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

April 10th, 2026

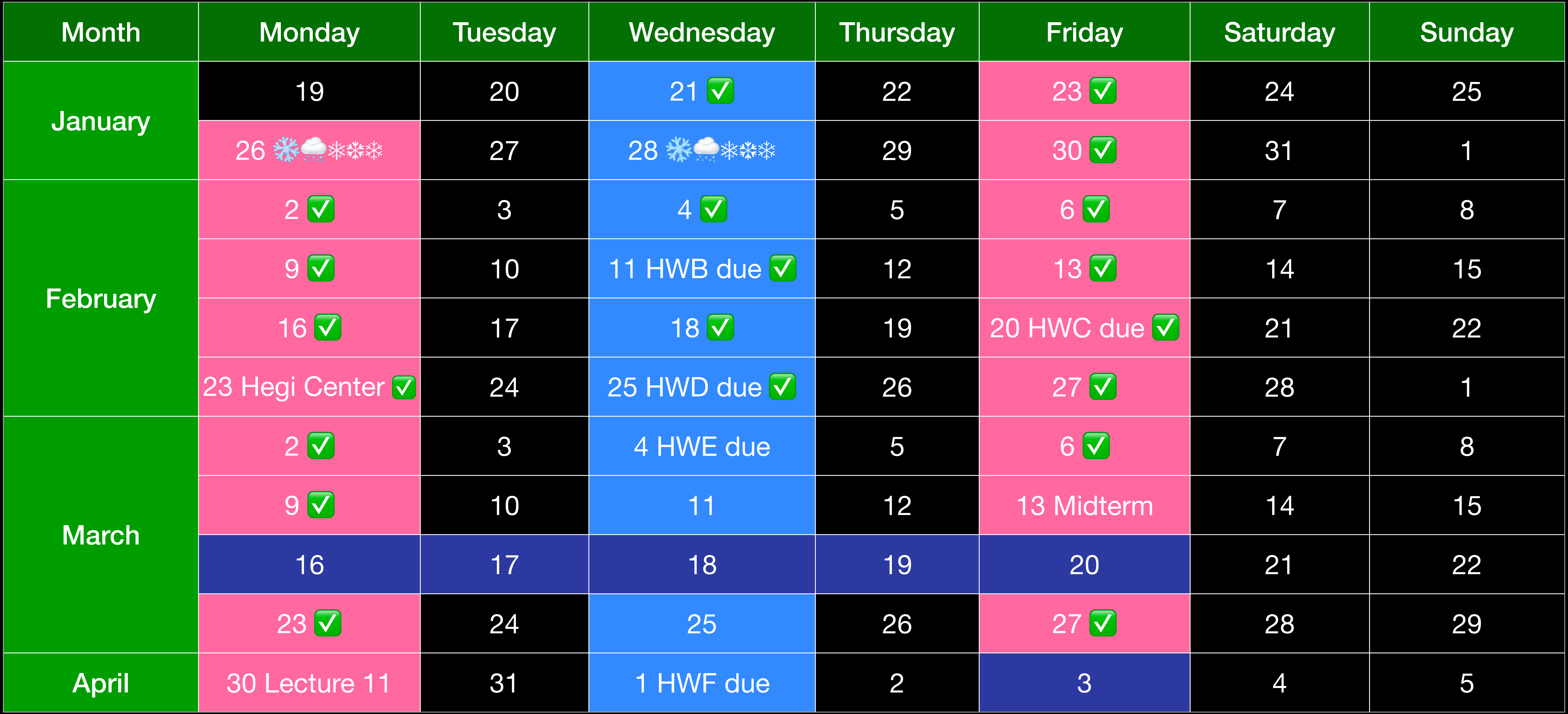
Based on Simon Dalley's lectures taught in Spring 2025

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 Midterm	14	15
	16	17	18	19	20	21	22
	23 ✅	24	25	26	27 ✅	28	29
April	30 Lecture 11	31	1 HWF due	2	3	4	5

Labs

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No class

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

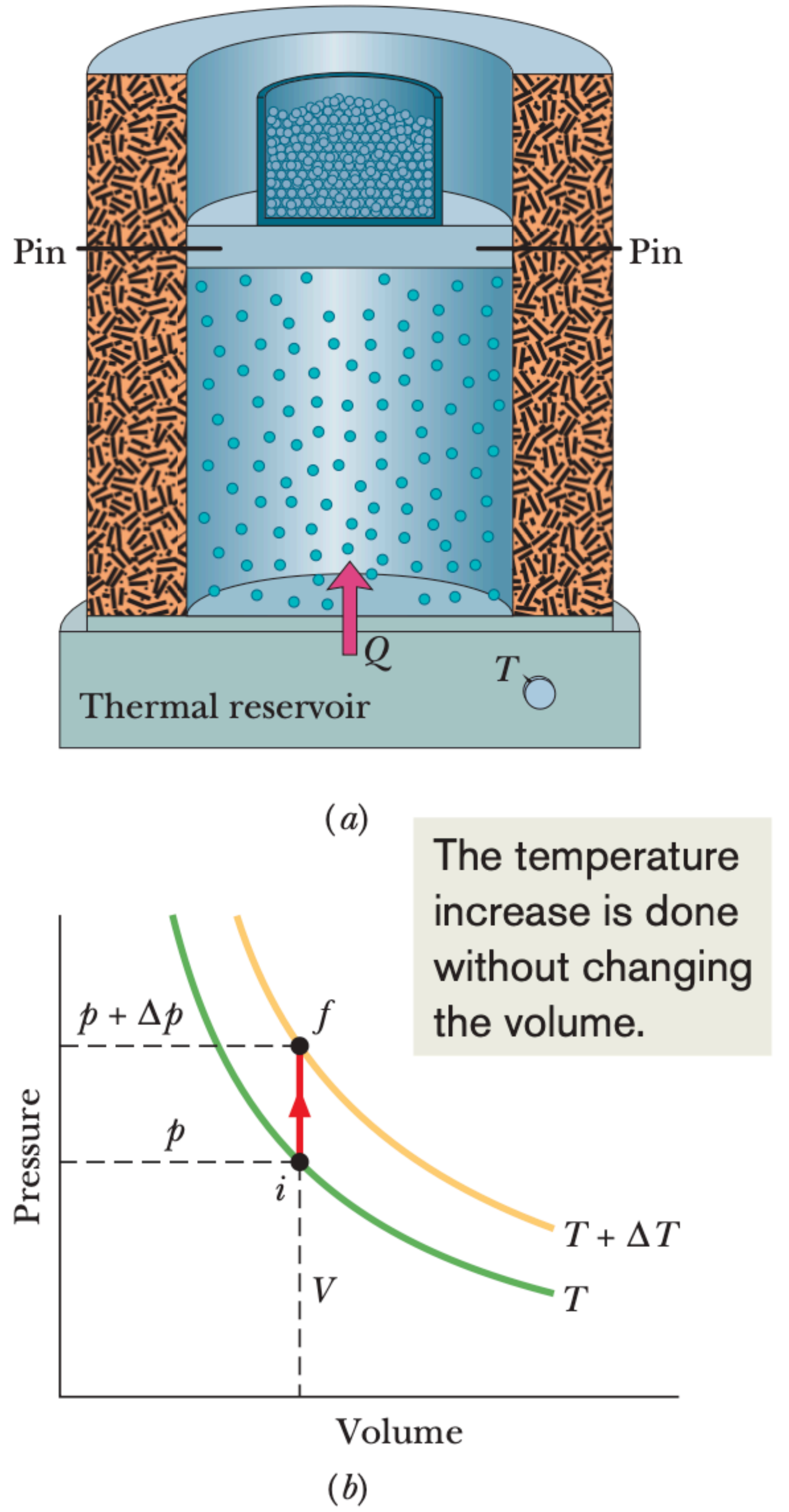
Halliday: 20.2 & 20.3

Key concepts: Adiabatic Expansion

- Let’s derive an expression for internal energy (E_{int}) of an ideal gas from molecular considerations
- The average translational kinetic energy of a single atom depends only on the gas temperature and is given by $K_{\text{avg}} = \frac{3}{2}kT$
- A sample of n moles of such a gas contains nN_A atoms. The internal energy E_{int} is then:
  - $E_{\text{int}} = (nN_A)k_{\text{avg}} = (nN_A)\left(\frac{3}{2}kT\right)$
  - $k = R/N_A$
  - $E_{\text{int}} = \frac{3}{2}nRT$ (monoatomic ideal gas)

