Chapter 19 Heat Engines and Refrigerators

Chapter Goal: To study the physical principles that govern the operation of heat engines and refrigerators.

Announcements

- Student evaluations today.

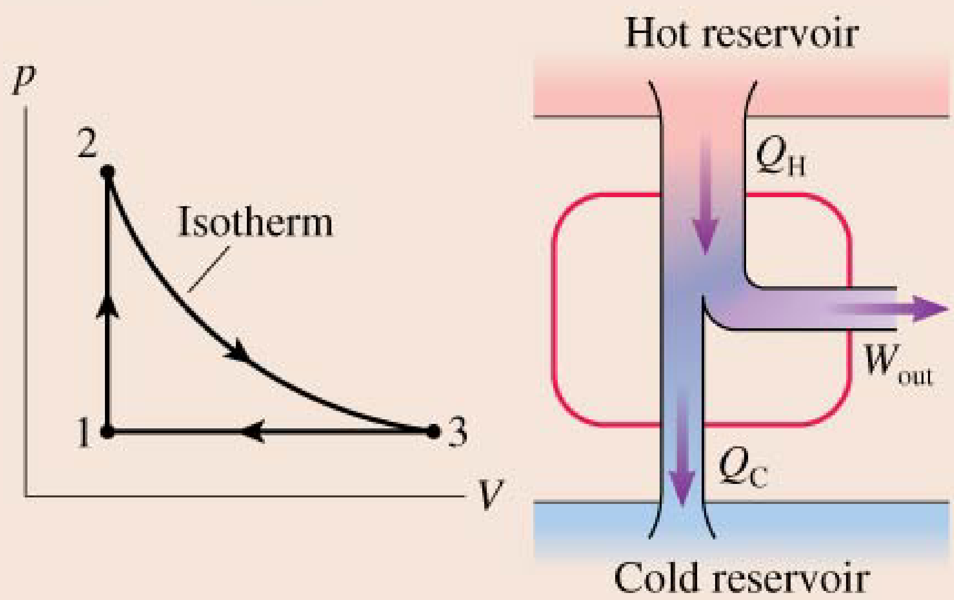
  Please pick up evaluation form at back or room.
  Complete form during class.
  Deliver to box at front at end of class.
  A student will take them to the physics office.

  Forms will be given to me only after final grades are turned in.

Announcements

- Homework: Ch 17 due today.
  Ch 18 due tomorrow, 9:00 am (extra credit).
  Ch 19 due Monday, 9:00 am (extra credit).
- End-of-semester postings: http://www.wsu.edu/~collins/201/
  Sample final exam, chapter notes, homework.
- Review for final exam, Monday, 11:00-13:00.
- Final exam: Wednesday, Dec. 11, 10:10-13:00.
  You must sit in assigned seat; attendance will be taken.
  Eight problems, equation sheet same as sample exam.
  Not responsible for sections 12.10 and 12.11.

Chapter 19 Preview



You will learn that heat engines

- Follow a cyclical process that can be shown on *pV* diagrams and on *energy-transfer diagrams.*
- Require not only a source of heat but also a source of cooling. These are called the *hot reservoir* and the *cold reservoir*.
- Are governed by the first and second laws of thermodynamics.

Chapter 19 Preview

Heat Engines

Heat engine is the generic name for any device that uses a cyclical process to transform heat energy into work.

The heat from burning fuel boils water to make high-pressure steam that then does work by spinning this turbine at an electric generating station.

Refrigerators

A **refrigerator** is a heat engine in reverse, using work to "pump energy uphill" from cold to hot.

In a refrigerator, a compressor does work to pump heat energy from the colder inside to the warmer room. Air conditioners are "refrigerators" pumping heat energy from the cool inside of a house to the hot outside.

Efficiency

How good is a heat engine at transforming heat into work? We'll define an engine's **thermal efficiency** as

$$\text{efficiency} = \frac{\text{work done}}{\text{heat required}}$$

You'll learn that the laws of thermodynamics set limits on the maximum possible efficiency. The fact that no heat engine can have an efficiency of 100% prevents us from extracting and using the vast thermal energy in the air and water around us.

The Carnot Engine

We'll use the second law of thermodynamics to show that a *perfectly reversible heat engine*—called a **Carnot engine**—has the maximum possible thermal efficiency.

You'll learn that the efficiency of a Carnot engine depends only on the temperatures of the hot and cold reservoirs. Any real engine's efficiency will be less—often much less.

Thermodynamics

- Thermodynamics is the branch of physics that studies the transformation of energy.
- Many practical devices are designed to transform energy from one form, such as the heat from burning fuel, into another, such as work.
- Chapters 17 and 18 established two laws of thermodynamics that any such device must obey:

First law Energy is conserved; that is, $\Delta E_{th} = W + Q$.

Second law Most macroscopic processes are irreversible. In particular, heat energy is transferred spontaneously from a hotter to a colder system but never from a colder system to a hotter system.

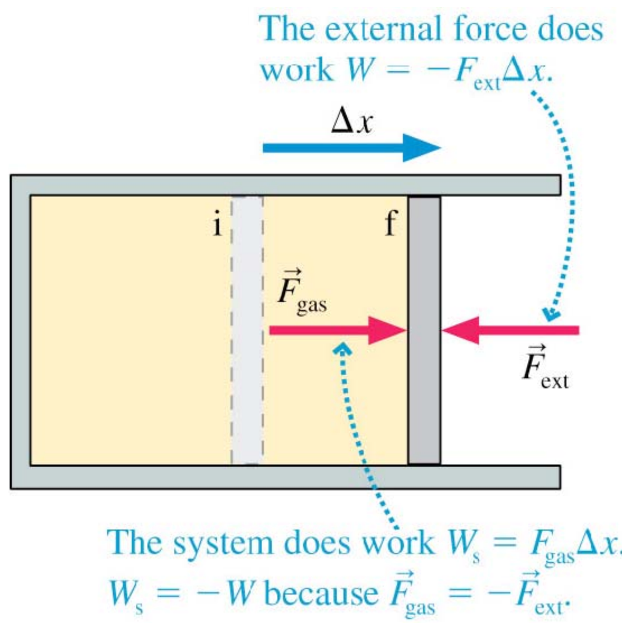
Work Done by the System

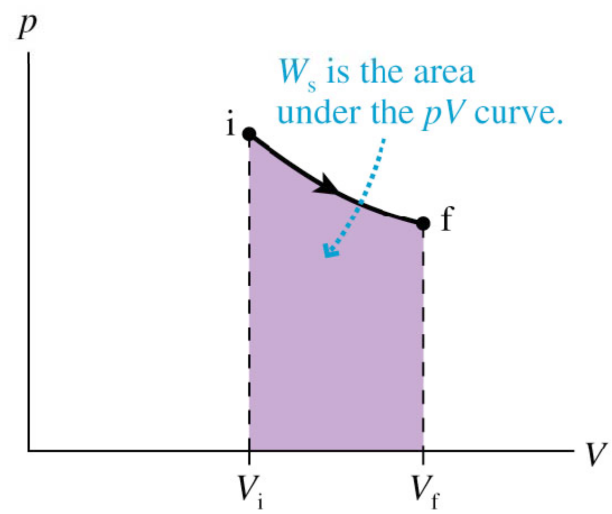
- The work W in the first law is the work done *on* the system by external forces from the environment.
- The work done *by* the system is called W_s:

$$W_s = -W = \text{the area under the } pV \text{ curve}$$

- In terms of W_s, the first law is:

$$Q = W_s + \Delta E_{th} \qquad \text{(first law of thermodynamics)}$$

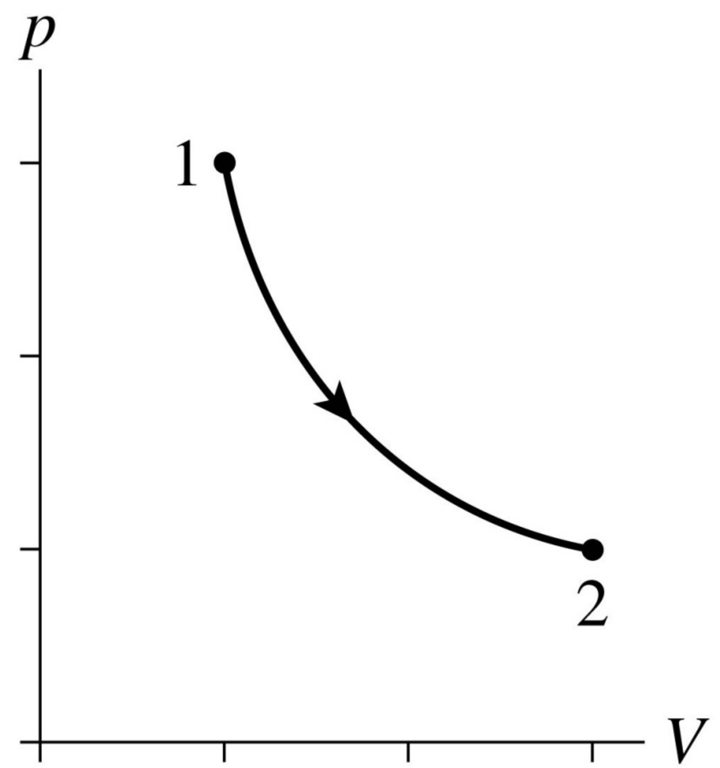




QuickCheck 19.1

In an isothermal expansion:

A. $W = 0$ and $W_s > 0$.
B. $W < 0$ and $W_s = 0$.
C. $W > 0$ and $W_s = 0$.
D. $W > 0$ and $W_s < 0$.
E. $W < 0$ and $W_s > 0$.



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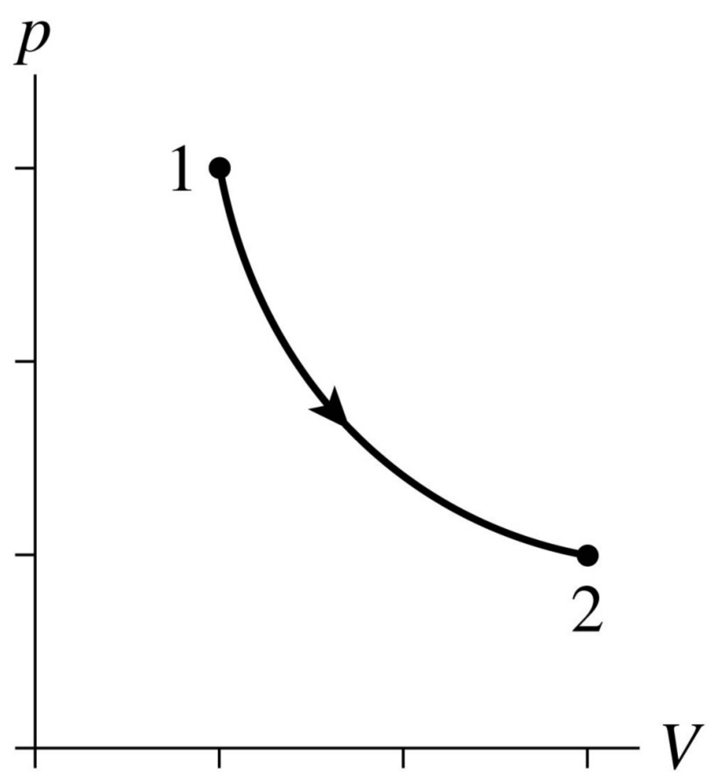
✔ **E. $W < 0$ and $W_s > 0$.**



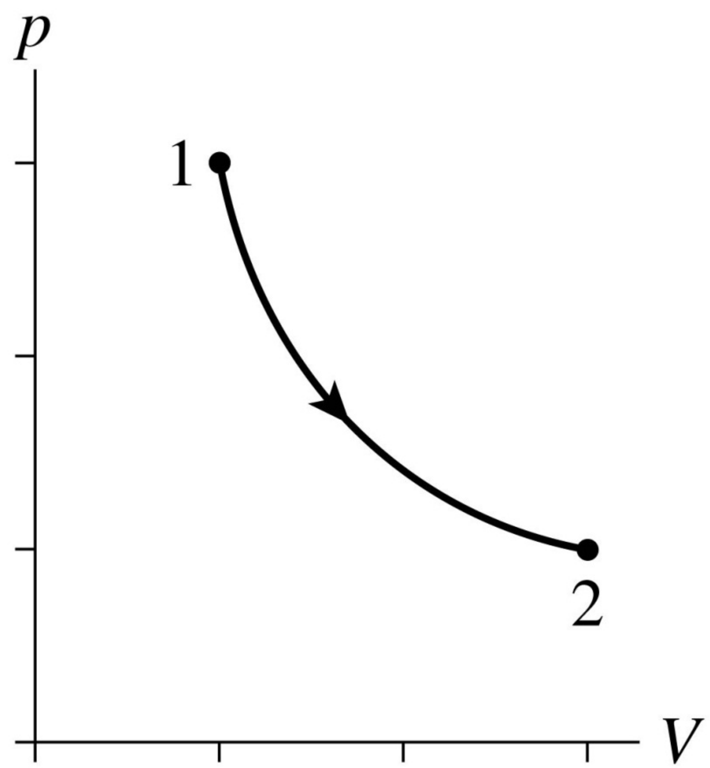
QuickCheck 19.2

In an isothermal expansion:

A. $Q > 0$.

B. $Q = 0$.

C. $Q < 0$.



QuickCheck 19.2

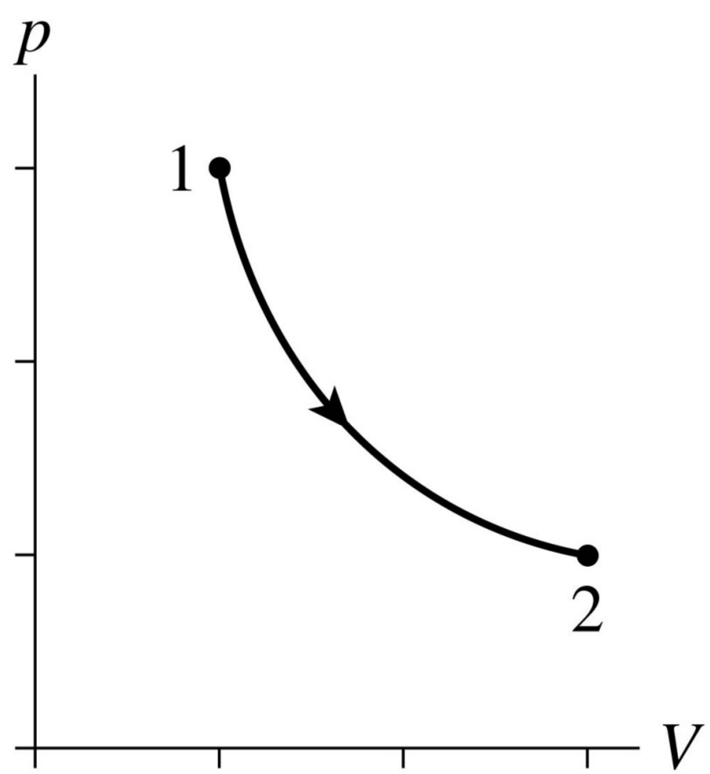
In an isothermal expansion:

✔ A. $\boldsymbol{Q > 0}$.

