Thermodynamics

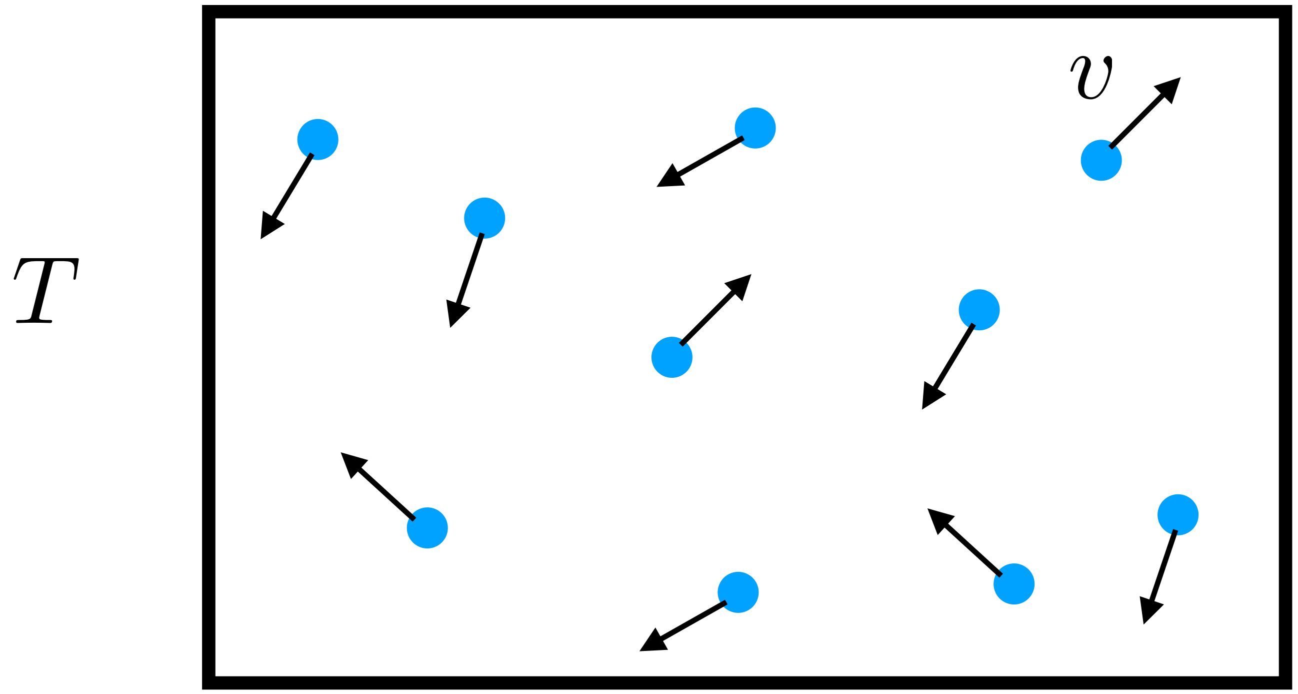
The goal of thermodynamics is to understand how heat can be converted to work

Main lesson:

Not all the heat energy can be converted to mechanical energy

This is because heat energy comes with disorder (entropy), and overall disorder cannot decrease

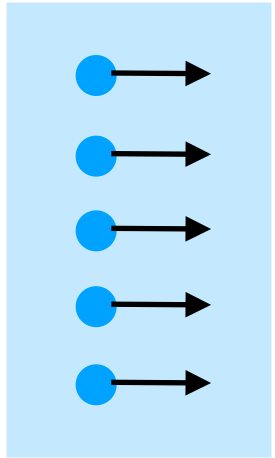
Temperature



Random directions of velocity

Higher temperature means higher velocities v

Add up energy of all molecules: Internal Energy of gas U



Mechanical energy: all atoms move in the same direction

$$\frac{1}{2}Mv^2$$

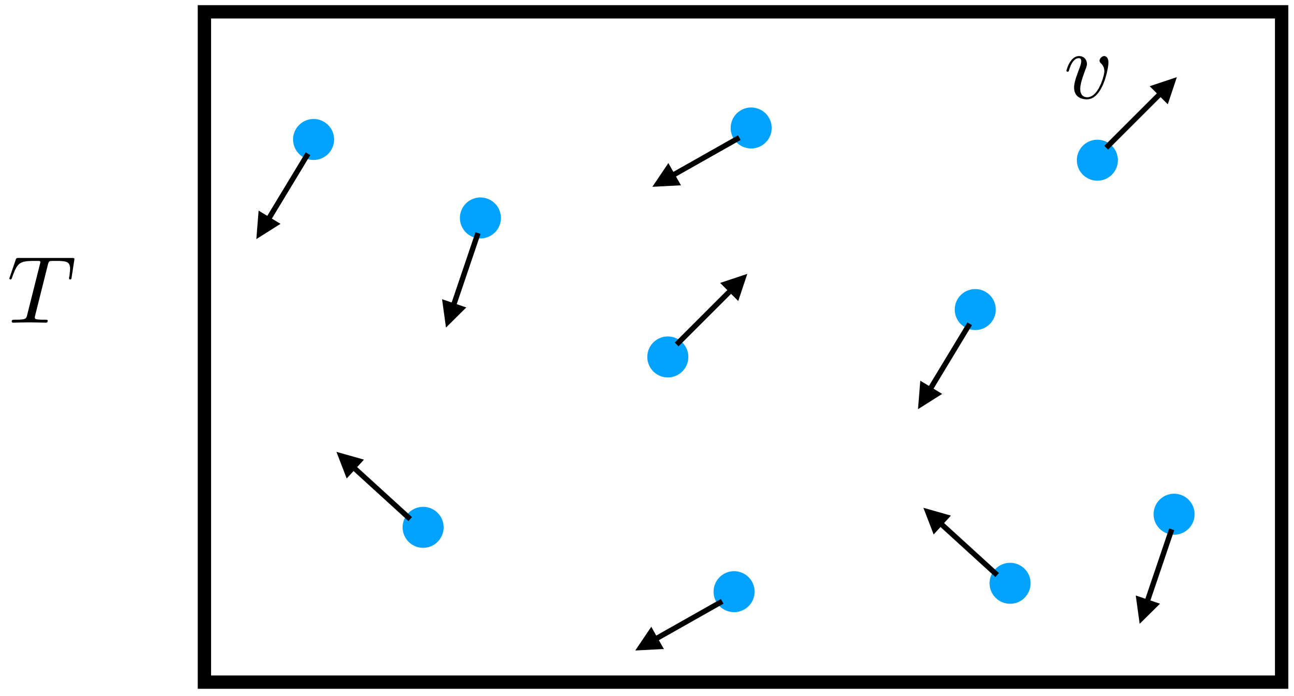
Statistical mechanics

For one atom

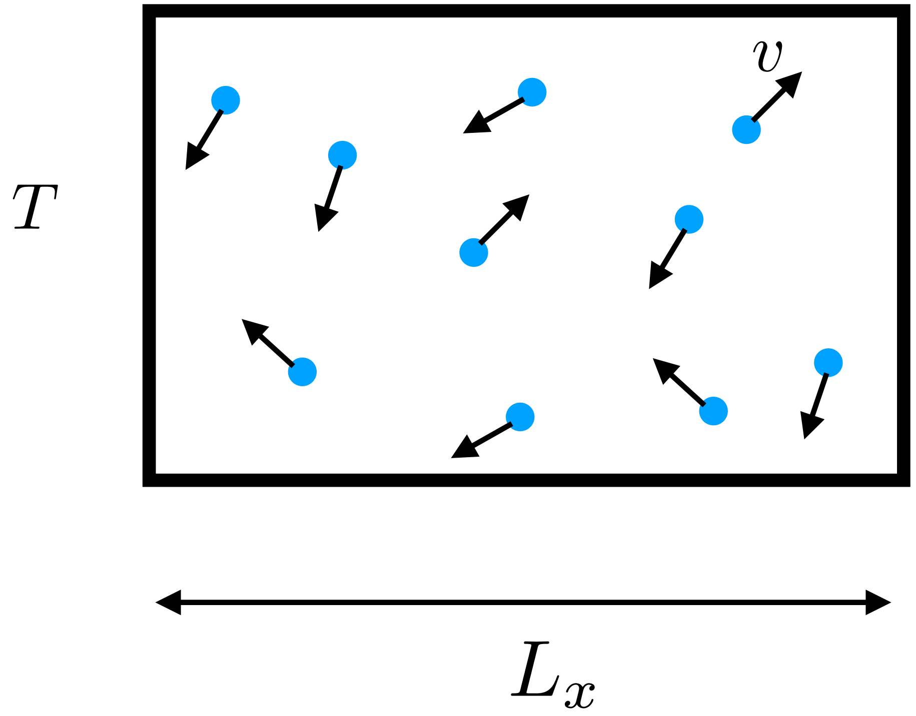
$$\langle E \rangle = \langle \frac{1}{2} m v_x^2 \rangle + \langle \frac{1}{2} m v_y^2 \rangle + \langle \frac{1}{2} m v_z^2 \rangle = \frac{1}{2} kT + \frac{1}{2} kT + \frac{1}{2} kT = \frac{3}{2} kT$$

Ideal gas: No Potential energy from attraction between atoms

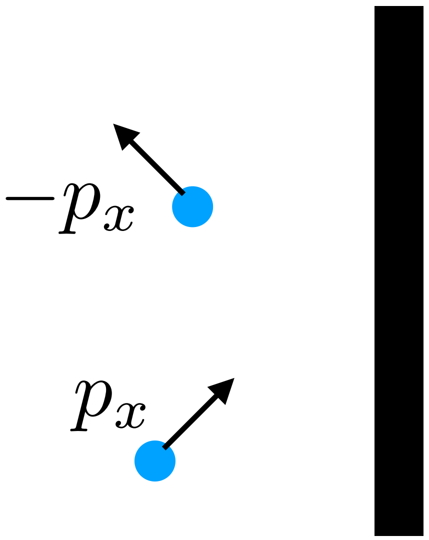
$$\langle U \rangle = \frac{3}{2} NkT$$



Pressure



Pressure is caused because atoms bounce off the wall



$$\Delta p_x = 2p_x$$

$$\Delta t = \frac{2L_x}{v_x}$$

$$F = \frac{\Delta p_x}{\Delta t} = \frac{2mv_x^2}{2L_x} = \frac{mv_x^2}{L_x}$$

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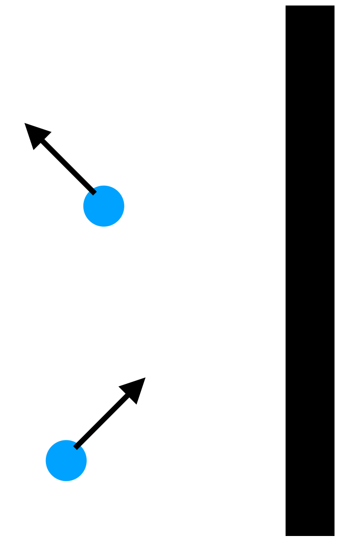
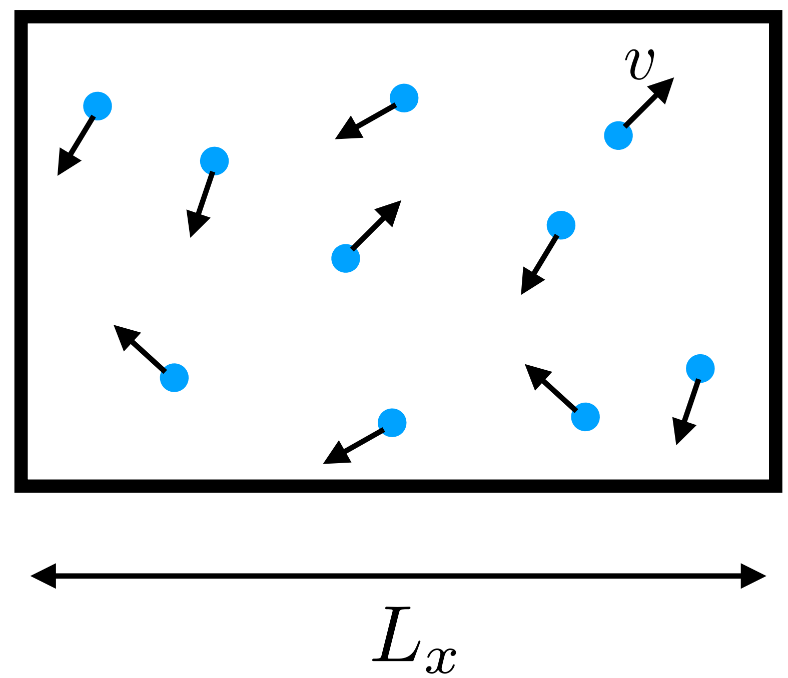