Key concepts: Adiabatic Expansion

- The gas temperature rises from T to $T + \Delta T$
- The pressure changes from p to $p + \Delta p$
- Heat:
  - $Q = nC_V\Delta T$ (constant volume)
  - C_V: molar specific heat at constant volume
- Using the first law:
  - $\Delta E_{\text{int}} = nC_V\Delta T - W$
  - If $W = 0$, $C_V = \dfrac{\Delta E_{\text{int}}}{n\Delta T}$
  - Change in internal energy: $\Delta E_{\text{int}} = \dfrac{3}{2}nR\Delta T$
  - $C_V = \dfrac{3}{2}R = 12.5\ \text{J/mol.K}$

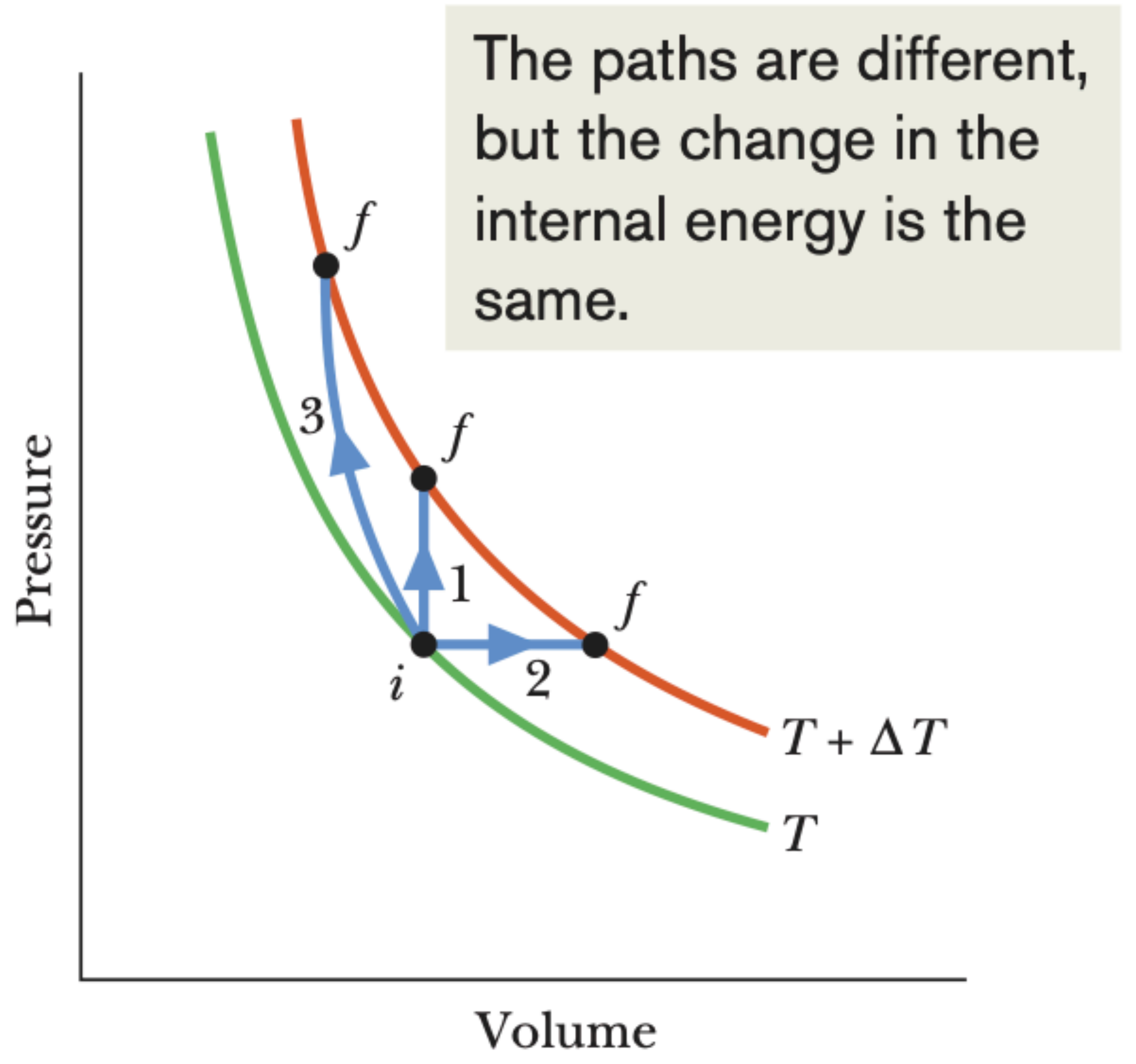


The temperature increase is done without changing the volume.

Figure 19-9 (*a*) The temperature of an ideal gas is raised from T to $T + \Delta T$ in a constant-volume process. Heat is added, but no work is done. (*b*) The process on a *p*-*V* diagram.

Key concepts: Molar specific heat at constant volume

- Heat Q is related to the temperature change by:
  - $Q = nC_V\Delta T$, C_V: molar specific heat at constant volume
  - $\Delta E_{\text{int}} = Q - W$
  - $\Delta E_{\text{int}} = nC_V\Delta T - W$
  - $W = 0,\ C_V = \dfrac{\Delta E_{\text{int}}}{n\Delta T}$
  - $\Delta E_{\text{int}} = \dfrac{3}{2}nR\Delta T$
  - $C_V = \dfrac{3}{2}R = 12.5\ \text{J/mol . K}$
- $\Delta E_{\text{int}} = Q - W$
  - $Q = nC_P\Delta T$
  - $W = p\Delta V = nR\Delta T$
  - Dividing by $n\Delta T$: $C_V = C_P - R$



The paths are different, but the change in the internal energy is the same.

Figure 19-10 Three paths representing three different processes that take an ideal gas from an initial state i at temperature T to some final state f at temperature $T + \Delta T$. The change ΔE_{int} in the internal energy of the gas is the same for these three processes and for any others that result in the same change of temperature.

