# Lectures: Physics 3306

Provides an introduction to a wide variety of topics in classical (pre-quantum) physics as a bridge to prepare students for subsequent upper-level courses in physics. The topics covered include thermodynamics, fluid mechanics, mechanical waves, optics, radiation, electromagnetic phenomena, atoms, and laboratory techniques. Prerequisites: C- or better in PHYS 1106; and in PHYS 1304 or PHYS 1308.

**Saptaparna Bhattacharya**

**March 2nd, 2026**

**Based on Simon Dalley's lectures taught in Spring 2025**

Labs

Lectures

# Schedule

No class

| Month | Monday | Tuesday | Wednesday | Thursday | Friday | Saturday | Sunday |
|---|---|---|---|---|---|---|---|
| January | 19 | 20 | 21 ✅ | 22 | 23 ✅ | 24 | 25 |
| | 26 ❄️🌨️❄❄❄ | 27 | 28 ❄️🌨️❄❄❄ | 29 | 30 ✅ | 31 | 1 |
| February | 2 ✅ | 3 | 4 ✅ | 5 | 6 ✅ | 7 | 8 |
| | 9 ✅ | 10 | 11 HWB due | 12 | 13 ✅ | 14 | 15 |
| | 16 ✅ | 17 | 18 | 19 | 20 HWC due ✅ | 21 | 22 |
| | 23 Hegi Center ✅ | 24 | 25 HWD due ✅ | 26 | 27 ✅ | 28 | 1 |
| March | 2 ✅ | 3 | 4 HWE due | 5 | 6 | 7 | 8 |
| | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| | 16 | 17 | 18 | 19 | 20 | 21 | 22 |
| | 23 | 24 | 25 | 26 | 27 | 28 | 29 |
| April | 30 | 31 | 1 | 2 | 3 | 4 | 5 |

Labs

Lectures

# Schedule

No class

| Month | Monday | Tuesday | Wednesday | Thursday | Friday | Saturday | Sunday |
|---|---|---|---|---|---|---|---|
| April | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
| | 20 | 21 | 22 | 23 | 24 | 25 | 26 |
| May | 27 | 28 | 29 | 30 | 1 | 2 | 3 |
| | 4 | 5 | 6 | 7 | 8 | 9 | 10 |

# The 1st law and heat transfer
# Halliday 18.5-18.6

# Key concepts: Work done

Let's look at how energy can be transferred as heat and work between a system and its environment

The upward force on the piston due to the pressure of the confined gas is equal to the weight of lead shot loaded onto the top of the piston

Pressure of confined gas balanced by $W$

The temperature of the thermal reservoir can be controlled by turning a knob

- Initial state ($i$): pressure $p_i$, volume $V_i$, temperature $T_i$
- Final state ($f$): pressure $p_f$, volume $V_f$, temperature $T_f$
- Process of changing from initial to final state:
  - Thermodynamic process

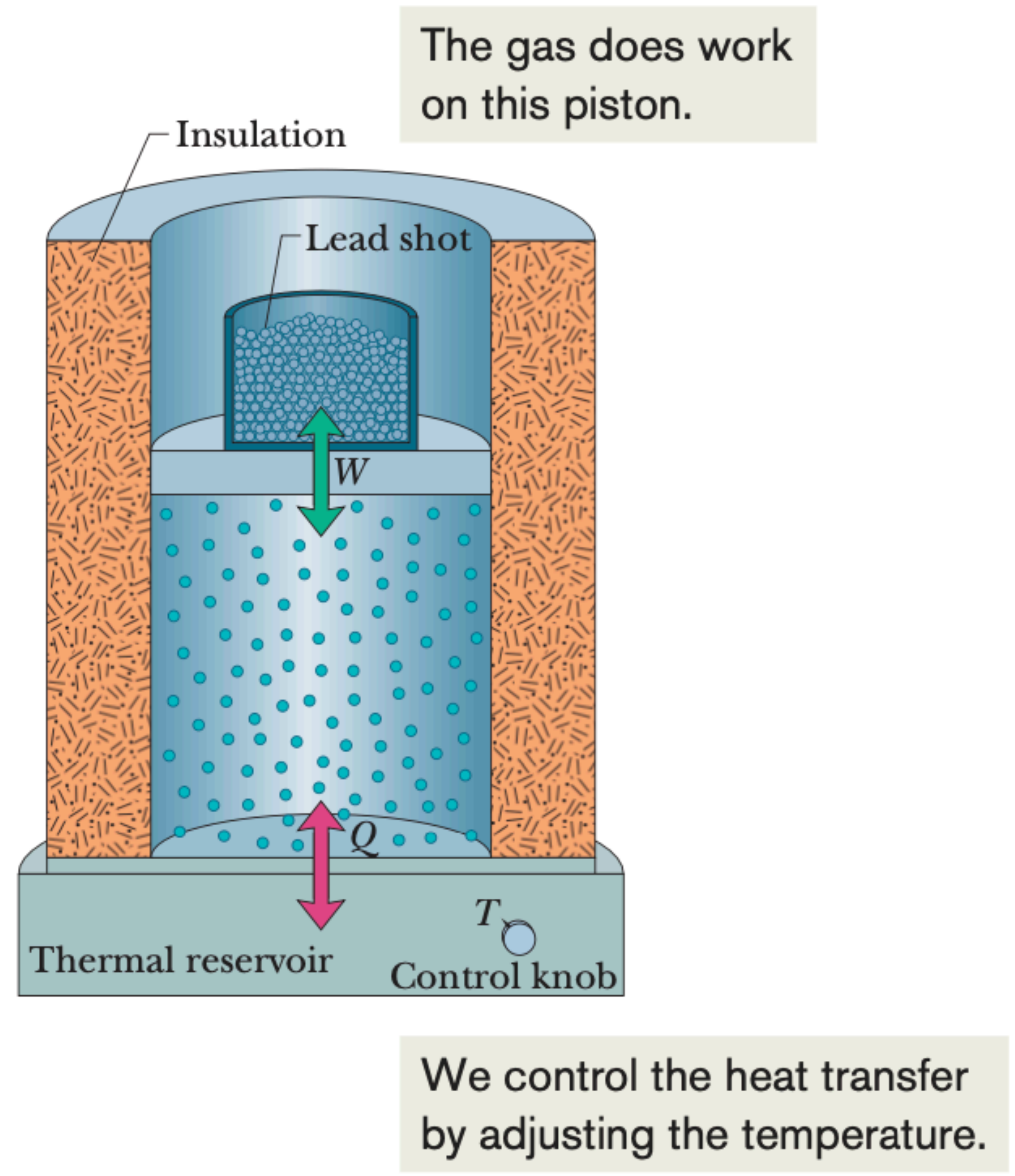
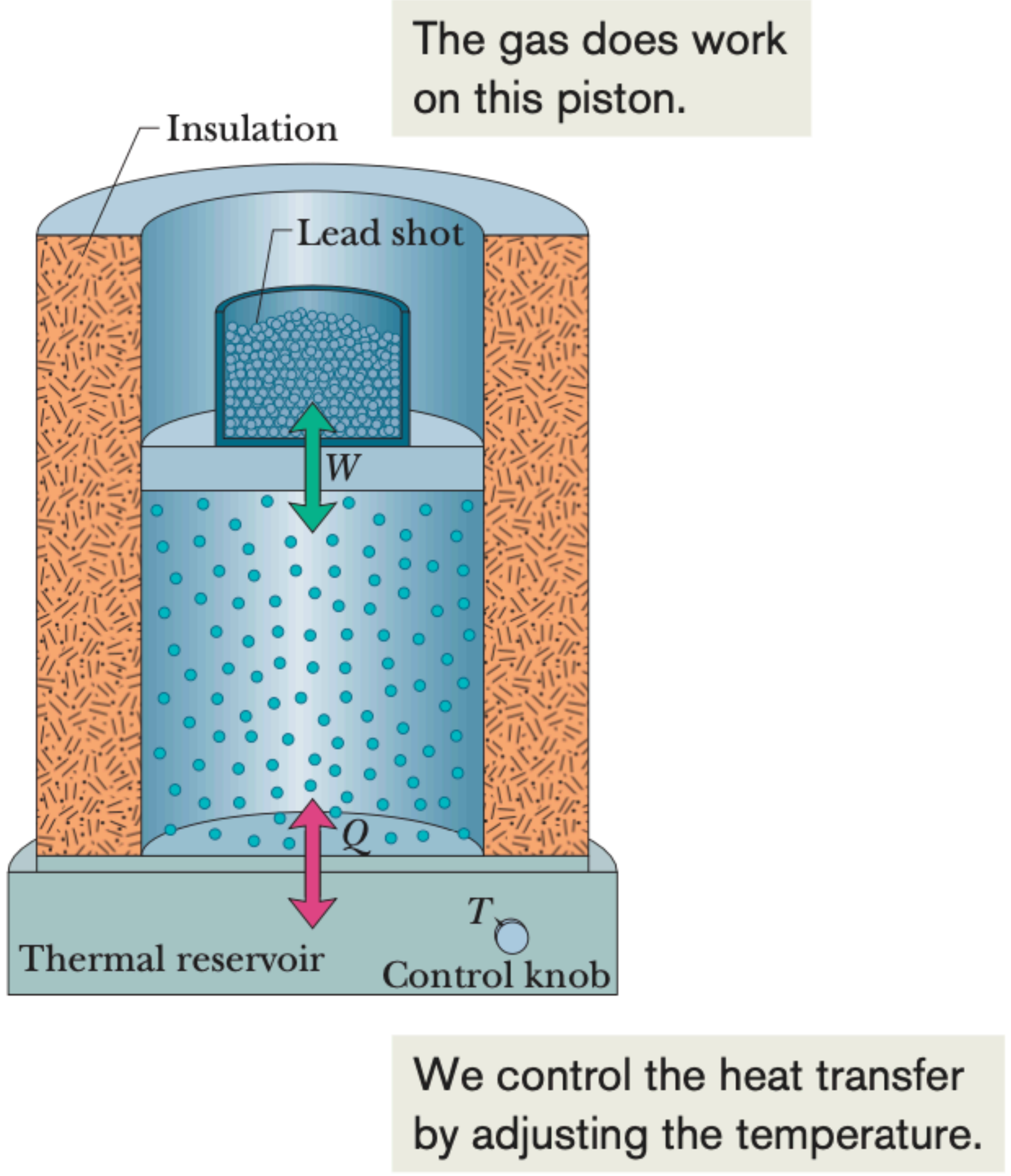



**Figure 18-13** A gas is confined to a cylinder with a movable piston. Heat $Q$ can be added to or withdrawn from the gas by regulating the temperature $T$ of the adjustable thermal reservoir. Work $W$ can be done by the gas by raising or lowering the piston.