$$\langle mv_x^2 \rangle = 2 \times \frac{1}{2}kT = kT$$

$$F = \frac{kT}{L_x}$$

Pressure

$$P = \frac{F}{A} = \frac{kT}{L_x}\frac{1}{L_y L_z} = \frac{kT}{V}$$



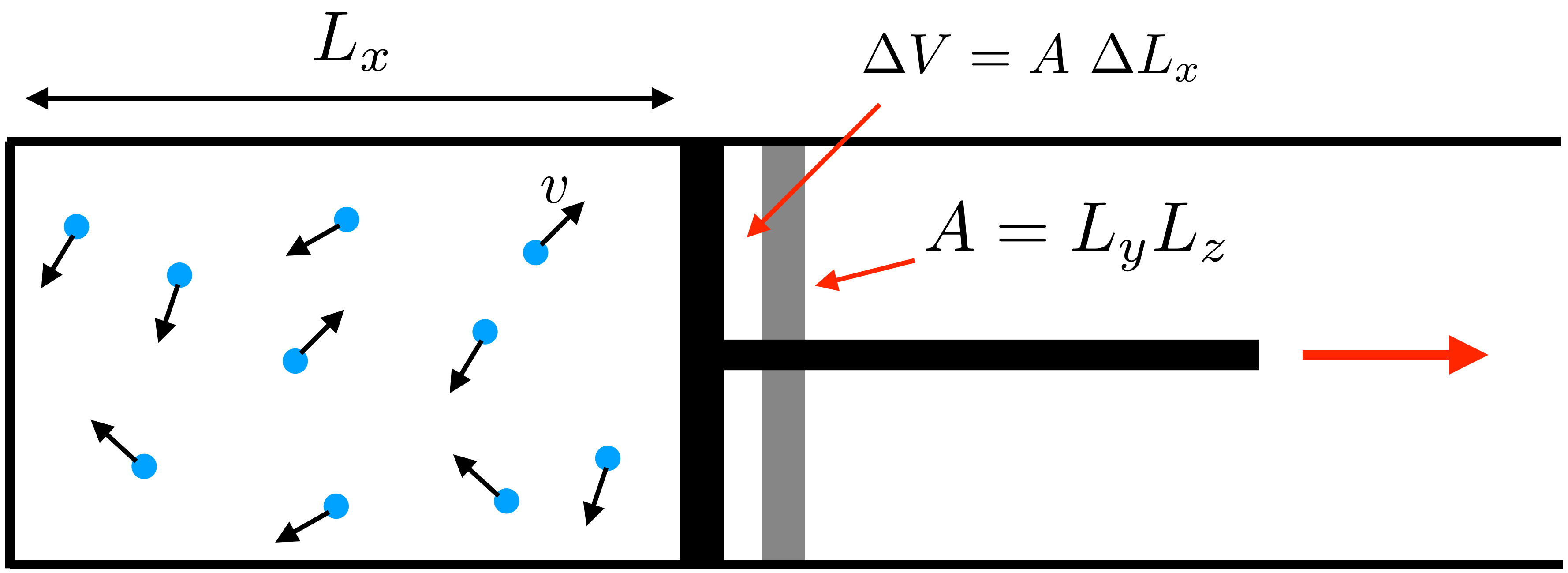
$$A = L_y L_z$$

Many particles $$P = \frac{NkT}{V}$$

$$\boxed{PV = NkT}$$

Volume $V = L_x L_y L_z$

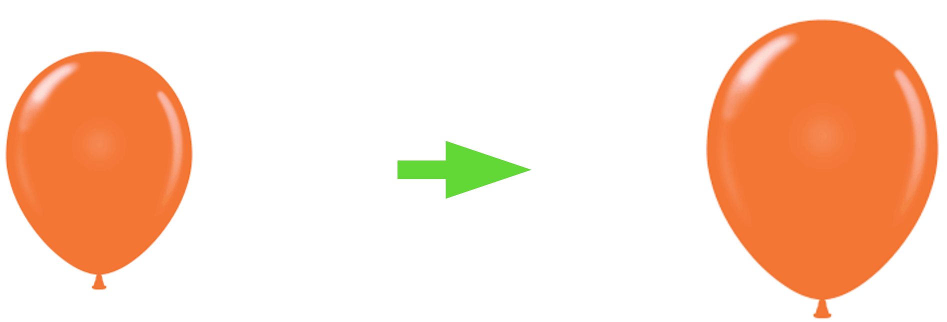
Work



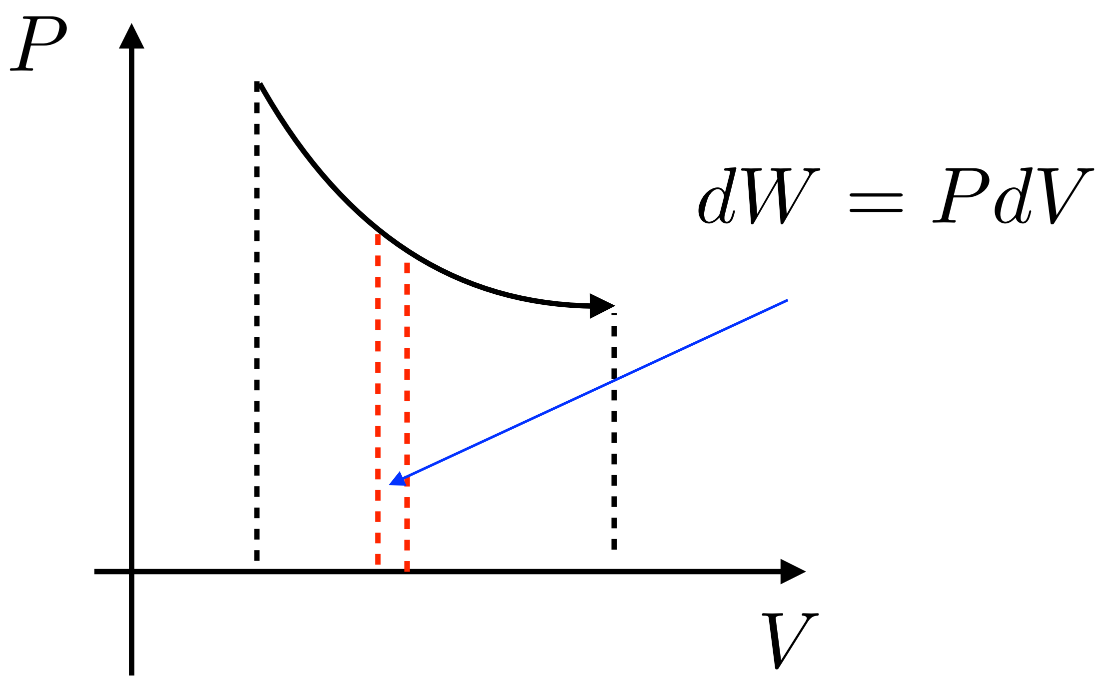
Work done BY the gas $\Delta W = F\ \Delta L_x$

We can write this as $\Delta W = (PA)\ \Delta L_x = P\Delta V$

This is useful because the body could have a generic shape

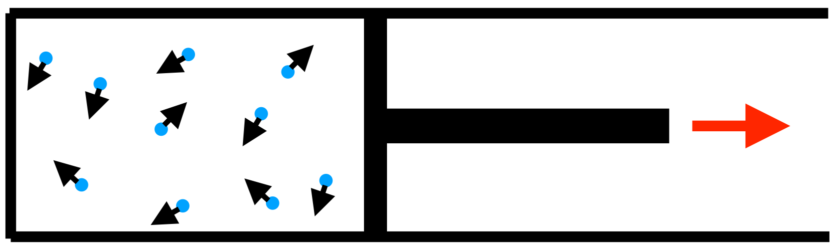


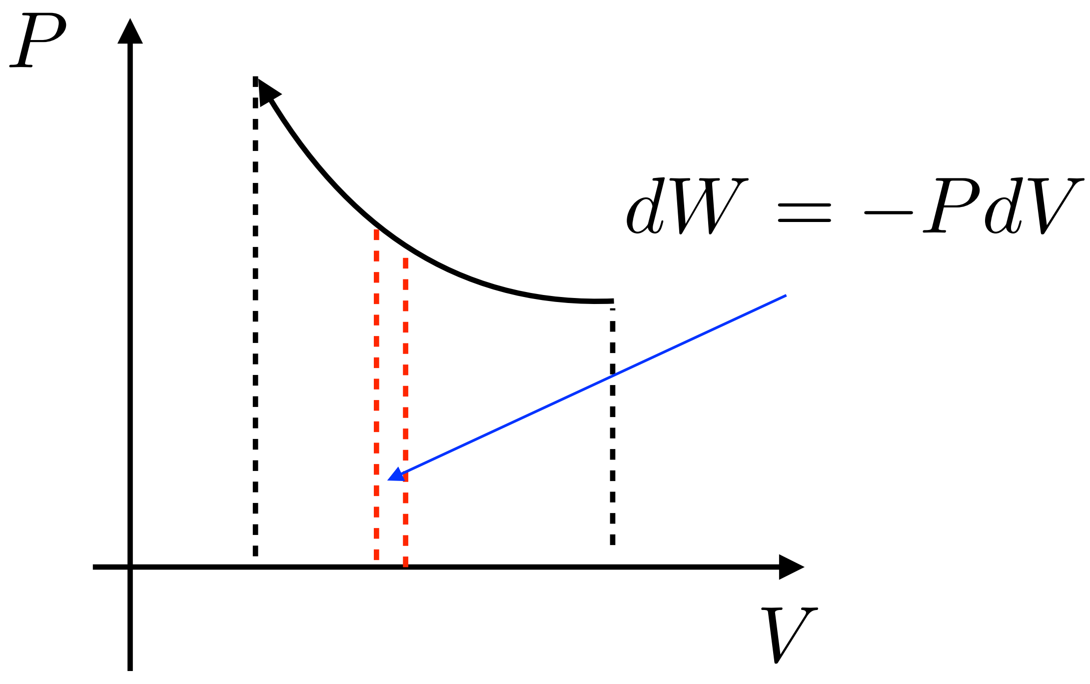
Internal energy of gas decreases $U \rightarrow U - \Delta W$



Gas expands, work is done BY the gas

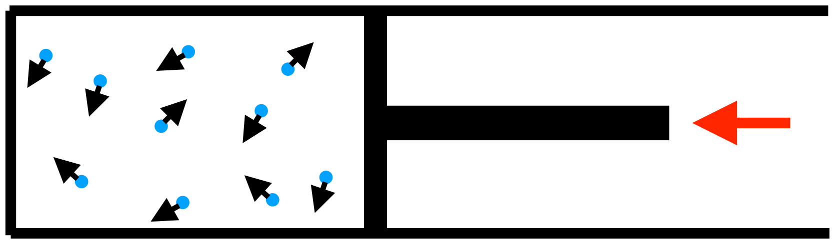
Work done is Area under curve





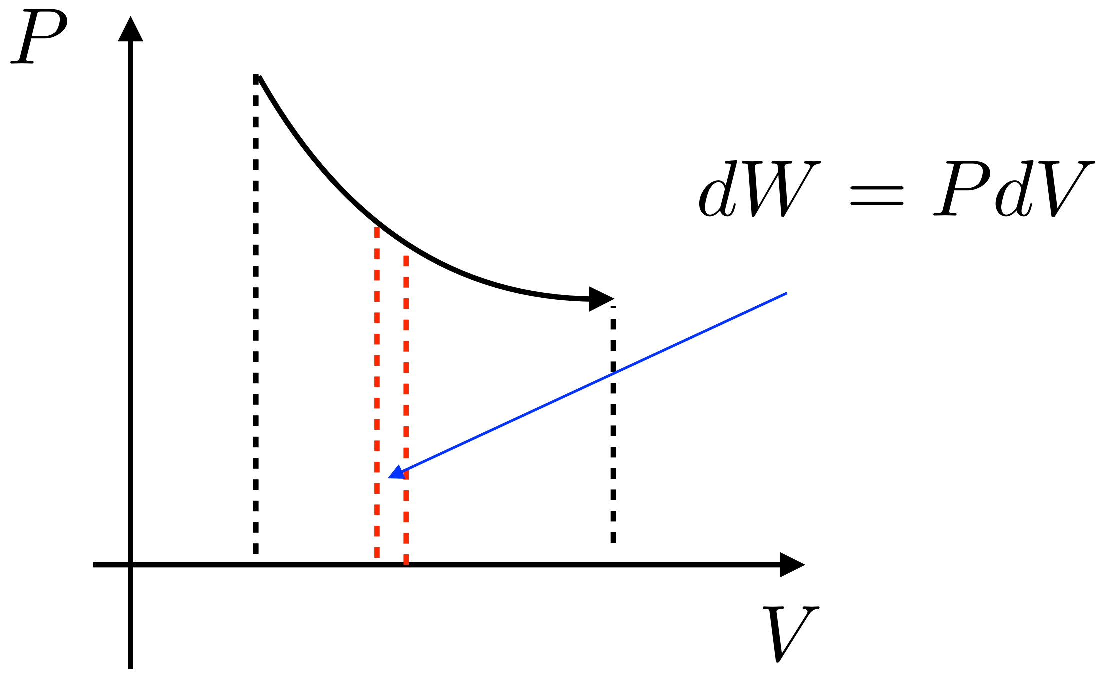
Gas is pushed in, work is done ON the gas

