but just depend on the initial and the final states of the process.

  >> No. $\mathrm{d}U$ depend on a process (path). What does not depend on the pathway is $\Delta U = U_{fin} - U_{ini}$, which only depends on the initial and final states.

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1.1.2. The first law of thermodynamics

1.2.1. Thermodynamic process

1.2.2. Thermodynamic cycle

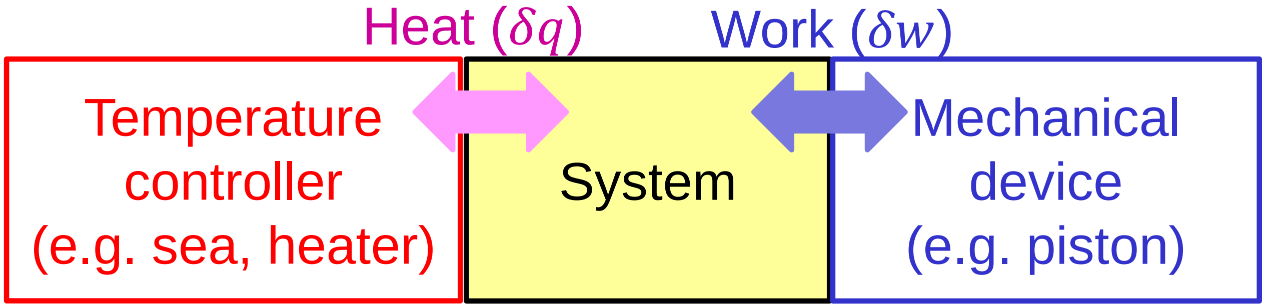
1.2.1. Thermodynamic process

- basics -

- ✓ "process" is an operation to cause a change of the system from one state (initial state) to another state (final state)".

- ✓ A process often accompanies an energy transfer as heat or/and work.
- ✓ During the process, the 1st law (and other 2nd and 3rd laws) should be preserved.

1st law: $\mathrm{d}U = \delta q + \delta w$



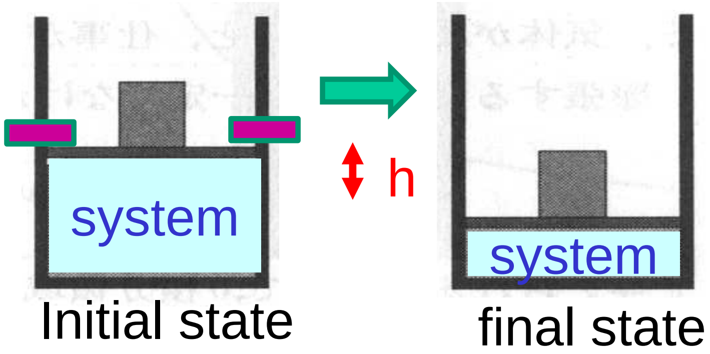
1.2.1. Thermodynamic process

- some widely-applied simplifications -

- ✓ In thermodynamics, we normally consider only P-V work.

$$\delta w = -P_{ext} dV$$

$$w = \int \delta w = -\int P_{ext} dV$$



- ✓ If we consider non P-V work, “$\delta w = -P_{ext} dV + \delta w_{non-PV}$”

**Hereafter, if not specified, work is only P-V work (*$\delta w_{non-PV} = 0$*)*

- ✓ If we consider enter/escape of some matter (e.g. molecules) to/from the system, the 1st law should be “$\mathrm{d}U = \delta q + \delta w + \delta z$”
where δz represents the energy gain/loss by enter/escape of some matter.

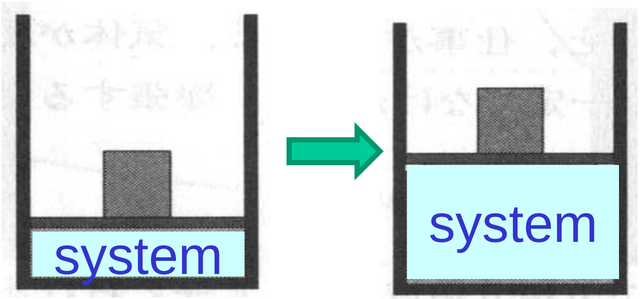
**Hereafter, if not specified, we assume* $\delta z = 0$
(assuming closed or isolated system)

1.2.1. Thermodynamic process

- expansion and compression to make energy transfer as work -

Here we focus on P-V work: $\delta w = -P_{ext}dV$ and $P_{ext} \geq 0$.

<Expansion>

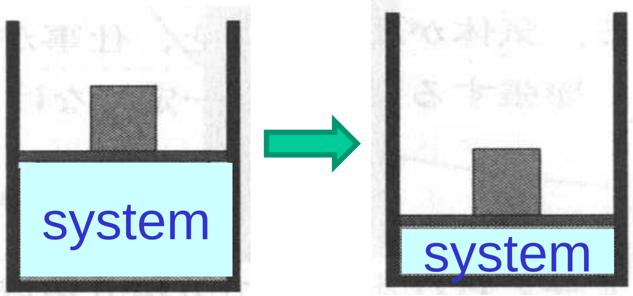


initial state final state

$dV > 0$ thus $\int \delta w = w \leq 0$

*The equal sign is achieved when $P_{ext} = 0$, namely expansion to a vacuum.