# Key concepts: Work done

- Process of changing from initial to final state:
  - Thermodynamic process
    - Energy transfer can occur
    - Work can be done by the system
    - Assume that these processes are slow enough that the system is always in thermal equilibrium
- Removing the lead shot from the piston, allowing the gas to push the piston through a differential displacement:
  - $d\vec{s}$ with an upward force $\vec{F}$ ($d\vec{s}$ is small $\Longrightarrow F$ is constant)

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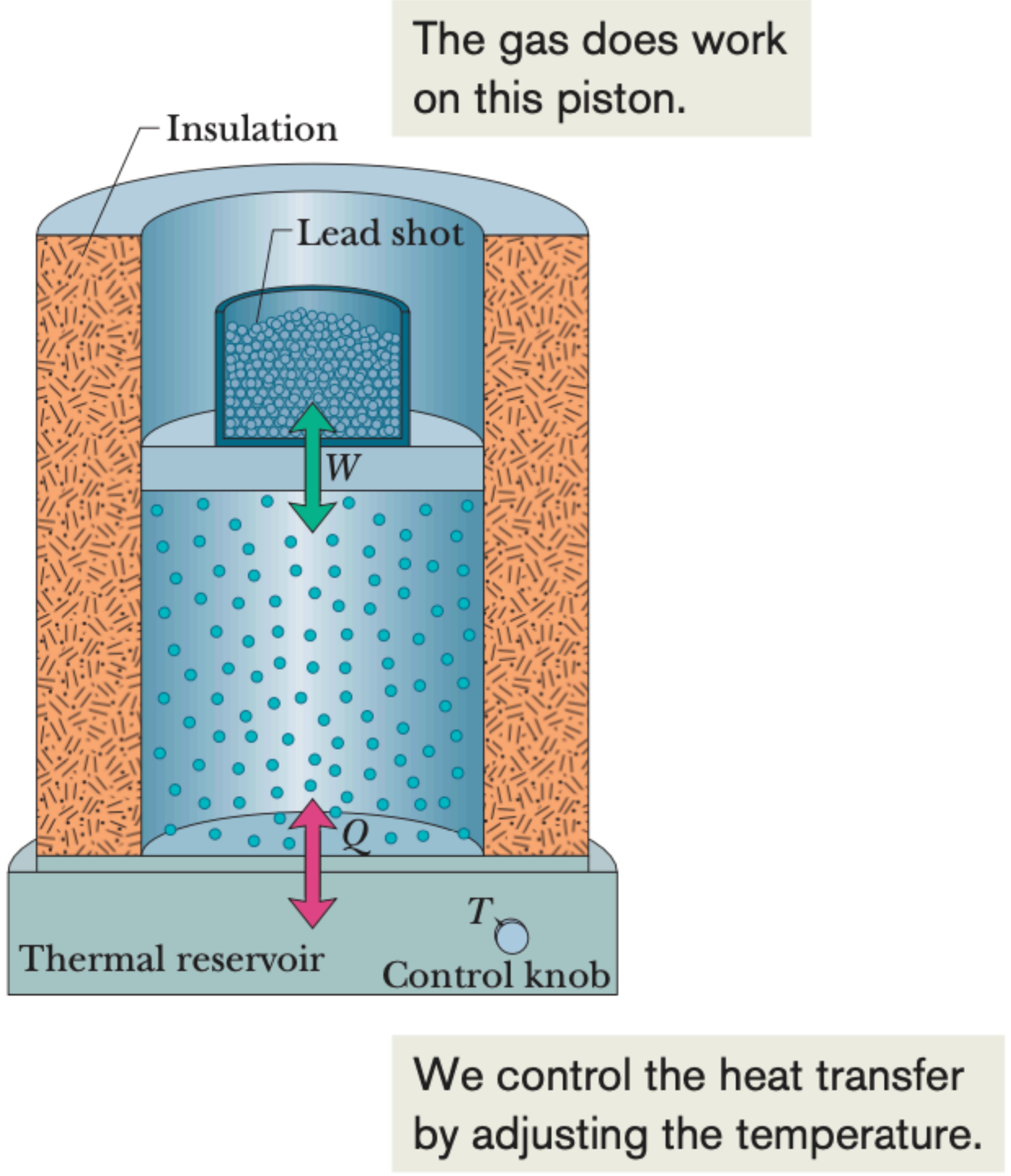
- Removing the lead shot from the piston, allowing the gas to push the piston through a differential displacement:
  - $d\vec{s}$ with an upward force $\vec{F}$ ($d\vec{s}$ is small $\Longrightarrow F$ is constant)
  - $|\vec{F}| = pA, p =$ pressure, $A =$ area
  - The differential work done $dW$:
    - $dW = \vec{F} \cdot d\vec{s}$
    - $dW = (pA)(ds)$
    - $dW = p(Ads)$
    - $dW = pdV$ ($dV$ = differential change in volume)

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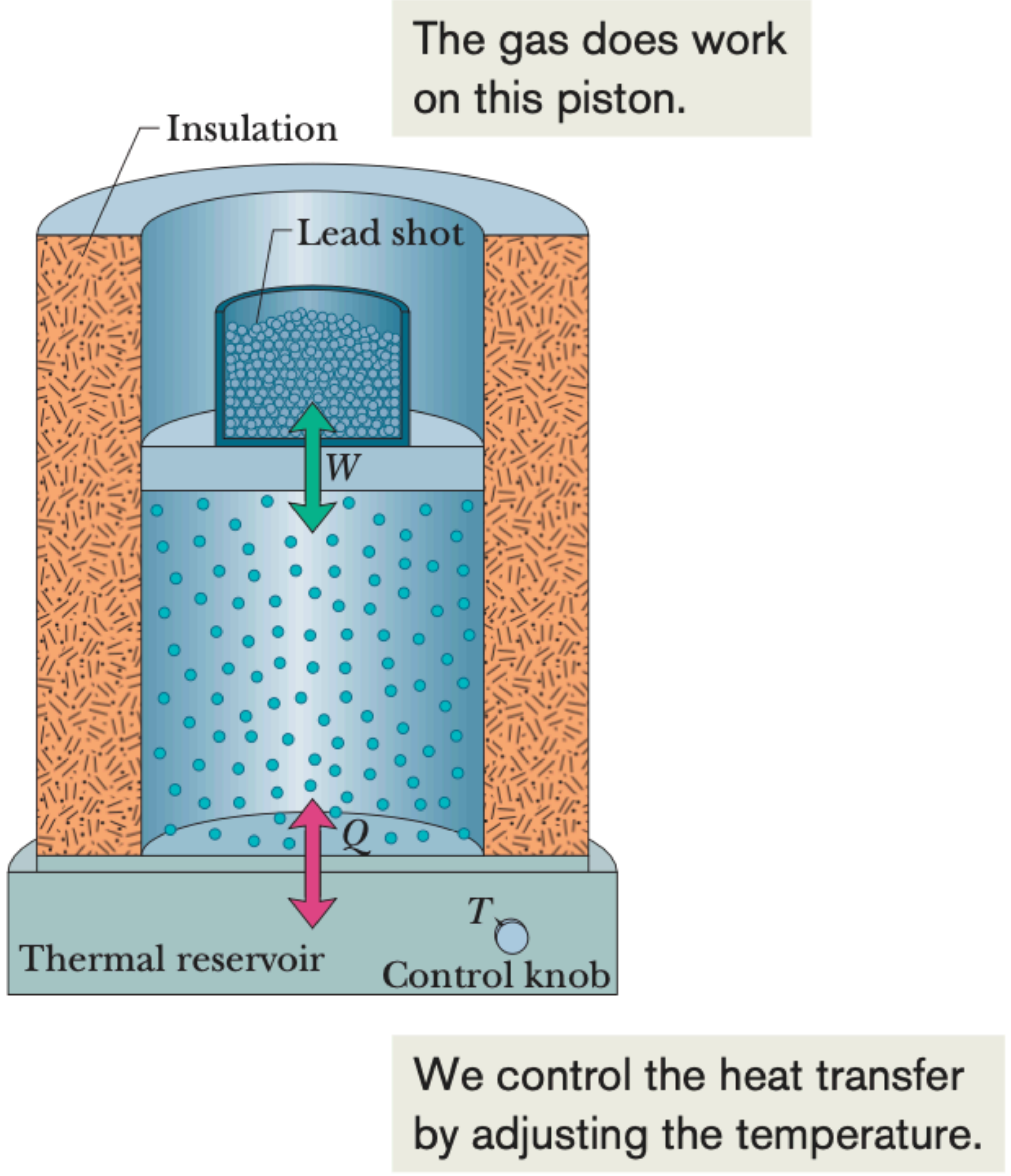
# Key concepts: Work done