Work done is negative of Area under curve

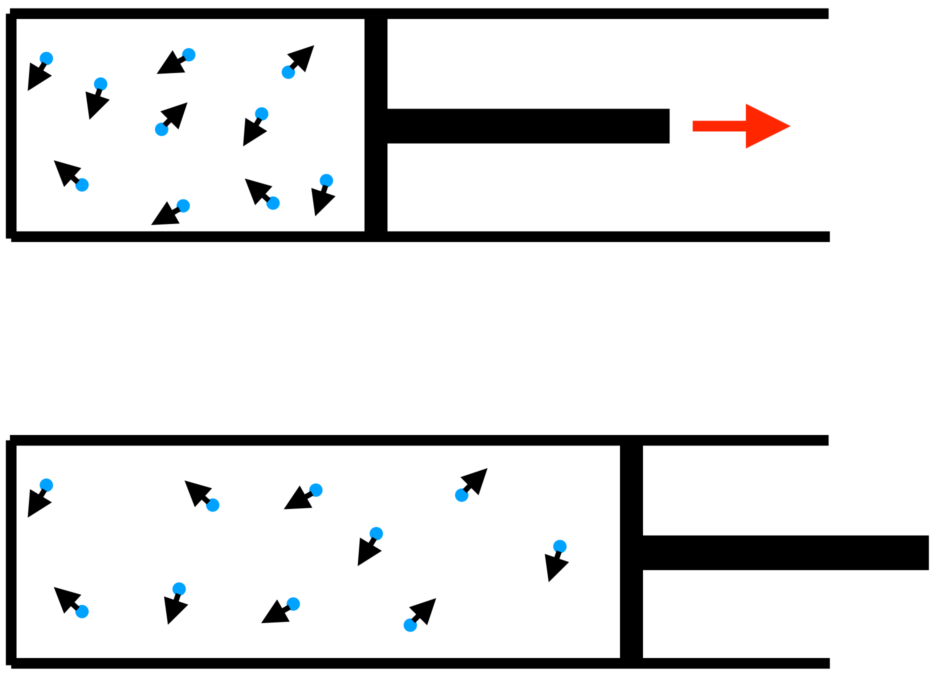


By convention, we use POSITIVE sign for work done BY the gas

Getting work from Heat



Gas expands, work is done BY the gas

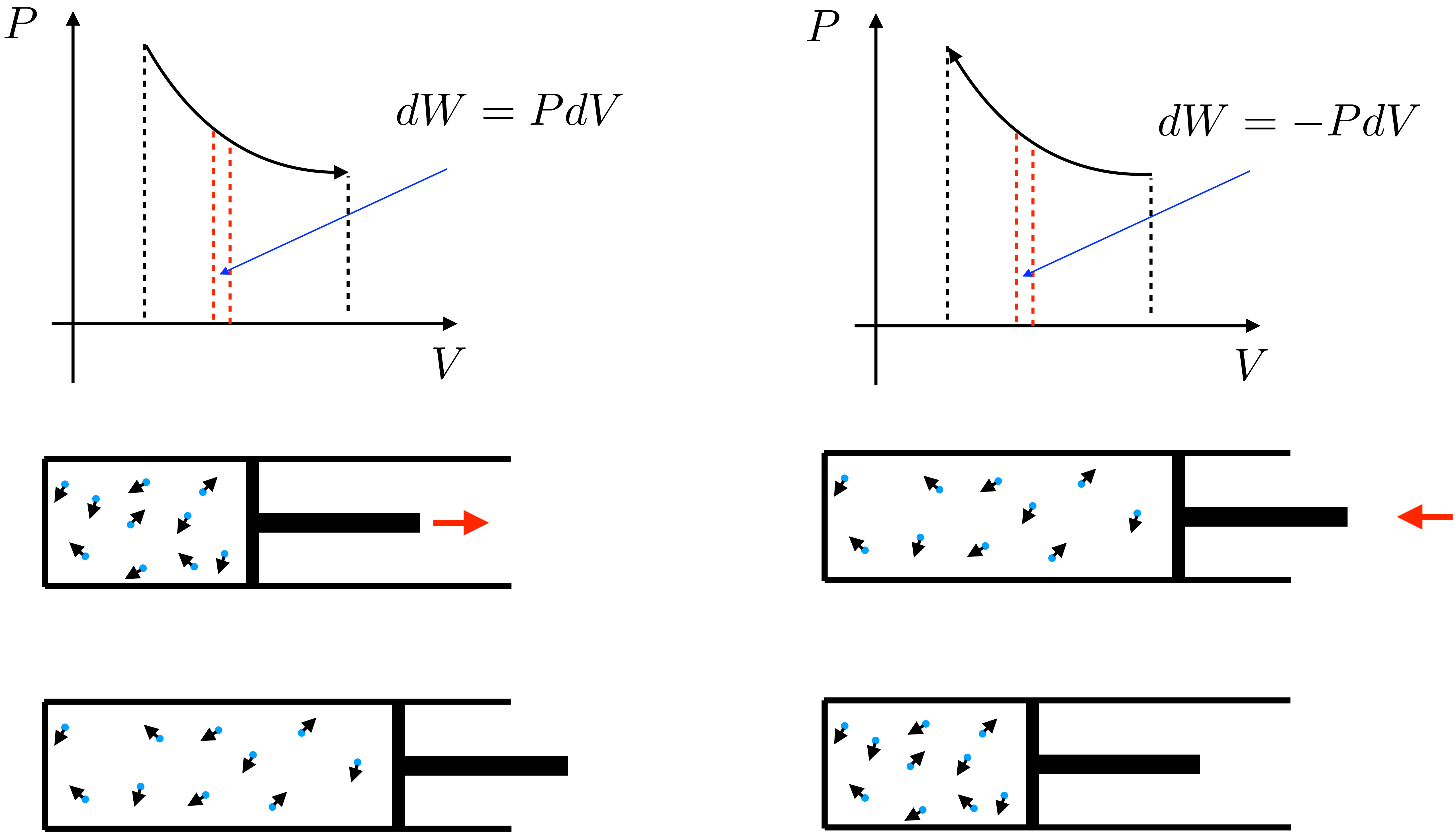


Volume in increases

Internal energy decreases ... this means Temperature decreases

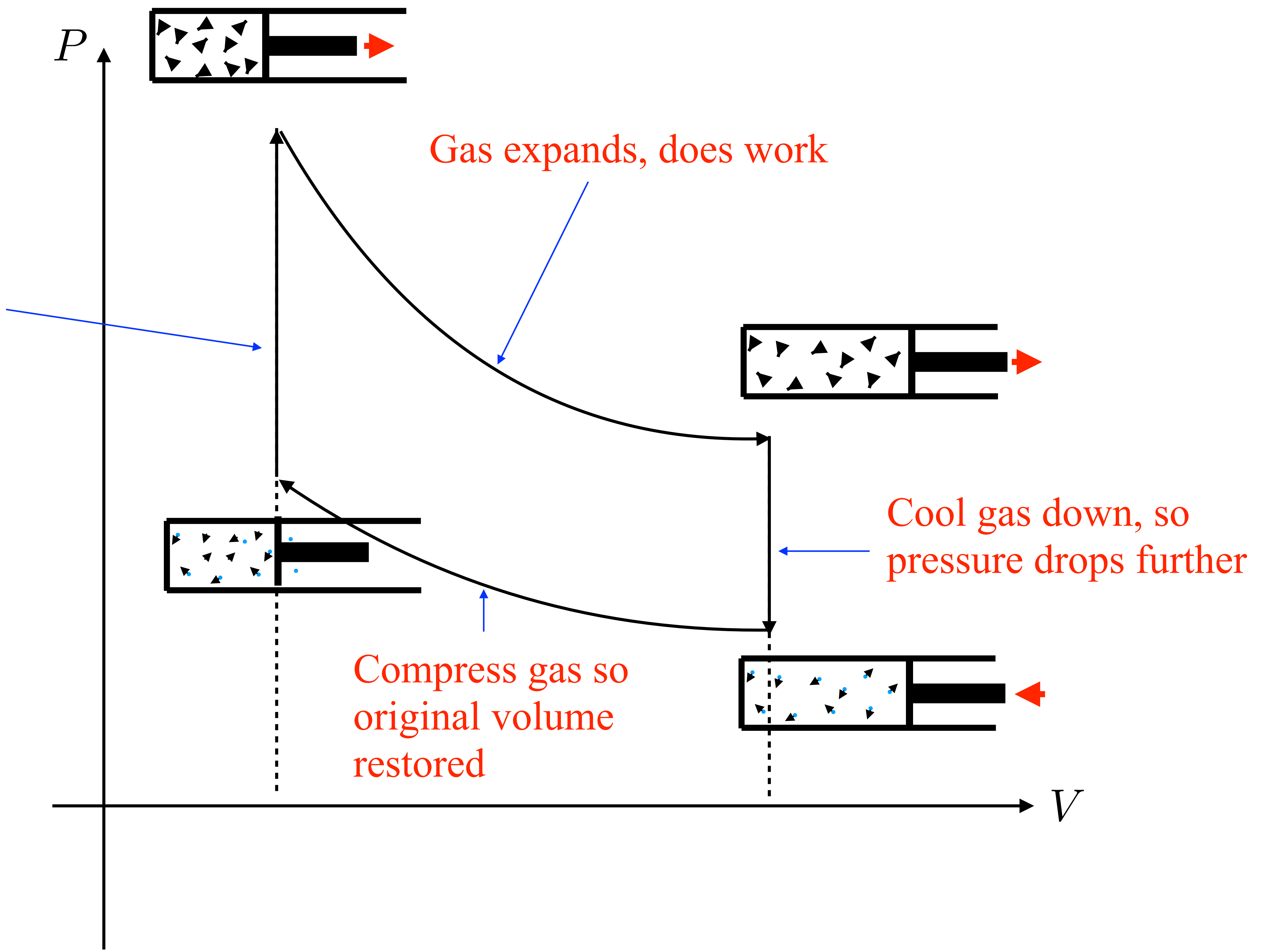
Pressure decreases

But how do we get the engine back to its initial state ?

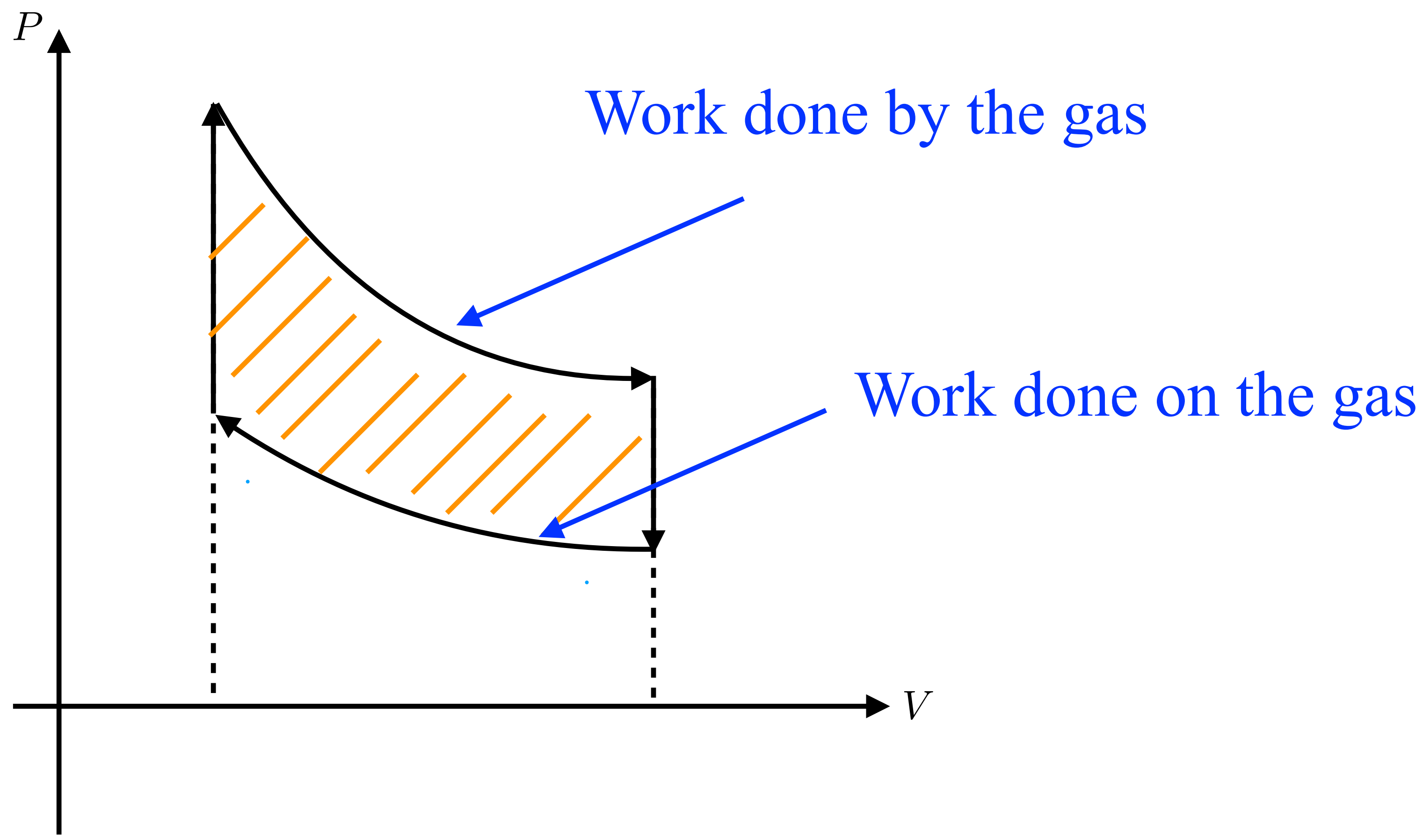


We will have to put in exactly as much work as we got out ...
so this does not help

The heat engine

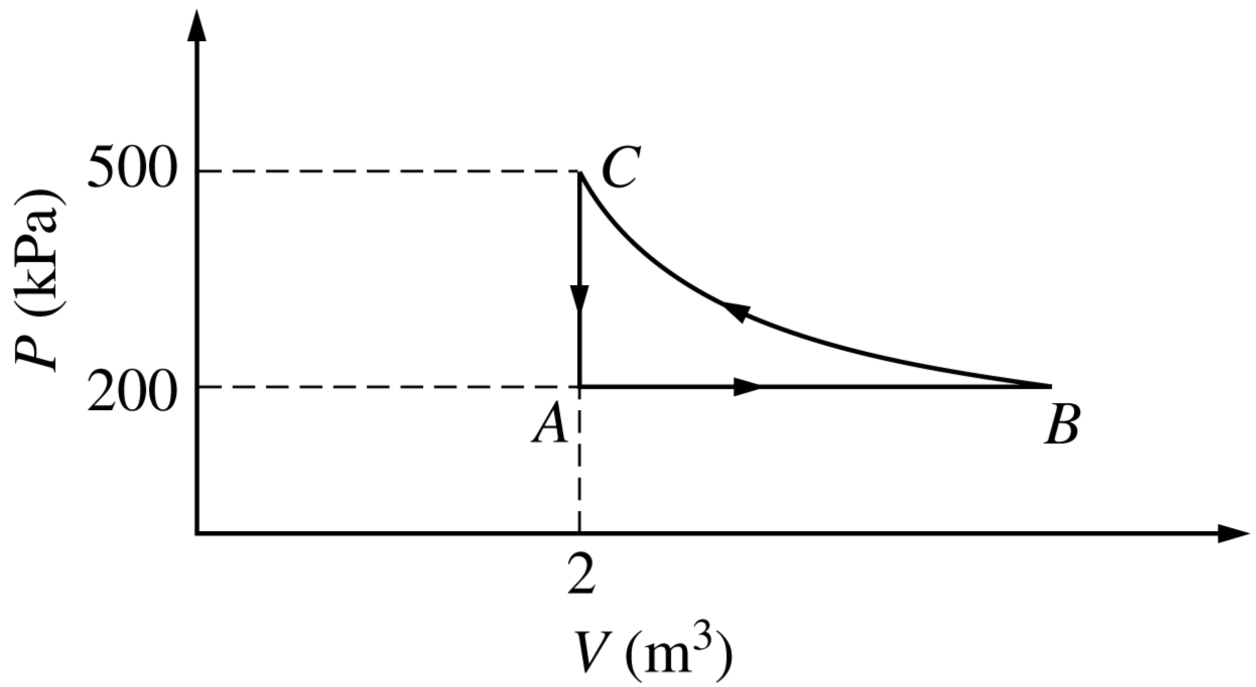


Two relations



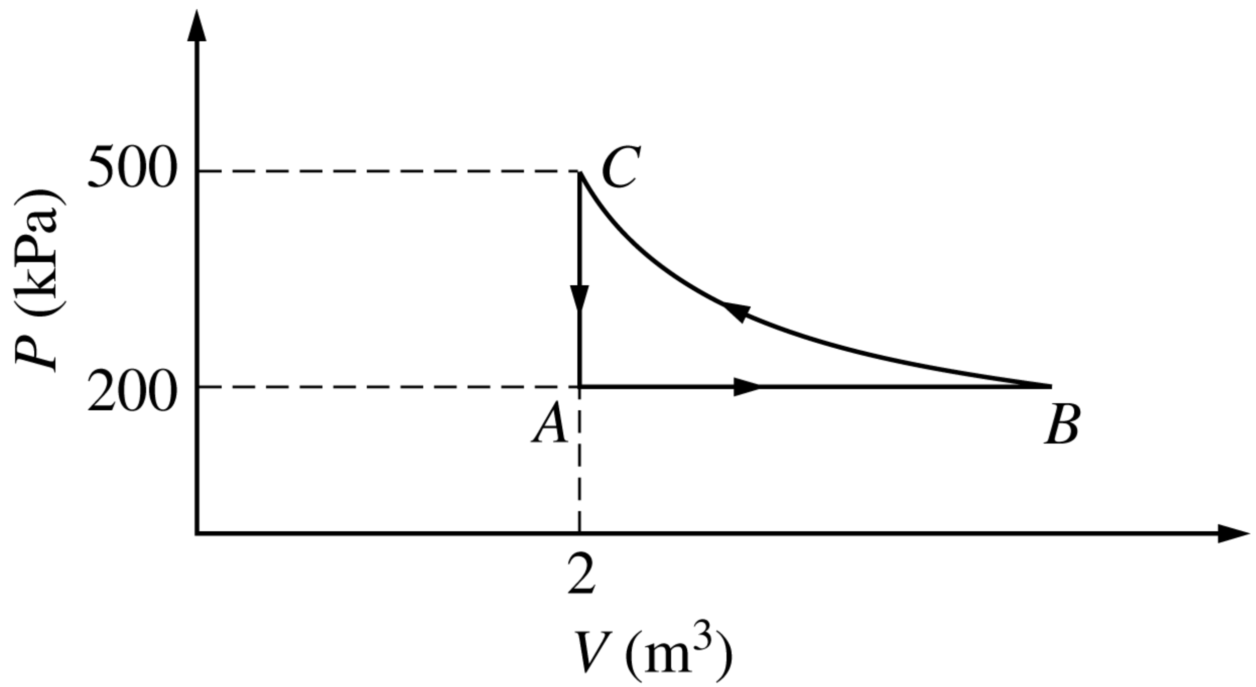
(1) Net work done equal Area inside cycle

(2) Net work done equals net heat added (since engine returns to original state)



37. A constant amount of an ideal gas undergoes the cyclic process *ABCA* in the *PV* diagram shown above. The path *BC* is isothermal. The work done by the gas during one complete cycle, beginning and ending at *A*, is most nearly