<Compression>



initial state final state

$dV < 0$ thus $\int \delta w = w \geq 0$

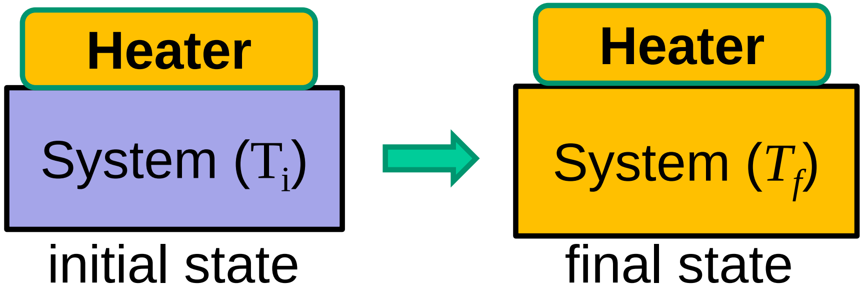
*The equal sign is achieved when $P = P_{ext} = 0$, namely both system and surroundings are vacuums.

1.2.1. Thermodynamic process

- heating and cooling to make energy transfer as heat -

Here we focus on heat.

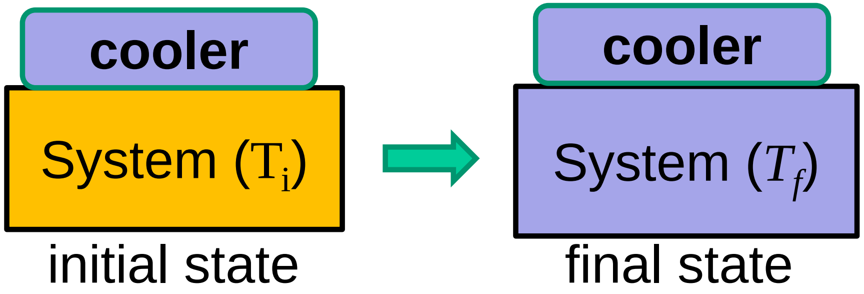
(3) Heating



$T_i < T_f$ **thus** $q = \int \delta q > 0$

*The energy q is transferred from the surroundings (heater) to the system as heat.

(4) Cooling



$T_i > T_f$ **thus** $q = \int \delta q < 0$

*The energy $-q$ is transferred from the system to the surroundings (cooler) as heat.

- ✓ Expansion & Compression: energy transfer by work
- ✓ Heat & Cooling: energy transfer by heat

1.2.1. Thermodynamic process

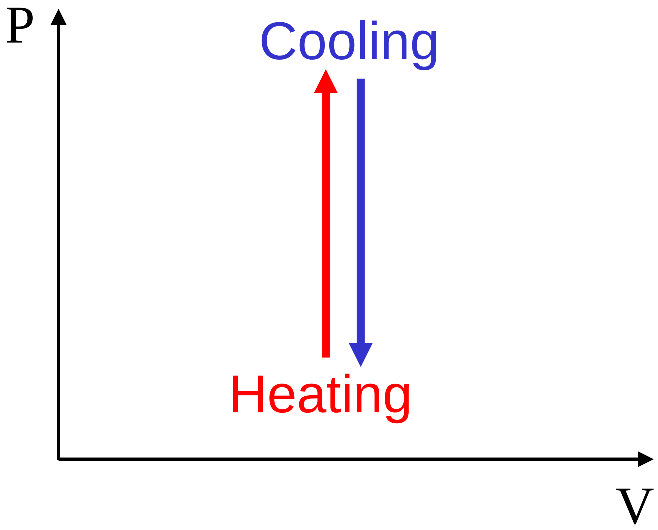
- constant-volume heating/cooling ($dV = 0$)-

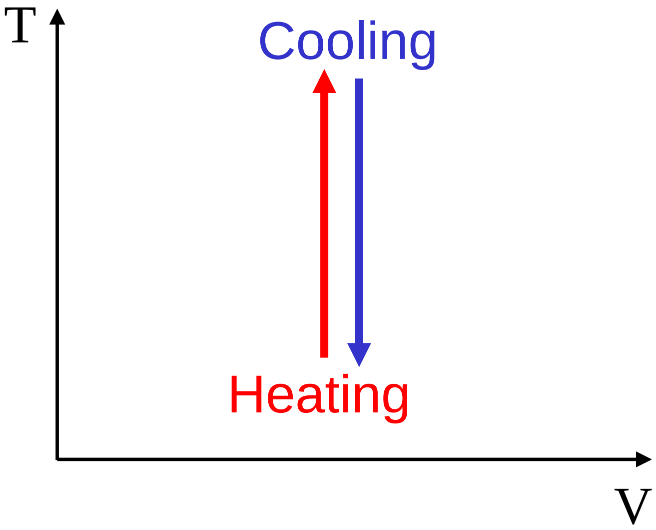
1st law: $dU = \delta q + \delta w$

(1) Constant-volume heating/cooling: $dV = 0$

- ✓ As we only consider P-V work:

  $\delta w = -P_{ext} dV = 0$ thus $dU = \delta q$.