- The differential work done $dW$:
  - $dW = \vec{F} \cdot d\vec{s}$
  - $dW = pdV$ ($dV$ = differential change in volume)
- Total work done:
  - $$W = \int dW = \int_{v_i}^{v_f} pdV$$
  - Many paths to go from $i$ to $f$

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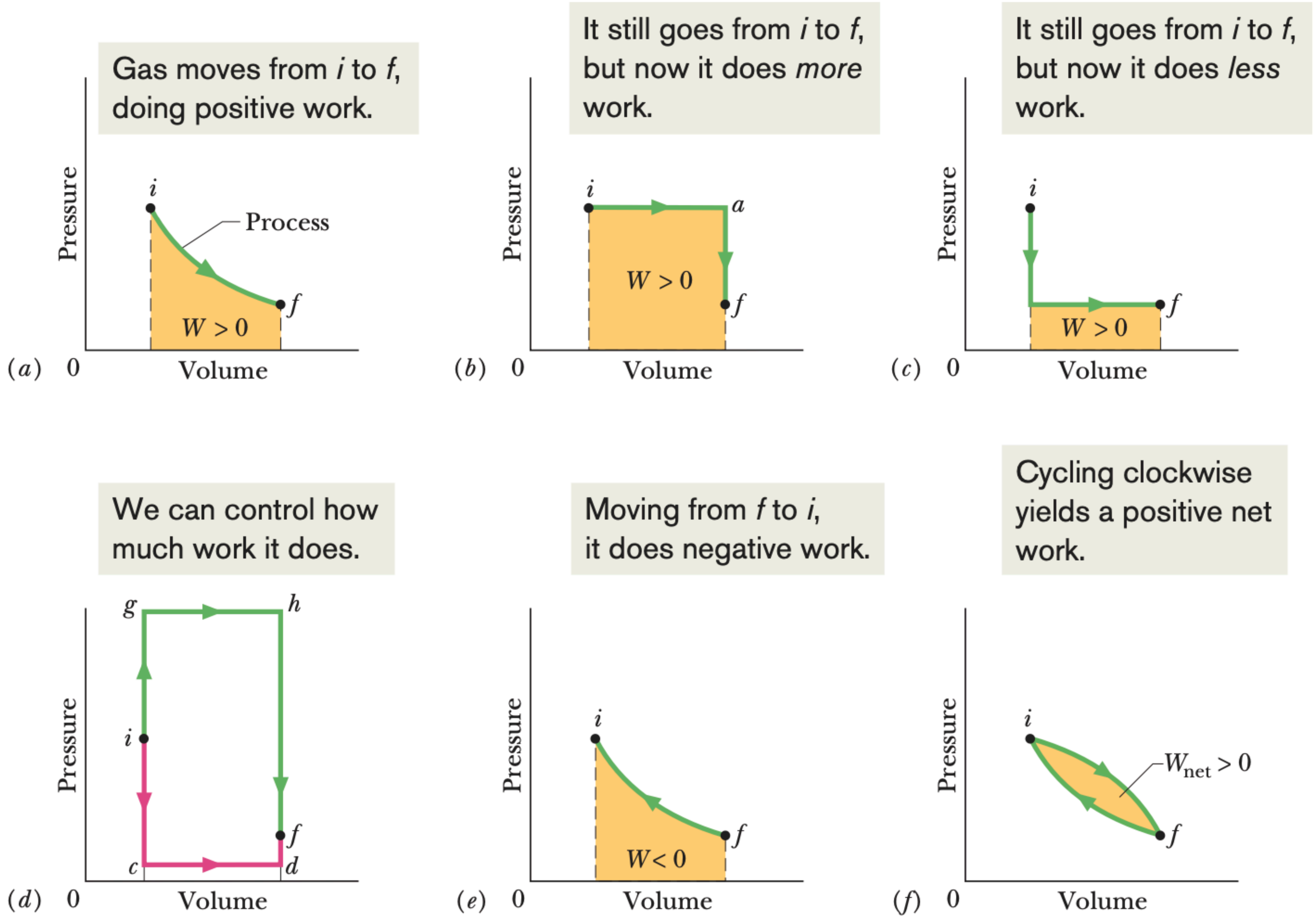
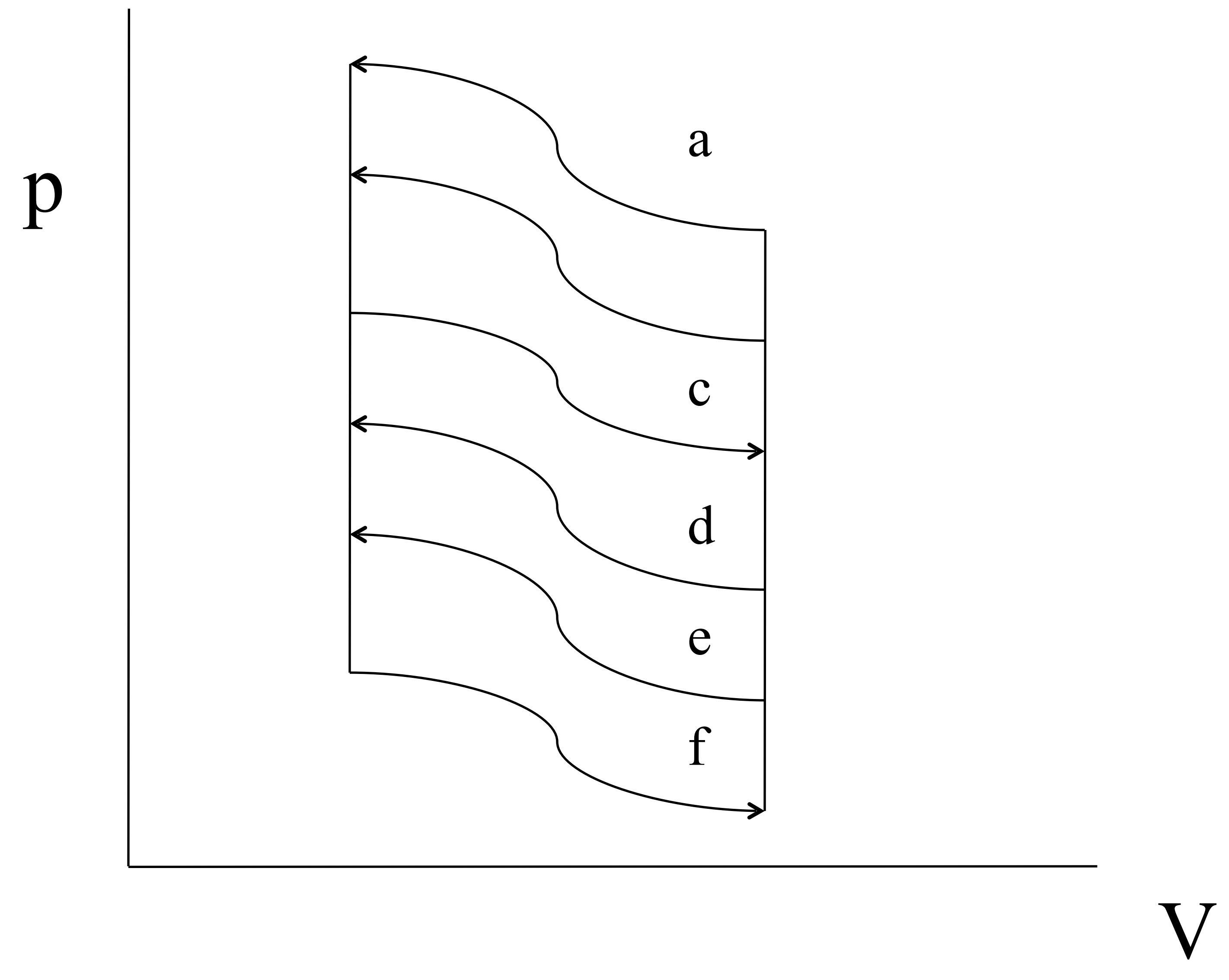