Key concepts: Adiabatic Expansion

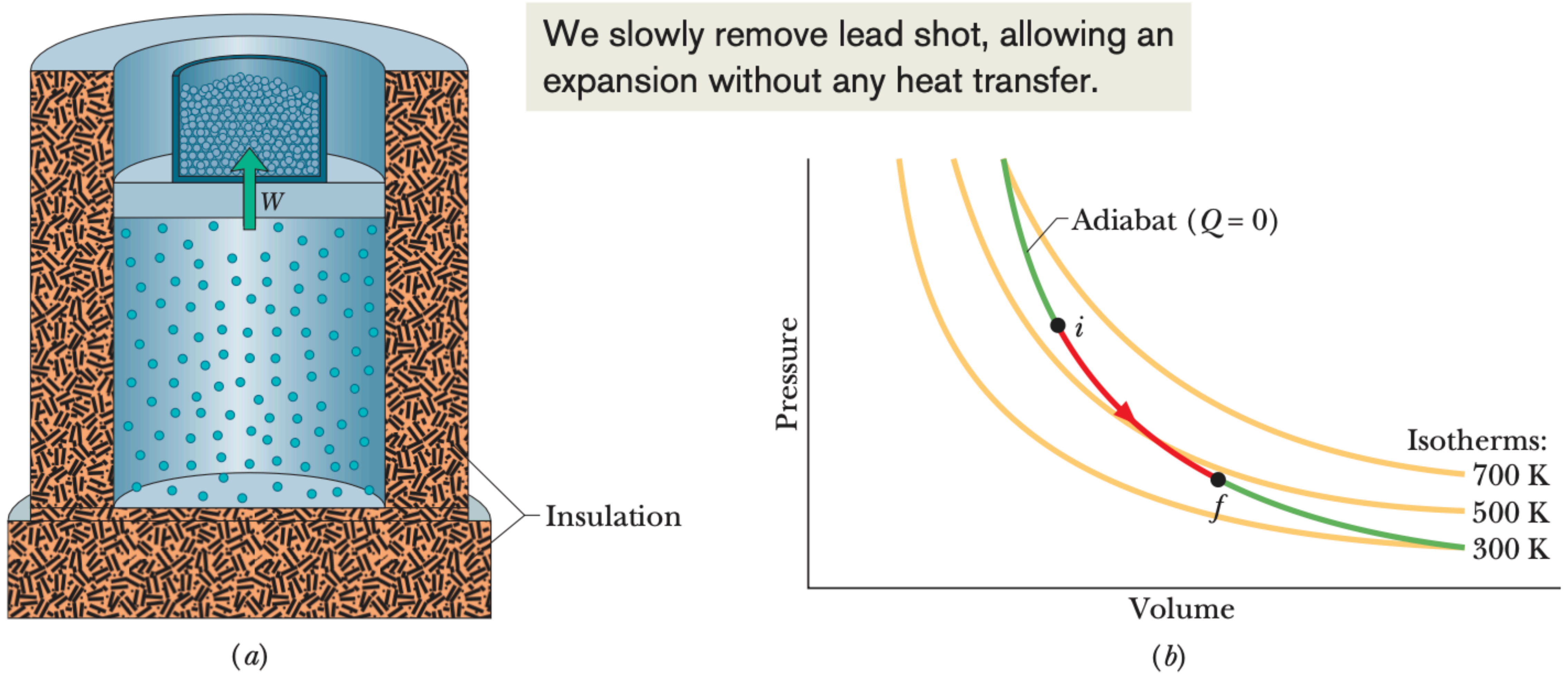

We slowly remove lead shot, allowing an expansion without any heat transfer.

Figure 19-15 (a) The volume of an ideal gas is increased by removing mass from the piston. The process is adiabatic ($Q = 0$). (b) The process proceeds from i to f along an adiabat on a p-V diagram.

- A process for which $Q = 0$ is an adiabatic process
- We can ensure that $Q = 0$ either by carrying out the process very quickly (as in sound waves) or by doing it (at any rate) in a well-insulated container

Key concepts: Adiabatic Expansion

- Remove some shot from the piston, allowing the ideal gas to push the piston and the remaining shot upward and thus to increase the volume by a differential amount dV
- The volume change is tiny,
  - assume that the pressure p of the gas on the piston is constant during the change
  - allows us to say that the work dW done by the gas during the volume increase $= pdV$
- First law of thermodynamics:
  - $dE_{\text{int}} = Q - pdV, Q = 0$
  - $dE_{\text{int}} = nC_V dT$
  - $ndT = -\dfrac{p}{C_V}dV$

Key concepts: Adiabatic Expansion

- First law of thermodynamics:
  - $dE_{\text{int}} = Q - pdV,\ Q = 0$
  - $dE_{\text{int}} = nC_V dT$
  - $ndT = -\dfrac{p}{C_V}dV$
- Ideal gas law ($PV = nRT$):
  - $pdV + Vdp = nRdT$
  - $R = C_P - C_V$
  - $ndT = \dfrac{pdV + Vdp}{C_P - C_V}$
  - $\dfrac{dp}{p} + \left(\dfrac{C_P}{C_v}\right)\dfrac{dV}{V} = 0$
  - $\ln p + \gamma \ln V = \text{constant},\ \gamma = \left(\dfrac{C_P}{C_v}\right)$
  - $PV^\gamma = \text{constant}$

Key concepts: Engines

- A **heat engine,** or more simply, an **engine,** is a device that extracts energy from its environment in the form of heat and does useful work
- Needs a working substance:
  - Water for steam engine
  - Gasoline for automobile engine
- Engine → work on a sustained basis, the working substance must operate in a *cycle*
- The working substance must pass through a closed series of thermodynamic processes