(A) 600 kJ
(B) 300 kJ
(C) 0
(D) −300 kJ
(E) −600 kJ



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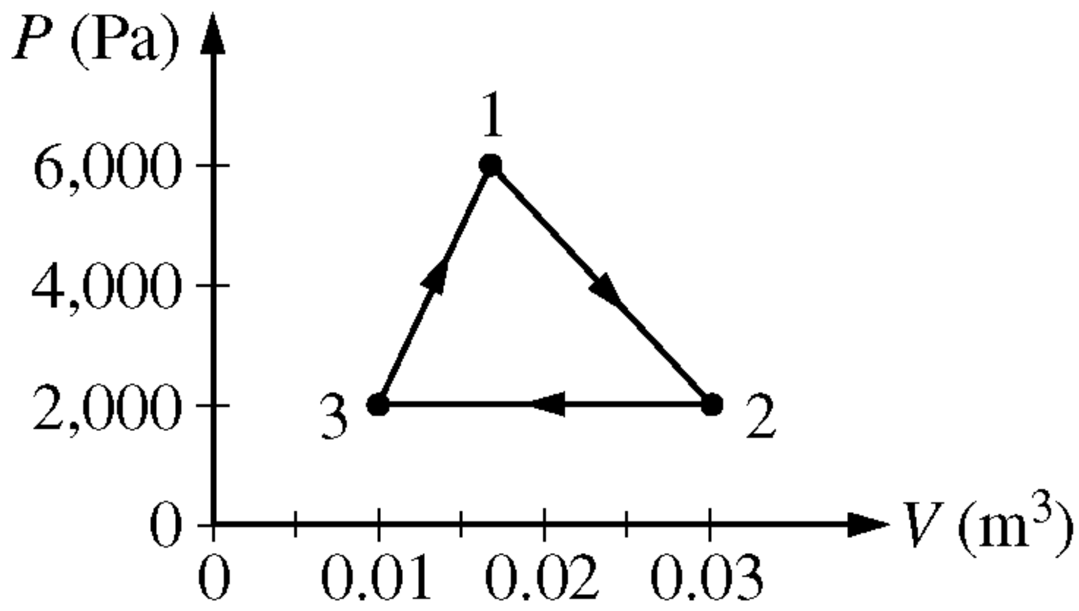
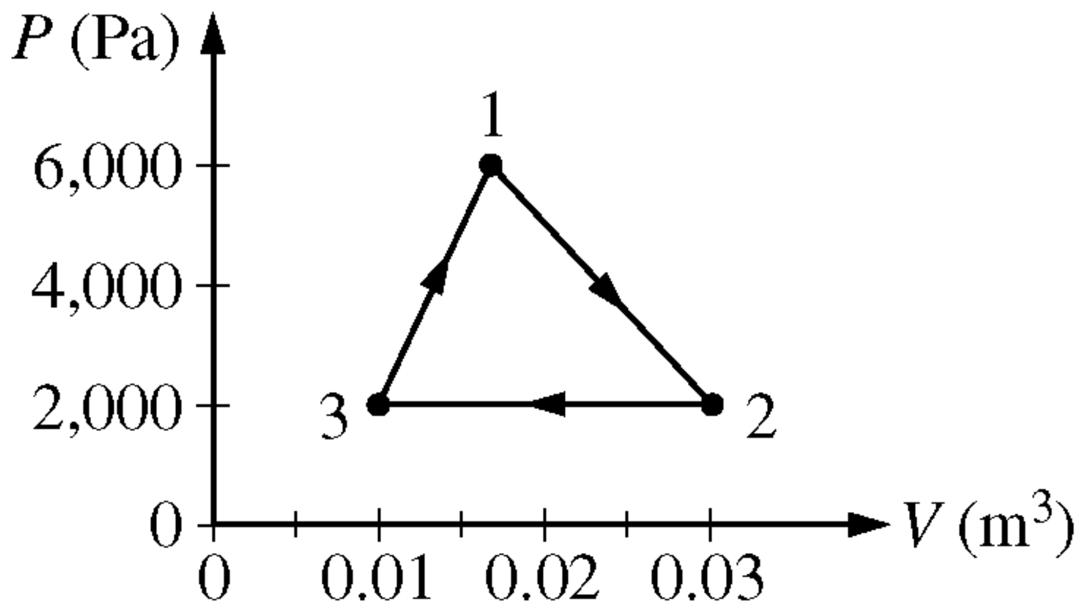


28. A sample of nitrogen gas undergoes the cyclic thermodynamic process shown above. Which of the following gives the net heat transferred to the system in one complete cycle $1 \rightarrow 2 \rightarrow 3 \rightarrow 1$?

(A) –80 J
(B) –40 J
(C) 40 J
(D) 80 J
(E) 180 J



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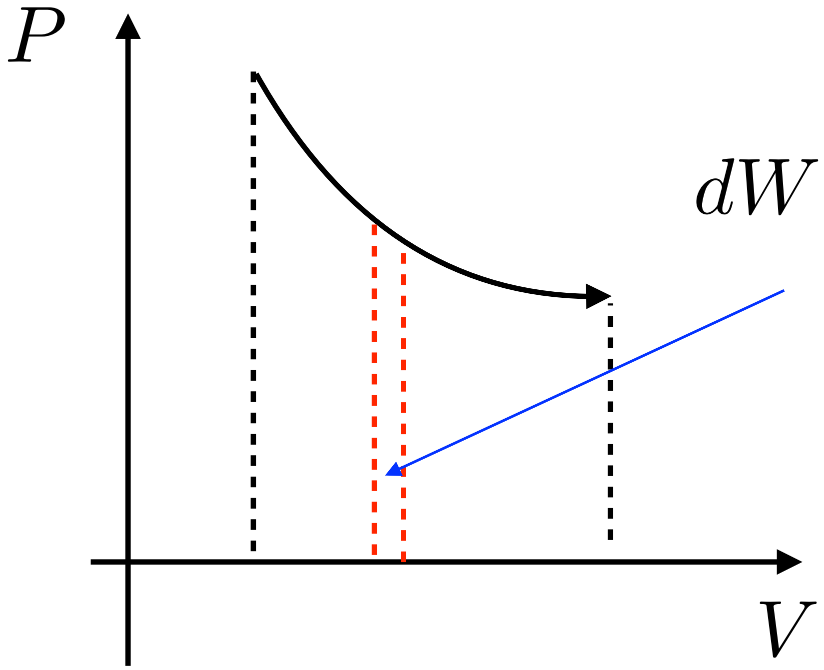
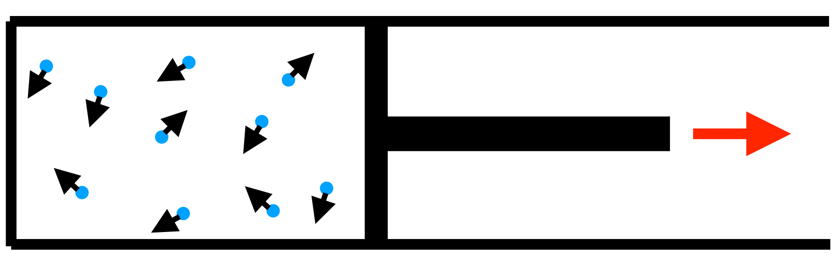


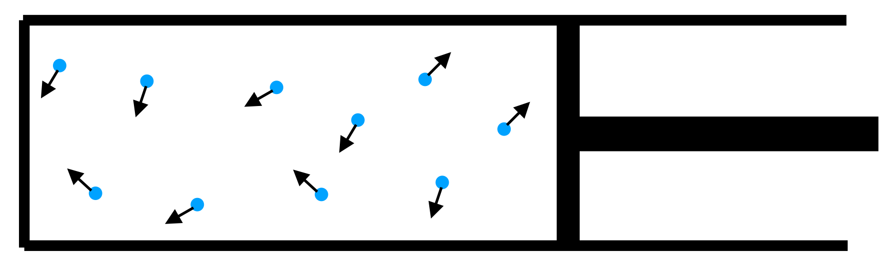
$$dW = PdV$$

Volume in increases

Temperature decreases (atoms slower)

Pressure decreases (atoms slower and also more distance to travel)

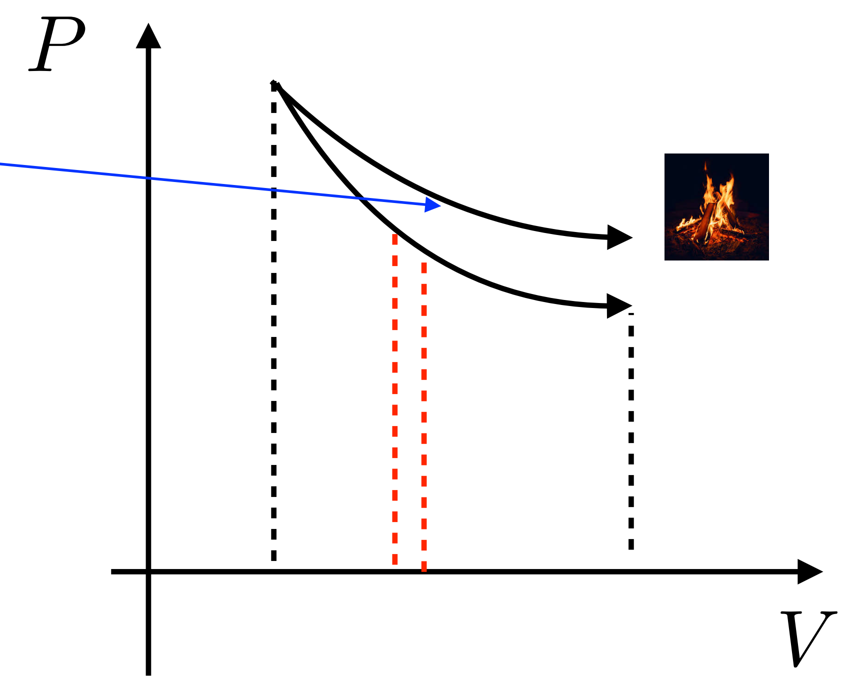




To keep temperature constant, add heat

Pressure still drops, since volume rises

To keep pressure constant, need to add even more heat

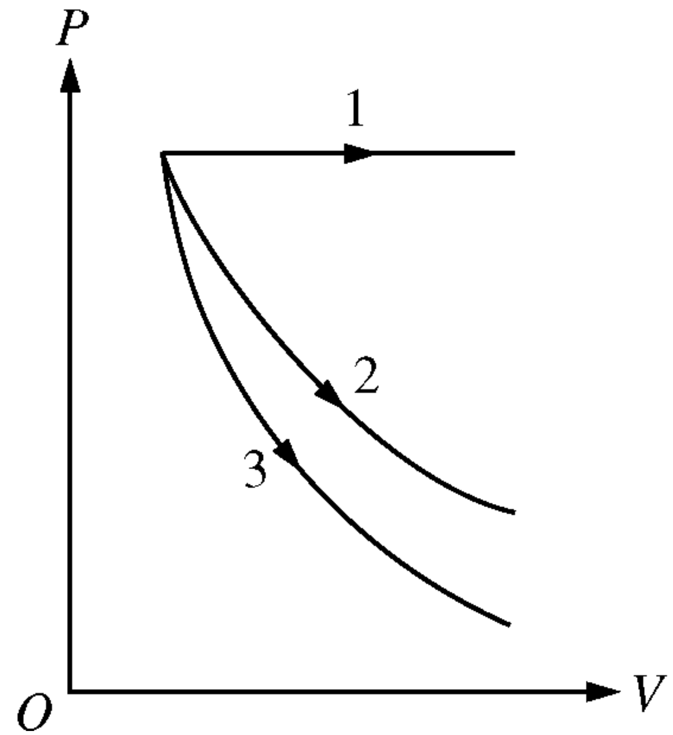


Terminology

Isothermal: constant temperature

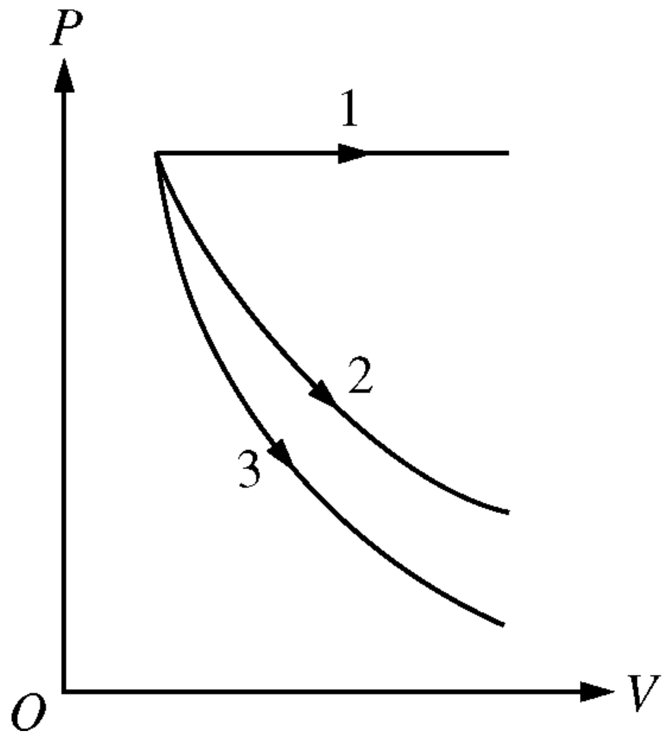
Isobaric: constant pressure

Adiabatic: no heat added or removed



29. For an ideal gas, consider the three thermodynamic processes—labeled 1, 2, and 3—shown in the PV diagram above. Each process has the same initial state and the same final volume. One process is adiabatic, one is isobaric, and one is isothermal. Which of the following correctly identifies the three processes?

	Adiabatic	Isobaric	Isothermal
(A)	1	2	3
(B)	2	1	3
(C)	2	3	1
(D)	3	1	2
(E)	3	2	1



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GRE0177

6. An ideal monatomic gas expands quasi-statically to twice its volume. If the process is isothermal, the work done by the gas is W_i. If the process is adiabatic, the work done by the gas is W_a. Which of the following is true?

(A) $W_i = W_a$
(B) $0 = W_i < W_a$
(C) $0 < W_i < W_a$
(D) $0 = W_a < W_i$
(E) $0 < W_a < W_i$

GRE0177

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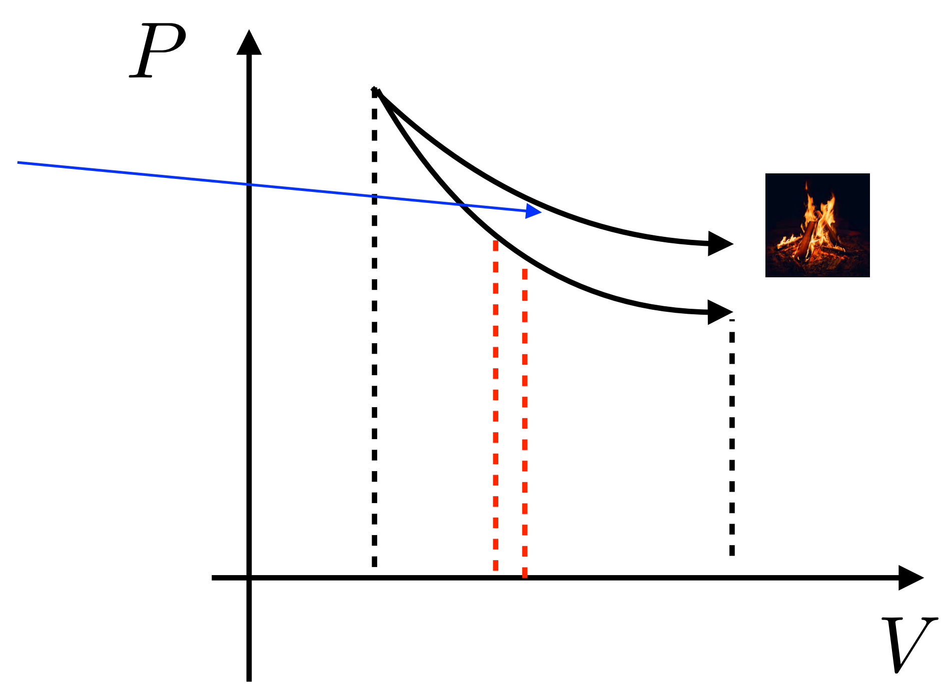
To keep temperature constant, add heat



8. For which of the following thermodynamic processes is the increase in the internal energy of an ideal gas equal to the heat added to the gas?