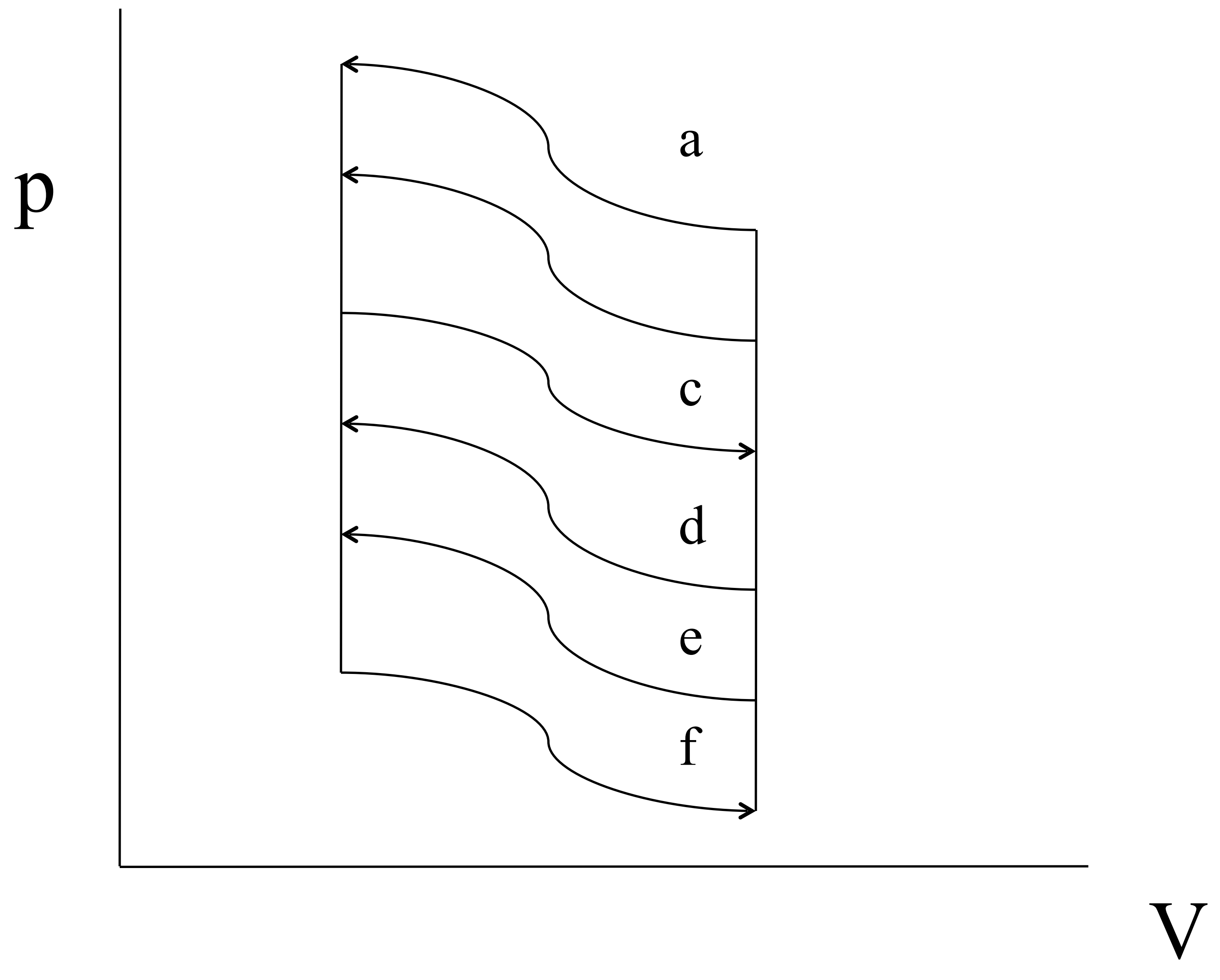

**Figure 18-14** (*a*) The shaded area represents the work $W$ done by a system as it goes from an initial state $i$ to a final state $f$. Work $W$ is positive because the system's volume increases. (*b*) $W$ is still positive, but now greater. (*c*) $W$ is still positive, but now smaller. (*d*) $W$ can be even smaller (path *icdf*) or larger (path *ighf*). (*e*) Here the system goes from state $f$ to state $i$ as the gas is compressed to less volume by an external force. The work $W$ done *by* the system is now negative. (*f*) The net work $W_{net}$ done by the system during a complete cycle is represented by the shaded area.

Which of the closed cycles (curved paths plus connecting verticals) have the maximum net work done by the system?




1. af
2. ce
3. cf
4. bc and ef
5. ab and de

Which of the closed cycles (curved paths plus connecting verticals) have the maximum net work done by the system?




1. af
2. ce
3. cf
4. bc and ef
5. ab and de

To determine the direction of each cycle, we have to look closely at the faint arrows drawn on the curved paths. For a cycle to be clockwise, the upper bounding curve must go to the right (→) and the lower bounding curve must go to the left (←).

Let's scan the regions provided in the options:

- Cycle c: Look at the curves bounding region 'c'. The curve above it has an arrowhead on the right, pointing right (→). The curve below it has an arrowhead on the left, pointing left (←). This forms a clockwise cycle.

- Cycle f: Look at the curves bounding region 'f'. The curve above it has an arrowhead pointing right (→). The curve below it has an arrowhead pointing left (←). This also forms a clockwise cycle.

- Cycle e (for contrast): Look at the curves bounding region 'e'. The curve above it points left (←), and the curve below it points right (→). This forms a counter-clockwise cycle, which means net negative work done by the system.

3. Conclusion

Cycles c and f are the clockwise cycles, meaning they represent positive net work done by the system. Assuming these curves represent a uniform family (like isotherms spaced by equal $\Delta T$), the areas of these clockwise cycles would be equal, tying them for the maximum positive net work.

# Key concepts: The first law of thermodynamics

- The heat $Q$ - work $W$ represents a change in some intrinsic property of the system
  - This intrinsic property is called internal energy ($E_{\text{int}}$):
    - $E_{\text{int}} = E_{\text{int},f} - E_{\text{int},i} = Q - W$
    - If the thermodynamic system undergoes only a differential change:
      - $dE_{\text{int}} = dQ - dW$
    - The internal energy $E_{\text{int}}$ of a system tends to increase if energy is added as heat $Q$ and tends to decrease if energy is lost as work $W$ done by the system

Which of the following scenarios violates the first law of thermodynamics?

1. An ideal spring that extends and retracts forever

2. An isolated electrochemical cell that indefinitely generates an electrical current.

3. A wind turbine that converts all of its energy from mechanical movement into electrical potential energy.

4. A machine that converts heat energy into work energy.

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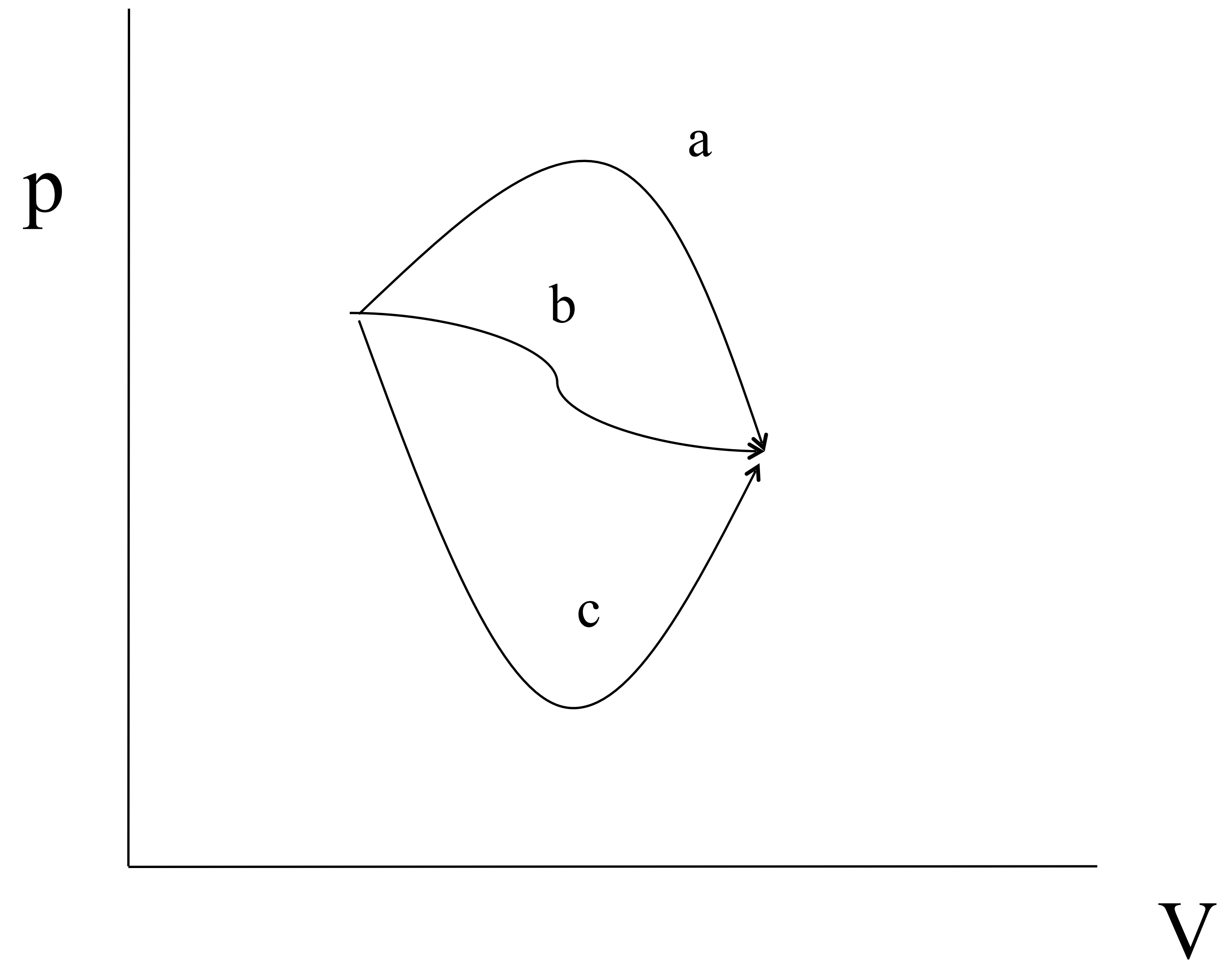
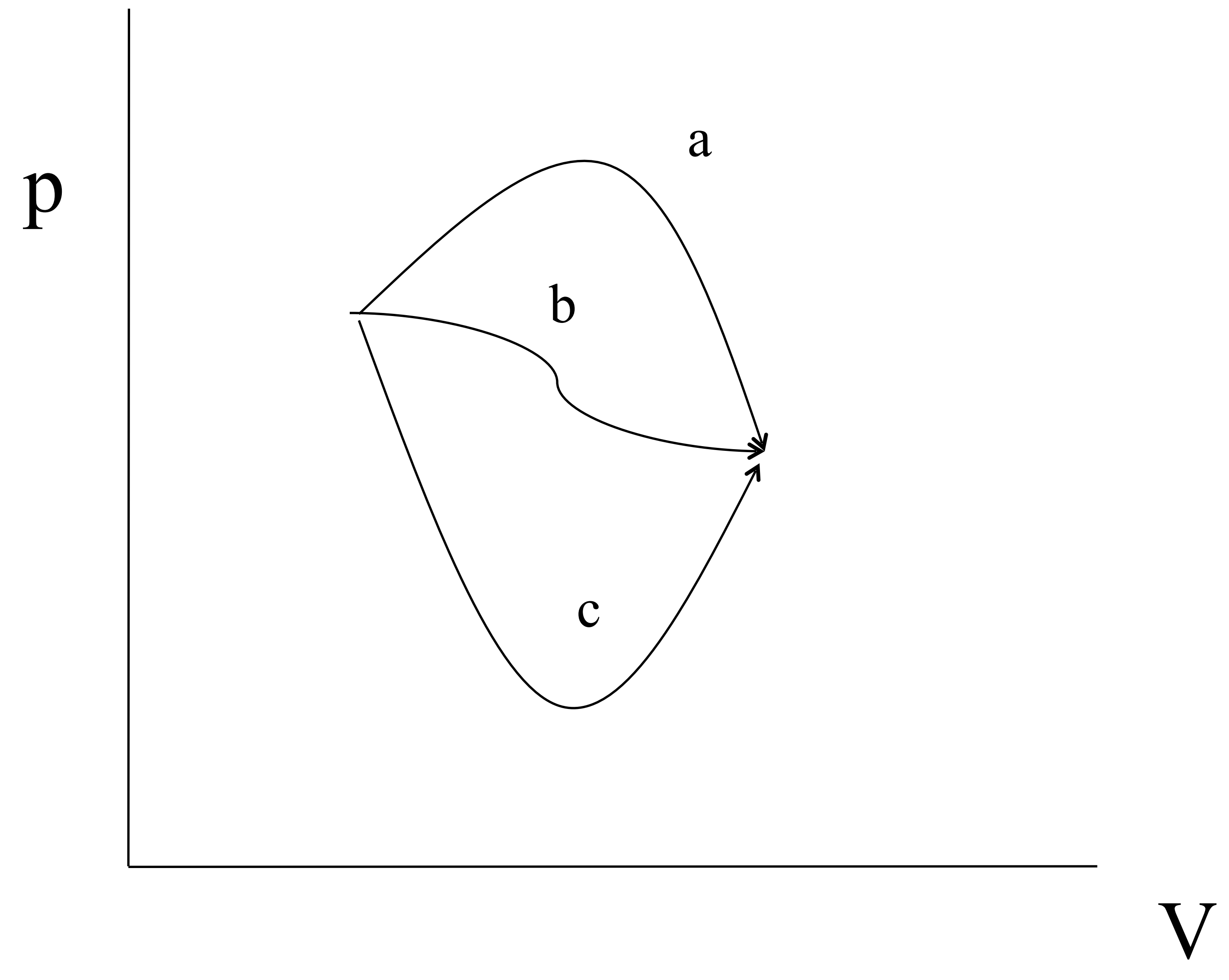
4. A machine that converts heat energy into work energy.