B. $Q = 0$.

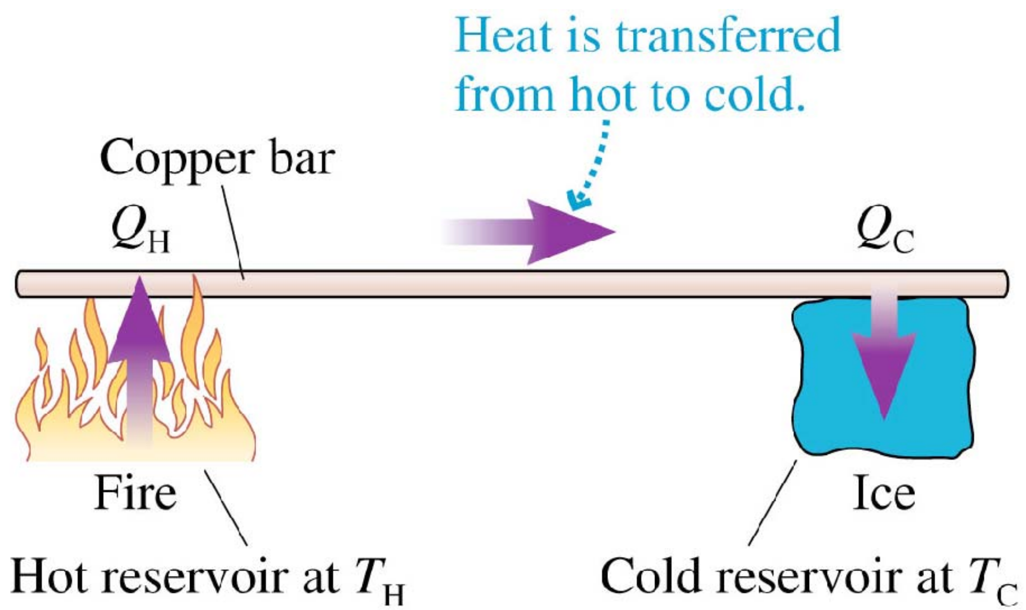
C. $Q < 0$.

First law: $Q = W_s + E_{th} + 0$

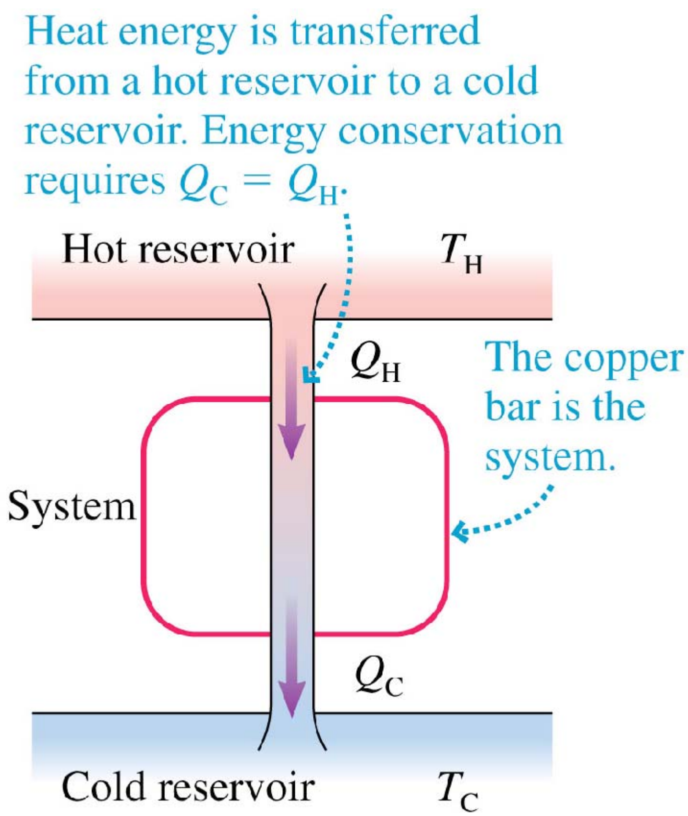


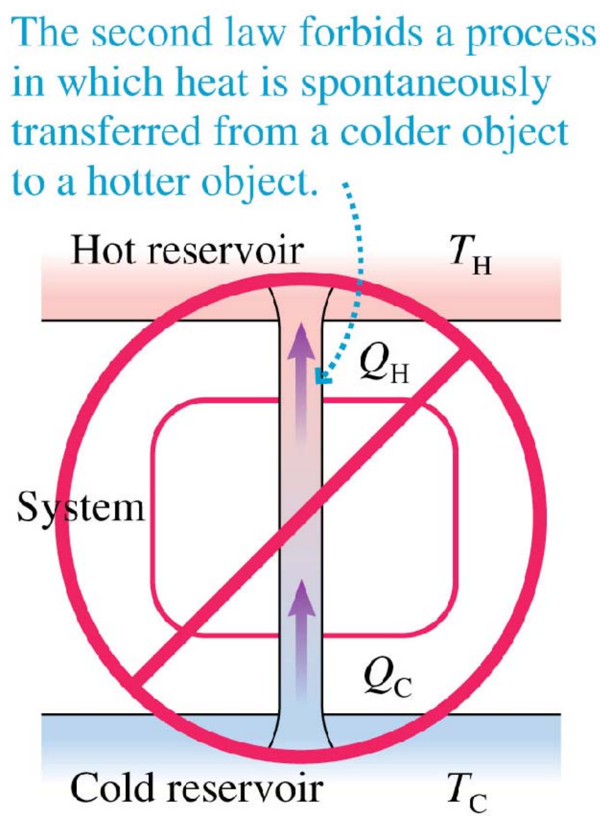
Energy Reservoirs

- An **energy reservoir** is an object or a part of the environment so large that its temperature does not change when heat is transferred between the system and the reservoir.
- A reservoir at a higher temperature than the system is called a *hot reservoir.*
- A reservoir at a lower temperature than the system is called a *cold reservoir.*

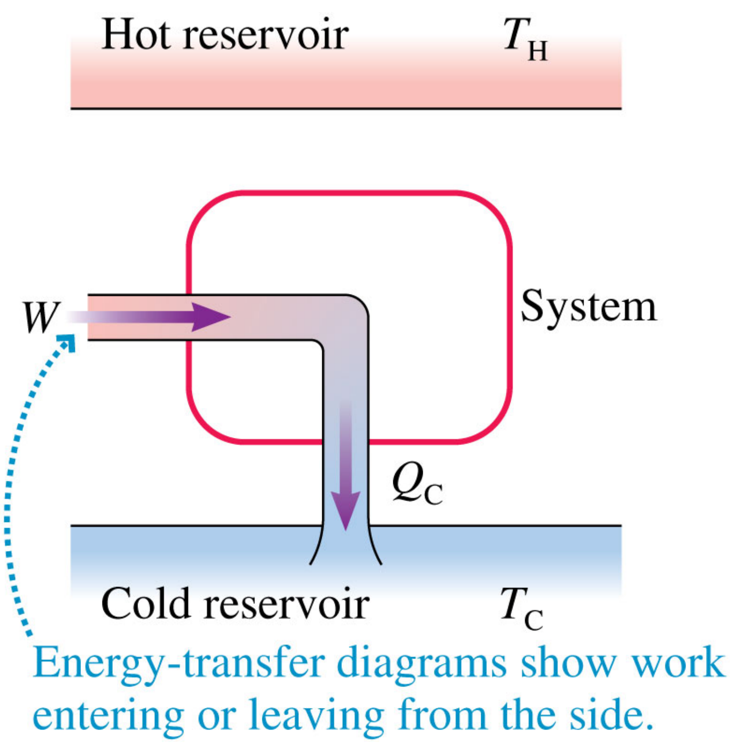


Energy-Transfer Diagrams





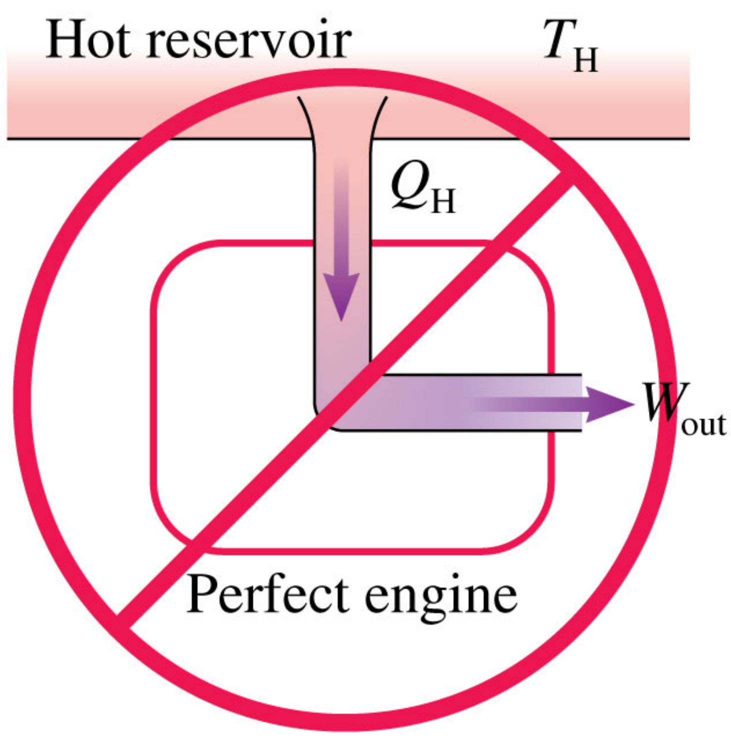
Work into Heat



- Turning work into heat is easy — just rub two objects together!
- Shown is the energy transfer diagram for this process.
- The conversion of work into heat is 100% efficient, in that all the energy supplied to the system as work is ultimately transferred to the environment as heat.

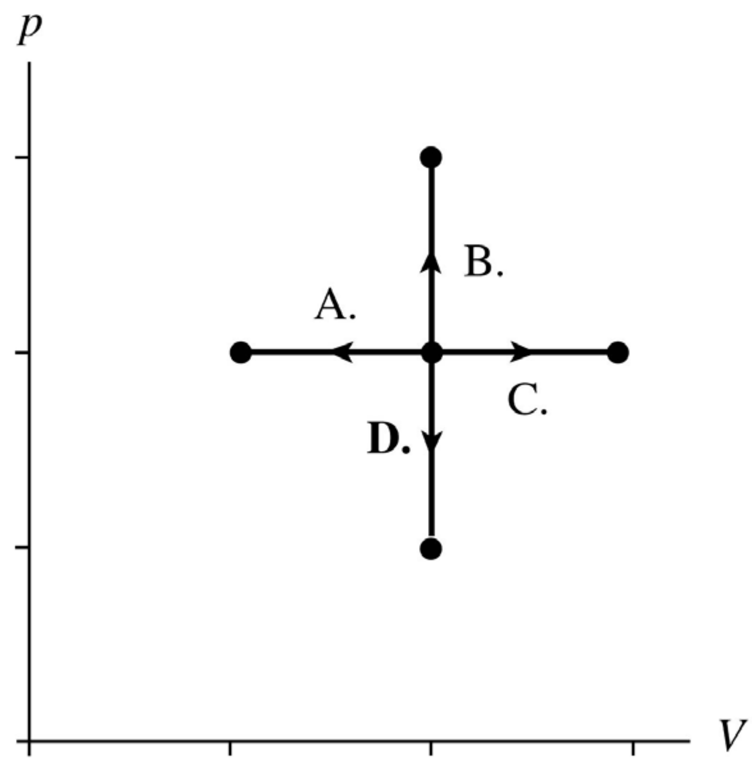
Heat into Work

- Transforming heat into work is not easy.
- To be practical, a device that transforms heat into work must return to its initial state at the end of the process and be ready for continued use.
- It is impossible to invent a “perfect engine” that transforms heat into work with 100% efficiency *and returns to its initial state* so that it can continue to do work as long as there is fuel.
- The second law of thermodynamics forbids a “perfect engine.”



QuickCheck 19.3

Which is an isochoric process in which heat is removed from the system?



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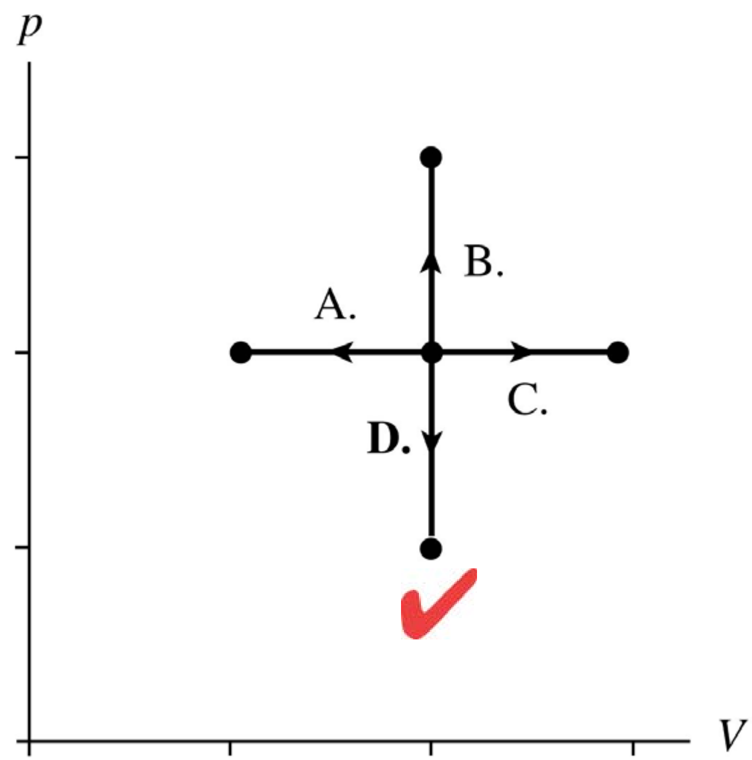

QuickCheck 19.4

In this process:

A. $Q = 0$ and $W_s > 0$.
B. $Q > 0$ and $W_s > 0$.
C. $Q > 0$ and $W_s < 0$.
D. $Q < 0$ and $W_s < 0$.
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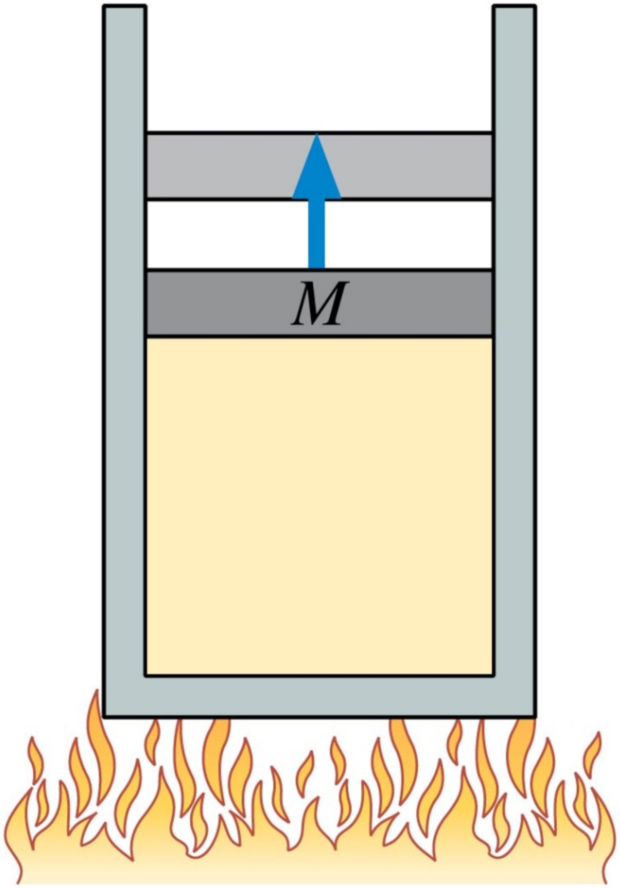

QuickCheck 19.4

In this process:

A. $Q = 0$ and $W_s > 0$.

✔ **B. $Q > 0$ and $W_s > 0$.**

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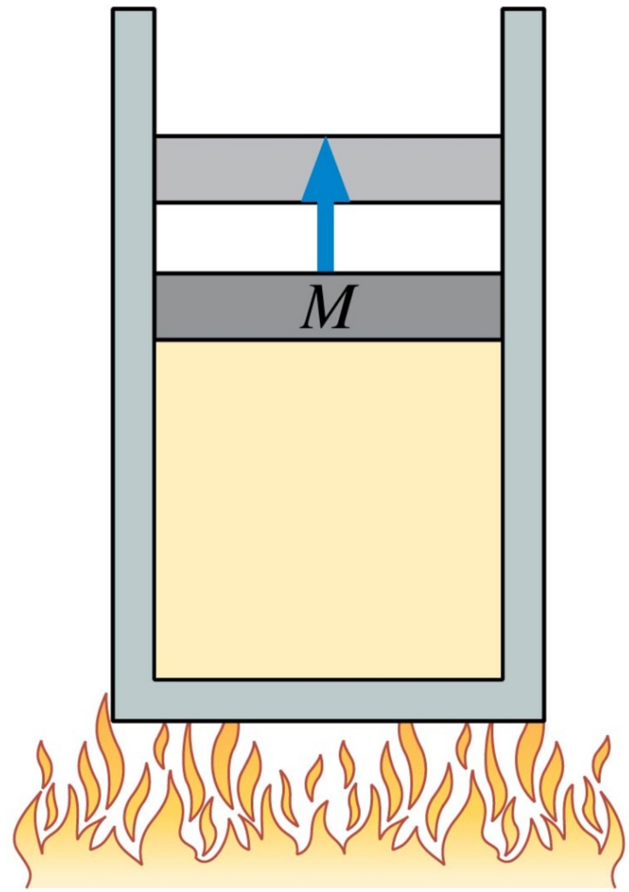


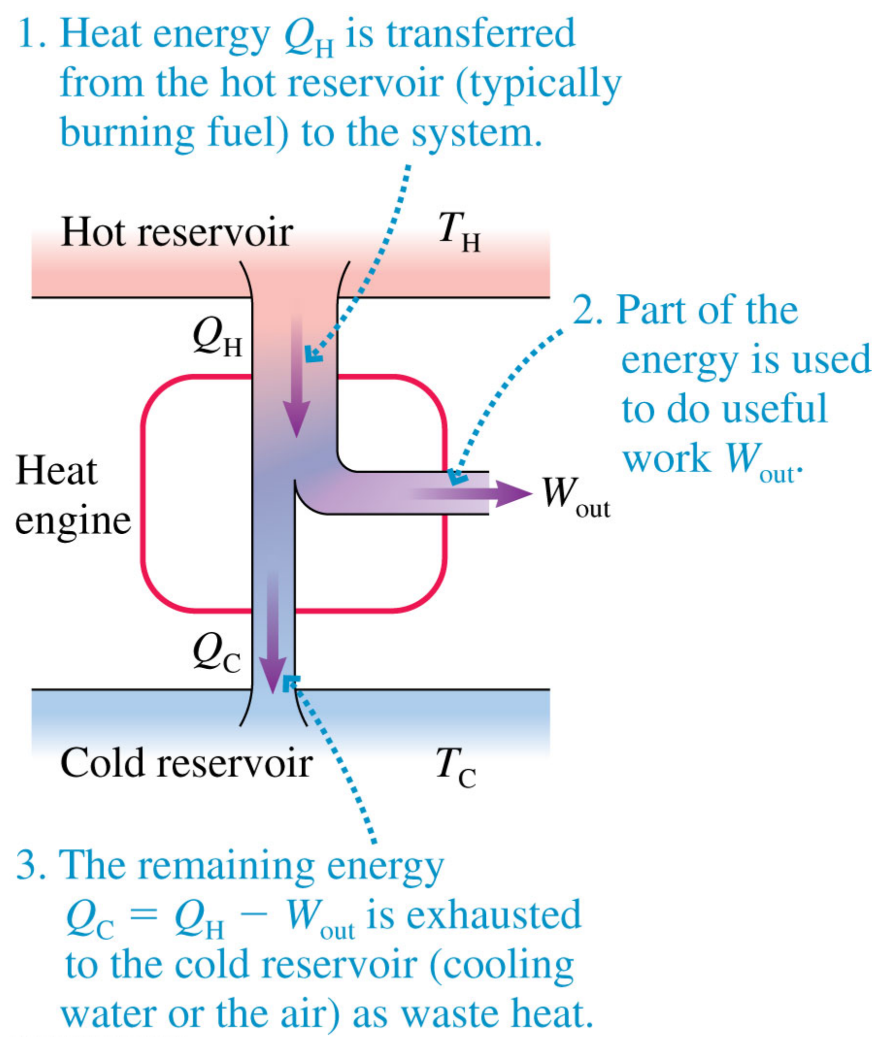
Heat Engines

- In a steam turbine of a modern power plant, expanding steam does work by spinning the turbine.
- The steam is then condensed to liquid water and pumped back to the boiler to start the process again**.**
- First heat is transferred *to* the water in the boiler to create steam, and later heat is transferred *out* of the water to an external cold reservoir, in the condenser.
- This steam generator is an example of a **heat engine.**

Heat Engines

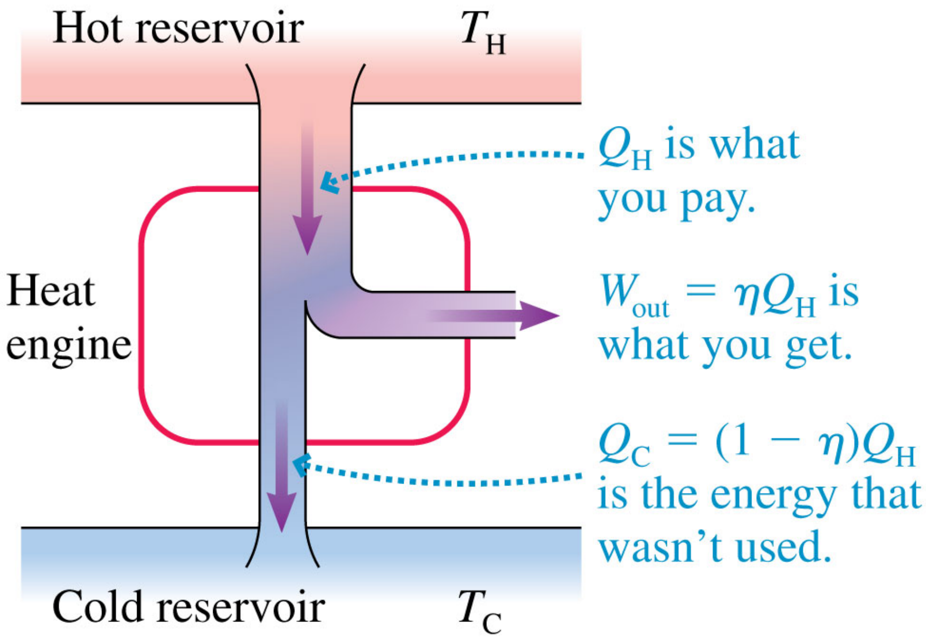
- Shown is the energy-transfer diagram of a heat engine.
- All state variables (pressure, temperature, thermal energy, etc.) return to their initial values once every cycle.
- The work done *per cycle* by a heat engine is:

$$W_{out} = Q_{net} = Q_H - Q_C$$



Heat Engines

- We can measure the performance of a heat engine in terms of its **thermal efficiency** η (lowercase Greek “eta”), defined as:



$$\eta = \frac{W_{out}}{Q_H} = \frac{\text{what you get}}{\text{what you had to pay}}$$

or

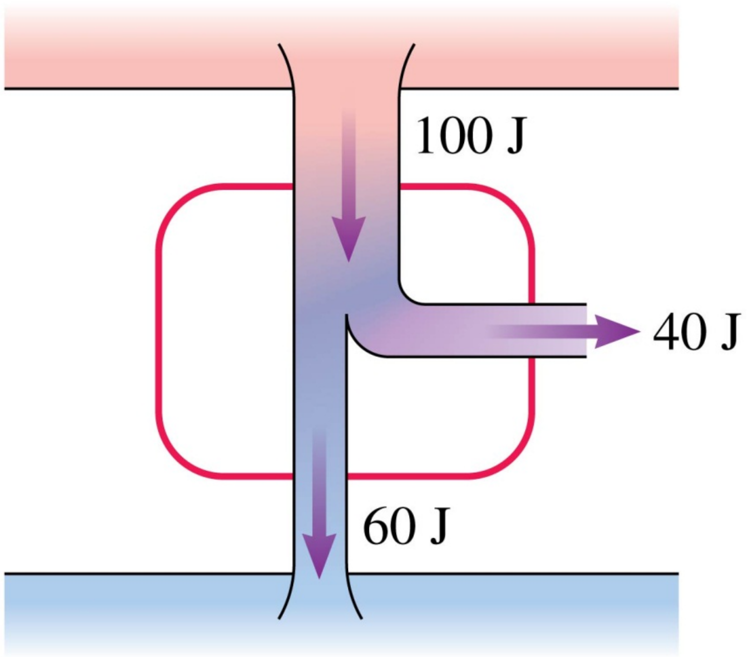
$$\eta = 1 - \frac{Q_C}{Q_H}$$

- Actual car engines and steam generators have $\eta \approx 0.1 - 0.5$.

QuickCheck 19.5

The efficiency of this heat engine is

A. 1.00.
B. 0.60.
C. 0.50.
D. 0.40.
E. 0.20.



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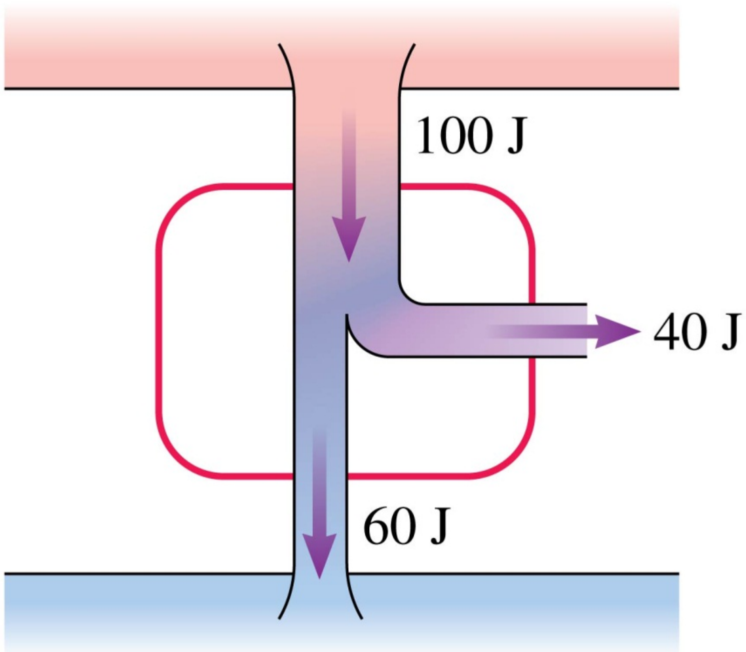
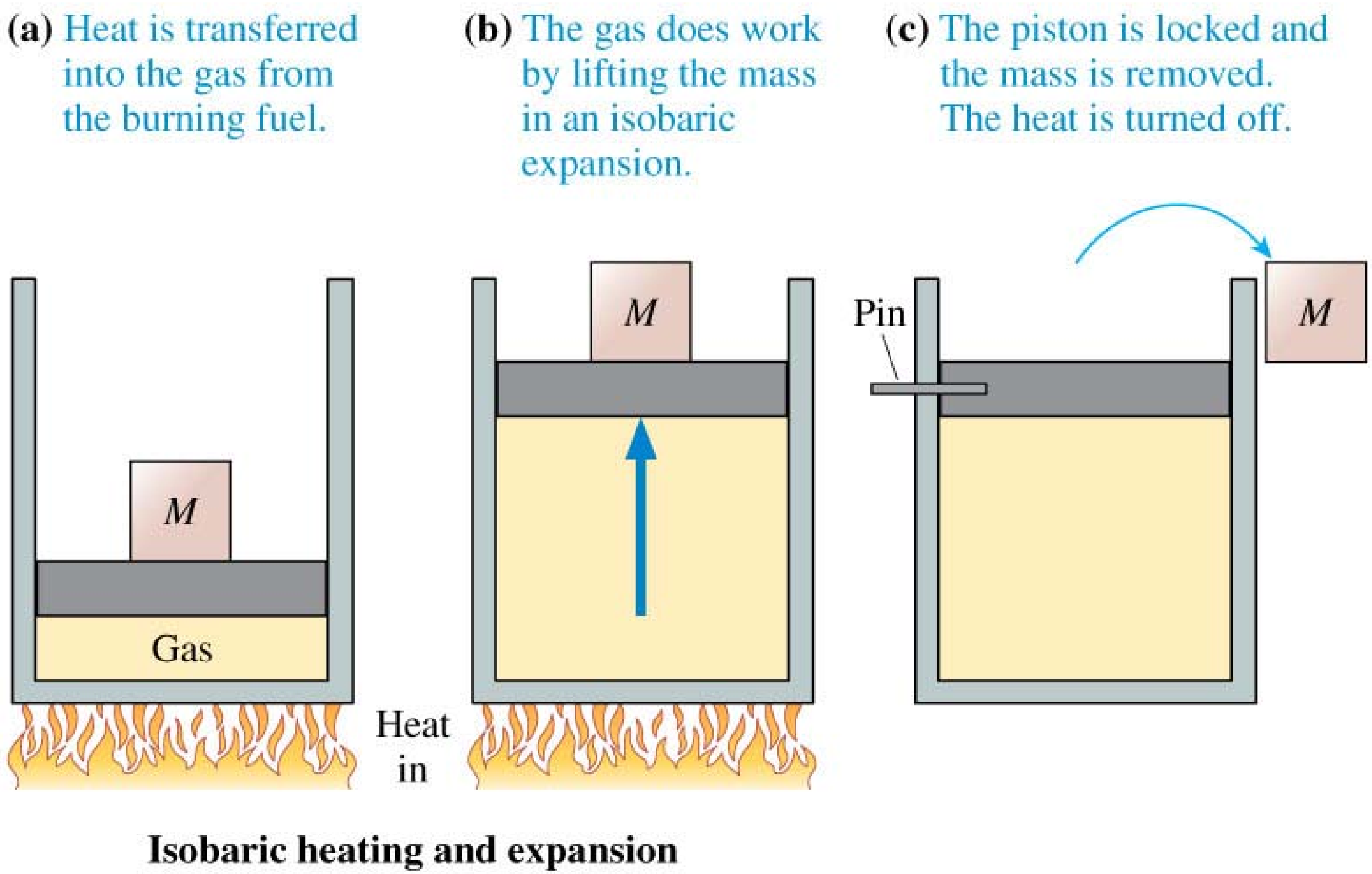
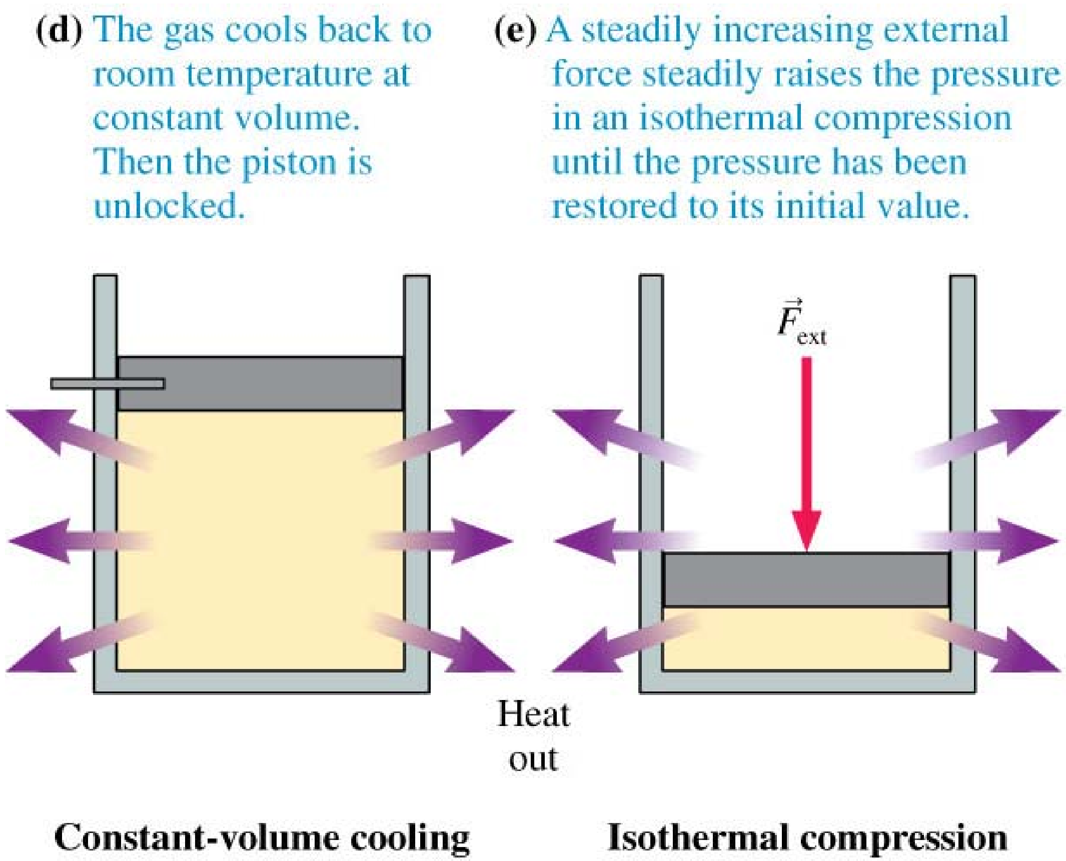