   (A) Constant temperature
   (B) Constant volume
   (C) Constant pressure
   (D) Adiabatic
   (E) Cyclic

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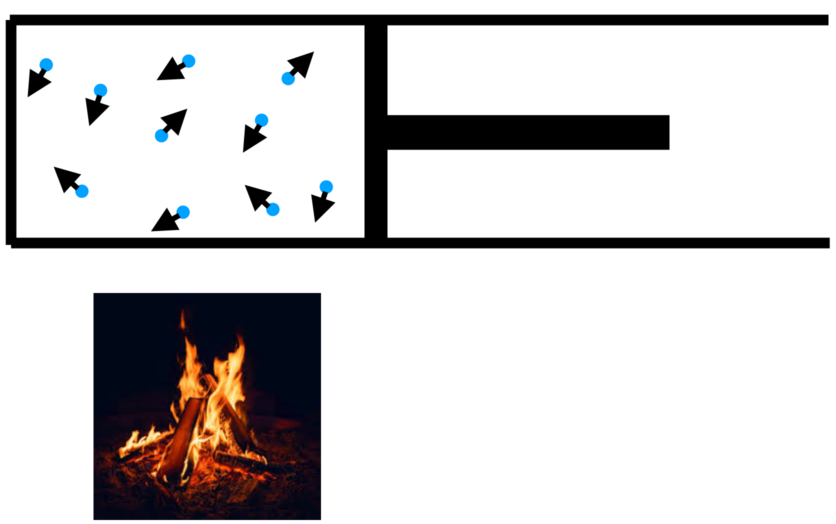
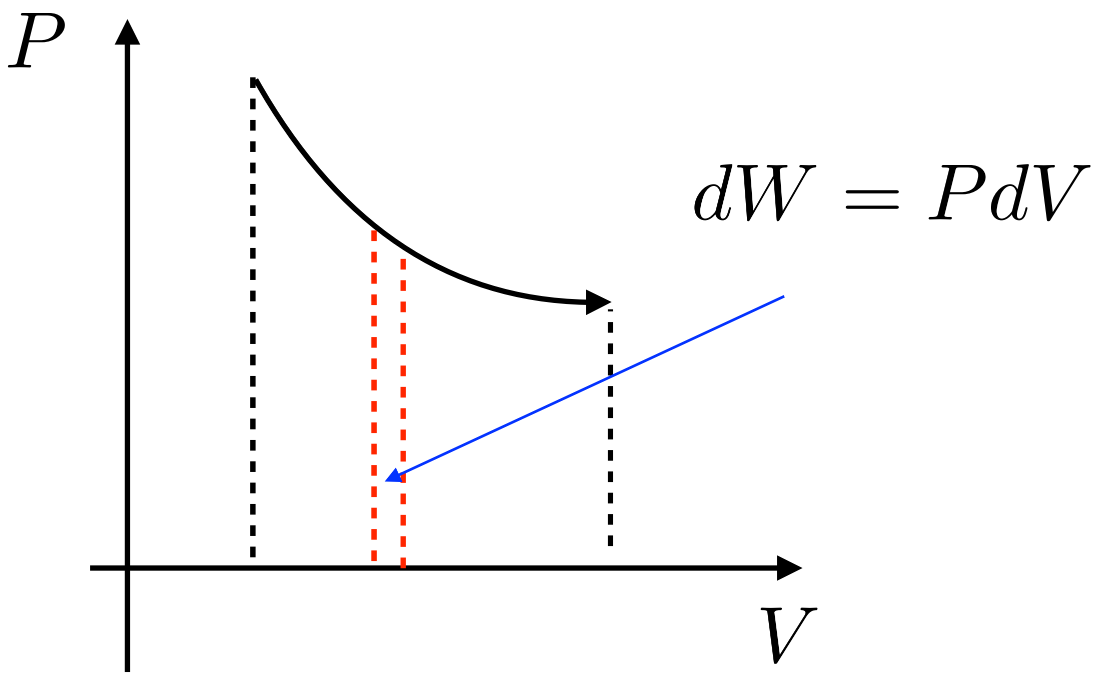
(C) Constant pressure
(D) Adiabatic
(E) Cyclic



Increase in internal energy equals heat added minus Work done by gas

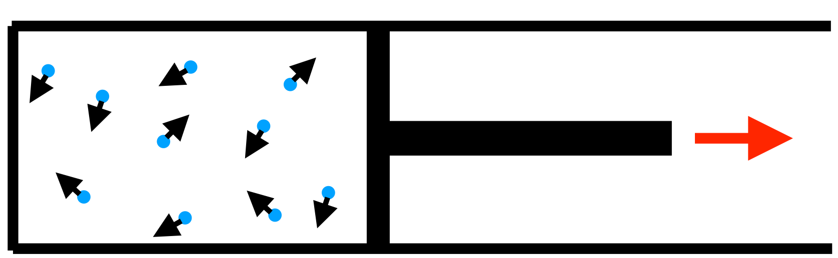
Entropy

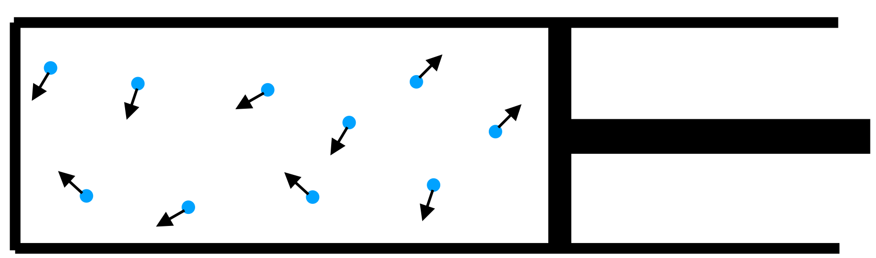


Volume in increases

Temperature decreases (atoms slower)

Pressure decreases (atoms slower and also more distance to travel)

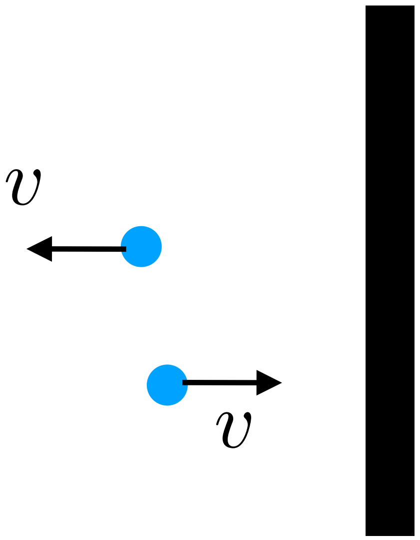




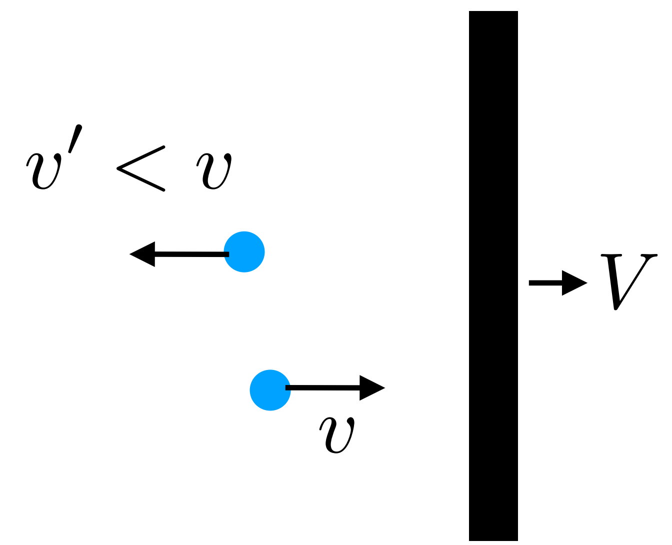
Does anything stay the SAME?

Why do the atoms slow down?

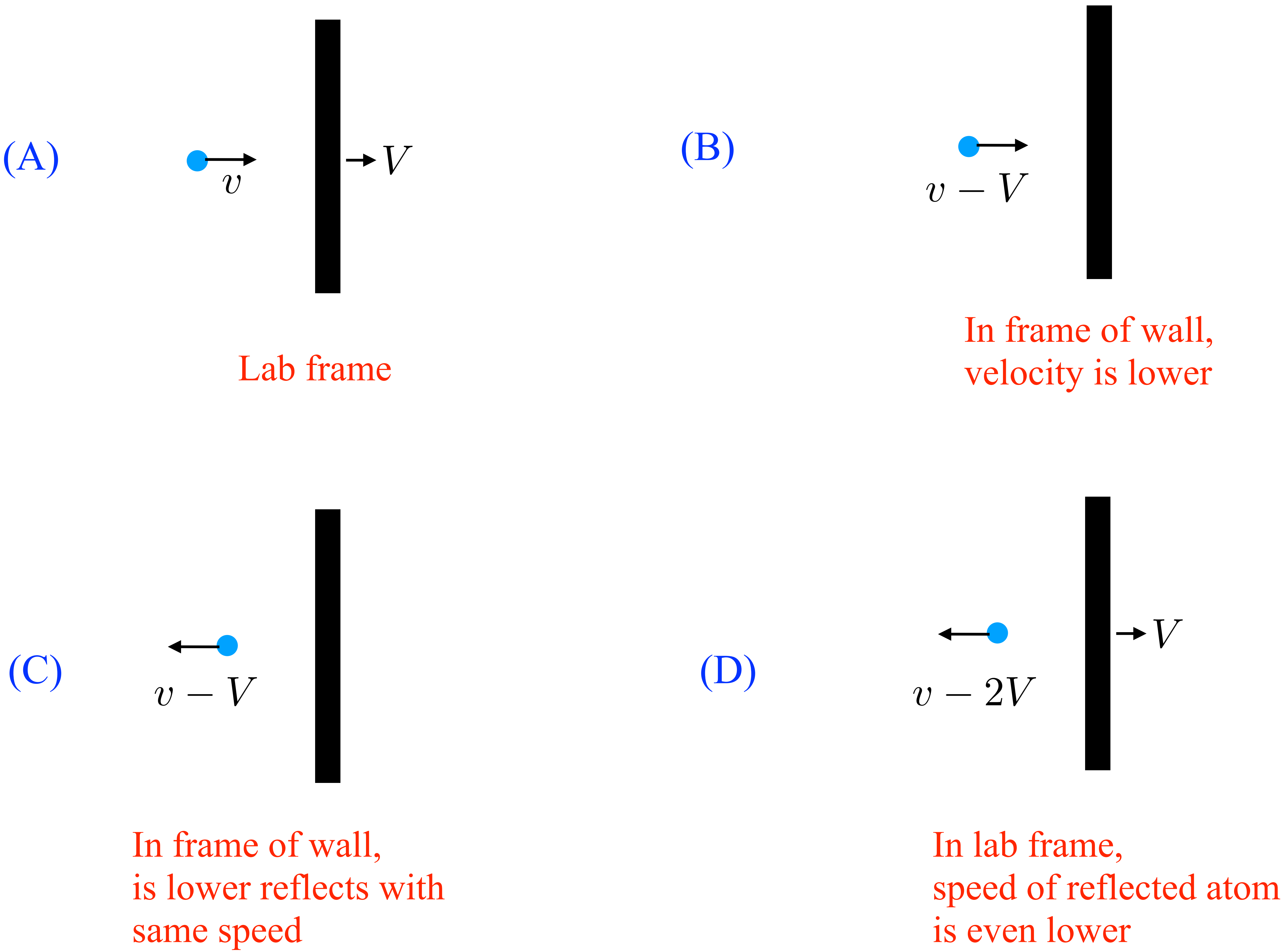
Stationary wall



Moving wall

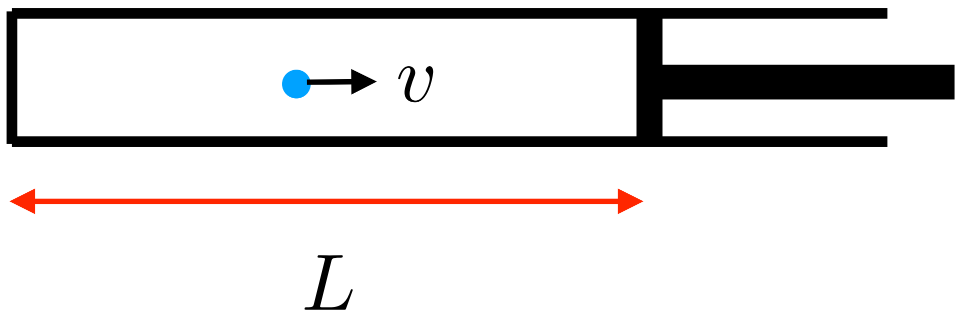


So atoms slow down when we expand the box ....



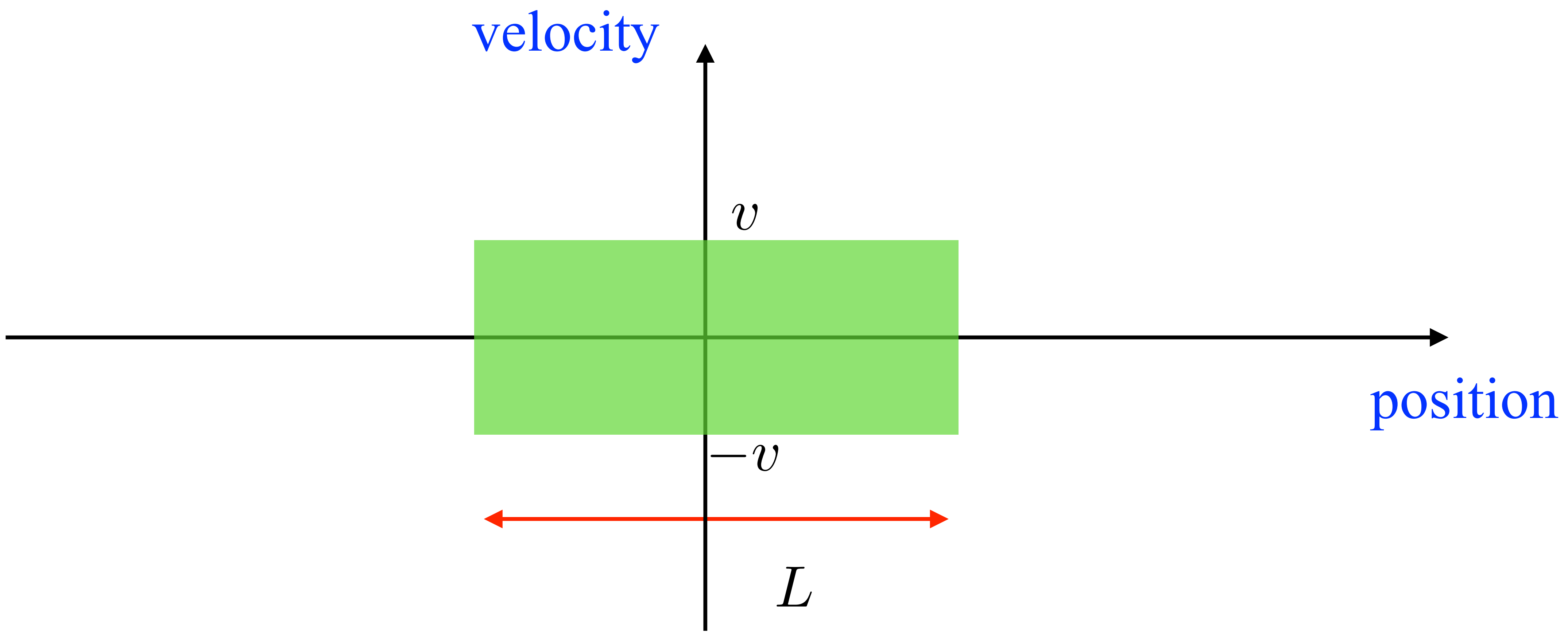
(A)
v
V
Lab frame
(B)
$v - V$
In frame of wall,
velocity is lower
(C)
$v - V$
In frame of wall,
is lower reflects with
same speed
(D)
$v - 2V$
V
In lab frame,
speed of reflected atom
is even lower

