Physical Principles in Biology
Biology 3550
Fall 2018

# Lecture 25

# Thermodynamics:

# Expansion and Compression of a Gas, Part II

Monday, 29 October

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# GCSC Seminar Series

210 ASB
(Aline Skaggs Building)

*ALL ARE WELCOME*

Refreshments & meet the speaker at 3:45

## Tuesday, October 30, 2018
## 4:00-5:00 PM

**Gabriel G. Katul**
Theodore S. Coile Professor of Hydrology and Micrometeorology,
Nicholas School of the Environment, Duke University

## "Evapotranspiration: From kinetic theory to the limits of plant life"

*Research in Katul's group focuses on micro-meteorology and near-surface hydrology with emphasis on heat, momentum, carbon dioxide, water vapor, ozone, particulate matter (including aerosols, pollen, and seeds) and water transport in the soil-plant-atmosphere system as well as their implications to a plethora of hydrological, ecological, atmospheric and climate change related problems.*

GLOBAL CHANGE AND SUSTAINABILITY CENTER
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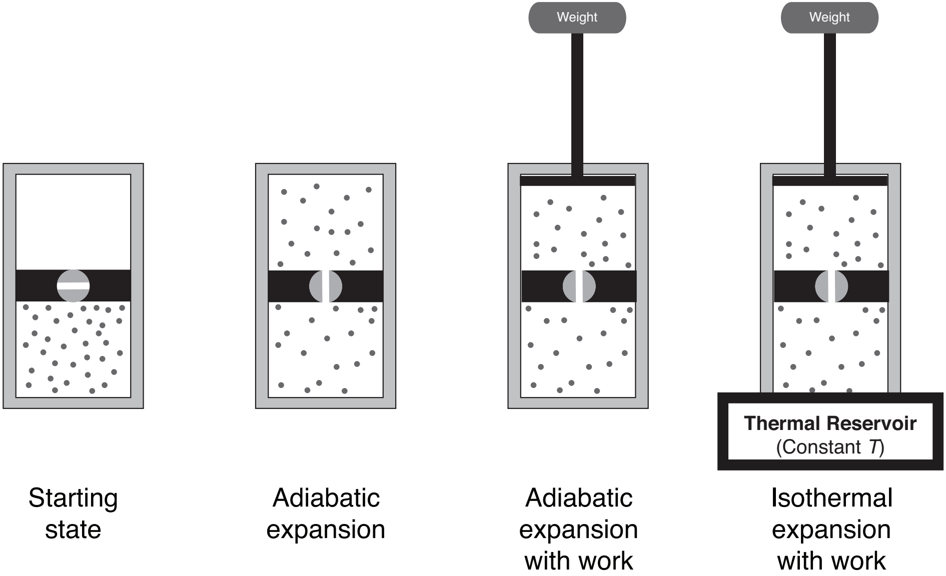
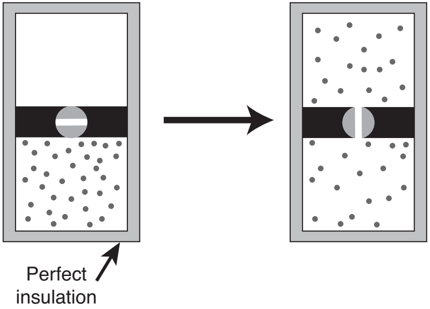
# Announcements

- Quiz 3: Friday, 2 November. First part of class.
- Problem Set 4 posted. Due, Friday, 9 November.
- No instructor office hours this week. My apologies!
- Discussion sessions:
  - Tuesdays, 11:00 AM – noon. Life Science 102
  - Wednesdays, 8:30 – 9:30 AM. Gardner Common 4680