Rank the paths corresponding to the change in internal energy of the system, greatest first.




1.a > b > c
2.c > b > c
3.a > c > b
4.b > c > a
5.a = b = c

Rank the paths corresponding to the change in internal energy of the system, greatest first.




1. a > b > c
2. c > b > c
3. a > c > b
4. b > c > a
5. a = b = c

The key to solving this problem lies in understanding the nature of **internal energy (U)**. In thermodynamics, internal energy is a **state function**.

This means that the internal energy of a system depends *only* on its current state (its pressure, volume, temperature, etc.) and completely ignores how the system got to that state.

## 2. Apply the Concept to the Diagram

Because internal energy is a state function, the **change in internal energy (ΔU)** during any process depends strictly on the difference between the final state and the initial state: $\Delta U = U_{final} - U_{initial}$

Now, look at the provided p-V diagram:

- **Initial State:** All three paths (a, b, and c) begin at the exact same starting point on the left side of the graph.

- **Final State:** All three paths end at the exact same point on the right side of the graph.

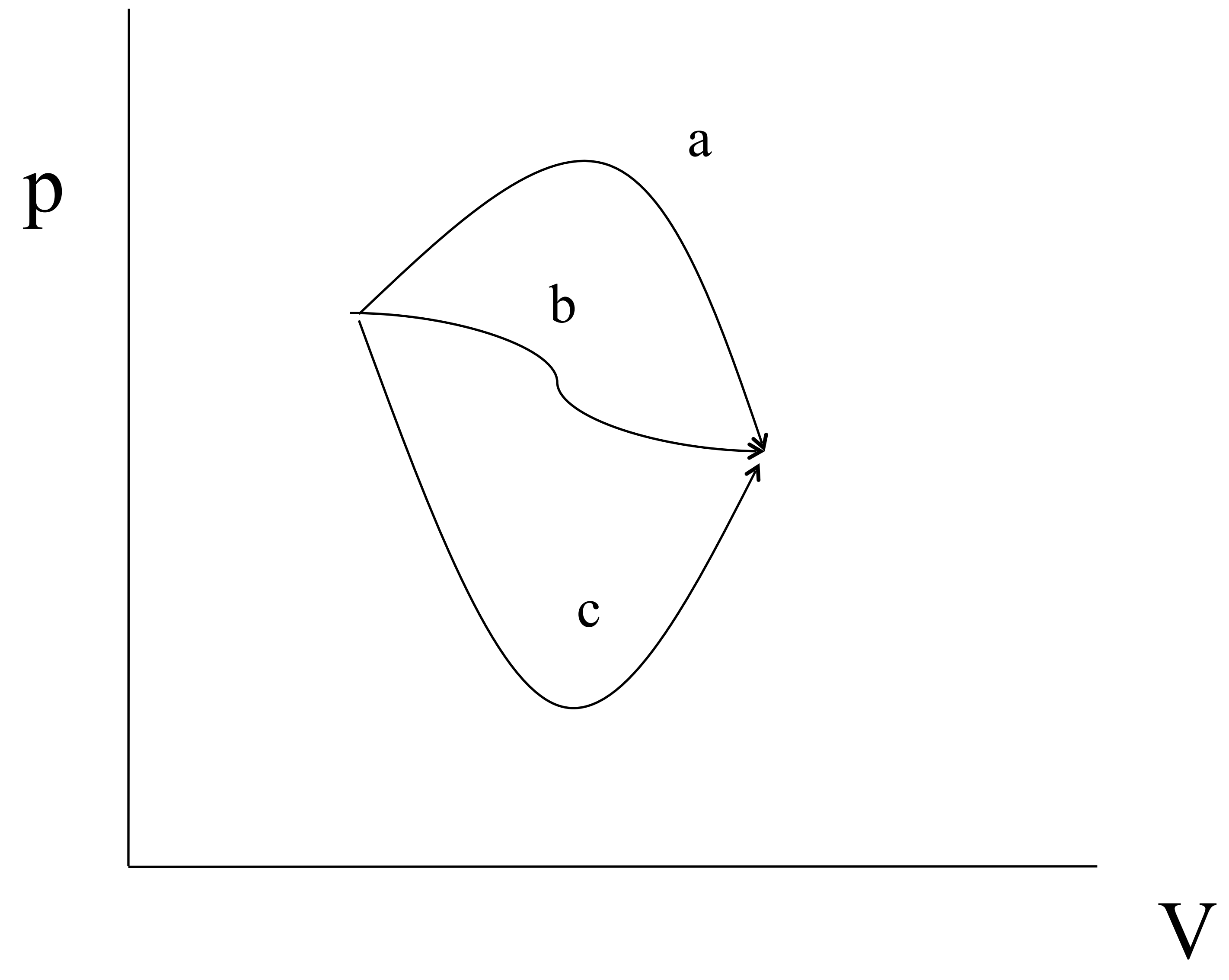
## 3. Conclusion

Since paths a, b, and c all share the identical initial state and the identical final state, the change in internal energy must be exactly the same for all three, regardless of the different routes they took on the p-V diagram.

Therefore, $\Delta U_a = \Delta U_b = \Delta U_c$ .

This corresponds to option **5. a = b = c**.

Rank the paths corresponding to the heat energy transferred into the system.




1. a > b > c
2. c > b > c
3. a > c > b
4. b > c > a
5. a = b = c

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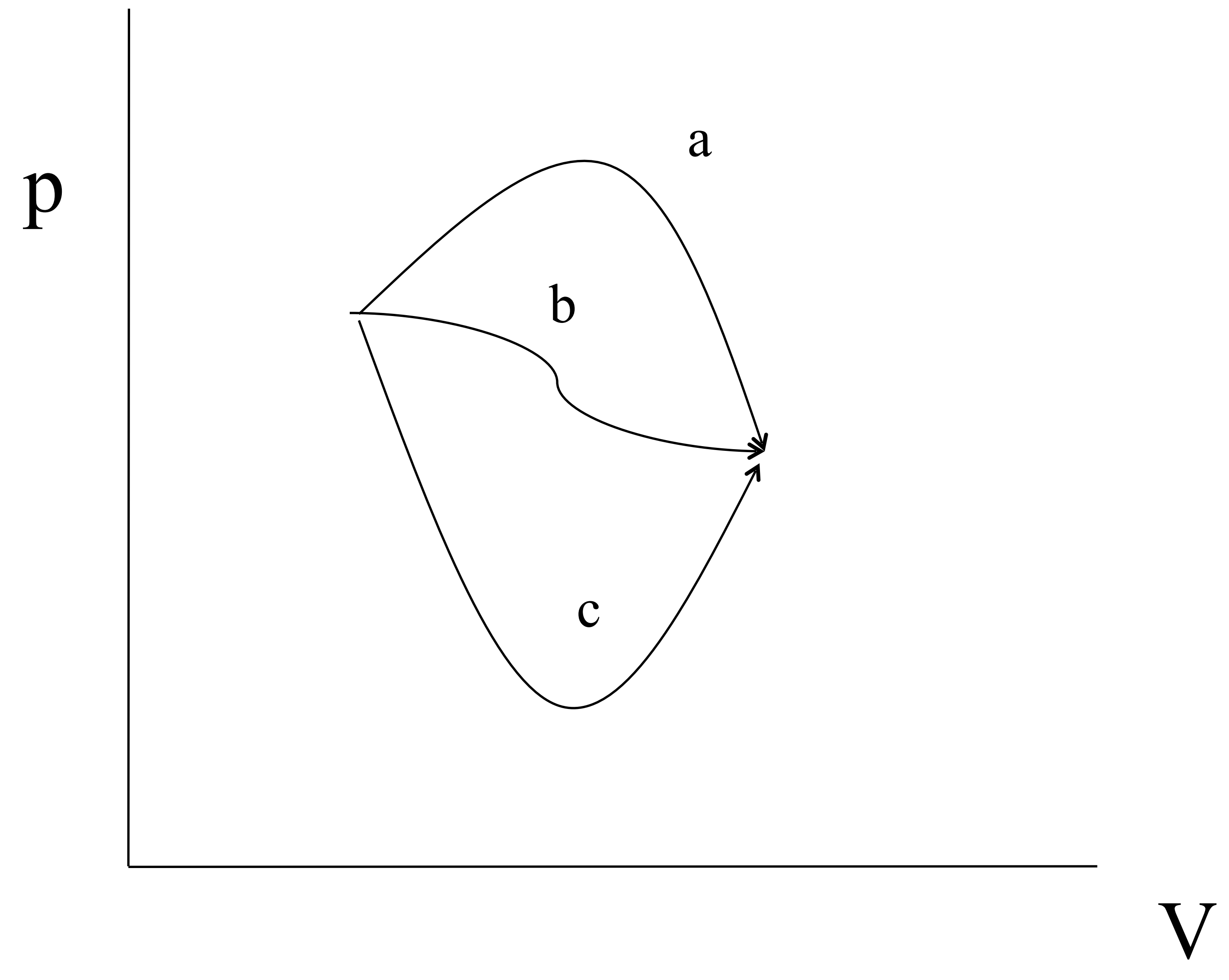