A Heat-Engine Example: Slide 1 of 3



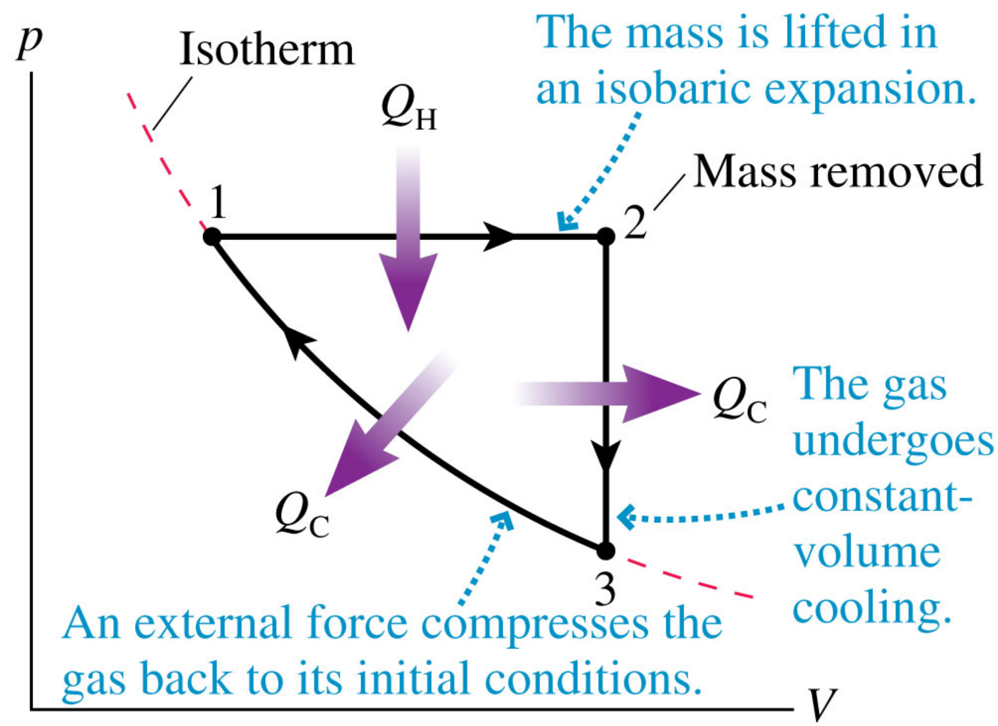
A Heat-Engine Example: Slide 2 of 3



A Heat-Engine Example: Slide 3 of 3

- Shown is the heat-engine process on a pV diagram.
- No work is done during the isochoric step $2 \rightarrow 3$.
- The net work per cycle is:

$$W_{\text{net}} = W_{\text{lift}} - W_{\text{ext}}$$



$$W_{\text{net}} = (W_s)_{1\rightarrow 2} + (W_s)_{3\rightarrow 1}$$

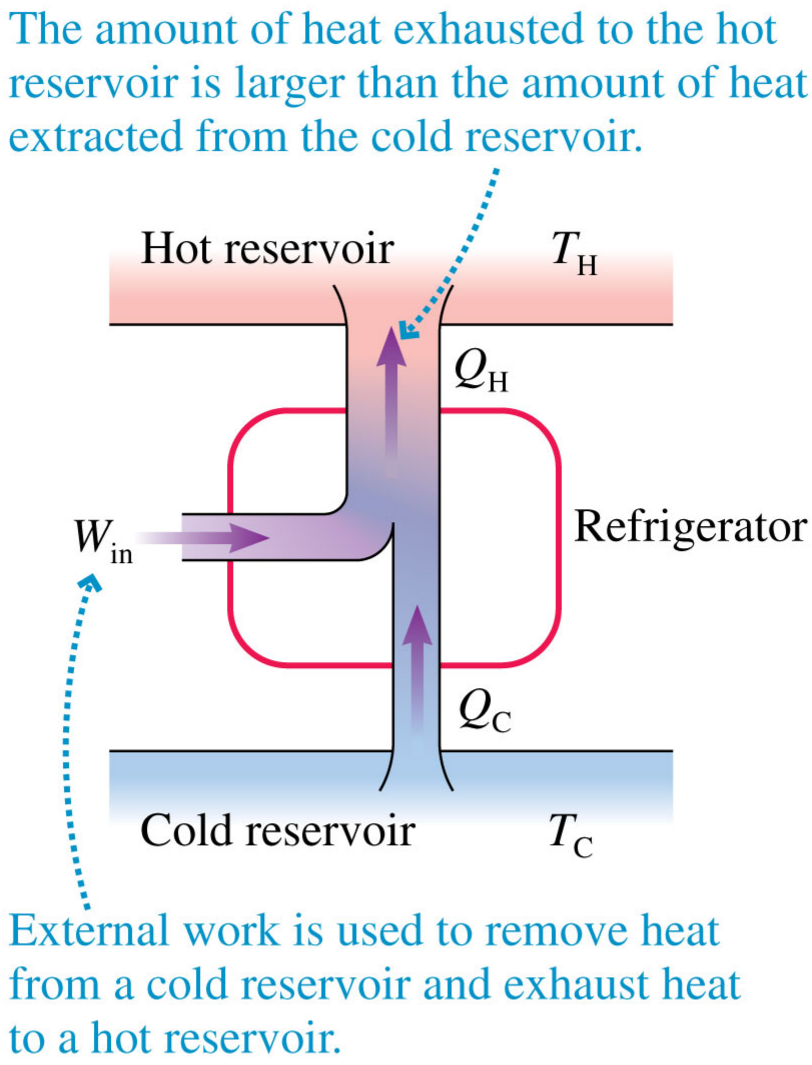
Refrigerators

- In a sense, a **refrigerator** or air conditioner is the *opposite* of a heat engine.
- In a heat engine, heat energy flows from a hot reservoir to a cool reservoir, and work W_{out} is produced.
- In a refrigerator, heat energy is somehow forced to flow from a cool reservoir to a hot reservoir, but it requires work W_{in} to make this happen.

Refrigerators

- Shown is the energy-transfer diagram of a refrigerator.
- All state variables (pressure, temperature, thermal energy, etc.) return to their initial values once every cycle.
- The heat exhausted *per cycle* by a refrigerator is:

$$Q_H = Q_C + W_{in}$$



Refrigerators

- The purpose of a refrigerator is to remove heat from a cold reservoir, and it requires work input to do this.
- We define the coefficient of performance K of a refrigerator to be:

$$K = \frac{Q_C}{W_{in}} = \frac{\text{what you get}}{\text{what you had to pay}}$$

- If a "perfect refrigerator" could be built in which $W_{in} = 0$, then heat would move *spontaneously* from cold to hot.
- This is expressly forbidden by the second law of thermodynamics:

Second law, informal statement #3 There are no perfect refrigerators with coefficient of performance $K = \infty$.

QuickCheck 19.6

The coefficient of performance of this refrigerator is

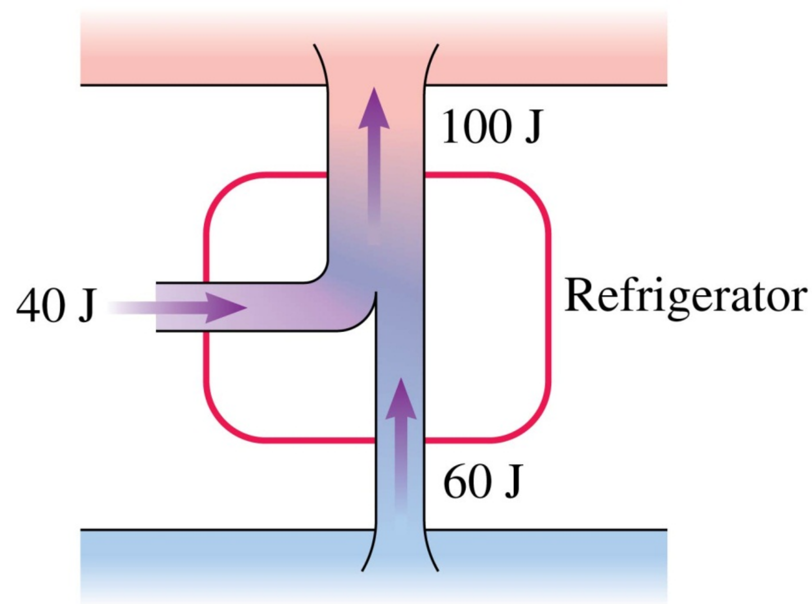
A. 0.40.

B. 0.60.

C. 1.50.

D. 1.67.

E. 2.00.



QuickCheck 19.6

The coefficient of performance of this refrigerator is

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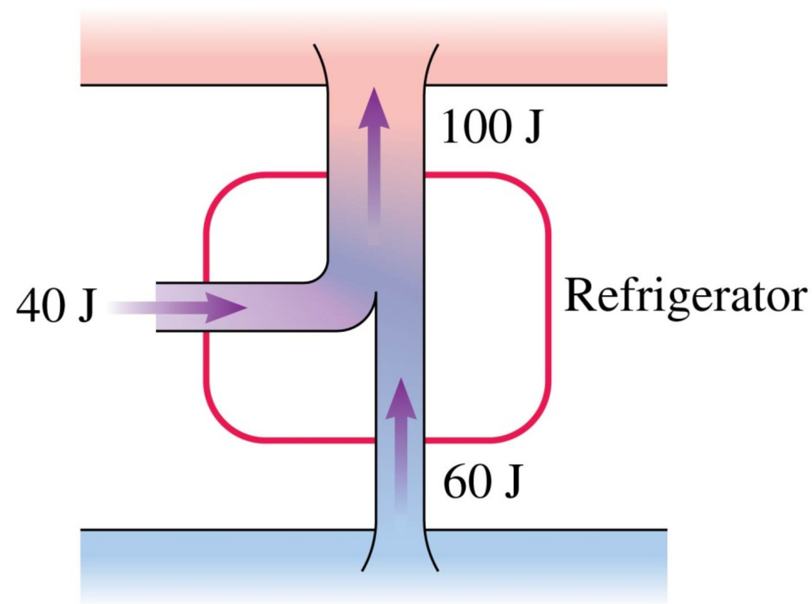
✔ **C. 1.50.**

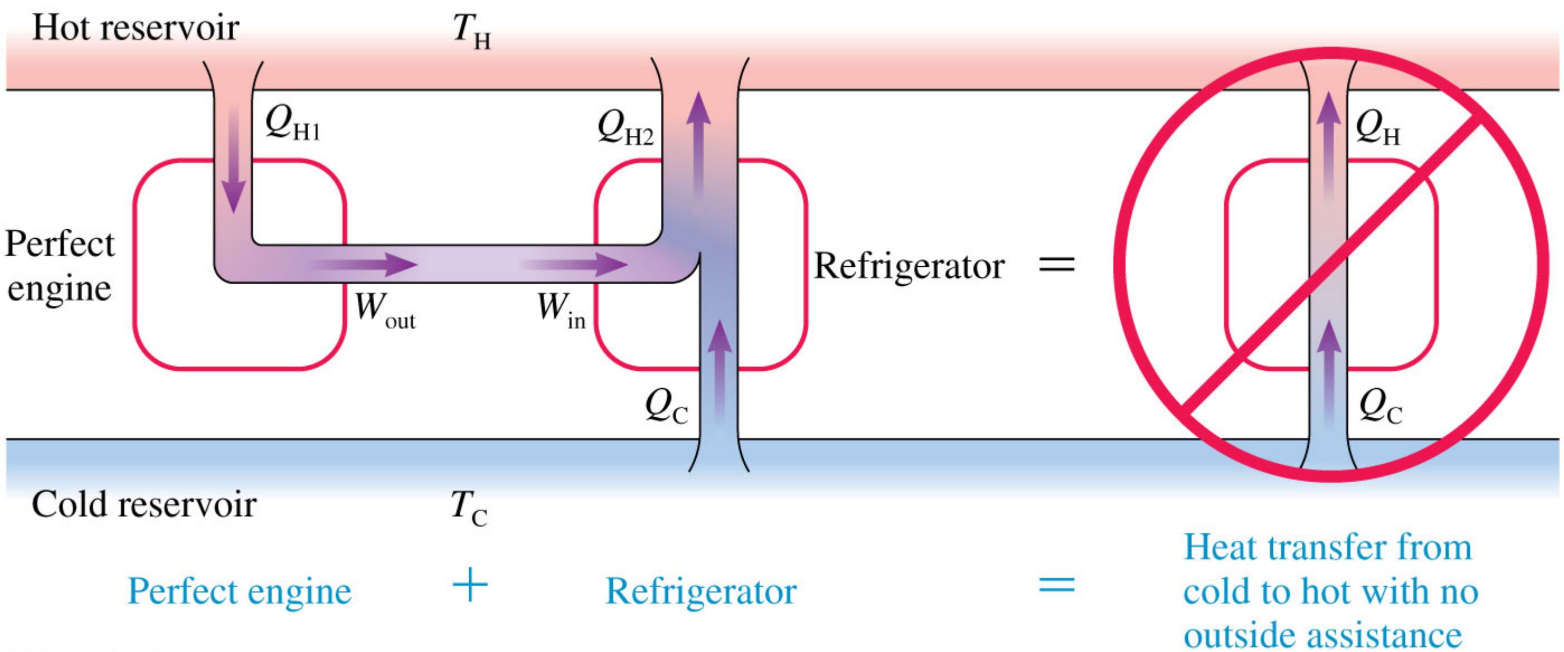
D. 1.67.

E. 2.00.



No Perfect Heat Engines

A perfect heat engine connected to a refrigerator would violate the second law of thermodynamics.

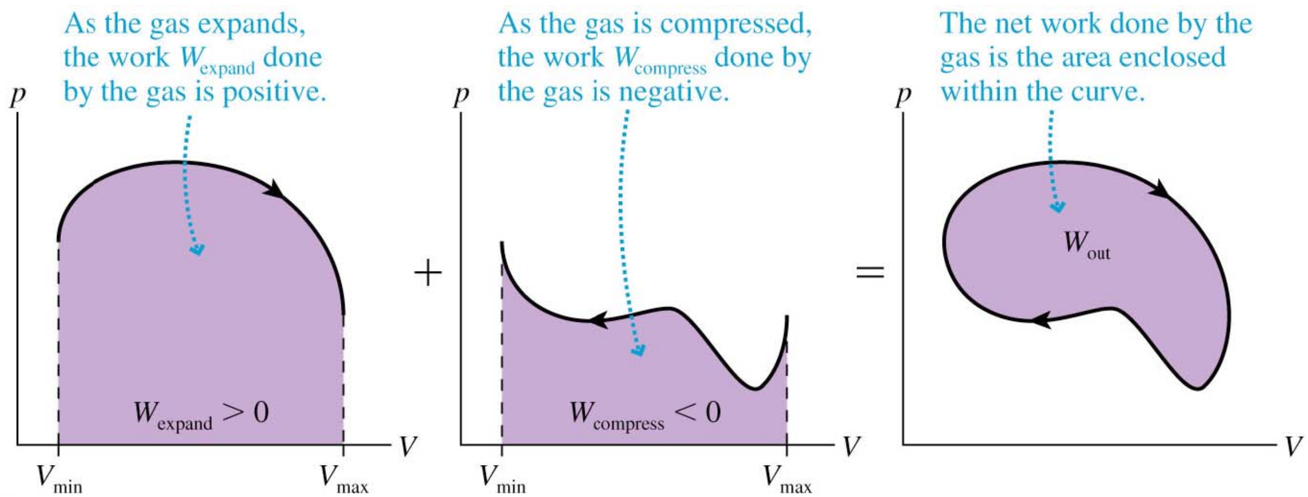


Second law, informal statement #4 There are no perfect heat engines with efficiency $\eta = 1$.