# Different Ways to Allow a Gas to Expand

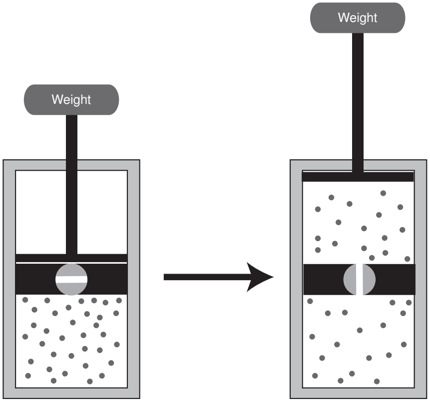


# Adiabatic (without heat flow) Expansion of a Gas



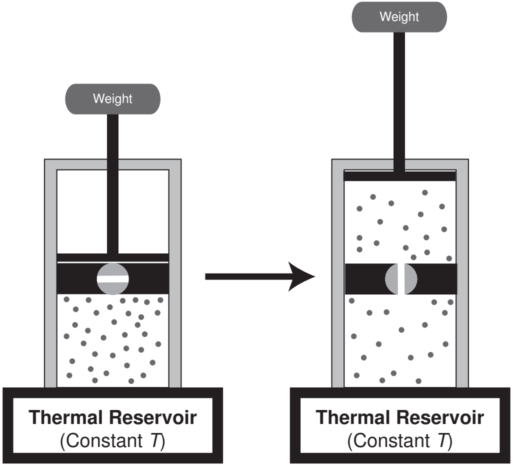

- Insulation prevents heat flow into or out of device.
- What changes?
  - Volume of gas increases.
  - Temperature stays constant.
  - Pressure of gas decreases ($P = nRT/V$)
  - Energy stays constant.
  - No work has been done.

# Adiabatic Gas Expansion With Work



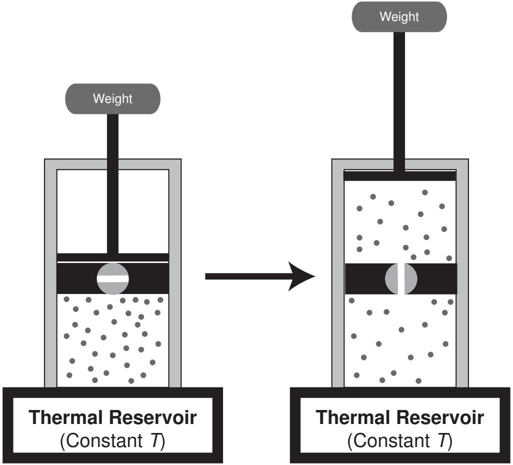

- Collisions of gas molecules with piston move the weight up.
- What changes?
  - Volume of gas increases.
  - Temperature decreases as energy is transferred to piston.
  - Pressure decreases, more than without the weight. ($P = nRT/V$)
  - Kinetic energy of gas molecules has decreased.
  - Work is done *by the system*, $w < 0$.

# Isothermal Expansion with Work




- Reservoir keeps the gas temperature constant. (isothermal)
- What changes?

# Clicker Question #1




Which of the following properties of the gas change?

A) Temperature

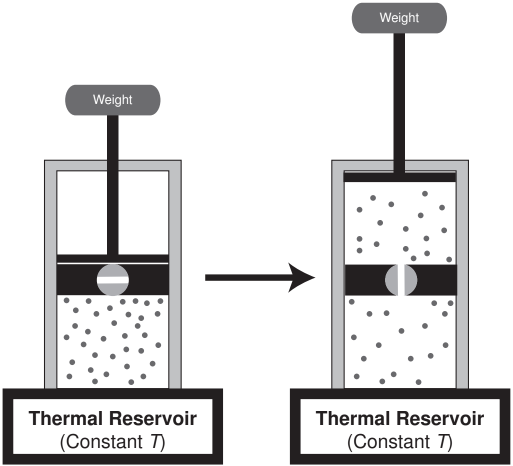
B) Pressure

C) Volume

D) Energy

Any answers count for now!