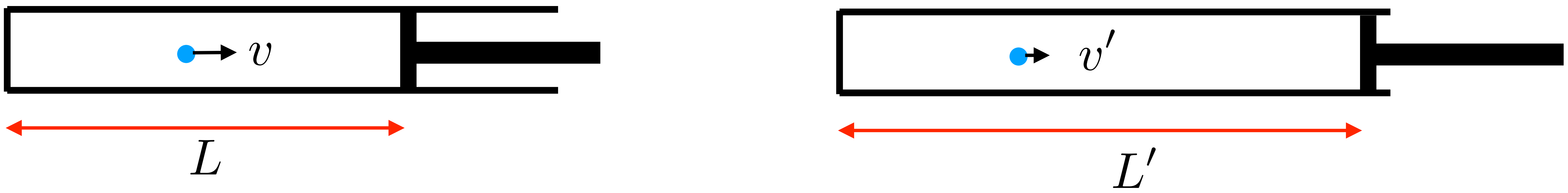
1-dimension

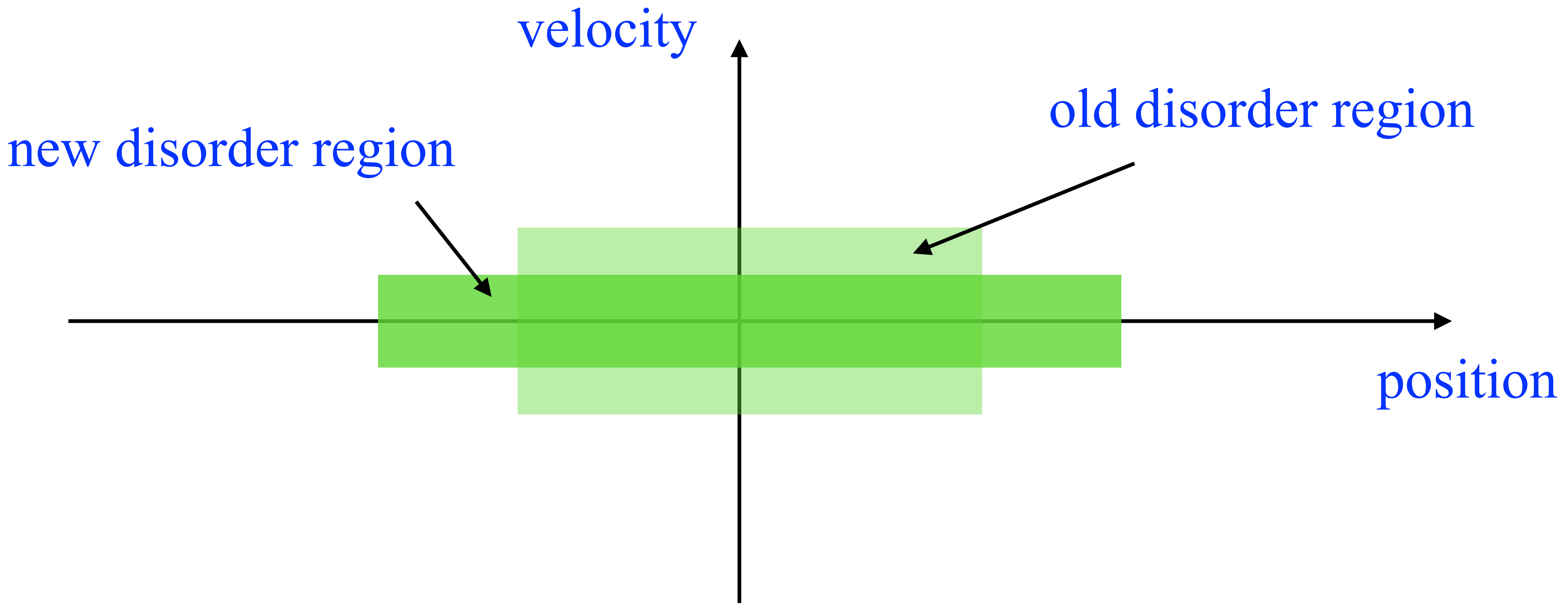


Disorder in position $\Delta x = L$

Disorder in velocity $\Delta v = 2v$



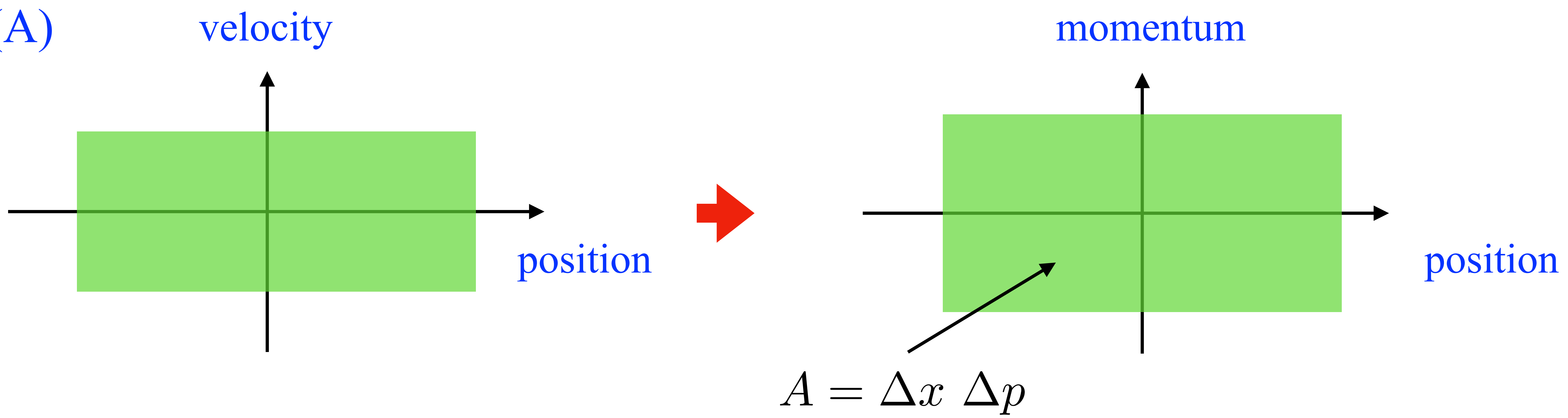




The Area of the two regions is the same → **Entropy**

Three notational modifications

(A)



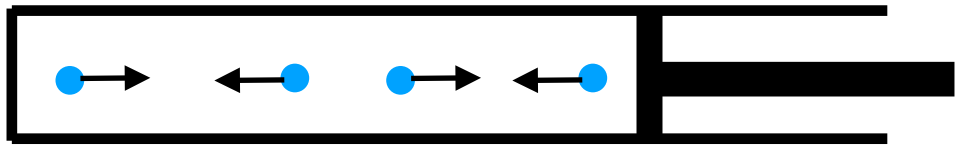
(B) Consider Log of Area instead of Area

$$\ln A = \ln(\Delta x \, \Delta p)$$

(C) Multiply by k

$$S = k \ln A = k \ln(\Delta x \, \Delta p)$$

Note: If there are N atoms then multiply entropy by N



$$S = N\,k\ln A = N\,k\ln(\Delta x\,\Delta p)$$

36. Consider the quasi-static adiabatic expansion of an ideal gas from an initial state i to a final state f. Which of the following statements is NOT true? **GRE0177**

(A) No heat flows into or out of the gas.
(B) The entropy of state i equals the entropy of state f.
(C) The change of internal energy of the gas is $-\int PdV$.
(D) The mechanical work done by the gas is $\int PdV$.
(E) The temperature of the gas remains constant.

GRE0177

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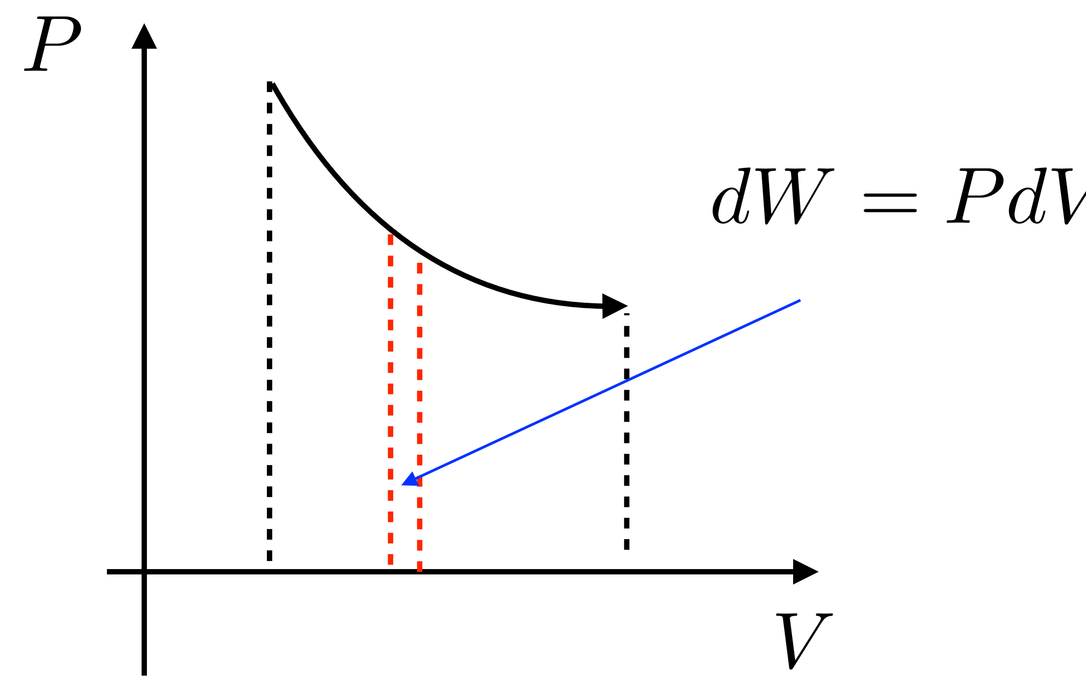
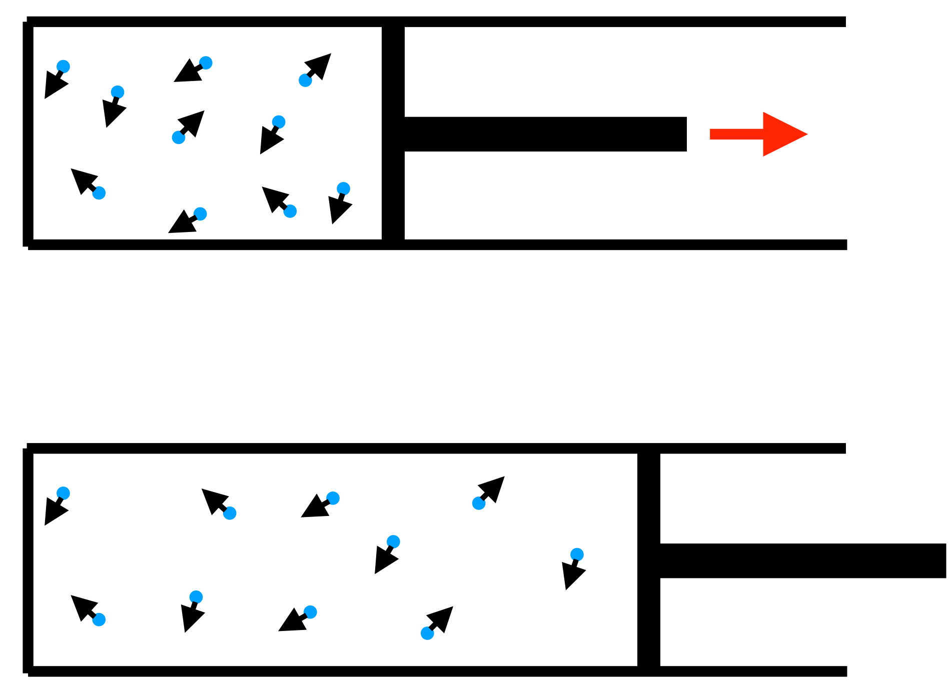
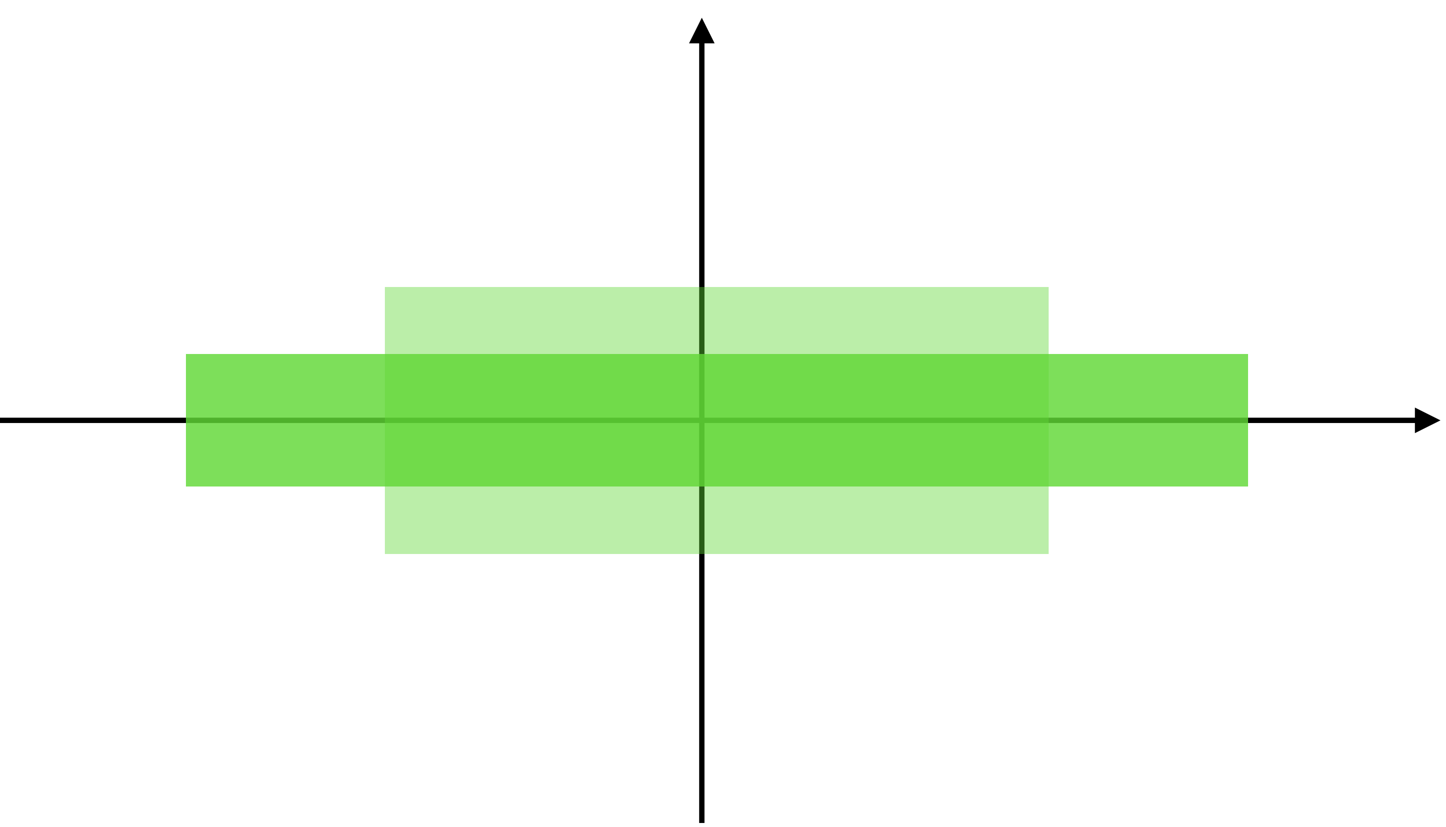
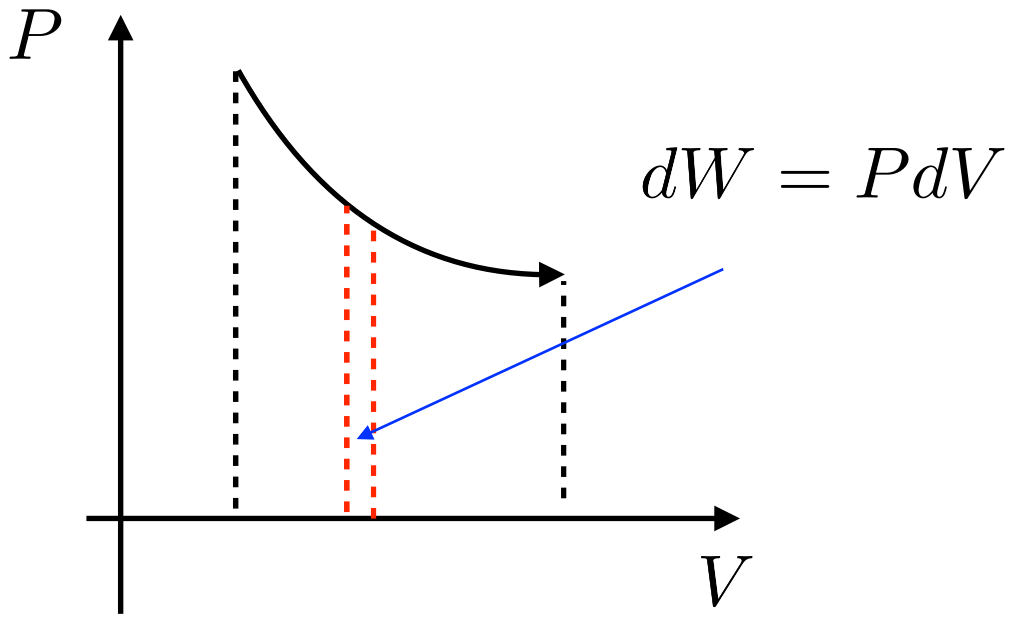
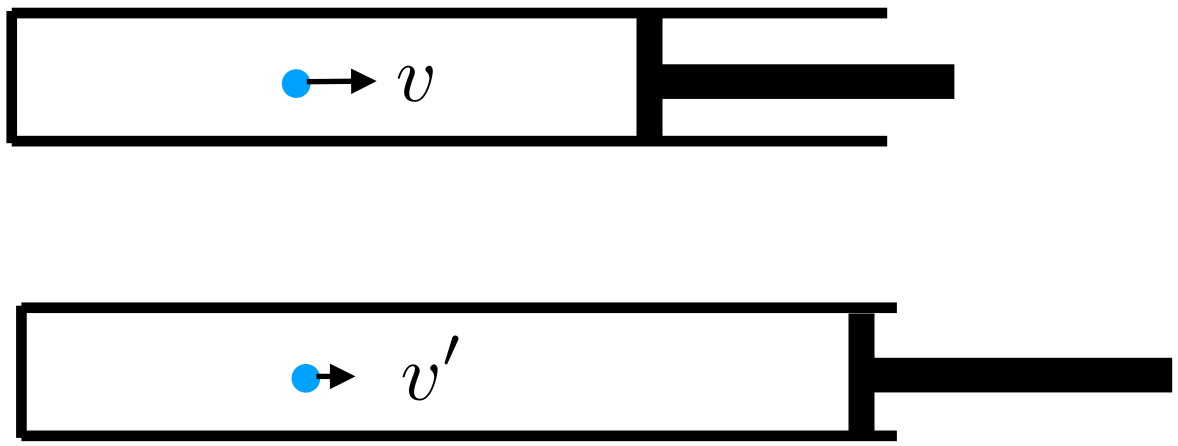
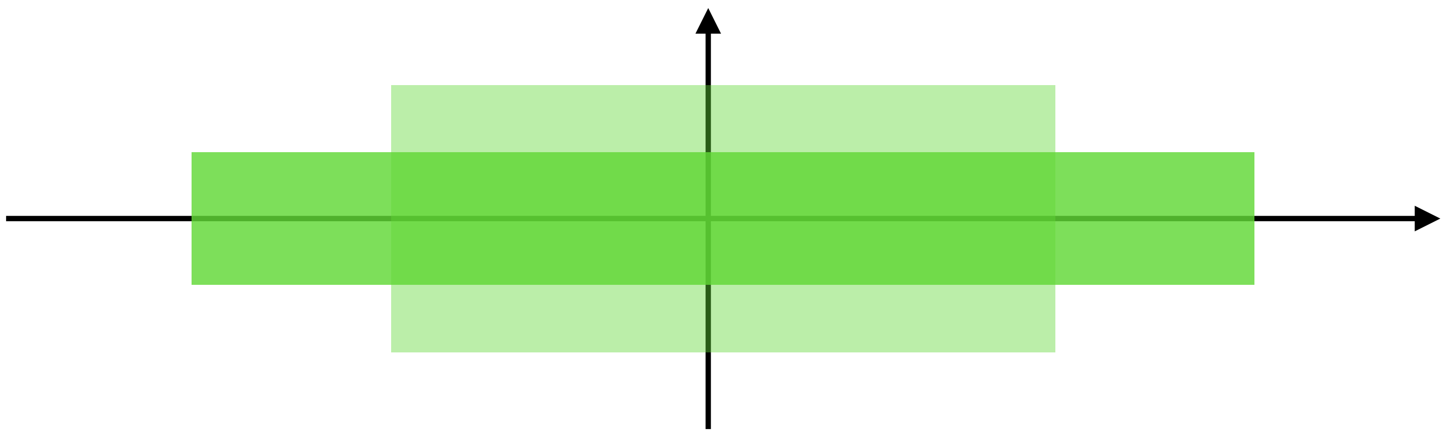