Ideal-Gas Heat Engines

- Some heat engines use an ideal gas as the *working substance.*
- A gas heat engine can be represented by a closed-cycle trajectory on a pV diagram.
- The net work done during a full cycle is:

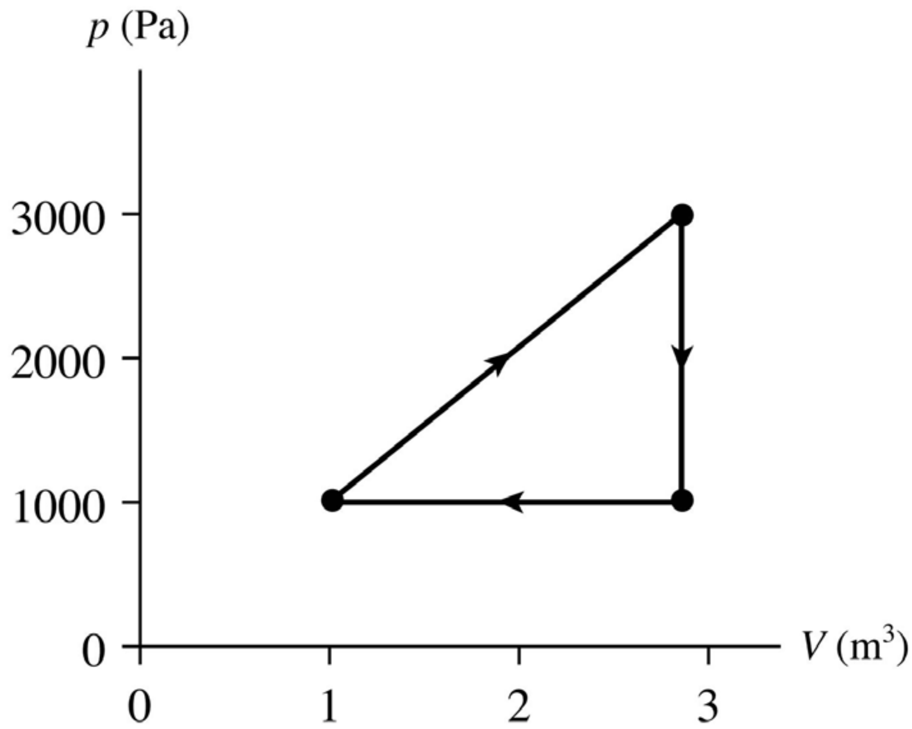
$$W_{\text{out}} = W_{\text{expand}} - \left|W_{\text{compress}}\right| = \text{area } \textit{inside} \text{ the closed curve}$$



QuickCheck 19.7

How much work is done in one cycle?

A. 9000 J.
B. 6000 J.
C. 3000 J.
D. 2000 J.
E. 1000 J.



QuickCheck 19.7

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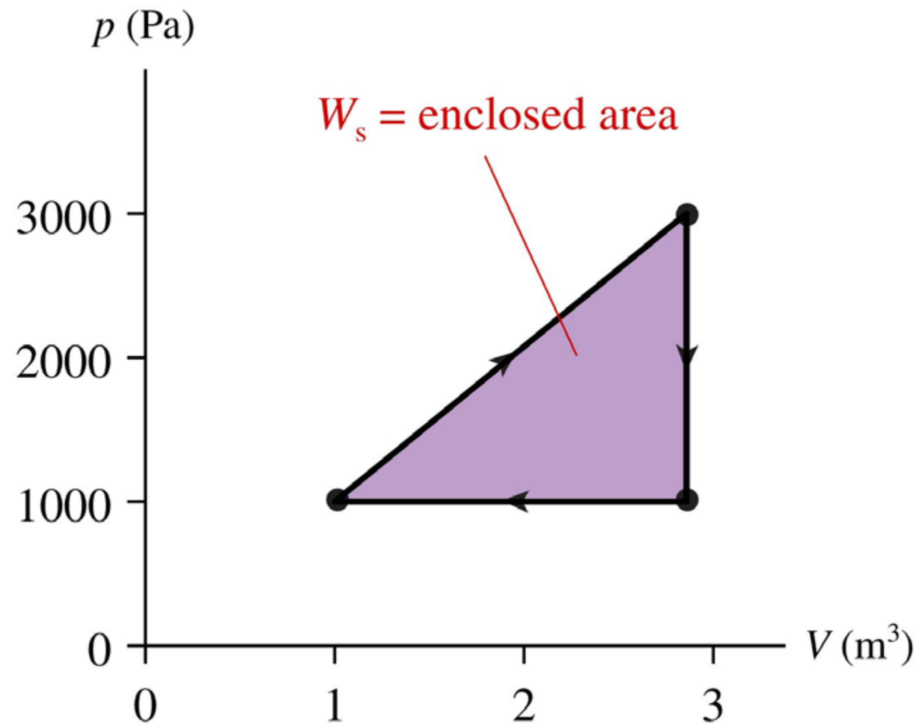
✔ **D. 2000 J.**

E. 1000 J.



Summary of Ideal-Gas Processes

Process	Gas law	Work W_s	Heat Q	Thermal energy
Isochoric	$p_i/T_i = p_f/T_f$	0	$nC_V\Delta T$	$\Delta E_{th} = Q$
Isobaric	$V_i/T_i = V_f/T_f$	$p\Delta V$	$nC_P\Delta T$	$\Delta E_{th} = Q - W_s$
Isothermal	$p_iV_i = p_fV_f$	$nRT\ln(V_f/V_i)$ $pV\ln(V_f/V_i)$	$Q = W_s$	$\Delta E_{th} = 0$
Adiabatic	$p_iV_i^\gamma = p_fV_f^\gamma$ $T_iV_i^{\gamma-1} = T_fV_f^{\gamma-1}$	$(p_fV_f - p_iV_i)/(1-\gamma)$ $-nC_V\Delta T$	0	$\Delta E_{th} = -W_s$
Any	$p_iV_i/T_i = p_fV_f/T_f$	area under curve		$\Delta E_{th} = nC_V\Delta T$

This table shows W_s, the work done *by* the system, so the signs are opposite those in Chapter 17.

Summary of Ideal-Gas Processes

- You learned in Chapter 18 that the thermal energy of an ideal gas depends only on its temperature.
- The table below lists the thermal energy, molar specific heats, and specific heat ratio $\gamma = C_P/C_V$ for monatomic and diatomic gases.

	Monatomic	Diatomic
E_{th}	$\frac{3}{2}nRT$	$\frac{5}{2}nRT$
C_V	$\frac{3}{2}R$	$\frac{5}{2}R$
C_P	$\frac{5}{2}R$	$\frac{7}{2}R$
γ	$\frac{5}{3} = 1.67$	$\frac{7}{5} = 1.40$

Problem-Solving Strategy: Heat-Engine Problems

PROBLEM-SOLVING STRATEGY 19.1 Heat-engine problems

MODEL Identify each process in the cycle.

VISUALIZE Draw the pV diagram of the cycle.

SOLVE There are several steps in the mathematical analysis.

- Use the ideal-gas law to complete your knowledge of n, p, V, and T at one point in the cycle.
- Use the ideal-gas law and equations for specific gas processes to determine p, V, and T at the beginning and end of each process.
- Calculate Q, W_s, and ΔE_{th} for each process.

Problem-Solving Strategy: Heat-Engine Problems

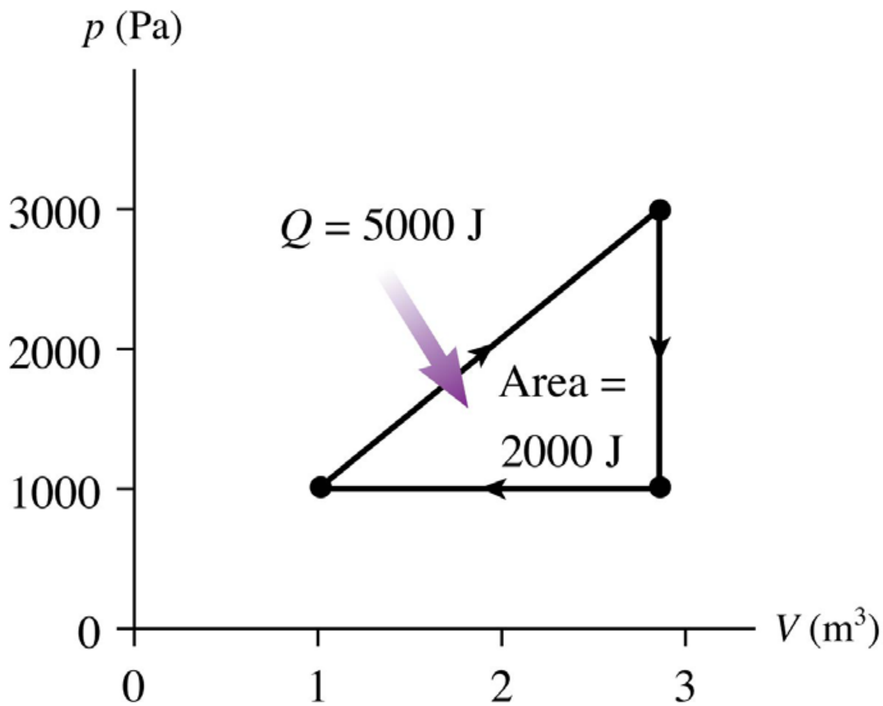
- Find W_{out} by adding W_s for each process in the cycle. If the geometry is simple, you can confirm this value by finding the area enclosed within the pV curve.
- Add just the *positive* values of Q to find Q_H.
- Verify that $(\Delta E_{th})_{net} = 0$. This is a self-consistency check to verify that you haven't made any mistakes.
- Calculate the thermal efficiency η and any other quantities you need to complete the solution.

ASSESS Is $(\Delta E_{th})_{net} = 0$? Do all the signs of W_s and Q make sense? Does η have a reasonable value? Have you answered the question?

QuickCheck 19.8

How much heat is exhausted to the cold reservoir?

A. 7000 J.
B. 5000 J.
C. 3000 J.
D. 2000 J.
E. 0 J.



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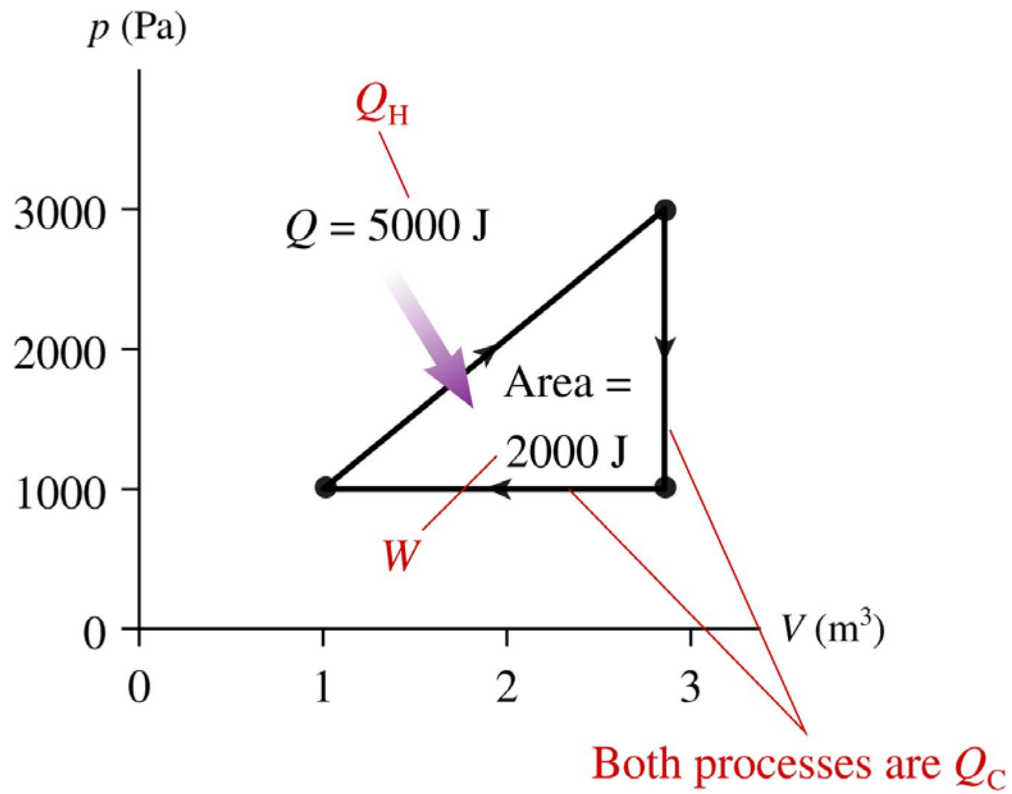
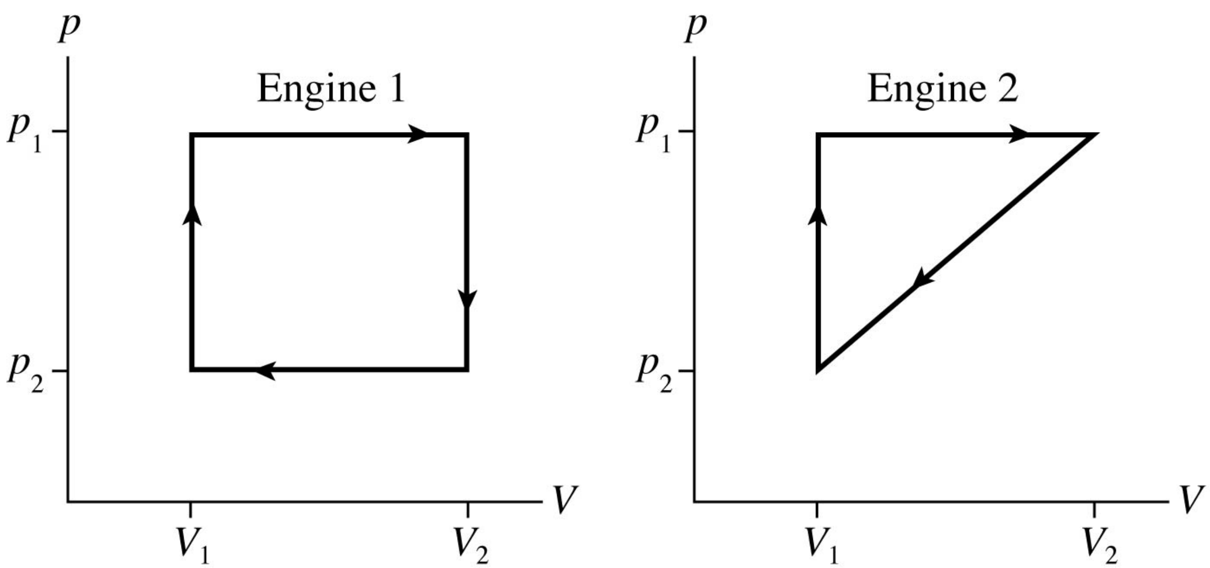


QuickCheck 19.9

Which heat engine has the larger efficiency?