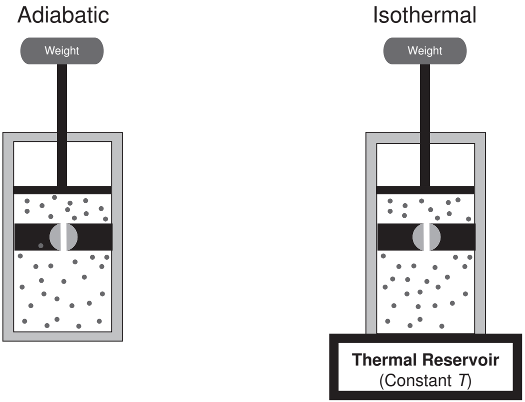
# Isothermal Expansion with Work




- Reservoir keeps the gas temperature constant. (isothermal)
- What changes?
  - Heat flows to keep gas temperature the same as the reservoir (which doesn't change).
  - As piston is pushed up, gas molecules lose energy, and temperature drops.
  - Heat flows from reservoir to restore temperature.
  - At the end, temperature is the same as at the beginning, *and* work has been done!

# Is More Work Done in the Adiabatic or Isothermal Expansion?

Part way through the two expansion processes:

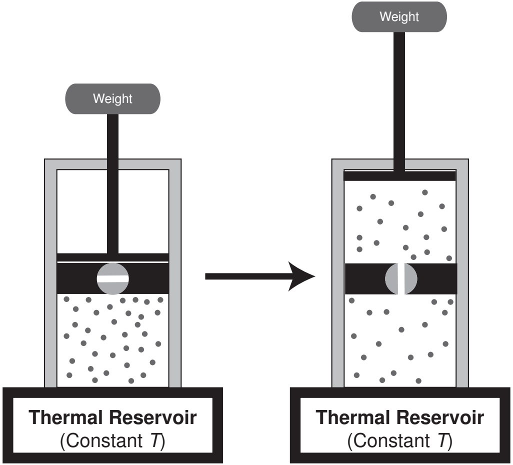



- $V_{ad} = V_{isot}$
- $T_{ad} < T_{isot}$
- $P_{ad} < P_{isot}$
- $F_{ad} < F_{isot}$

  $P$= Force/area.
- $w = -\int F dx$
- $w_{isot} < w_{ad}$

- A more negative value of $w$ means that the system does more work on the surroundings.

# Isothermal Expansion with Work




- The scorecard:
  - $\Delta E = 0$, temperature hasn't changed.
  - $w < 0$, because the system did work.
  - $\Delta E \neq w$
  - Where did the energy for work come from?
  - Heat flow into the system.

# Scorecard for Isothermal Expansion with Work

- Energy, $E$. Temperature at start and end are equal, $\Delta E = 0$.
- Work, $w$. Work has been done by the system, $w < 0$.
- A new quantity: Heat, $q$.
  - $q > 0$, when heat flows into the system.
  - $q < 0$, when heat flows out of the system into the surroundings.
  - For both work, $w$, and heat, $q$, a positive value indicates a transfer to the system from the surroundings.
- For this case, $q > 0$.

# The First Law of Thermodynamics

- Common statements in words:
  - "The energy of the universe is conserved"
  - "Energy can not be created or destroyed"
  - Later modified to account for interconversion of mass and energy. (Einstein's $E = mc^2$)
- The formal mathematical statement: For any process,

$$\Delta E = q + w$$

  - Any change in the energy of the system has to be accounted for by work or heat.
  - Work and heat represent the transfer of energy from the surroundings to the system.
- We can apply the first law to the three gas expansion experiments.

# Clicker Question #2

Which of the following is true?

A) $q < 0$

B) $q = 0$

C) $q > 0$

D) $w < 0$

E) $w = 0$

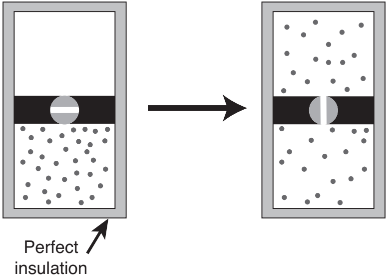
F) $w > 0$

G) $\Delta E < 0$

H) $\Delta E = 0$

I) $\Delta E > 0$

Adiabatic Expansion Without Work




$$\Delta E = q + w = 0$$

Up to 3 answers accepted.