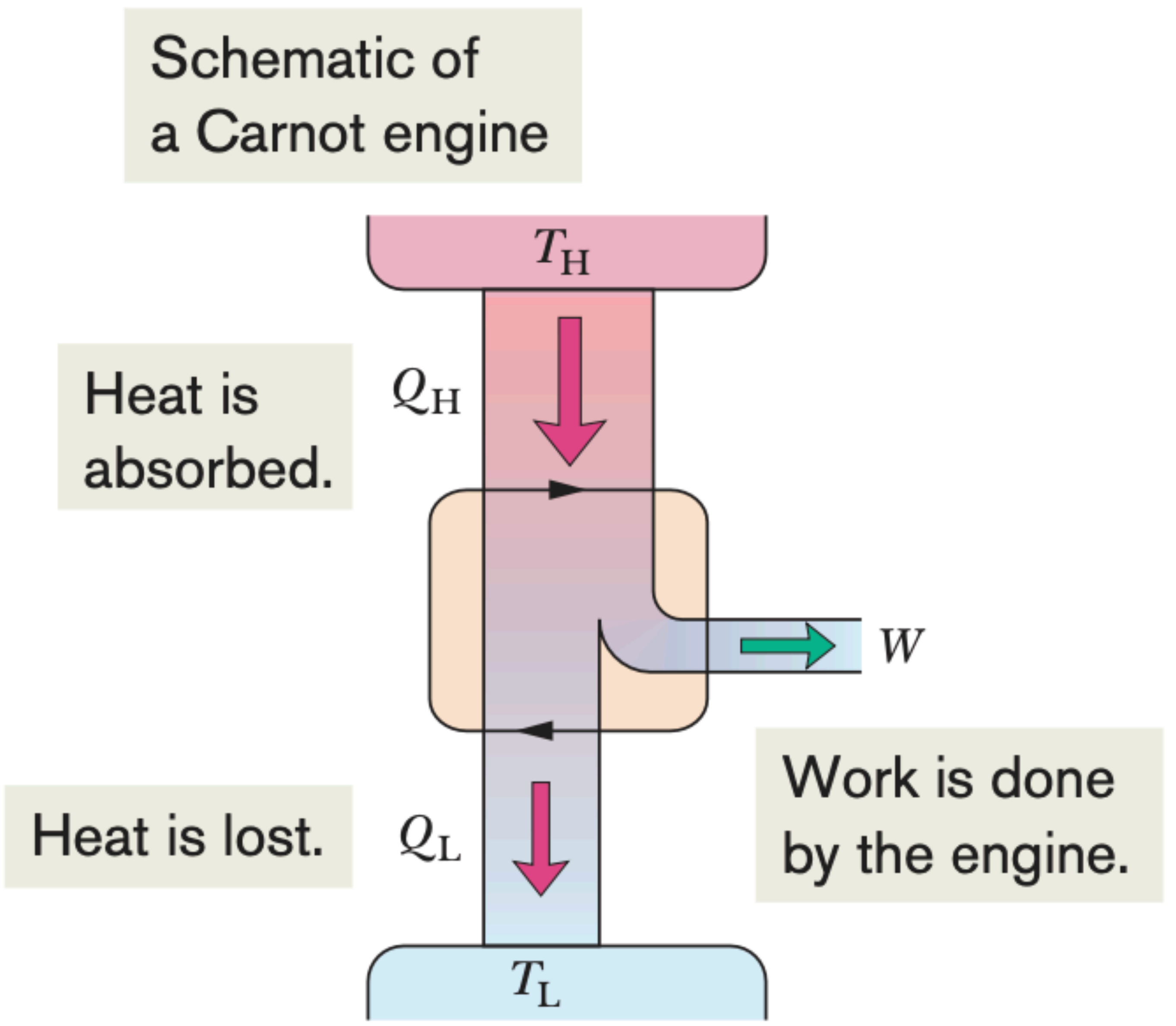
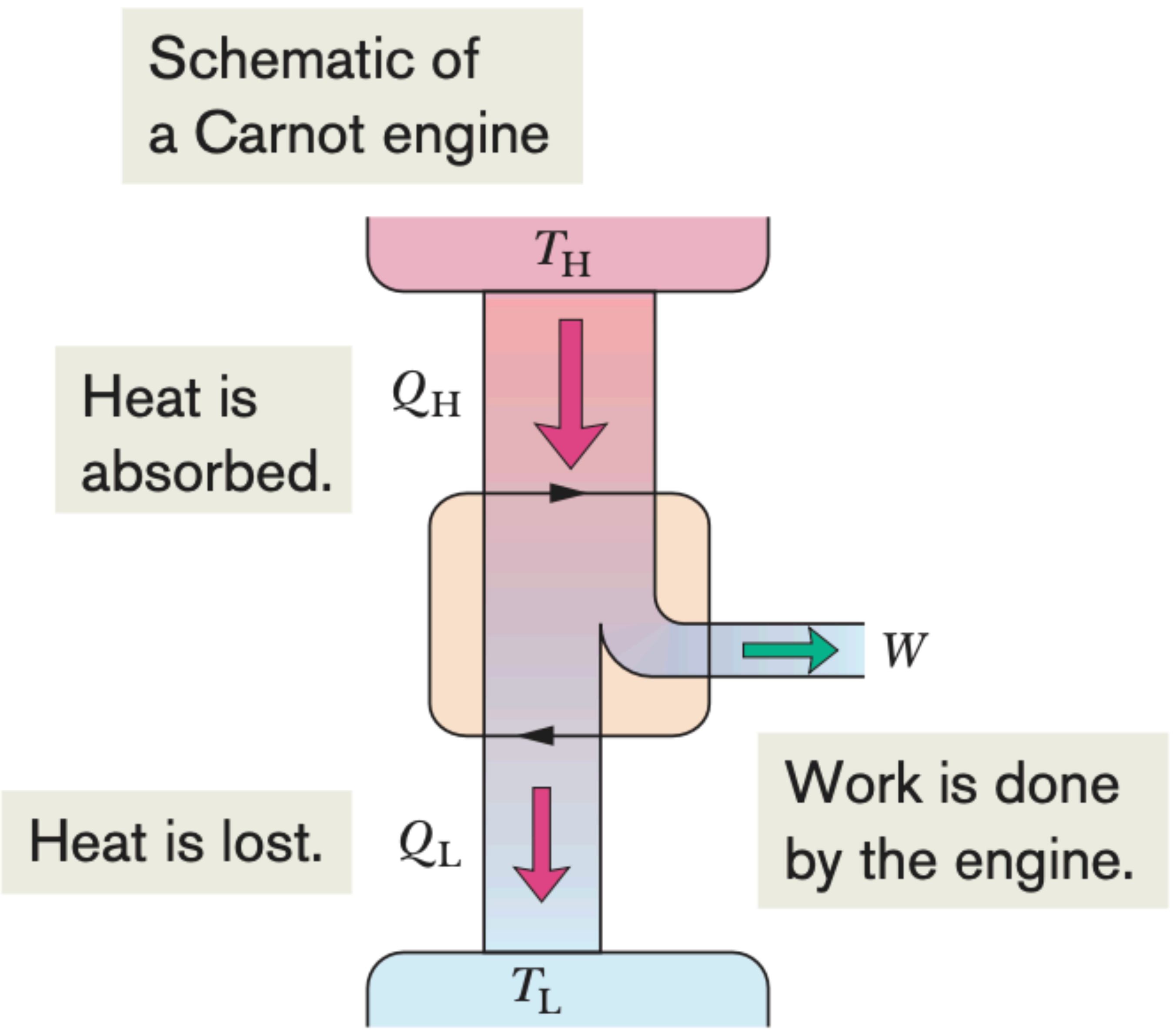


Figure 20-8 The elements of a Carnot engine. The two black arrowheads on the central loop suggest the working substance operating in a cycle, as if on a p-V plot. Energy $|Q_H|$ is transferred as heat from the high-temperature reservoir at temperature T_H to the working substance. Energy $|Q_L|$ is transferred as heat from the working substance to the low-temperature reservoir at temperature T_L. Work W is done by the engine (actually by the working substance) on something in the environment.

Key concepts: Carnot Engines

- We can learn much about real gases by analyzing an ideal gas, which obeys the simple law $PV = nRT$
- Although an ideal gas does not exist, any real gas approaches ideal behavior if its density is low enough
- Similarly, we can study real engines by analyzing the behavior of an **ideal engine**
- Focus on the Carnot Engine:
    - During each cycle of the engine, the working substance absorbs energy $|Q_H|$ as heat from a thermal reservoir at constant temperature T_H and discharges energy $|Q_L|$ as heat to a second thermal reservoir at a constant lower temperature T_L



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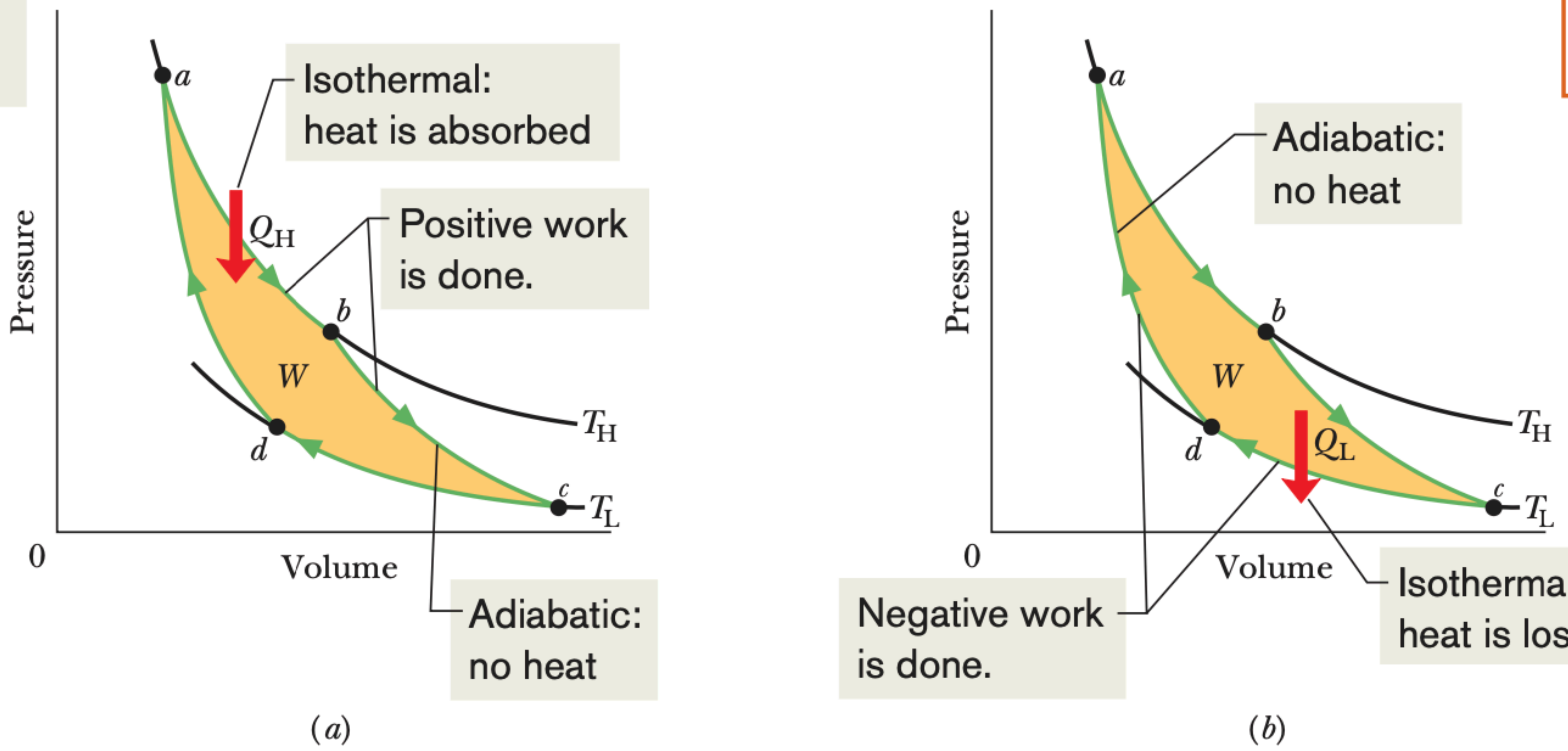
Key concepts: Carnot Engines