1. a > b > c
2. c > b > c
3. a > c > b
4. b > c > a
5. a = b = c

**1. The First Law of Thermodynamics**

To find the heat transferred into the system (Q), we need to use the First Law of Thermodynamics, which relates heat, internal energy ($\Delta U$), and work (W):

$Q = \Delta U + W$
Where:

- **Q** is the heat added to the system.
- **$\Delta U$** is the change in internal energy.
- **W** is the work done *by* the system.

**2. Analyze the Change in Internal Energy ($\Delta U$)**

As established in similar problems, internal energy is a **state function**. Because paths **a**, **b**, and **c** all start at the exact same initial state and end at the exact same final state, the change in internal energy is i

$\Delta U_a = \Delta U_b = \Delta U_c$
**3. Analyze the Work Done (W)**

In a pressure-volume (p-V) diagram, the work done *by* the system during an expansion is equal to the **area under the curve** .

Looking at the three paths:

- **Path a** is the highest curve on the graph, meaning it has the largest area underneath it. Therefore, it does the most work ($W_a$ is greatest).
- **Path b** is in the middle, so it has an intermediate area and does an intermediate amount of work.
- **Path c** is the lowest curve, meaning it has the smallest area underneath it. Therefore, it does the least work ($W_c$ is smallest).

This gives us the ranking for work: $\mathbf{W_a > W_b > W_c}$

**4. Determine the Heat Transferred (Q)**

Now we go back to the First Law equation ($Q = \Delta U + W$).

Since $\Delta U$ is a constant value for all three paths, the heat transferred (Q) depends entirely on the work done (W). The path that does the most work will require the most heat to be added to the system to ach
energy state.

- $Q_a = \Delta U + W_a$ (Largest W means largest Q)
- $Q_b = \Delta U + W_b$
- $Q_c = \Delta U + W_c$ (Smallest W means smallest Q)

Therefore, the ranking for heat energy transferred into the system is: **a > b > c**

This corresponds to option **1**.

At constant pressure P, the volume of a gas increases from $V_1$ to $V_2$ when 'Q' amount of heat is removed from the system.

What will happen to internal energy?

a) Remain the same if $Q = P(V_1 - V_2)$

b) Decrease by an amount $P(V_2 - V_1) - Q$

c) Decrease by an amount $Q + P(V_2 - V_1)$

d) Increase by some unknown amount

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d) Increase by some unknown amount

**Analyze the Work Done (Wout )**

The problem states the process happens at a **constant pressure P** and the **volume increases** from V1 to V2 .

Because the gas is expanding, it is doing work *on* its surroundings. The work done *by* the gas is:

Wout =P(V2 −V1 )
Since V2 >V1 , this work term is a positive value. Energy is leaving the system as work.

**Analyze the Heat Transferred (Qin )**

The problem explicitly states that Q amount of heat is **removed** from the system.

Because heat is leaving the system, the heat added *to* the system is negative:

Qin =−Q

**Calculate the Change in Internal Energy**

Substitute these terms back into the First Law equation:

ΔU=(−Q)−P(V2 −V1 )
ΔU=−[Q+P(V2 −V1 )]

**Conclusion**

The overall negative sign indicates that the internal energy of the system **decreases**. The magnitude of that decrease is Q+P(V2 −V1 ).

This exactly matches option **c**.

Which way is heat transfer believed to take place in a long, hollow cylinder that is kept at the same temperature on its inner and on its outer surfaces, but different temperatures inner and outer?

a)Unpredictable

b)Radial only

c)No heat transfer takes place

d)Axial only

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a)Unpredictable

b)Radial only

c)No heat transfer takes place

d)Axial only

Because the only temperature gradient exists along the radius of the cylinder, the heat transfer occurs exclusively in the radial direction.

This corresponds to option **b) Radial only**.

# Key concepts: Special cases of the first law

Adiabatic process:

- An adiabatic process is one that occurs so rapidly or occurs in a system that is so well insulated that *no transfer of energy as heat* occurs between the system and its environment

Constant volume process:

- If the volume of a system (such as a gas) is held constant, that system can do no work

Cyclical process:

- These are processes in which, after certain interchanges of heat and work, the system is restored to its initial state

# Key concepts: Heat transfer

We have discussed the transfer of energy as heat between a system and its environment

There are three transfer mechanisms:

- conduction
- convection
- radiation

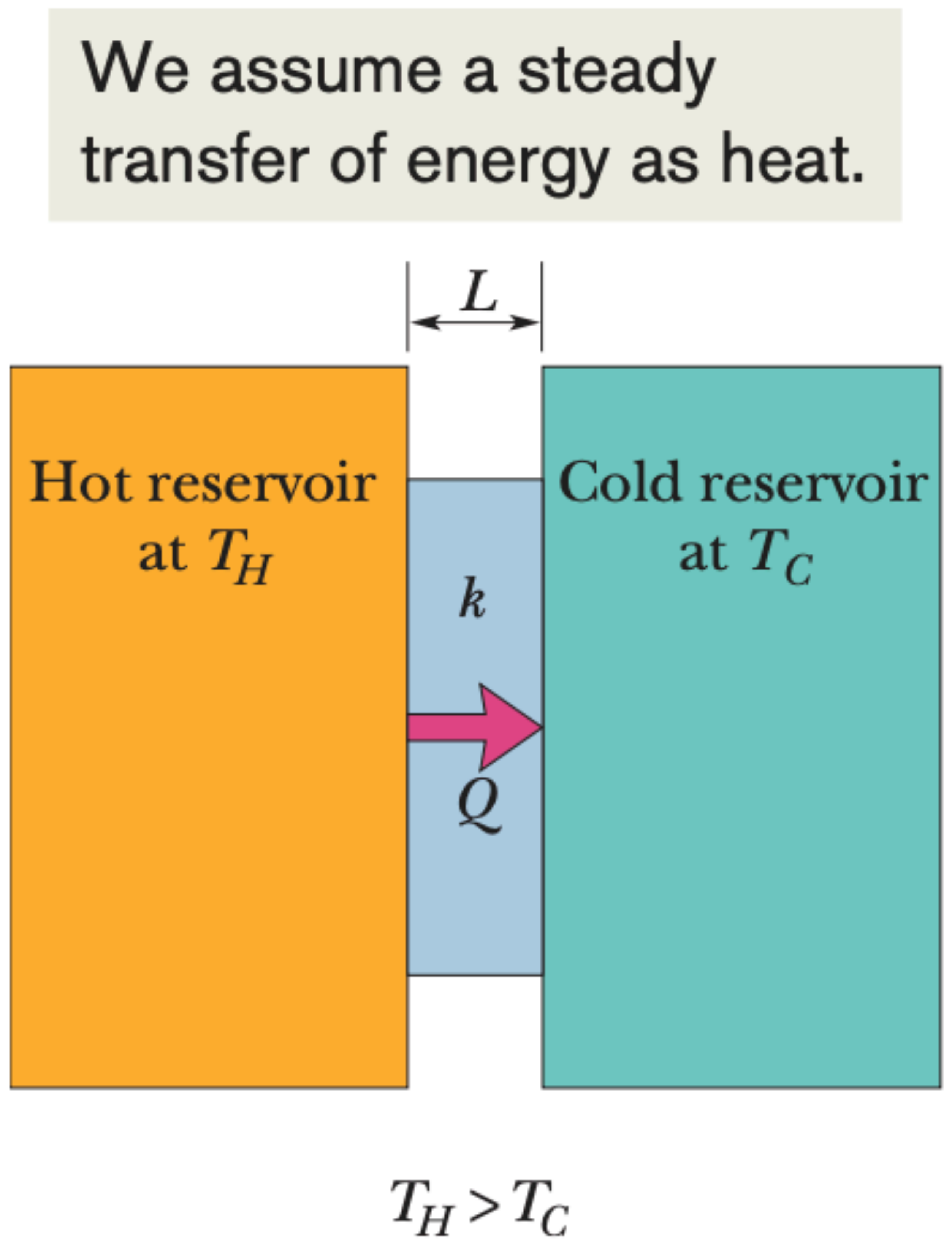



**Figure 18-18** Thermal conduction. Energy is transferred as heat from a reservoir at temperature $T_H$ to a cooler reservoir at temperature $T_C$ through a conducting slab of thickness $L$ and thermal conductivity $k$.