Correct answers are worth $\frac{1}{2}$ point.

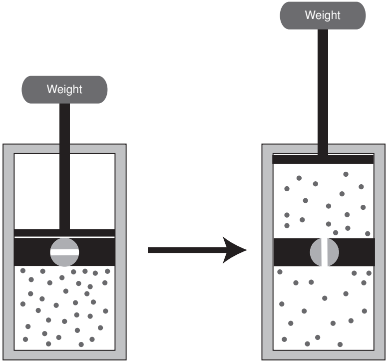
Wrong answers cost $\frac{1}{2}$ point.

Total guaranteed to be $\geq 0$.

# Clicker Question #3

Which of the following is true?

Adiabatic Expansion
With Work




A) $q < 0$

B) $q = 0$

C) $q > 0$

D) $w < 0$

E) $w = 0$

F) $w > 0$

G) $\Delta E < 0$

H) $\Delta E = 0$

I) $\Delta E > 0$

$$\Delta E = q + w < 0$$

Up to 3 answers accepted.

Correct answers are worth $\frac{1}{2}$ point.

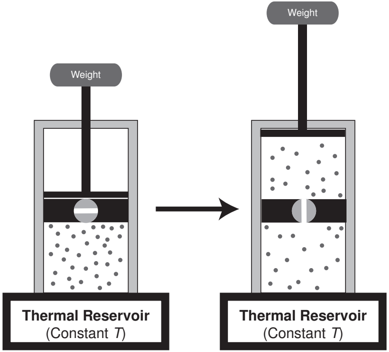
Wrong answers cost $\frac{1}{2}$ point.

Total guaranteed to be $\geq 0$.

# Clicker Question #4

Which of the following is true?

Isothermal Expansion
With Work




A) $q < 0$

B) $q = 0$

C) $q > 0$

D) $w < 0$

E) $w = 0$

F) $w > 0$

G) $\Delta E < 0$

H) $\Delta E = 0$

I) $\Delta E > 0$

$$\Delta E = q + w = 0$$

$$q = -w$$

Up to 3 answers accepted.

Correct answers are worth $\frac{1}{2}$ point.

Wrong answers cost $\frac{1}{2}$ point.

Total guaranteed to be $\geq 0$.

# Laws and Thermodynamics

- The laws of thermodynamics cannot be derived or proven!
- The laws are postulates, which no one has been able to disprove.

  And people have tried really hard!
- In 1775 the French Royal Academy of Sciences made the first law of thermodynamics (before it was called that) a legal law!

  Declared that the French patent office would no longer accept applications to patent perpetual motion machines.

# State Functions and Path-dependent Functions

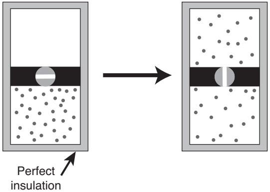
- State functions of a system depend only on the current state of the system and do not depend on history.
  Examples:
  - Temperature, $T$
  - Pressure, $P$
  - Volume, $V$
  - Energy, $E$
- For any change in a system, the change in a state function depends only on the beginning and ending states.

$$\Delta T = T_{\text{final}} - T_{\text{start}}$$
$$\Delta P = P_{\text{final}} - P_{\text{start}}$$
$$\Delta V = V_{\text{final}} - V_{\text{start}}$$
$$\Delta E = E_{\text{final}} - E_{\text{start}}$$

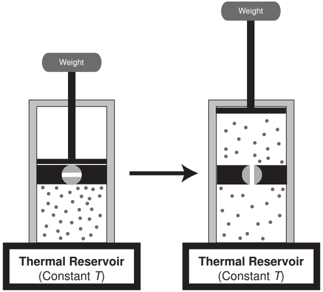
- Work, $w$, and heat, $q$, are not state functions.