A. Engine 1.

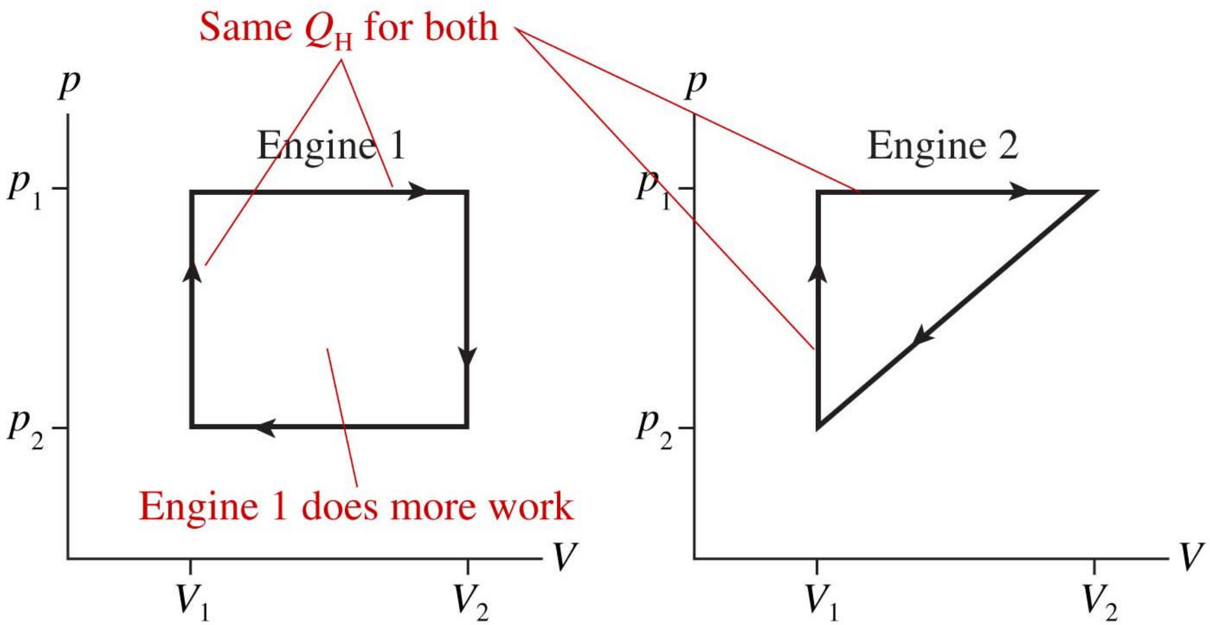
B. Engine 2.

C. They have the same efficiency.

D. Can't tell without knowing the number of moles of gas.

QuickCheck 19.9

Which heat engine has the larger efficiency?



✔ **A. Engine 1.**

B. Engine 2.

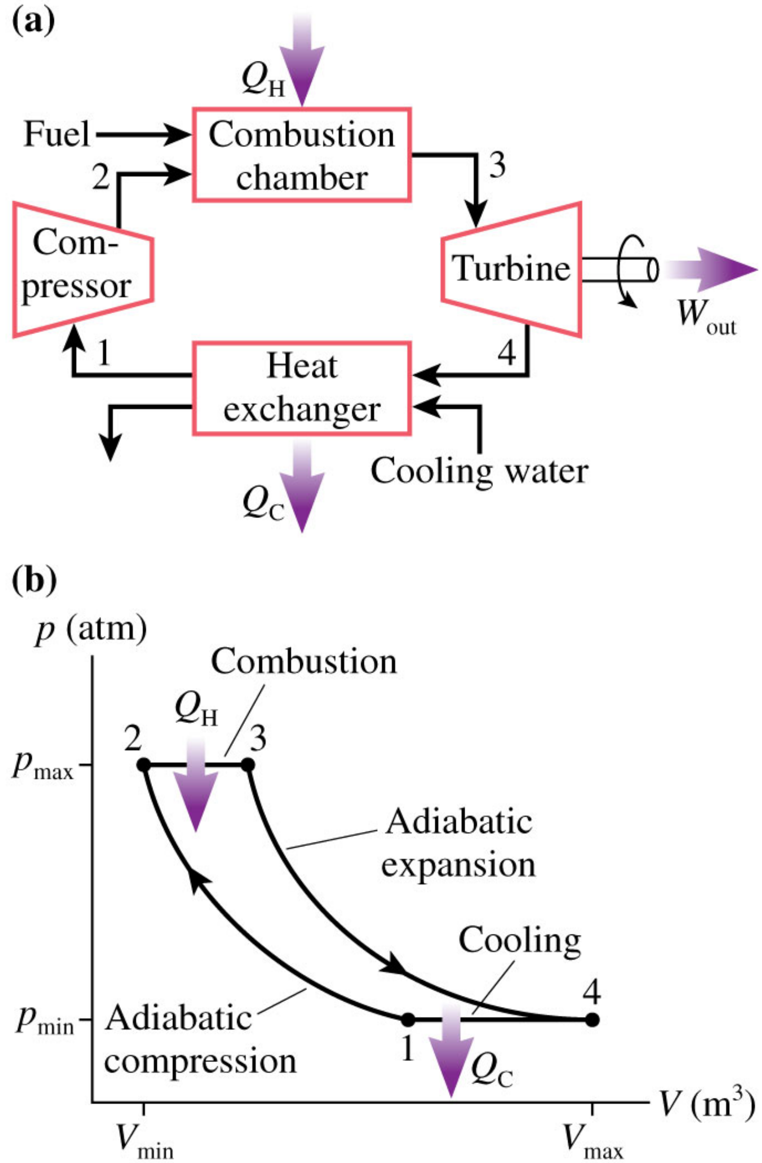
C. They have the same efficiency.

D. Can't tell without knowing the number of moles of gas.

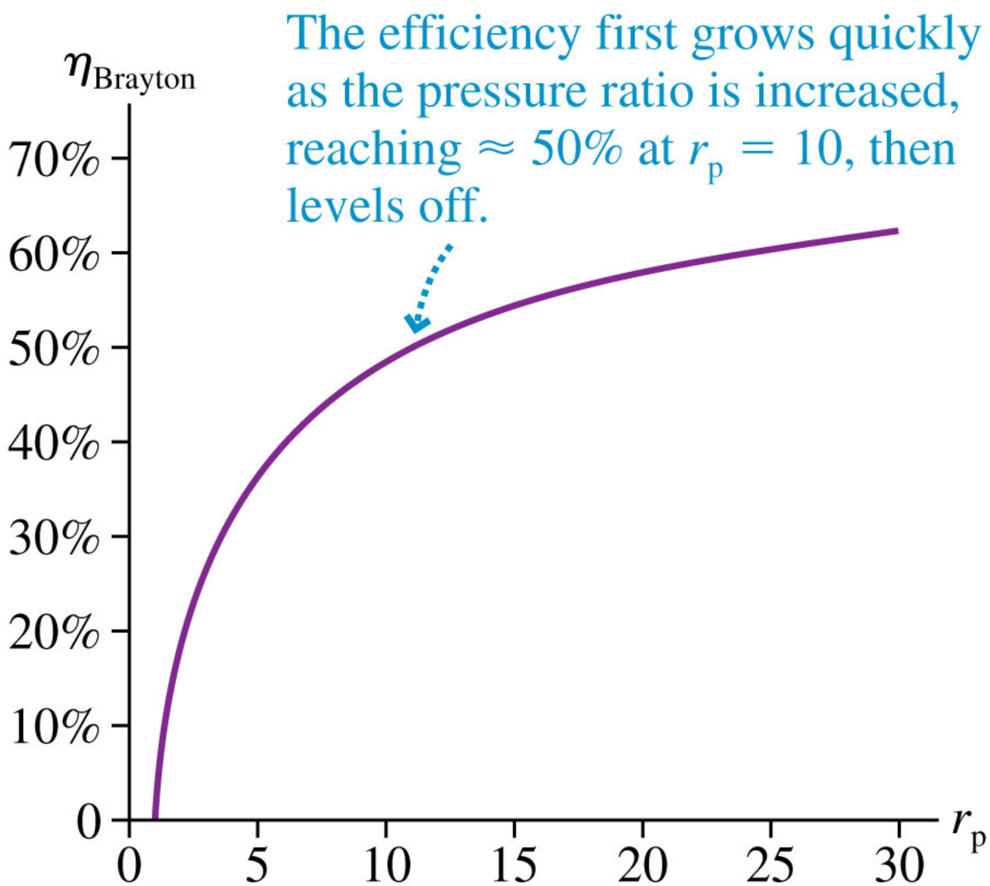
The Brayton Cycle

- Many ideal-gas heat engines, such as jet engines in aircraft, use the *Brayton Cycle*, as shown.
- The cycle involves adiabatic compression (1-2), isobaric heating during combustion (2-3), adiabatic expansion which does work (3-4), and isobaric cooling (4-1).
- The efficiency is:

$$\eta_B = 1 - \frac{1}{r_p^{(\gamma-1)/\gamma}}$$



Efficiency of a Brayton Cycle

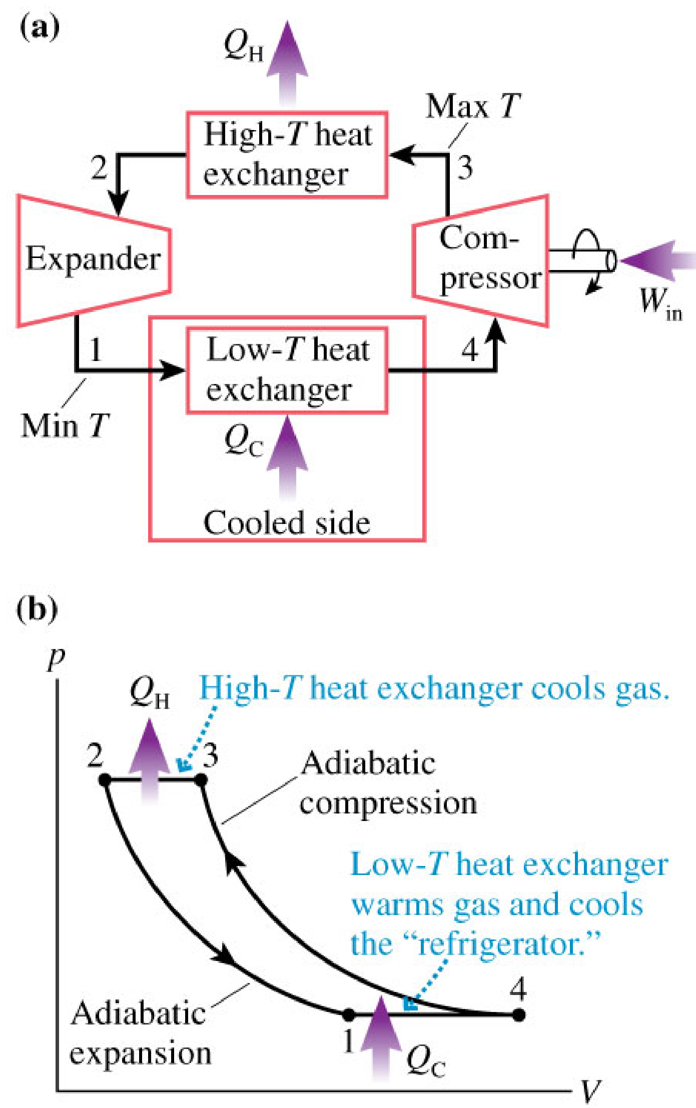


Any increase in efficiency beyond ≈ 50% has to be weighed against the higher costs of a better compressor that can achieve a much higher pressure ratio.

$r_P = p_{max}/p_{min}$ is the ratio of the maximum to minimum pressure in the cycle.

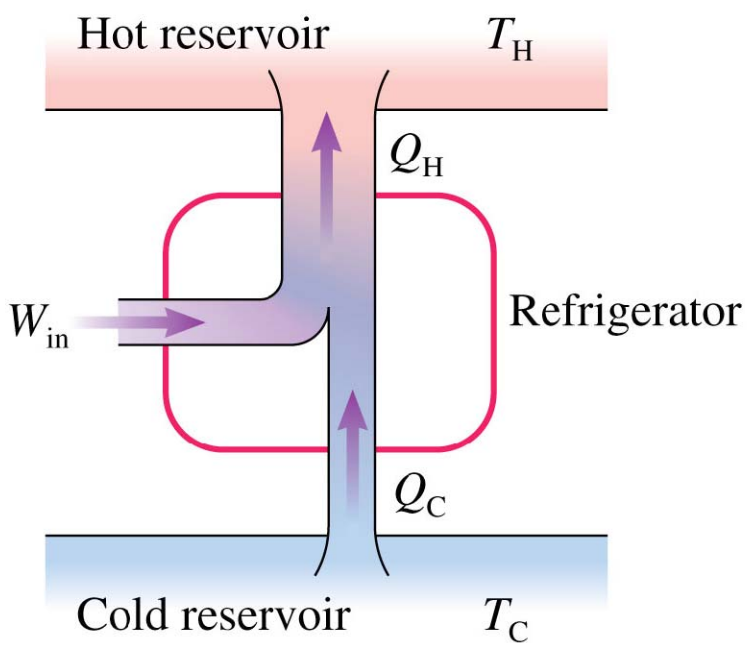
Ideal-Gas Refrigerators

- An ideal-gas refrigerator can use a Brayton cycle in *reverse.*
- A gas is compressed adiabatically to make it extremely hot (4-3).
- Then heat is lost to the hot reservoir (3-2).
- Then the gas expands adiabatically (2-1) making it extremely cold.
- Lastly, heat flows into the gas from the cool reservoir (1-4).



Ideal-Gas Refrigerators

- Even in a refrigerator, heat is always transferred from a hotter object to a colder.
- The gas in a refrigerator can extract heat Q_C from the cold reservoir only if the gas temperature is lower than the cold-reservoir temperature T_C.
- The gas in a refrigerator can exhaust heat Q_H to the hot reservoir only if the gas temperature is higher than the hot-reservoir temperature T_H.



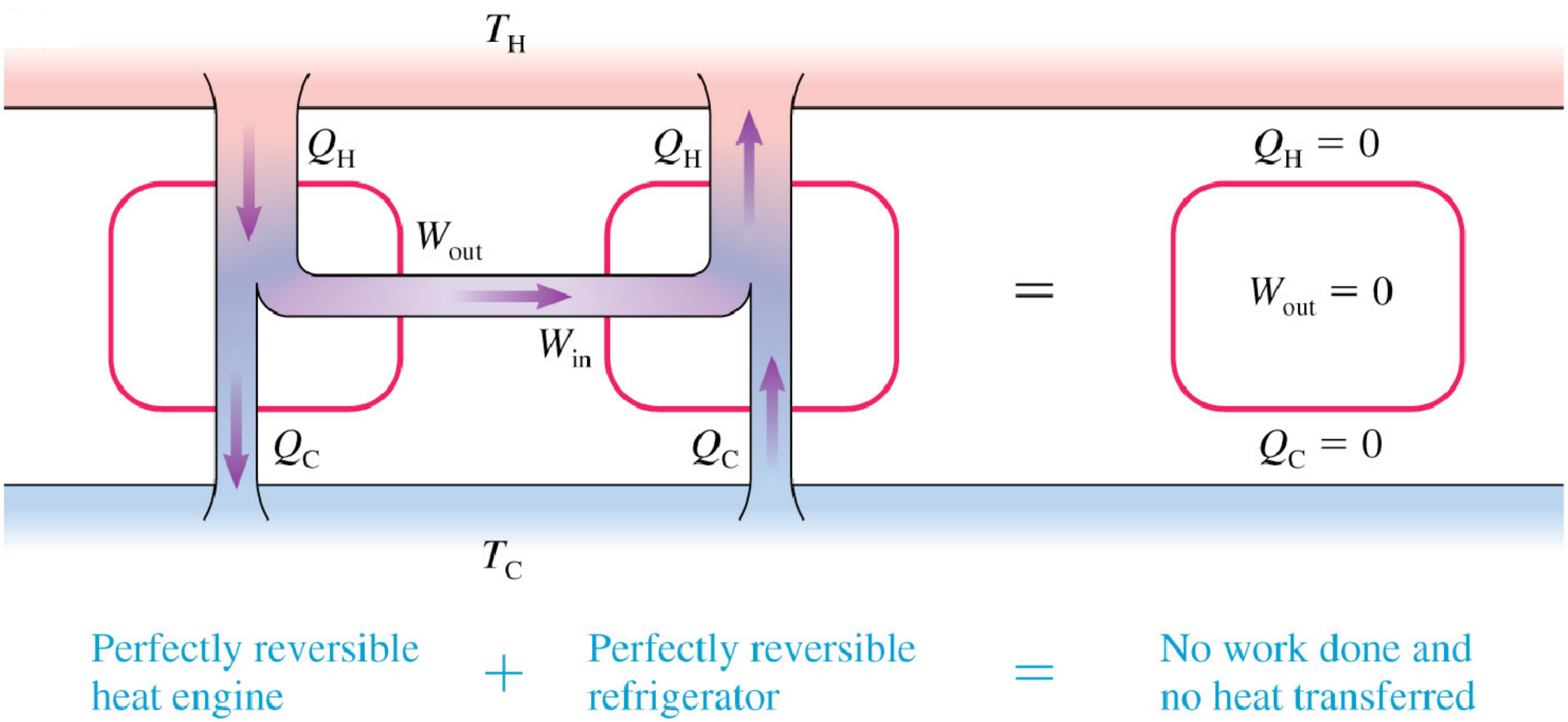
The Limits of Efficiency

Everyone knows that heat can produce motion. That it possesses vast motive power no one can doubt, in these days when the steam engine is everywhere so well known. . . . Notwithstanding the satisfactory condition to which they have been brought today, their theory is very little understood. The question has often been raised whether the motive power of heat is unbounded, or whether the possible improvements in steam engines have an assignable limit.