Stages of a Carnot engine



Isothermal: heat is absorbed

Positive work is done.

Adiabatic: no heat

Adiabatic: no heat

Negative work is done.

Isothermal: heat is lost

Figure 20-9 A pressure–volume plot of the cycle followed by the working substance of the Carnot engine in Fig. 20-8. The cycle consists of two isothermal (*ab* and *cd*) and two adiabatic processes (*bc* and *da*). The shaded area enclosed by the cycle is equal to the work *W* per cycle done by the Carnot engine.

Key concepts: Carnot Engines

- Net work done:
  - From first law ($\Delta E_{\text{int}} = Q - W$)
  - $\Delta E_{\text{int}} = 0$
  - Working substance must return again and again to any arbitrarily selected state in the cycle
  - If X represents any state property of the working substance, such as pressure, temperature, volume, internal energy, or entropy, we must have $\Delta X = 0$ for every cycle
- $W = |Q_H| - |Q_L|$

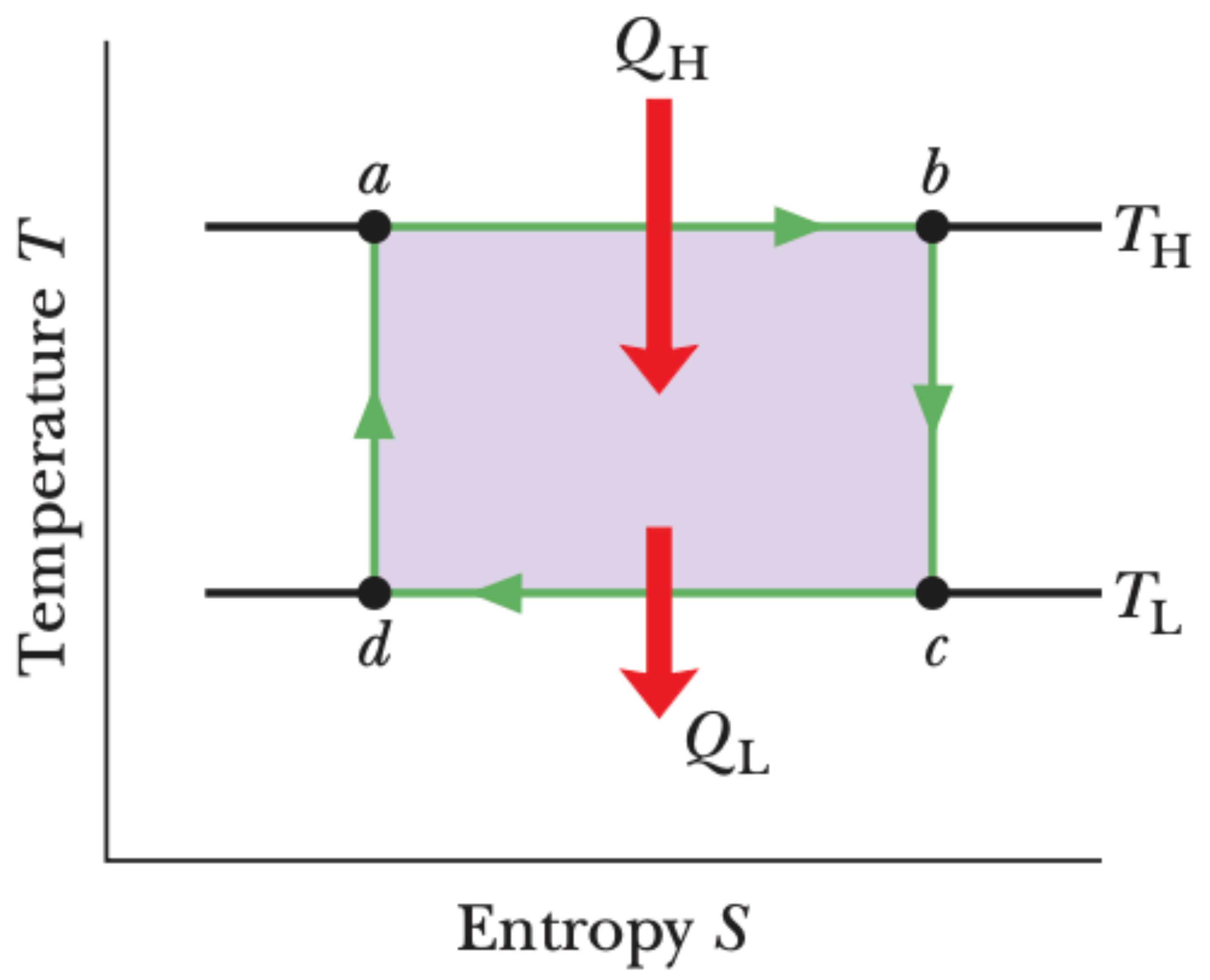


Figure 20-10 The Carnot cycle of Fig. 20-9 plotted on a temperature–entropy diagram. During processes *ab* and *cd* the temperature remains constant. During processes *bc* and *da* the entropy remains constant.