- ✓ If we also consider non-PV work:

  $dU = \delta q + \delta w_{PV} + \delta w_{non-PV} = \delta q + \delta w_{non-PV}$.

1.2.1. Thermodynamic process

- constant-pressure heating/cooling ($dP = 0$)-

1

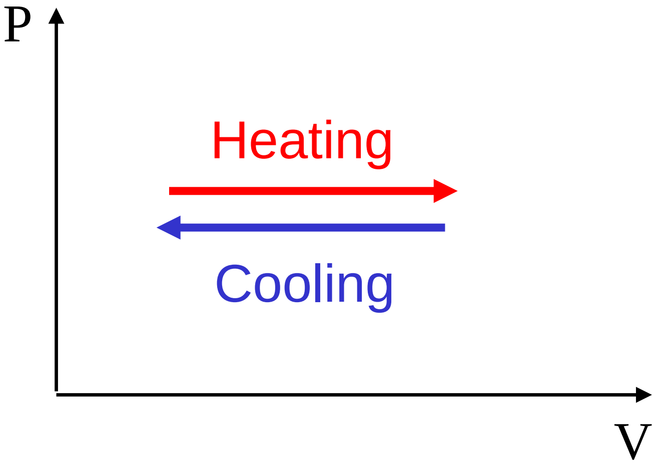
1^{st} law: $\mathrm{d}U = \delta q + \delta w$

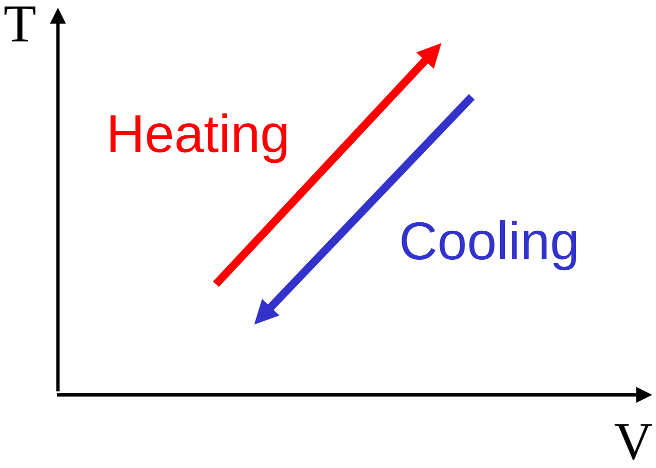
(2) Constant-pressure heating/cooling: $dP = 0$ ($P = const.$)

- ✓ As we only consider P-V work:

$$\delta w = -P_{ext}dV \quad \text{thus} \quad \Delta U = q + w = \int \delta q - P_{ext} \int dV = q - P_{ext}\Delta V,$$

where $\Delta V = V_{final} - V_{initial}$





*In the right graph, if the system is an ideal gas, the volume is linearly change with the temperature, as $PV = nRT$.

- ✓ If we further assume the process is reversible, where $P = P_{ext}$, $T = T_{ext}$, etc, then:

$$\delta w = -PdV \quad \text{thus} \quad \Delta U = q - P\Delta V$$

Quiz

- ✓ [Q04] A system goes through a reversible constant-volume heating process at 0.020 m^3 from 300 K to 500 K. The system is composed by 1 mole of ideal gas whose energy is defined as $U = \frac{3}{2}nRT$. Please determine (1) ΔU, (2) w and (3) q in this process.

Quiz

- ✓ [Q04] A system goes through a reversible constant-volume heating process at 0.020 m^3 from 300 K to 500 K. The system is composed by 1 mole of ideal gas whose energy is defined as $U = \frac{3}{2}nRT$. Please determine (1) ΔU , (2) w and (3) q in this process.

  Because constant-volume process ($dV = 0$), $\delta w = -PdV = 0$.

  Hence, $w = \int \delta w = 0$.

  Using the energy expression of ideal gas,

  $$\Delta U = \frac{3}{2}nR\Delta T = \frac{3}{2} \times 1 \times 8.31 \times (300 - 500) = 2.5 \times 10^3 \text{ [J]}$$

  According to 1st law, $\mathrm{d}U = \delta q + \delta w = \delta q$. Thus, $\Delta U = q$.

  Hence, $\Delta U = q = 2.5 \times 10^3$ [J], $w = 0$ [J].