Sadi Carnot

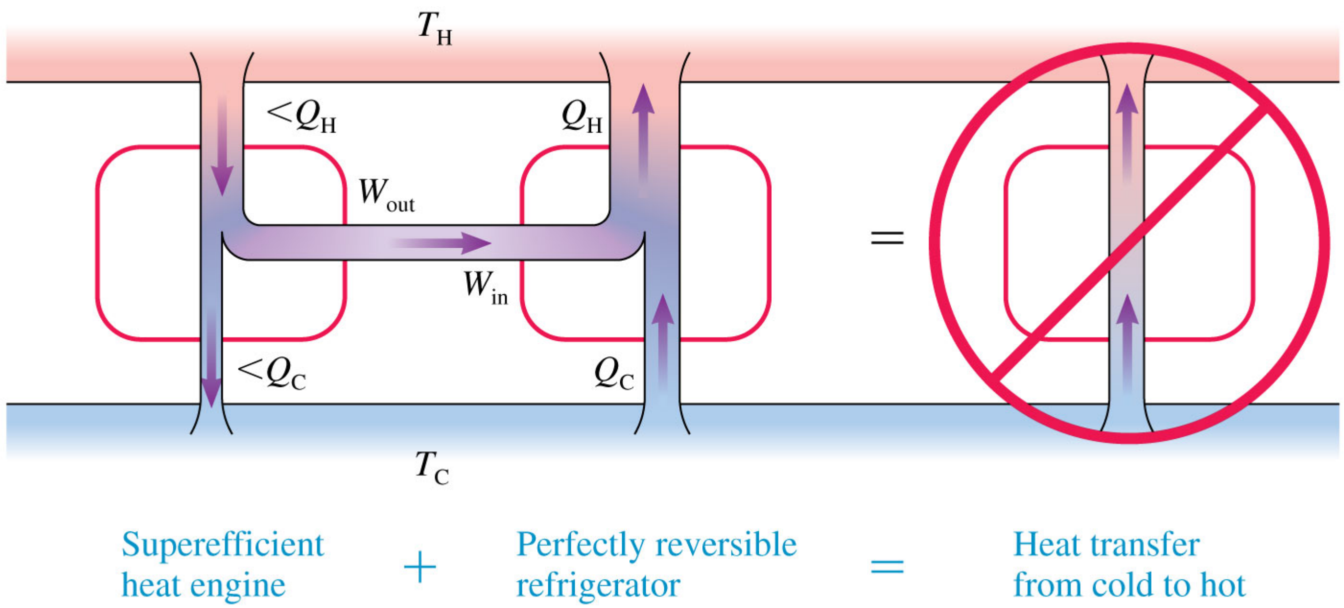
The Limits of Efficiency

If a perfectly reversible heat engine is used to operate a perfectly reversible refrigerator, the two devices exactly cancel each other.



The Limits of Efficiency

A heat engine more efficient than a perfectly reversible engine could be used to violate the second law of thermodynamics.



Second law, informal statement #5 No heat engine operating between reservoirs at temperatures T_H and T_C can be more efficient than a perfectly reversible engine operating between these temperatures.

The Limits of Efficiency

- The maximum possible efficiency of a heat engine η_{max} is that of a perfectly reversible engine.
- The maximum possible coefficient of performance of a refrigerator K_{max} is that of a perfectly reversible refrigerator.

Second law, informal statement #6 No refrigerator operating between reservoirs at temperatures T_H and T_C can have a coefficient of performance larger than that of a perfectly reversible refrigerator operating between these temperatures.

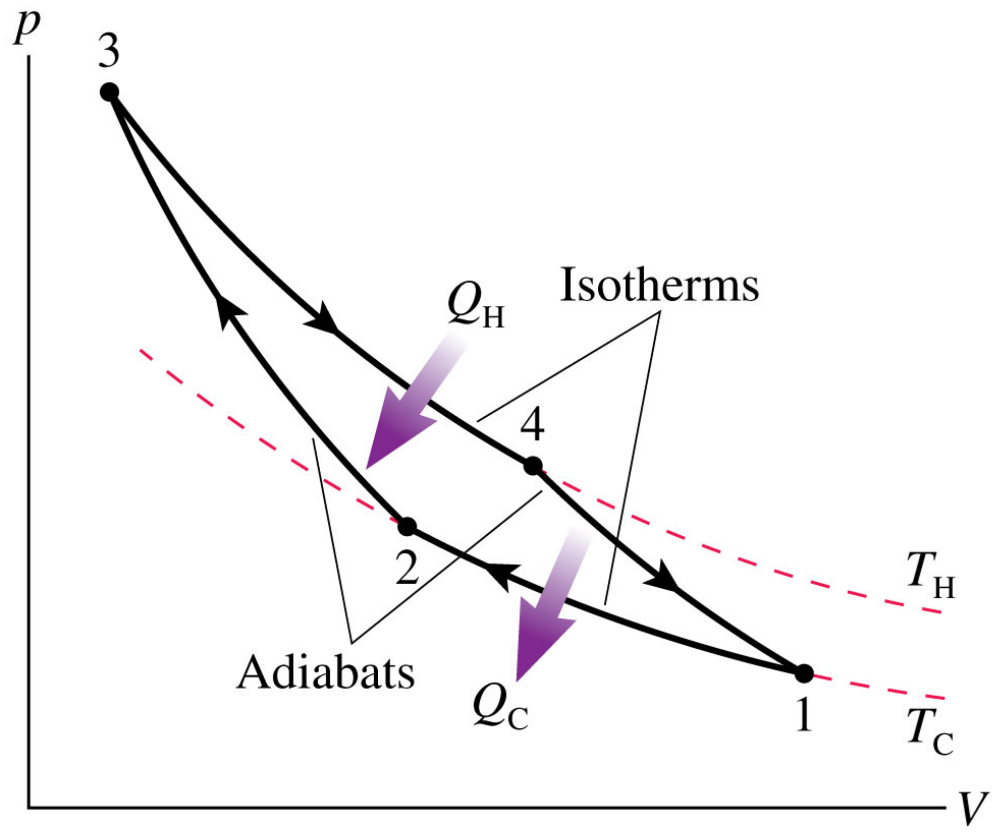
The Limits of Efficiency

- A perfectly reversible engine must use only two types of processes:
  1. Frictionless mechanical interactions with no heat transfer ($Q = 0$).
  2. Thermal interactions in which heat is transferred in an isothermal process ($\Delta E_{th} = 0$).
- Any engine that uses only these two types of processes is called a **Carnot engine**.

A Carnot engine is a perfectly reversible engine; it has the maximum possible thermal efficiency η_{max} and, if operated as a refrigerator, the maximum possible coefficient of performance K_{max}.

The Carnot Cycle

- The Carnot cycle is an ideal-gas cycle that consists of the two adiabatic processes ($Q = 0$) and the two isothermal processes ($\Delta E_{th} = 0$) shown.
- These are the two types of processes allowed in a perfectly reversible gas engine.



The Carnot Cycle

As a Carnot cycle operates:

1. The gas is isothermally compressed at T_C. Heat energy $Q_C = |Q_{12}|$ is removed.
2. The gas is adiabatically compressed, with $Q = 0$, until the gas temperature reaches T_H.
3. After reaching maximum compression, the gas expands isothermally at temperature T_H. Heat $Q_H = Q_{34}$ is transferred into the gas.
4. The gas expands adiabatically, with $Q = 0$, until the temperature decreases back to T_C.

Work is done in all four processes of the Carnot cycle, but heat is transferred only during the two isothermal processes.

The Maximum Efficiency

Second law, informal statement #7 No heat engine operating between energy reservoirs at temperatures T_H and T_C can exceed the Carnot efficiency

$$\eta_{Carnot} = 1 - \frac{T_C}{T_H}$$

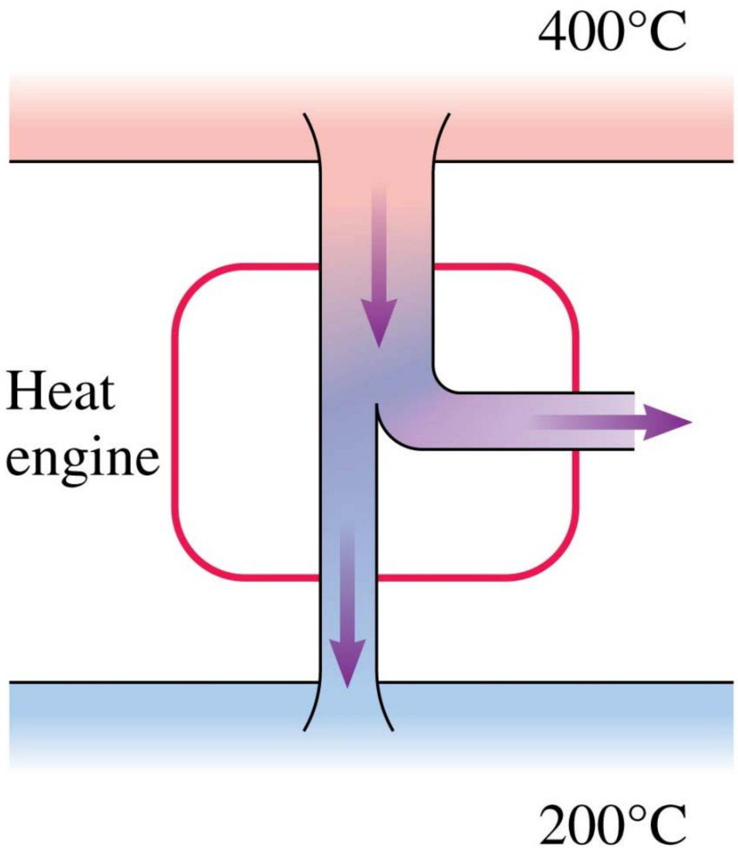
Second law, informal statement #8 No refrigerator operating between energy reservoirs at temperatures T_H and T_C can exceed the Carnot coefficient of performance

$$K_{Carnot} = \frac{T_C}{T_H - T_C}$$

QuickCheck 19.10

The efficiency of this Carnot heat engine is

A. Less than 0.5.
B. 0.5.
C. Between 0.5 and 1.0.
D. 1.0.
E. 2.0.



QuickCheck 19.10

The efficiency of this Carnot heat engine is

✔**A. Less than 0.5.**

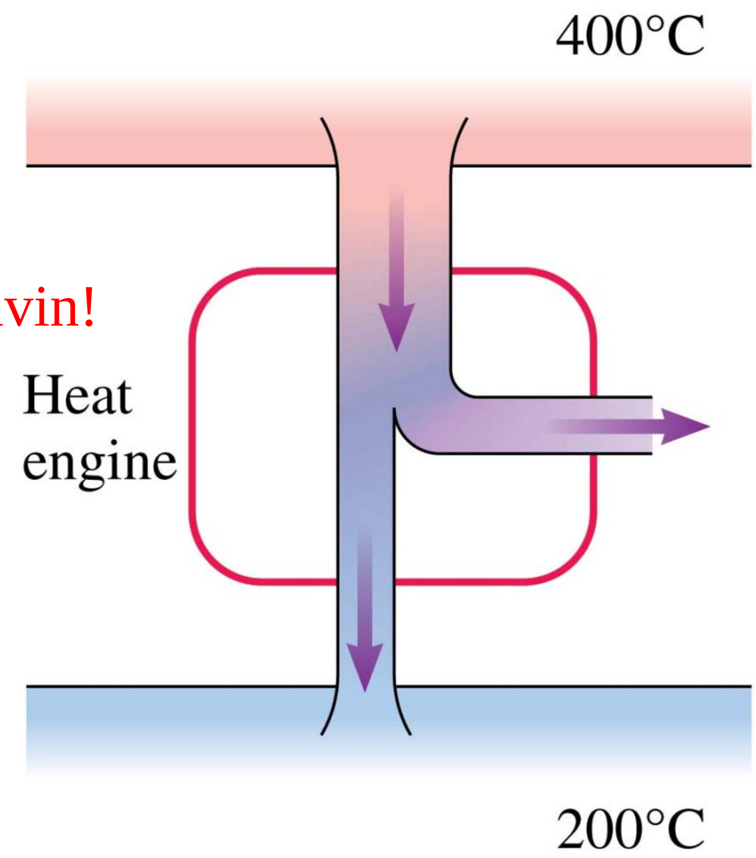
B. 0.5.

C. Between 0.5 and 1.0.

D. 1.0.

E. 2.0.

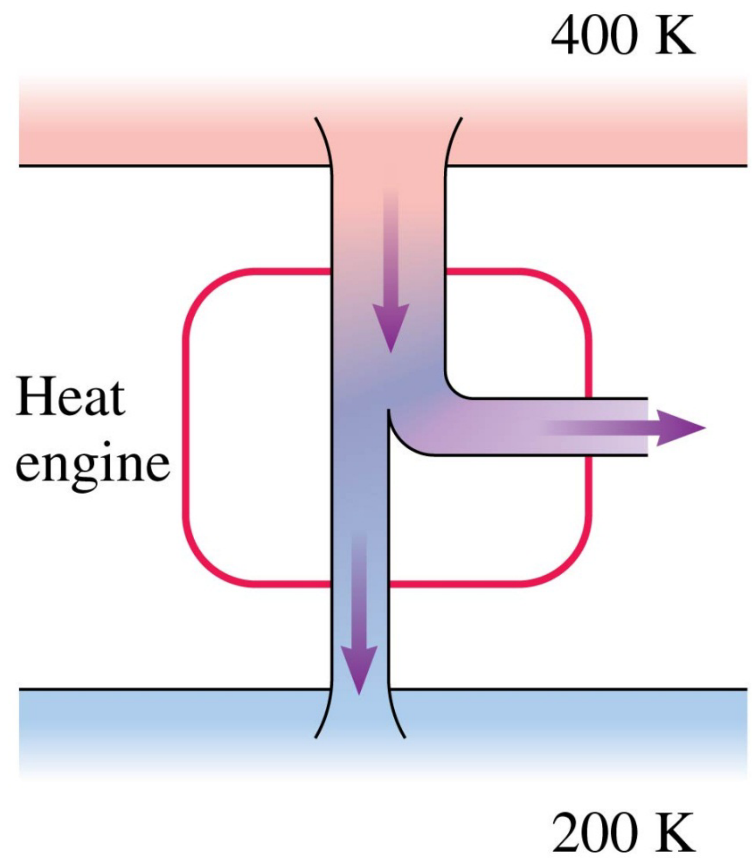
Temperatures must be in kelvin!