Key concepts: Carnot Engines

- Net entropy change:
  - $\Delta S = S_H + S_L$
  - ΔS_H is positive because energy $|Q_H|$ is *added to* the working substance as heat (an increase in entropy) and ΔS_L is negative because energy $|Q_L|$ is *removed from* the working substance as heat (a decrease in entropy)
  - Entropy is a state function, we must have $\Delta S = 0$ for a complete cycle
  - $$\frac{|Q_H|}{T_H} = \frac{|Q_L|}{T_L}$$

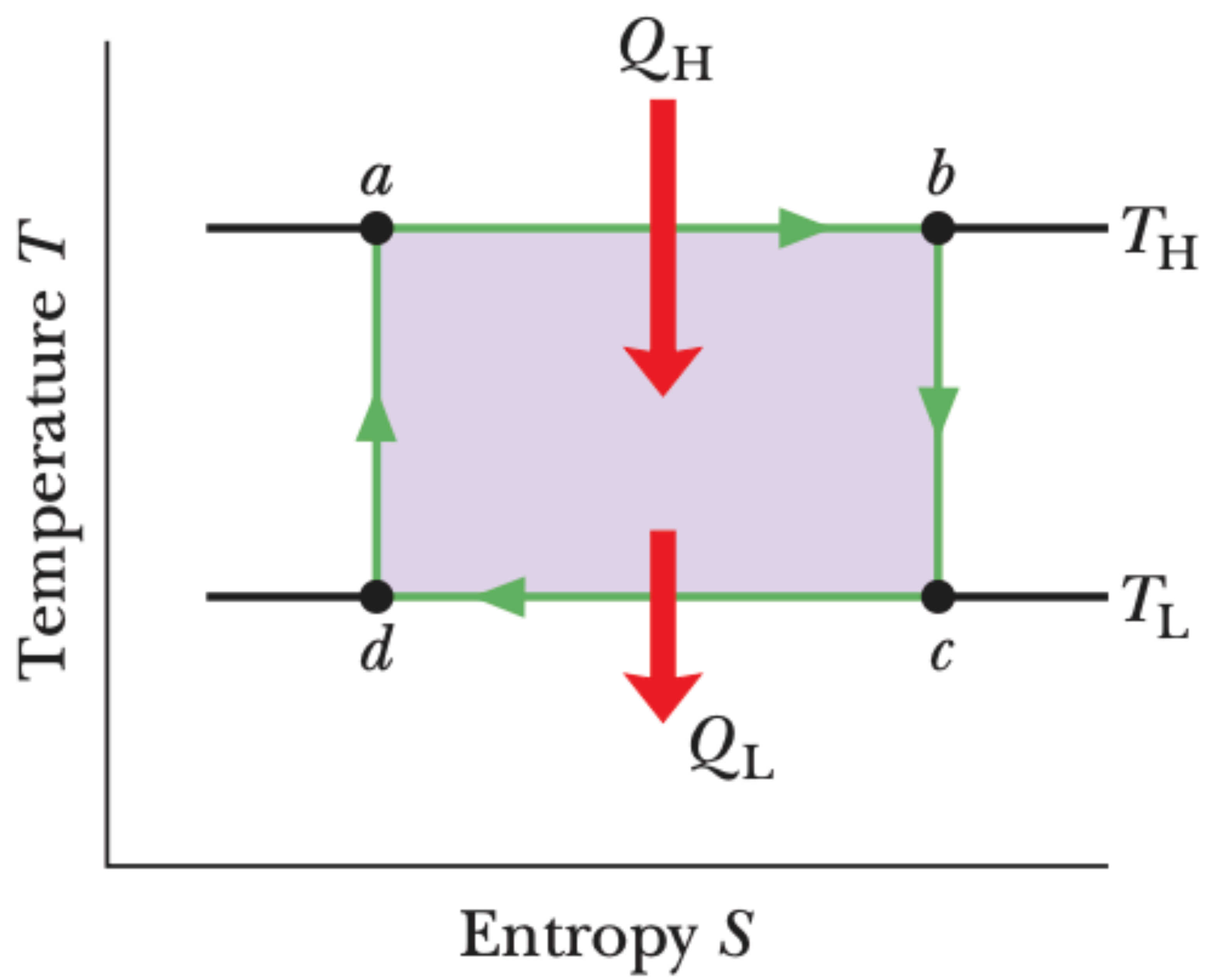


Figure 20-10 The Carnot cycle of Fig. 20-9 plotted on a temperature–entropy diagram. During processes *ab* and *cd* the temperature remains constant. During processes *bc* and *da* the entropy remains constant.

What is the correct order of steps for a Carnot cycle?

a) Isothermal expansion, adiabatic expansion, isothermal compression, adiabatic compression

b) Isothermal compression, adiabatic expansion, isothermal expansion, adiabatic compression

c) Adiabatic compression, adiabatic expansion, isothermal expansion, isothermal compression

d) Adiabatic compression, isothermal expansion, adiabatic expansion, isothermal compression

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a) Isothermal expansion, adiabatic expansion, isothermal compression, adiabatic compression.

Here is a breakdown of why this sequence makes up the ideal Carnot cycle:

The Carnot cycle operates as a heat engine between two temperature reservoirs—a hot reservoir at temperature TH and a cold reservoir at temperature TC . It consists of four distinct, reversible steps:

1. **Isothermal Expansion:** The cycle begins with the working fluid (like a gas) in thermal contact with the hot reservoir. The gas expands, doing work on its surroundings while absorbing heat from the reservoir. Because this process is *isothermal*, the temperature of the gas remains constant at TH .
2. **Adiabatic Expansion:** The gas is then thermally isolated so no heat can enter or leave. It continues to expand, doing more work. Because this is an *adiabatic* process (no heat exchange), the expansion causes the gas to cool down until it reaches the temperature of the cold reservoir, TC .
3. **Isothermal Compression:** The gas is now placed in contact with the cold reservoir. The surroundings do work on the gas to compress it. As it compresses, it expels waste heat to the cold reservoir. The temperature remains constant at TC throughout this step.
4. **Adiabatic Compression:** Finally, the gas is thermally isolated once again. The surroundings do more work to compress the gas back to its original volume. With no heat able to escape, this compression raises the temperature of the gas from TC back to the starting temperature TH , completing the cycle.

Key concepts: Efficiency

- Purpose of any engine is to transform as much of the extracted energy $|Q_H|$ into work as possible
- We measure its success in doing so by its **thermal efficiency,** ϵ
  - $\epsilon = \dfrac{\text{energy we get}}{\text{energy we pay for}} = \dfrac{|W|}{|Q_H|}$
- Substituting for W
  - $\epsilon_C = \dfrac{|Q_H| - |Q_L|}{|Q_H|} = 1 - \dfrac{|Q_L|}{|Q_H|}$
  - $\epsilon_C = 1 - \dfrac{|T_L|}{|T_H|}$

Three Carnot engines operate between reservoirs at temperatures

1)400 K and 500K
2)600K and 800 K
3)400K and 600 K

Rank them according to their thermal efficiencies, greatest first.

a) 3 > 2 > 1

b) 2 > 3 > 1

c) 1 = 3 > 2

d) 2 = 3 > 1

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a) 3 > 2 > 1.

The thermal efficiency (η) of an ideal Carnot engine depends only on the temperatures of its cold reservoir (TC) and hot reservoir (TH), measured in Kelvin. The formula is:

$\eta = 1 - TH/TC$
Let's calculate the efficiency for each of the three engines:

- **Engine 1:**
    - TC =400 K
    - TH =500 K
    - Eff1 =1−500/400 =1−0.80=0.20 (or 20%)
- **Engine 2:**
    - TC =600 K
    - TH =800 K
    - Eff2 =1−800/600 =1−0.75=0.25 (or 25%)
- **Engine 3:**
    - TC =400 K
    - TH =600 K
    - Eff3 =1−600/400 =1−0.667≈0.333 (or 33.3%)

Comparing the efficiencies, we get 0.333>0.25>0.20, which corresponds to Engine 3 > Engine 2 > Engine 1.

Key concepts: Stirling Engine

- Comparison with the Carnot cycle:
  - Each engine has isothermal heat transfers at temperatures T_H and T_L
  - However, the two isotherms of the Stirling engine cycle are connected, not by adiabatic processes as for the Carnot engine but by constant-volume processes
  - To increase the temperature of a gas at constant volume reversibly from T_L to T_H requires a transfer of energy as heat to the working substance from a thermal reservoir whose temperature can be varied smoothly between those limits
  - Reverse transfer is required in process *bc*. Thus, reversible heat transfers (and corresponding entropy changes) occur in all four of the processes that form the cycle of a Stirling engine, not just two processes as in a Carnot engine.
  - The efficiency of an ideal Stirling engine is lower than that of a Carnot engine operating between the same two temperatures.
  - Real Stirling engines have even lower efficiencies.