# Key concepts: conduction

Consider a slab of face area $A$ and thickness $L$

Faces maintained at temperature:

- $T_H$: maintained by a hot reservoir at $T_H$
- $T_C$: maintained by a cold reservoir at $T_C$

Let $Q$ be the energy that is transferred as heat through the slab, from its hot face to its cold face, in time $t$

Experiment shows that the conduction rate $P_{\text{cond}}$ (the amount of energy transferred per unit time):

$$P_{\text{cond}} = \frac{Q}{t} = kA\frac{T_H - T_C}{L}$$

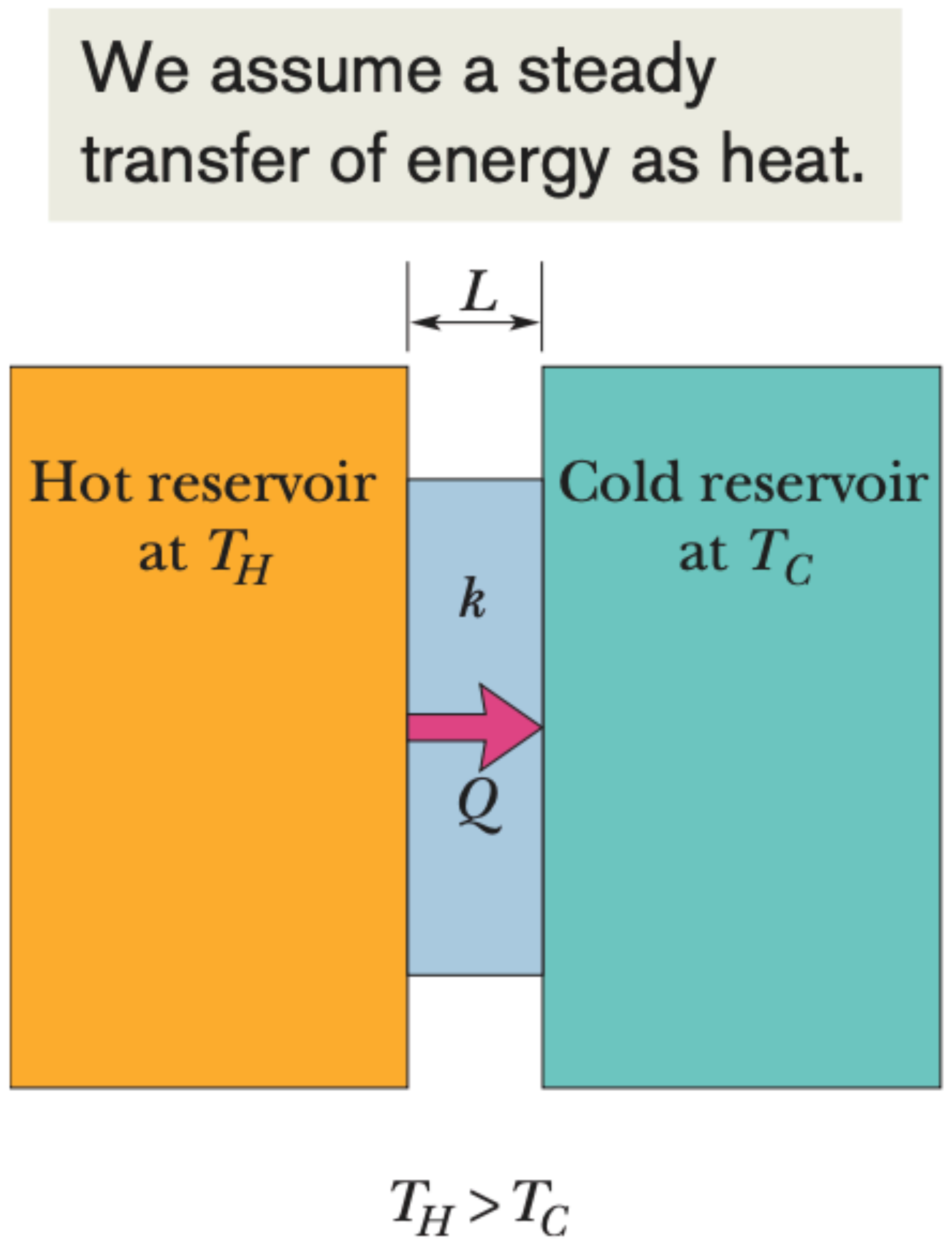



**Figure 18-18** Thermal conduction. Energy is transferred as heat from a reservoir at temperature $T_H$ to a cooler reservoir at temperature $T_C$ through a conducting slab of thickness $L$ and thermal conductivity $k$.

# Key concepts: conduction

$$P_{\text{cond}} = \frac{Q}{t} = kA\frac{T_H - T_C}{L}$$

$k$ = thermal conductivity

- Depends on the material of which the slab is made
- A material that transfers energy by conduction is a *good thermal conductor* and has a high value of $k$

To reduce heat transfer, we care about thermal resistance:

$R = \frac{L}{k}$ (associated with a slab of specific thickness and not a function of the material)

**Table 18-6 Some Thermal Conductivities**

| Substance | $k$ (W/m·K) |
|---|---|
| *Metals* | |
| Stainless steel | 14 |
| Lead | 35 |
| Iron | 67 |
| Brass | 109 |
| Aluminum | 235 |
| Copper | 401 |
| Silver | 428 |
| *Gases* | |
| Air (dry) | 0.026 |
| Helium | 0.15 |
| Hydrogen | 0.18 |
| *Building Materials* | |
| Polyurethane foam | 0.024 |
| Rock wool | 0.043 |
| Fiberglass | 0.048 |
| White pine | 0.11 |
| Window glass | 1.0 |

# Key concepts: conduction

For a composite slab:

$$P_{\text{cond}} = \frac{k_2 A(T_H - T_C)}{L_2} = \frac{k_1 A(T_X - T_C)}{L_1}$$

$$T_X = \frac{k_1 L_2 T_C + k_2 L_1 T_H}{k_1 L_2 + k_2 L_1}$$

$$P_{\text{cond}} = \frac{A(T_H - T_C)}{L_1/k_1 + L_2/k_2}$$

For $n$ materials making up a slab:

$$P_{\text{cond}} = \frac{A(T_H - T_C)}{\sum (L/k)} = \frac{A(T_H - T_C)}{\sum_i (L_i/k_i)}$$

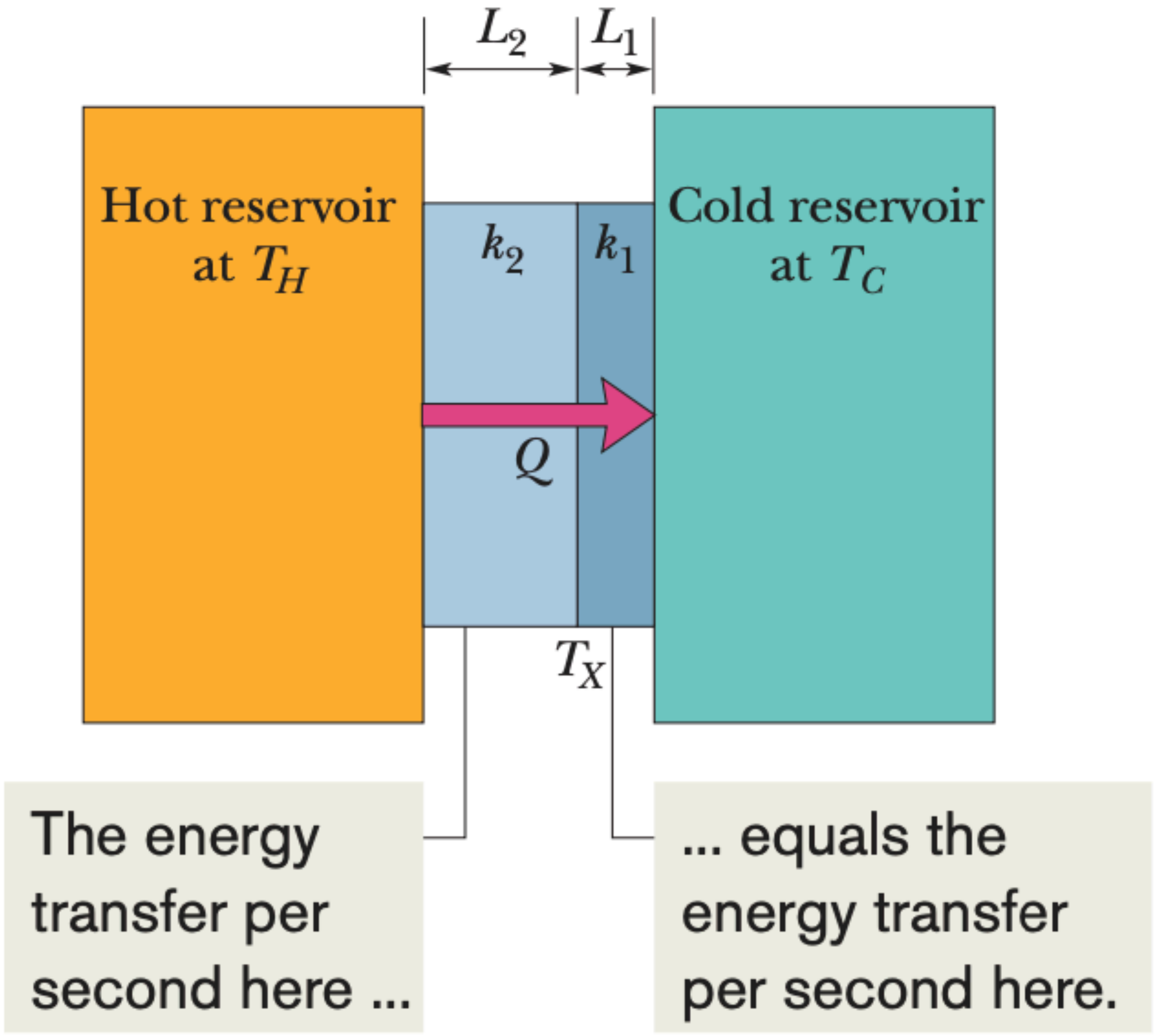
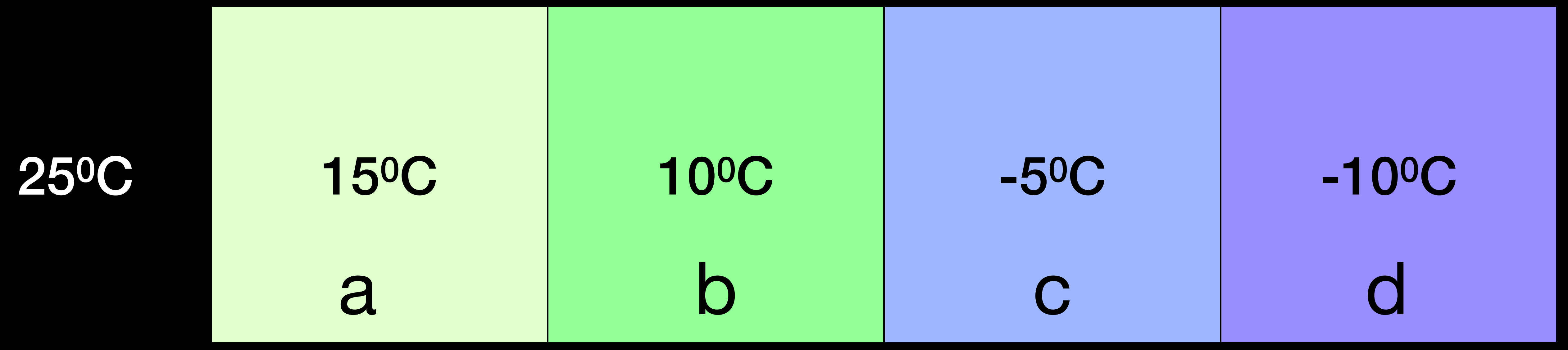