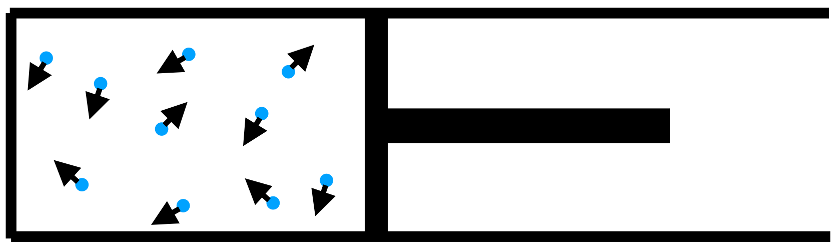


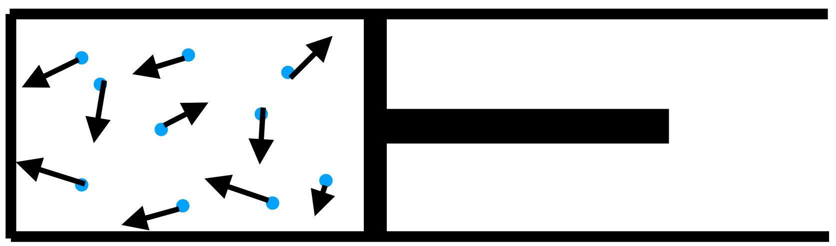
If entropy does not change in such processes, then how *DOES* it change ?

Two ways: (A) Add heat

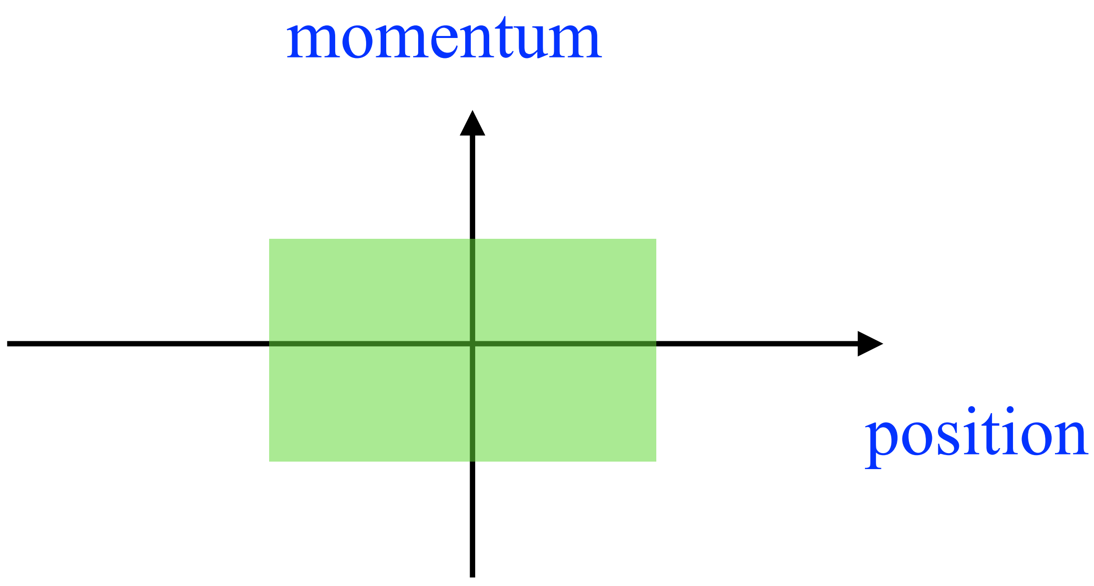
(B) Change things quickly (irreversible process)

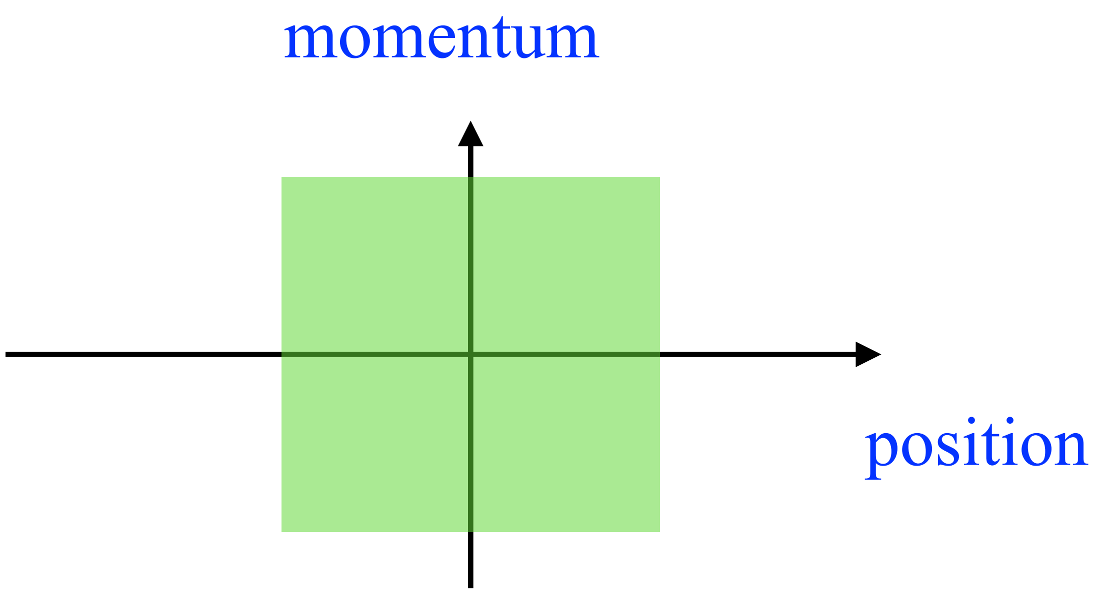
(A) Add heat





ΔQ

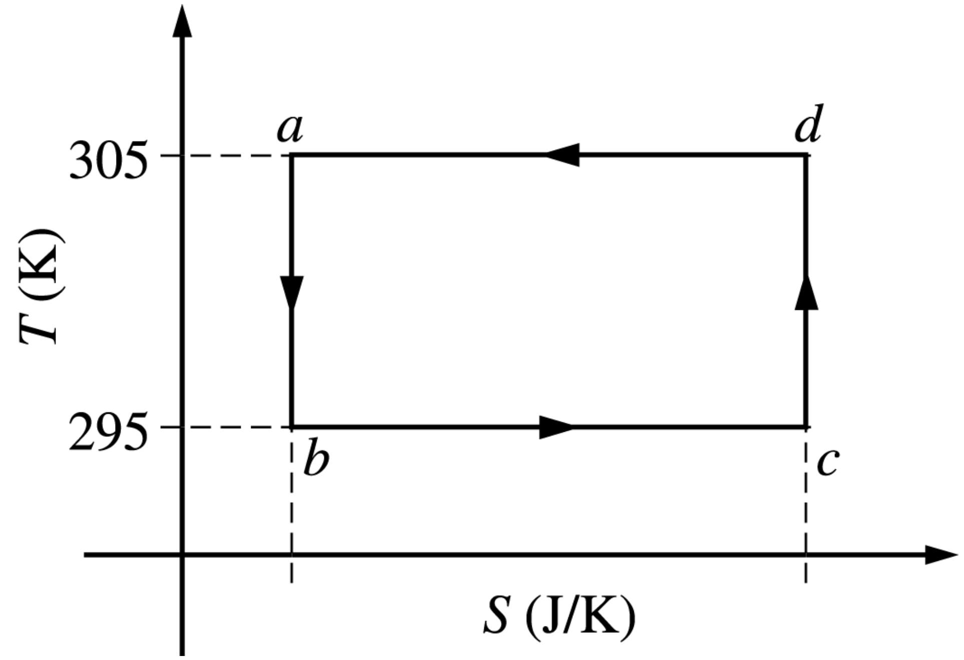




$$\Delta Q \propto \Delta S$$

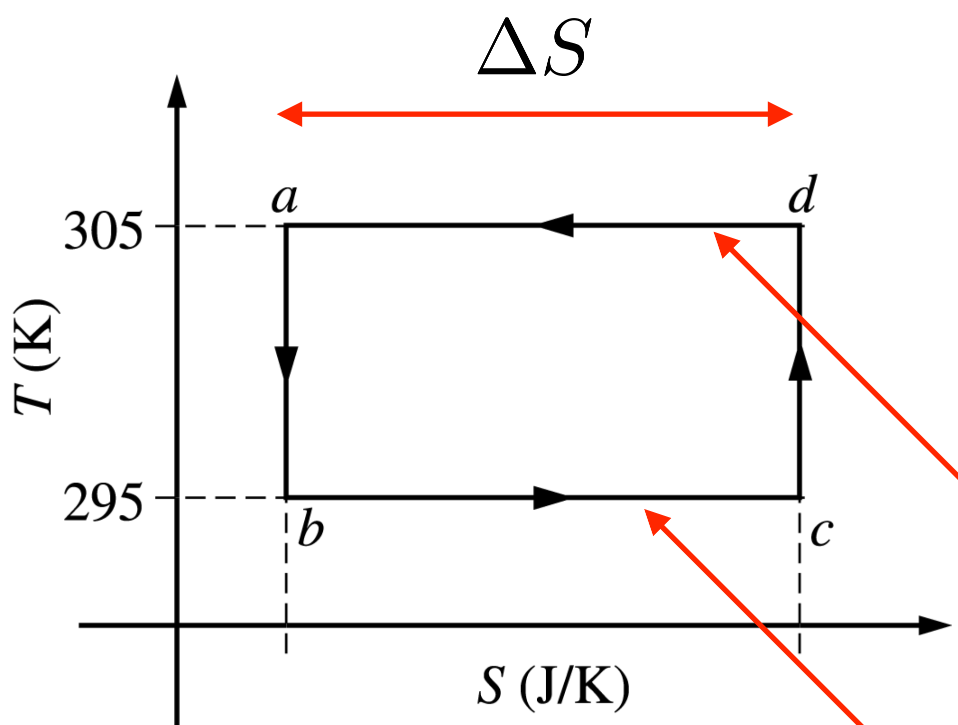
$$\boxed{\Delta Q = T \Delta S}$$

(Definition of temperature
in thermodynamics)



91. The diagram above shows a Carnot cycle for an ideal air conditioner, which is to cool a house on a hot summer day. The air conditioner absorbs heat at the lower temperature inside and pumps it to the environment at the higher temperature outside. Which of the following gives the ratio of the heat Q_{bc} absorbed in the house (i.e., between points b and c on the cycle) to the work done during the cycle?

(A) 0
(B) 0.033
(C) 0.97
(D) 1.0
(E) 30.



Total work done = Total heat absorbed

$$\Delta Q = T\,\Delta S$$

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$$Q_{emitted} = 305\Delta S$$

$$Q_{absorbed} = 295\Delta S$$

$$W = 10\Delta S$$

$$\frac{Q_{absorbed}}{W} = \frac{295}{10} \approx 30$$

58. A monatomic ideal gas changes from an initial state $(P_i,\ V_i,\ T_i,\ n_i)$ to a final state $(P_f,\ V_f,\ T_f,\ n_f)$, where $P_i < P_f$, $V_i = V_f$, $T_i < T_f$ and $n_i = n_f$. Which of the following gives the change in entropy of the gas?