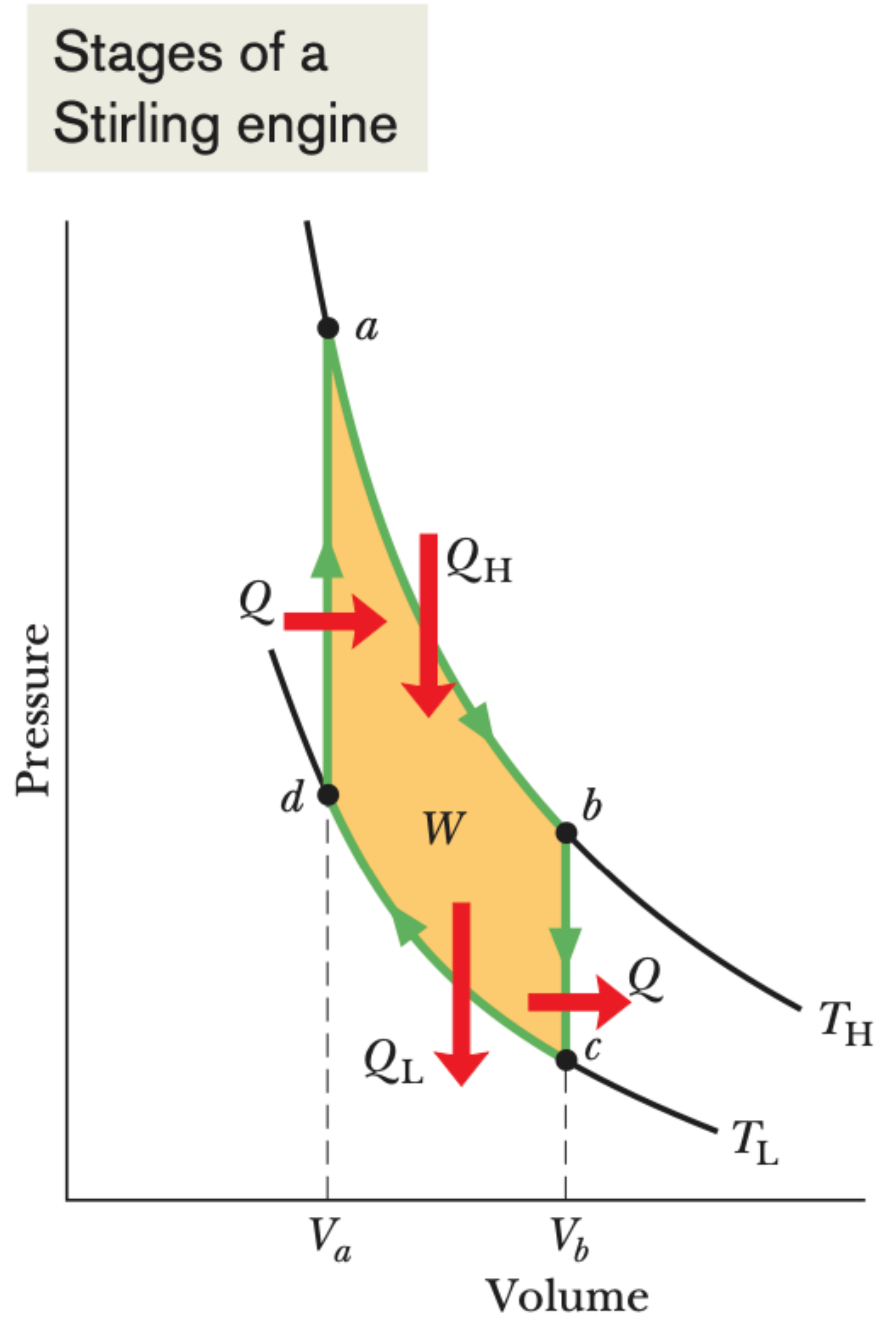

Figure 20-13 A p-V plot for the working substance of an ideal Stirling engine, with the working substance assumed for convenience to be an ideal gas.

The Key Components

- **The Heat Source (Bottom Right):** The small burner provides a constant blue flame.
- **The Hot Cylinder (Glass Tube):** Located directly above the flame. If you look closely inside the spinning blur of the glass tube, there is a large, loose-fitting piston called the **displacer**. Its job isn't to push hard, but simply to move air back and forth.
- **The Cold Cylinder (Finned Brass Section):** Located in the middle. The horizontal ridges (fins) act as a heat sink to cool the air inside. Hidden inside this section is a tight-fitting **power piston**.
- **The Flywheel (Left):** The large rotating wheel. It stores momentum to keep the engine spinning smoothly through the parts of the cycle that don't produce power.

The 4-Step Cycle

The entire engine works on a simple principle: **gases expand when heated and contract when cooled.** The engine is a closed system filled with a fixed amount of air.

- **Heating and Expansion (Power Stroke):** The flame heats the air inside the glass tube. The hot air rapidly expands, increasing the pressure inside the entire engine. This high pressure pushes outward against the tight-fitting **power piston** (inside the finned cylinder). The power piston moves outward, turning the flywheel. This is the part of the cycle that actually generates power.
- **Transferring the Air (Hot to Cold):** As the flywheel turns, its momentum pushes the loose **displacer piston** towards the hot end of the glass tube. Because the displacer is loose, it doesn't compress the air; instead, it shoves the hot air past it, moving the air out of the hot glass tube and into the finned cooling section.
- **Cooling and Contraction:** Now residing in the finned brass cylinder, the air cools down. As it cools, the gas contracts, causing the pressure inside the engine to drop. This lower pressure (along with the flywheel's momentum) pulls the power piston back inward.
- **Transferring the Air (Cold to Hot):** The flywheel continues to spin, pulling the displacer piston back away from the flame. This shoves the cooled air back into the glass tube where the flame is waiting to heat it up again.

The cycle then instantly repeats. The displacer and the power piston are connected to the flywheel in a way that puts them out of sync (usually by 90 degrees), which perfectly times the heating and cooling phases to keep the wheel spinning.

The efficiency of a Stirling cycle compared to a Carnot cycle is

a)greater

b)less

c)equal to

d)Not enough information

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d)Not enough information

- **Carnot's Principle:** This principle states that no heat engine operating between two heat reservoirs (a hot one at TH and a cold one at TC) can be more efficient than a perfectly reversible engine operating between those same two reservoirs. Furthermore, *all* reversible engines operating between the same two temperatures have the exact same efficiency, which is given by $\eta=1-TH/TC$.
- **The Ideal Stirling Cycle:** An ideal Stirling cycle consists of two isothermal (constant temperature) processes and two isochoric (constant volume) processes.