**Figure 18-19** Heat is transferred at a steady rate through a composite slab made up of two different materials with different thicknesses and different thermal conductivities. The steady-state temperature at the interface of the two materials is $T_X$.

# Problem 1

The figure shows four materials of identical thickness through which the heat flow is steady, with the interface temperatures shown.

Rank the materials according to their thermal conductivity, greatest first.




1. a > b > c > d
2. d > c > b > a
3. c > a > b = d
4. a = b = c = d
5. b = d > a > c

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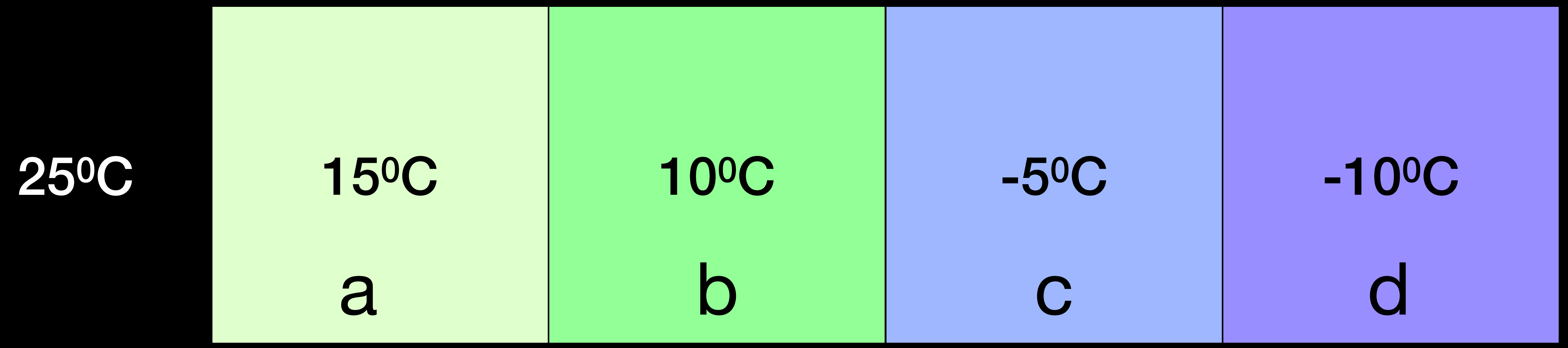


1. a > b > c > d
2. d > c > b > a
3. c > a > b = d
4. a = b = c = d
5. b = d > a > c

The problem deals with heat conduction through a series of materials. The rate of heat transfer (heat flow) through a material is given by Fourier's law of thermal conduction:

$$P=\frac{k\cdot A\cdot \Delta T}{L}$$

Where:

- $P$ is the rate of heat flow
- $k$ is the thermal conductivity of the material
- $A$ is the cross-sectional area
- $\Delta T$ is the temperature difference across the material
- $L$ is the thickness of the material

**2. Identify Constants and Relationships**

The problem provides a few key clues that simplify this equation:

- **"Steady heat flow":** This means the rate of heat flow ($P$) is constant and equal through all four materials.
- **"Identical thickness":** The thickness ($L$) is the same for all materials.
- **Implied constant area:** Because they are stacked in a series, the cross-sectional area ($A$) is the same.

Since $P$, $A$, and $L$ are all constant, we can see that the product of thermal conductivity and temperature difference must be a constant:

$$k\cdot \Delta T=\text{constant}$$

This means that thermal conductivity ($k$) is **inversely proportional** to the temperature difference ($\Delta T$).

- A **larger** $\Delta T$ means a **smaller** $k$ (the material is a good insulator, so it takes a larger temperature drop to push the same amount of heat through).
- A **smaller** $\Delta T$ means a **larger** $k$ (the material is a good conductor, so heat flows easily with very little temperature drop).

**3. Calculate the Temperature Differences ($\Delta T$)**

Let's find the temperature change across each specific material:

- **Material a:** $\Delta T_a = 25^\circ C - 15^\circ C =$ $\mathbf{10^\circ C}$
- **Material b:** $\Delta T_b = 15^\circ C - 10^\circ C =$ $\mathbf{5^\circ C}$
- **Material c:** $\Delta T_c = 10^\circ C - (-5^\circ C) = 10 + 5 =$ $\mathbf{15^\circ C}$
- **Material d:** $\Delta T_d = -5^\circ C - (-10^\circ C) = -5 + 10 =$ $\mathbf{5^\circ C}$

**4. Rank the Thermal Conductivities**

To rank the materials by thermal conductivity ($k$) from greatest to least, we need to rank them by their temperature difference ($\Delta T$) from smallest to largest:

1. **Smallest $\Delta T$ (Greatest $k$):** Materials **b** and **d** both have a $\Delta T$ of $5^\circ C$. Therefore, $k_b = k_d$.
2. **Next smallest $\Delta T$:** Material **a** has a $\Delta T$ of $10^\circ C$.
3. **Largest $\Delta T$ (Smallest $k$):** Material **c** has a $\Delta T$ of $15^\circ C$.

Putting it all together, the ranking from greatest to least thermal conductivity is: **b = d > a > c**

This matches option **5**.

Thermal conductivity is defined as the heat flow per unit time

a) When the temperature gradient is unity

b) Across no temperature gradient

c) Through a unit thickness

d) Across unit area where the temperature gradient is unity

e) None of the above

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e) None of the above

$$P_{\text{cond}} = \frac{Q}{t} = kA\frac{T_H - T_C}{L}$$

# Key concepts: convection

When you look at the flame of a candle or a match, you are watching thermal energy being transported upward by **convection**

Other examples?

# Key concepts: radiation

A third method by which an object and its environment can exchange energy as heat is via electromagnetic waves (visible light is one kind of electromagnetic wave)

- The rate at which an object emits energy via electromagnetic radiation depends on the object's surface area $A$ and temperature $T$ of that area in kelvins and is given by:
  - $P_{\text{rad}} = \sigma \epsilon A T^4$
  - Here $\sigma$ = 5.6704 X $10^{-8}\ W/m^2 \cdot K^4$
    - Called the Stefan-Boltzmann constant
    - Surface with maximum emissivity ($\epsilon$: 1.0-0.0) of 1.0 is called a *blackbody radiator*

# Key concepts: radiation

A third method by which an object and its environment can exchange energy as heat is via electromagnetic waves (visible light is one kind of electromagnetic wave)

- The rate $P_{\text{abs}}$ at which an object absorbs energy via thermal radiation from its environment, which we take to be at uniform temperature $T_{\text{env}}$ (in kelvins), is:
  - $P_{\text{abs}} = \sigma \epsilon A T_{\text{env}}^4$
- An object both emits and absorbs thermal radiation, its net rate $P_{\text{net}}$ of energy exchange due to thermal radiation is:
  - $P_{\text{net}} = P_{\text{abs}} - P_{\text{rad}} = \sigma \epsilon A (T_{\text{env}}^4 - T^4)$

## A perfect “black body”

a) Absorbs all the incident radiation

b) Allow all the incident radiation to pass through it

c) Reflects all the incident radiation

d) Is black on the surface

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If the emitted radiant energy is to be increased by a factor of 16, by what factor must the surface temperature of a body be raised?

a)1/2

b)1

c)2

d)4

e)16

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