(A) $\frac{3}{2} nR \ln\left(\frac{T_f}{T_i}\right)$

(B) $\frac{3}{2} nR \ln\left(\frac{T_i}{T_f}\right)$

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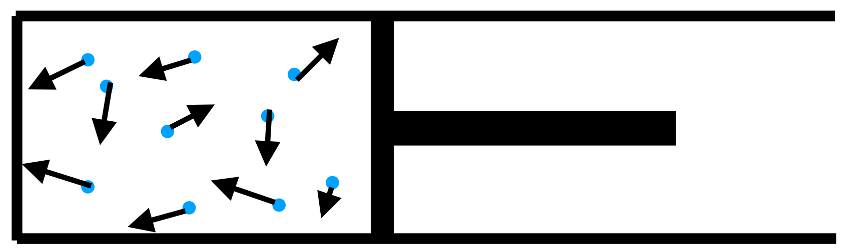


ΔQ

$$\Delta Q = T\,\Delta S$$

$$\Delta S = \frac{\Delta Q}{T}$$

No work $\Delta Q = \Delta U$

$$U = \frac{3}{2}NkT = \frac{3}{2}nRT$$

$$\Delta U = \frac{3}{2}nR\Delta T$$

$$\Delta S = \frac{3}{2}nR\frac{\Delta T}{T}$$

$$S_f - S_i = \frac{3}{2}nR\int_{T_i}^{T_f}\frac{dT}{T}$$

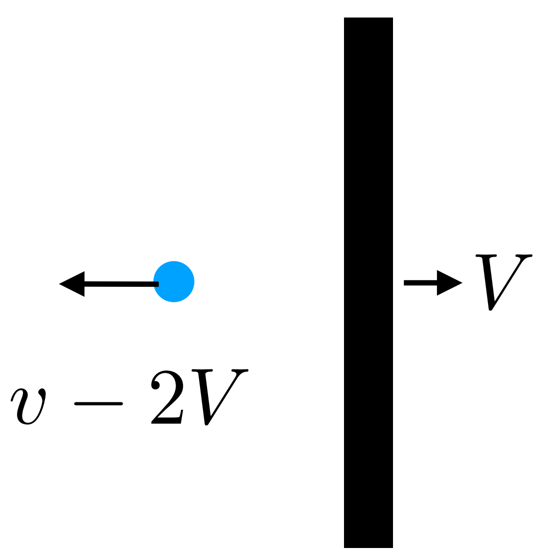
$$= \frac{3}{2}nR\ln\frac{T_f}{T_i}$$

Irreversibility

How do we increase entropy ?

Two ways: (A) Add heat

(B) Change things quickly (irreversible process)



What is we move the piston at half the speed?

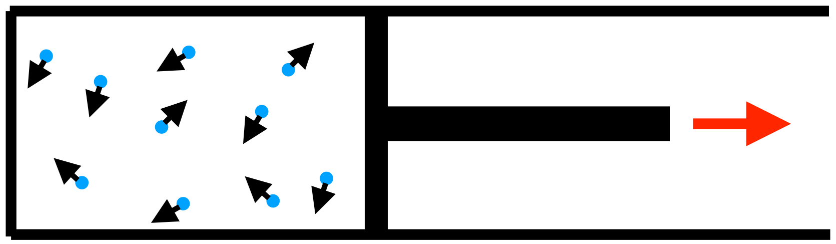
In each bounce, half as much slowdown

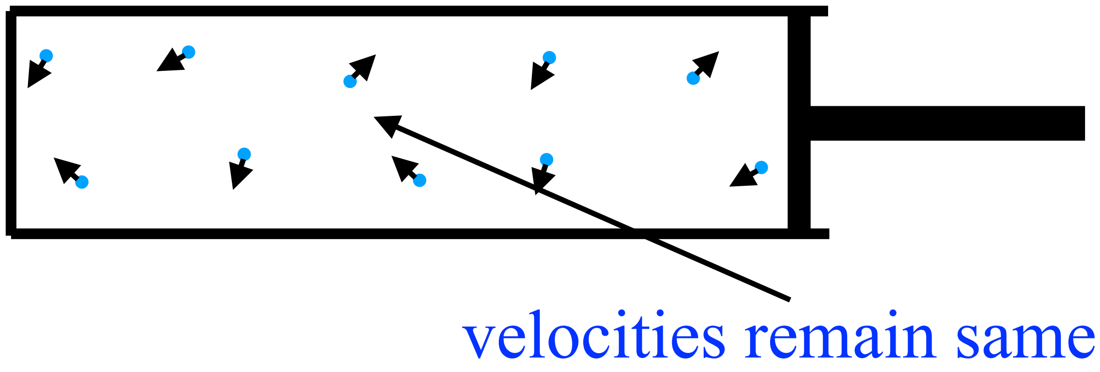
But there will be twice as many bounces ...

So total slowdown will be the same ...

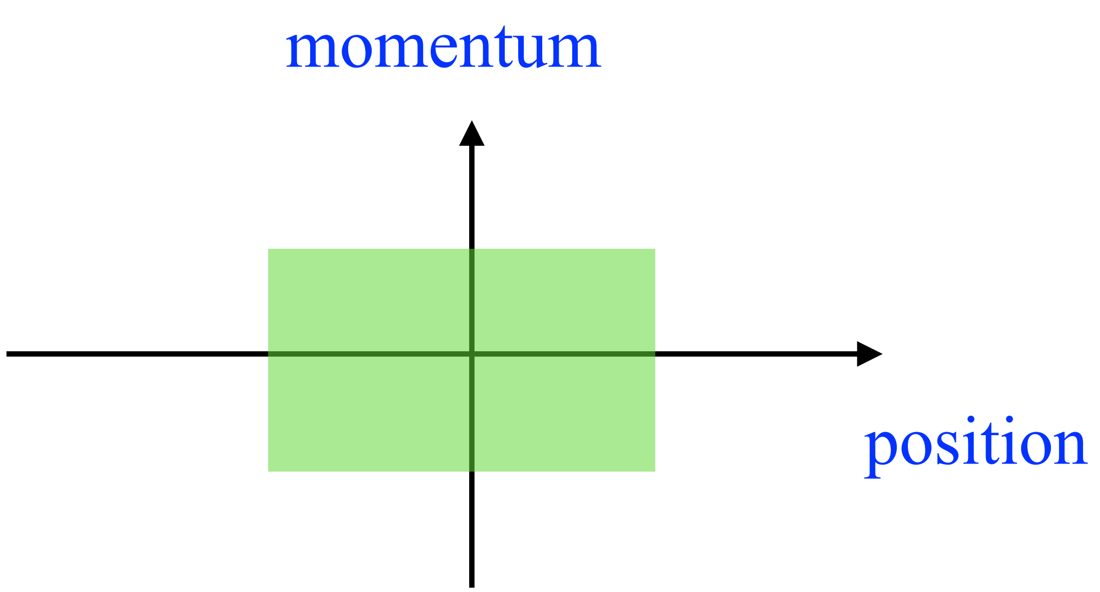
So we don't have to specify the speed of the piston ...

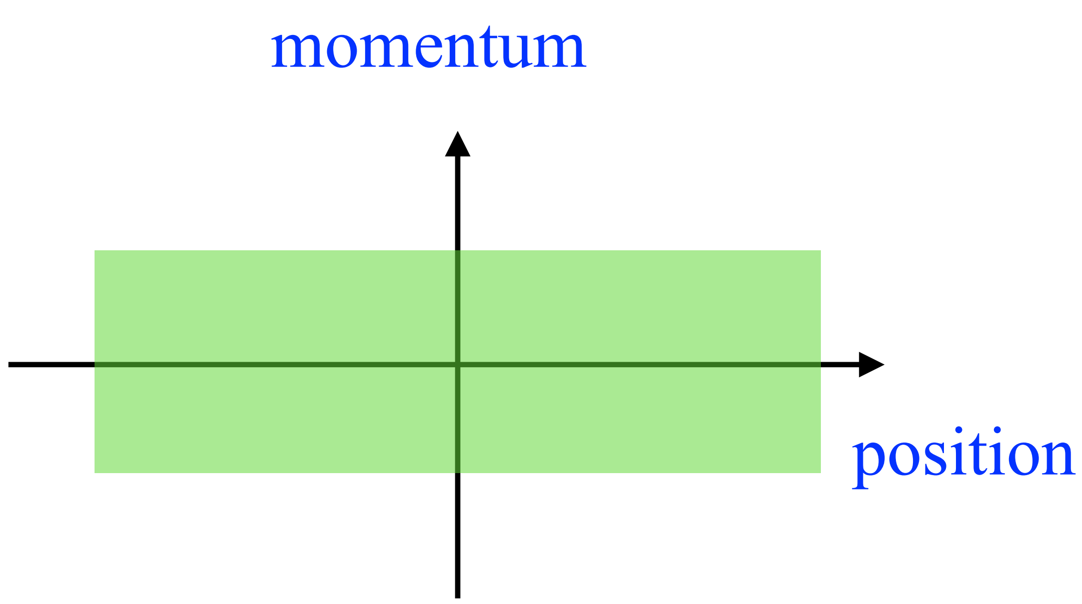
But what happens if we move the piston VERY fast?





Atoms don't touch the piston, so they don't slow down !





Entropy increases !

47. A sealed and thermally insulated container of total volume V is divided into two equal volumes by an impermeable wall. The left half of the container is initially occupied by n moles of an ideal gas at temperature T. Which of the following gives the change in entropy of the system when the wall is suddenly removed and the gas expands to fill the entire volume?

(A) $2nR \ln 2$

(B) $nR \ln 2$

(C) $\frac{1}{2}nR \ln 2$

(D) $-nR \ln 2$

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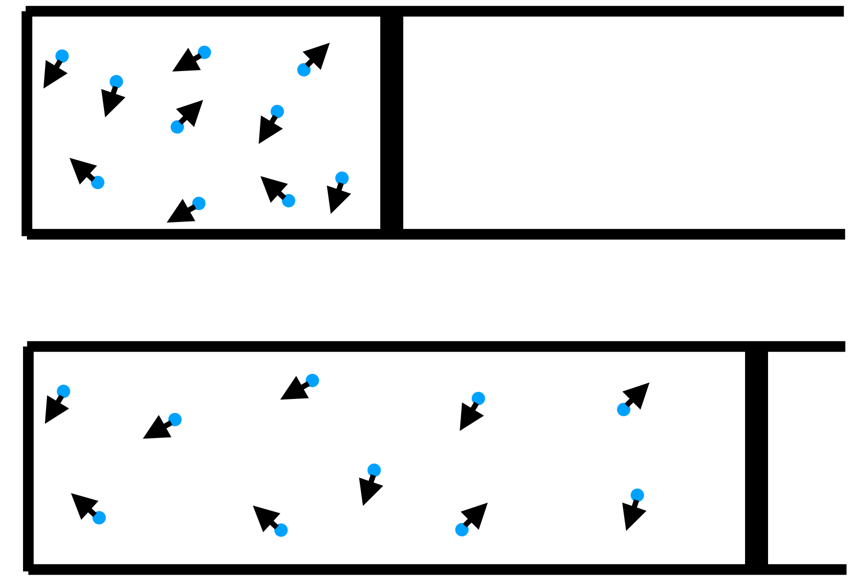

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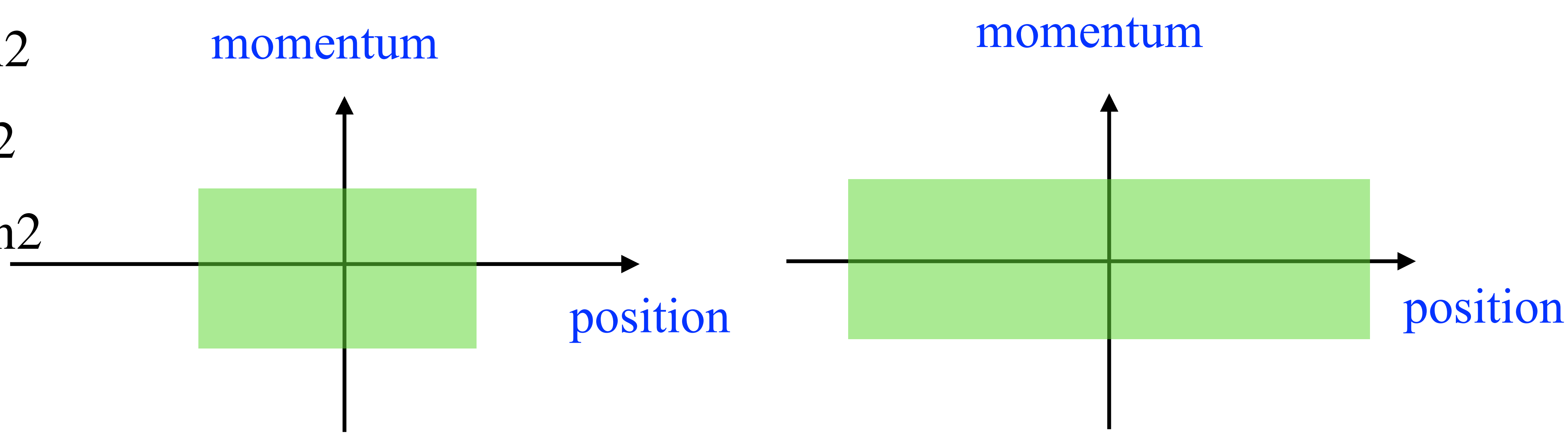
$L \rightarrow 2L \qquad v \rightarrow v$

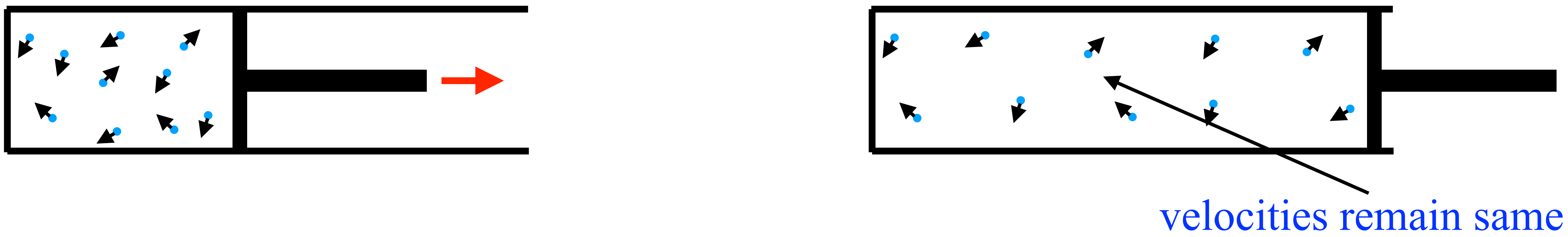


$A \rightarrow 2A$

$$S = k\ln A \rightarrow k\ln(2A) = k\ln A + k\ln 2$$

$$\Delta S_{total} = Nk\ln 2 = nR\ln 2$$

Irreversibility



Can we reverse this process ? NO !

If we try to move piston back, it WILL hit the atoms and speed them up ...

Slow process are called QUASISTATIC. They are REVERSIBLE. There is NO net increase in entropy

Sudden changes are IRREVERSIBLE. There IS a net increase in entropy (disorder)

Entropy can increase but never decrease

7. Which of the following is true about any system that undergoes a reversible thermodynamic process?

   (A) There are no changes in the internal energy of the system.
   (B) The temperature of the system remains constant during the process.
   (C) The entropy of the system and its environment remains unchanged.
   (D) The entropy of the system and its environment must increase.
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