Key concepts: Refrigerators

- A **refrigerator** is a device that uses work in order to transfer energy from a low temperature reservoir to a high temperature reservoir as the device continuously repeats a set series of thermodynamic processes
  - In a household refrigerator, work is done by an electrical compressor to transfer energy from the food storage compartment (a low-temperature reservoir) to the room (a high-temperature reservoir)
- Air conditioners and heat pumps are also refrigerators
  - For an air conditioner, the low-temperature reservoir is the room that is to be cooled and the high-temperature reservoir is the warmer outdoors
  - A heat pump is an air conditioner that can be operated in reverse to heat a room; the room is the high temperature reservoir, and heat is transferred to it from the cooler outdoors

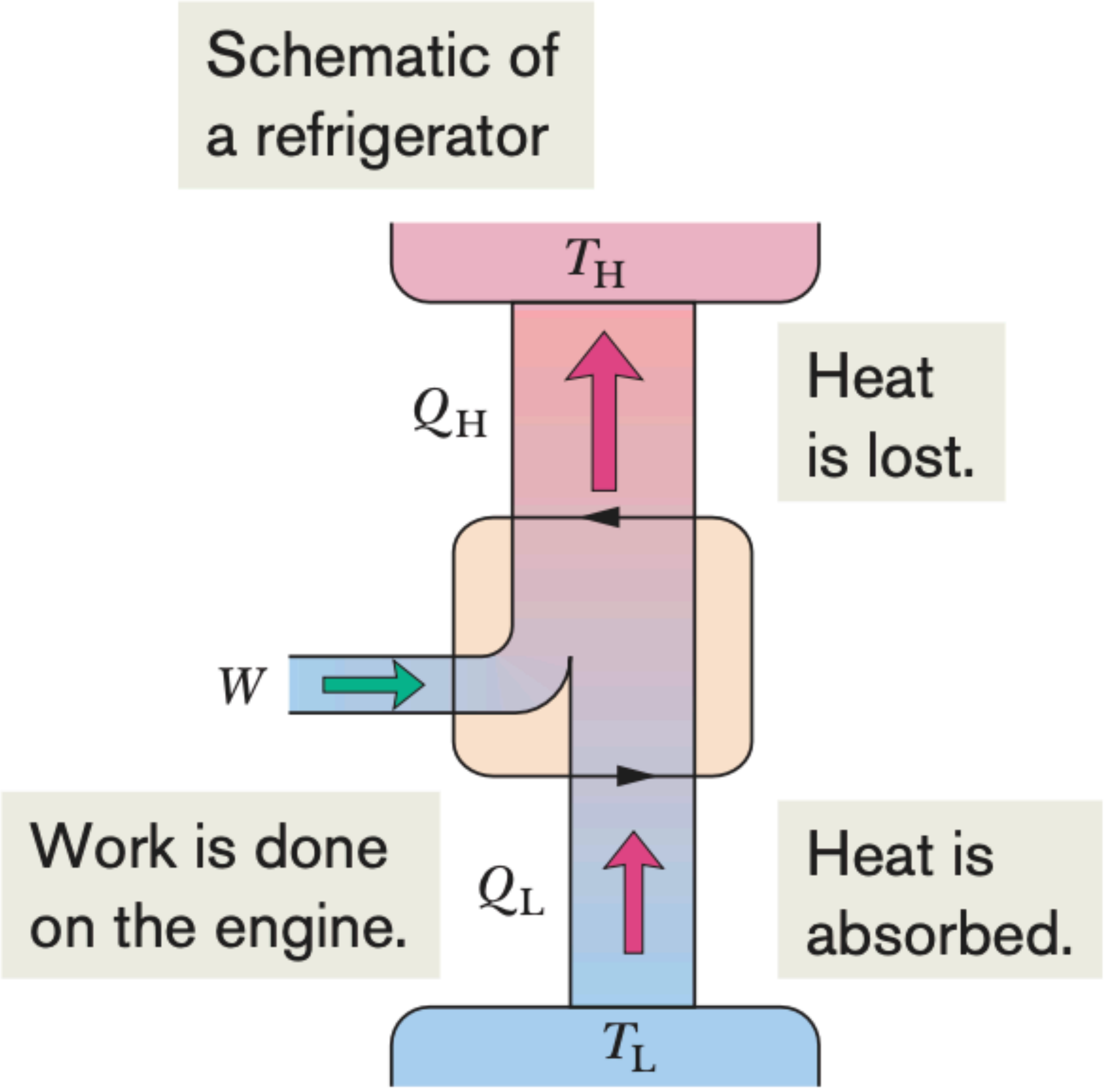

Figure 20-14 The elements of a refrigerator. The two black arrowheads on the central loop suggest the working substance operating in a cycle, as if on a p-V plot. Energy is transferred as heat Q_L to the working substance from the low-temperature reservoir. Energy is transferred as heat Q_H to the high-temperature reservoir from the working substance. Work W is done on the refrigerator (on the working substance) by something in the environment.

Key concepts: Coefficient of Performance

- A refrigerator is designed to extract as much energy $|Q_L|$ as possible from a low-temperature reservoir for the least amount of work $|W|$ (what we pay for)
- Measure of the efficiency of a refrigerator is:
  - $K = \dfrac{\text{what we want}}{\text{what we pay for}}$
  - $K = \dfrac{\text{what we want}}{\text{what we pay for}} = \dfrac{|Q_L|}{|W|}$
  - $K =$ coefficient of performance
- For a Carnot refrigerator, the first law of thermodynamics gives:
  - $K_C = \dfrac{|Q_L|}{|Q_H| - |Q_L|}$
- Carnot refrigerator is a Carnot engine operating in reverse
  - $K_C = \dfrac{|T_L|}{|T_H| - |T_L|}$

The coefficient of performance for a reverse Carnot refrigerator is 5.

The ratio of the highest temperature to lowest temperature will be

a)5

b)6/5

c)5/4

d)Not enough information

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$$\text{COP} = \frac{T_C}{T_H - T_C}$$

$$5 = \frac{T_C}{T_H - T_C}$$

$$5(T_H - T_C) = T_C$$

$$5T_H - 5T_C = T_C$$

$$5T_H = 6T_C$$

$$\frac{T_H}{T_C} = \frac{6}{5}$$

A car engine operates with a thermal efficiency of 25%. Assume the air-conditioner has a coefficient of performance of 2 working as a reverse-Carnot refrigerator cooling the inside using the engine for work.

How much fuel energy should be spent to remove 1 kJ from the inside?

a)0.5 kJ

b)1 kJ

c)2 kJ

d)none of the above

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Step 1: Calculate work required by the air conditioner

$$COP = \frac{Q_c}{W}$$

$$2 = \frac{1\text{ kJ}}{W}$$

$$W = 0.5\text{ kJ}$$

Step 2: Calculate fuel energy required by the engine

$$K = \frac{W}{Q_h}$$

$$0.25 = \frac{0.5\text{ kJ}}{Q_h}$$

$$Q_h = \frac{0.5\text{ kJ}}{0.25}$$

$$Q_h = 2\text{ kJ}$$

Which is **not** a statement of the 2nd law of thermodynamics?

a)Heat can never pass from a colder to a warmer body without some other change.

b)It is impossible for a cycle to absorb heat from a reservoir and to deliver an equivalent amount of work.

c) The sum of entropies of all bodies taking part in a process is increased, but for reversible processes the sum remains unchanged.

d)It is impossible to construct an engine which will work in a cycle and produce continuous work from nothing.

e) Matter and energy have the tendency to reach a state of maximum disorder.

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e) Matter and energy have the tendency to reach a state of maximum disorder.

d) It is impossible to construct an engine which will work in a cycle and produce continuous work from nothing.

Here is a breakdown of why this is the correct choice:

- **a) Heat can never pass from a colder to a warmer body without some other change:** This is the **Clausius statement** of the Second Law. It explains why refrigerators require an energy input (work) to function.
- **b) It is impossible for a cycle to absorb heat from a reservoir and to deliver an equivalent amount of work:** This is the **Kelvin-Planck statement** of the Second Law. It means no heat engine can be 100% efficient; some heat must always be rejected to a colder reservoir.
- **c) The sum of entropies...:** The Second Law dictates that the total entropy (a measure of disorder or unavailable energy) of an isolated system can never decrease over time. It increases for irreversible processes and remains constant for reversible ones.
- **d) Continuous work from nothing:** Producing "work from nothing" implies creating energy out of thin air. This violates the conservation of energy, which is the **First Law of Thermodynamics**, not the Second Law. A hypothetical device that does this is called a perpetual motion machine of the first kind.
- **e) Tendency to reach maximum disorder:** This is a common, conceptual interpretation of the Second Law, describing the natural tendency of systems to move toward a state of higher entropy (disorder).