# Adiabatic vs. Isothermal Gas Expansion

Adiabatic




Isothermal




- The two processes start and end in the same states:

$$\Delta V_{\text{ad}} = \Delta V_{\text{isot}} > 0 \qquad \Delta P_{\text{ad}} = \Delta P_{\text{isot}} < 0$$

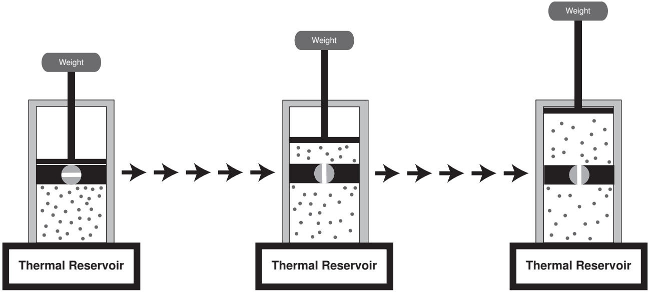
$$\Delta T_{\text{ad}} = \Delta T_{\text{isot}} = 0 \qquad \Delta E_{\text{ad}} = \Delta E_{\text{isot}} = 0$$

- But, the heat and work for the two processes are different:

$$w_{\text{ad}} = 0 \qquad w_{\text{isot}} < 0 \qquad q_{\text{ad}} = 0 \qquad q_{\text{isot}} > 0$$

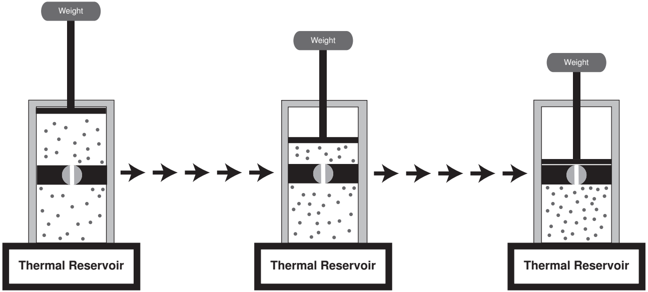
- Heat and work are "path-dependent" functions.

# The Maximum-work Path for Gas Expansion



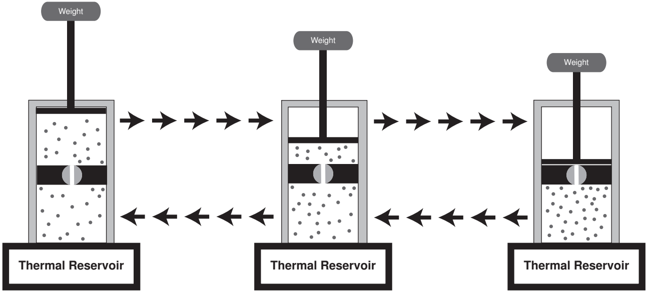

- Piston is allowed to move upward in infinitesimally small steps.
- Temperature is never allowed to drop.
- Pressure drops as gas expands, so less work is done per step.
- If larger steps are ever taken:
  - The temperature drops.
  - The pressure drops more than it would in an infinitesimal step.
  - Less work is produced.

# The *Minimum*-work Path for Gas *Compression*




- Piston is pushed down in infinitesimally small steps.
- Energy is transferred from piston to gas molecules.
- Temperature is never allowed to increase.
- Excess energy flows to the reservoir as heat.
- *P* increases as gas is compressed, so more work is required per step.
- If larger steps are ever taken, more work is required.

# A Reversible Cycle of Compression and Expansion




- Steps in both directions are infinitesimal.
- Compression and expansion are exactly the reverse of one another.

$$w_{\text{comp}} = -w_{\text{exp}} = -q_{\text{comp}} = q_{\text{exp}}$$

- For the complete cycle:

$$\Delta E = 0 \qquad w = 0 \qquad q = 0$$

- Either compression or expansion can be reversed at any point by an infinitesimal force in the opposite direction.