QuickCheck 19.11

The efficiency of this Carnot heat engine is

A. Less than 0.5.
B. 0.5.
C. Between 0.5 and 1.0.
D. 2.0.
E. Can't say without knowing Q_H.



QuickCheck 19.11

The efficiency of this Carnot heat engine is

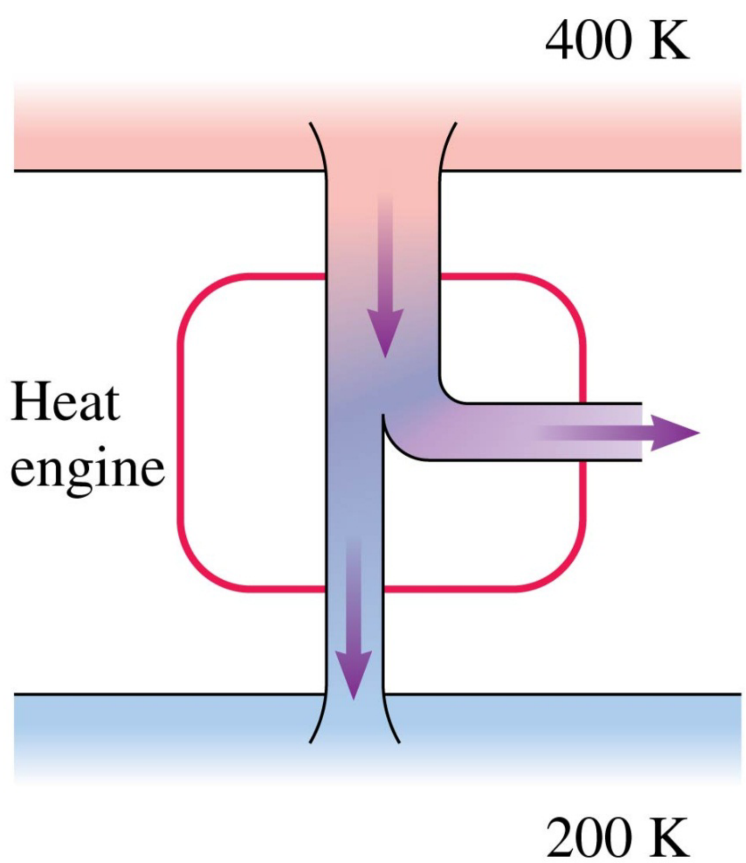
A. Less than 0.5.

✔ **B. 0.5.**

C. Between 0.5 and 1.0.

D. 2.0.

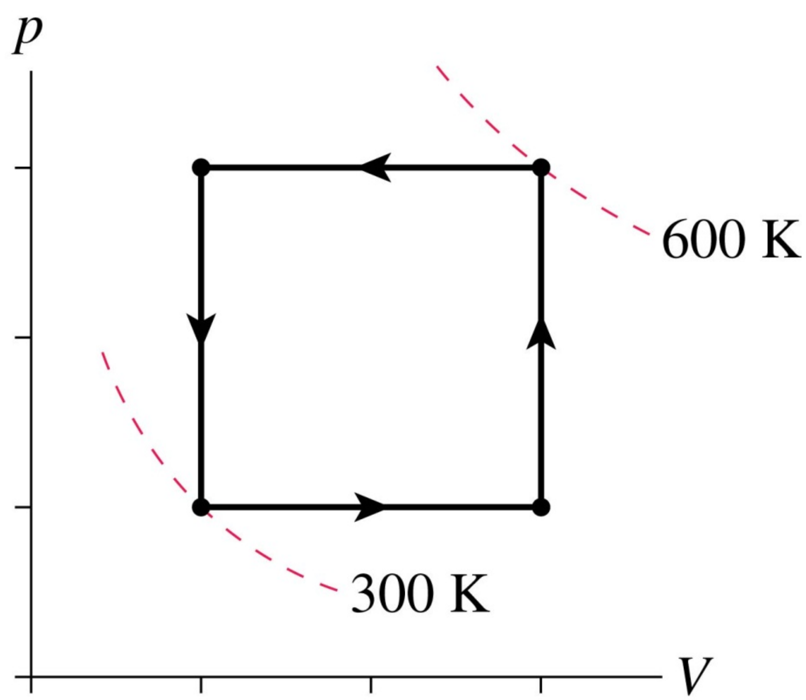
E. Can’t say without knowing Q_H.



QuickCheck 19.12

The efficiency of this heat engine is

A. Less than 0.5.
B. 0.5.
C. Between 0.5 and 1.0.
D. 1.0.
E. 2.0.



QuickCheck 19.12

The efficiency of this heat engine is

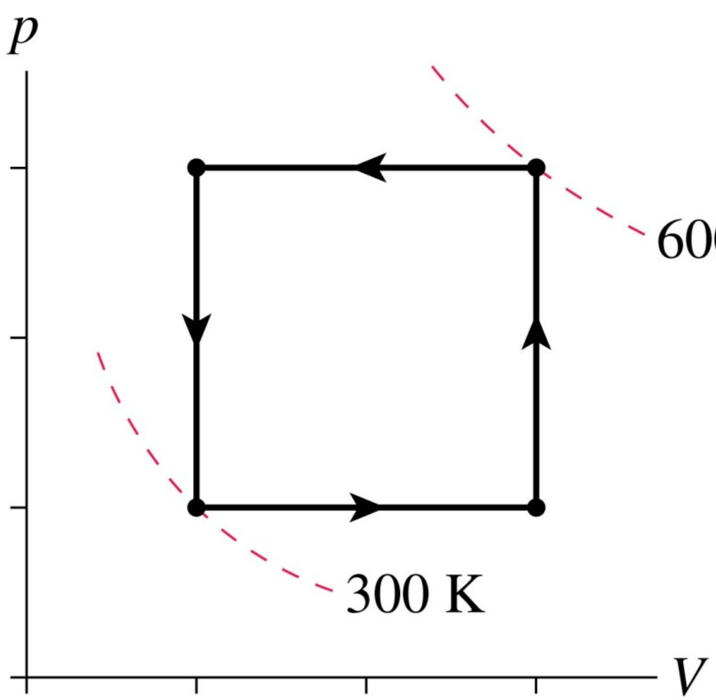
✔ **A. Less than 0.5.**

B. 0.5.

C. Between 0.5 and 1.0.

D. 1.0.

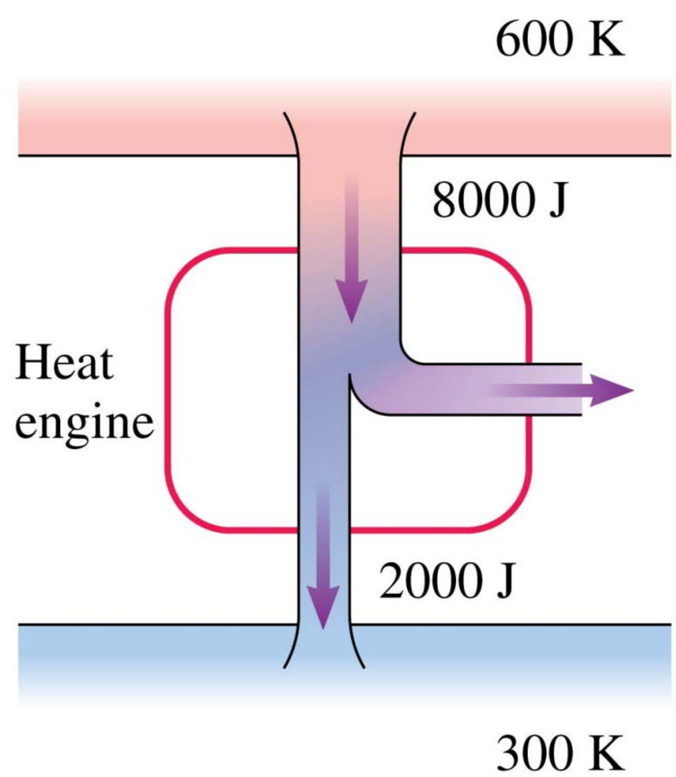
E. 2.0.



QuickCheck 19.13

This heat engine is

A. A reversible Carnot engine.
B. An irreversible engine.
C. An impossible engine.



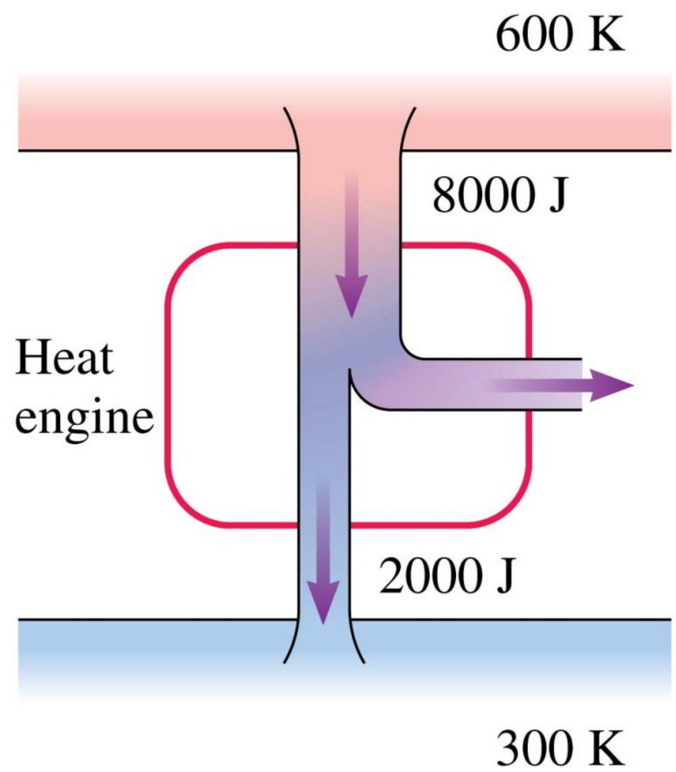
QuickCheck 19.13

This heat engine is

A. A reversible Carnot engine.

B. An irreversible engine.

✔ **C. An impossible engine.**



Example 19.4 A Carnot Engine

EXAMPLE 19.4 **A Carnot engine**

A Carnot engine is cooled by water at $T_C = 10°C$. What temperature must be maintained in the hot reservoir of the engine to have a thermal efficiency of 70%?

MODEL The efficiency of a Carnot engine depends only on the temperatures of the hot and cold reservoirs.

SOLVE The thermal efficiency $\eta_{Carnot} = 1 - T_C/T_H$ can be rearranged to give

$$T_H = \frac{T_C}{1 - \eta_{Carnot}} = 943 \text{ K} = 670°C$$

where we used $T_C = 283$ K.

ASSESS A "real" engine would need a higher temperature than this to provide 70% efficiency because no real engine will match the Carnot efficiency.

Example 19.5 A Real Engine

EXAMPLE 19.5 A real engine

The heat engine of Example 19.2 had a highest temperature of 2700 K, a lowest temperature of 300 K, and a thermal efficiency of 15%. What is the efficiency of a Carnot engine operating between these two temperatures?

SOLVE The Carnot efficiency is

$$\eta_{\text{Carnot}} = 1 - \frac{T_C}{T_H} = 1 - \frac{300\text{ K}}{2700\text{ K}} = 0.89 = 89\%$$

ASSESS The thermodynamic cycle used in Example 19.2 doesn't come anywhere close to the Carnot efficiency.

Example 19.6 Brayton Versus Carnot

EXAMPLE 19.6 Brayton versus Carnot

The Brayton-cycle refrigerator of Example 19.3 had coefficient of performance $K = 1.1$. Compare this to the limit set by the second law of thermodynamics.

SOLVE Example 19.3 found that the reservoir temperatures had to be $T_C \geq 250$ K and $T_H \leq 381$ K. A Carnot refrigerator operating between 250 K and 381 K has

$$K_{Carnot} = \frac{T_C}{T_H - T_C} = \frac{250\text{ K}}{381\text{ K} - 250\text{ K}} = 1.9$$

ASSESS This is the minimum value of K_{Carnot}. It will be even higher if $T_C > 250$ K or $T_H < 381$ K. The coefficient of performance of the reasonably realistic refrigerator of Example 19.3 is less than 60% of the limiting value.

Example 19.7 Generating Electricity

EXAMPLE 19.7 Generating electricity

An electric power plant boils water to produce high-pressure steam at 400°C. The high-pressure steam spins a turbine as it expands, then the turbine spins the generator. The steam is then condensed back to water in an ocean-cooled heat exchanger at 25°C. What is the *maximum* possible efficiency with which heat energy can be converted to electric energy?

MODEL The maximum possible efficiency is that of a Carnot engine operating between these temperatures.

SOLVE The Carnot efficiency depends on absolute temperatures, so we must use $T_H = 400°C = 673$ K and $T_C = 25°C = 298$ K. Then

$$\eta_{max} = 1 - \frac{298}{673} = 0.56 = 56\%$$

Example 19.7 Generating Electricity

EXAMPLE 19.7 Generating electricity

ASSESS This is an upper limit. Real coal-, oil-, gas-, and nuclear-heated steam generators actually operate at $\approx 35\%$ thermal efficiency, converting only about one-third of the fuel energy to electric energy while exhausting about two-thirds of the energy to the environment as waste heat. (The heat *source* has nothing to do with the efficiency. All it does is boil water.) Not much can be done to alter the low-temperature limit. The high-temperature limit is determined by the maximum temperature and pressure the boiler and turbine can withstand. The efficiency of electricity generation is far less than most people imagine, but it is an unavoidable consequence of the second law of thermodynamics.

Chapter 19 Summary Slides

Announcements

- <u>Student evaluations today</u>.

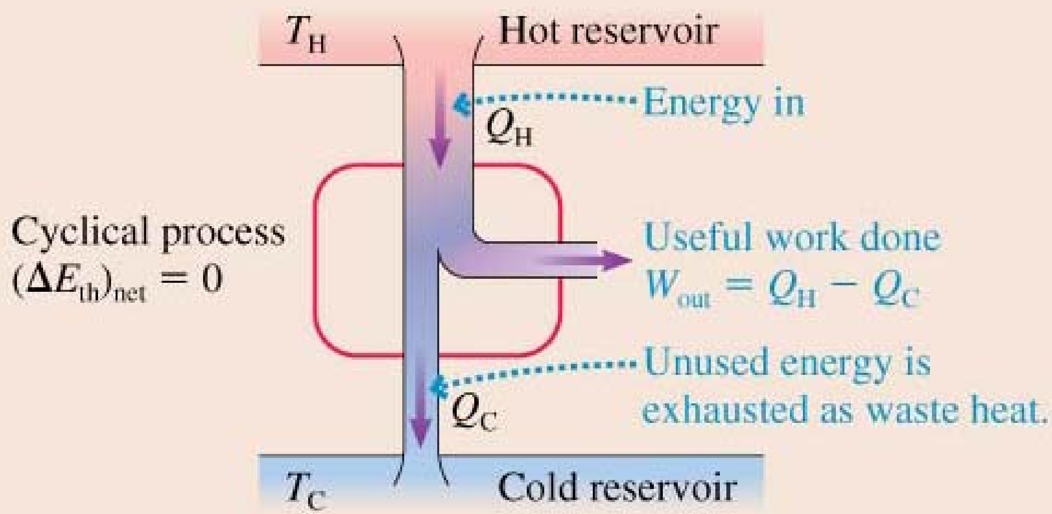
  Please pick up evaluation form at back or room.
  Complete form during class.
  Deliver to box at front at end of class.
  A student will take them to the physics office.

  Forms will be given to me only after final grades are turned in.

General Principles

Heat Engines

Devices that transform heat into work. They require two energy reservoirs at different temperatures.



Thermal efficiency

$$\eta = \frac{W_{out}}{Q_H} = \frac{\text{what you get}}{\text{what you pay}}$$

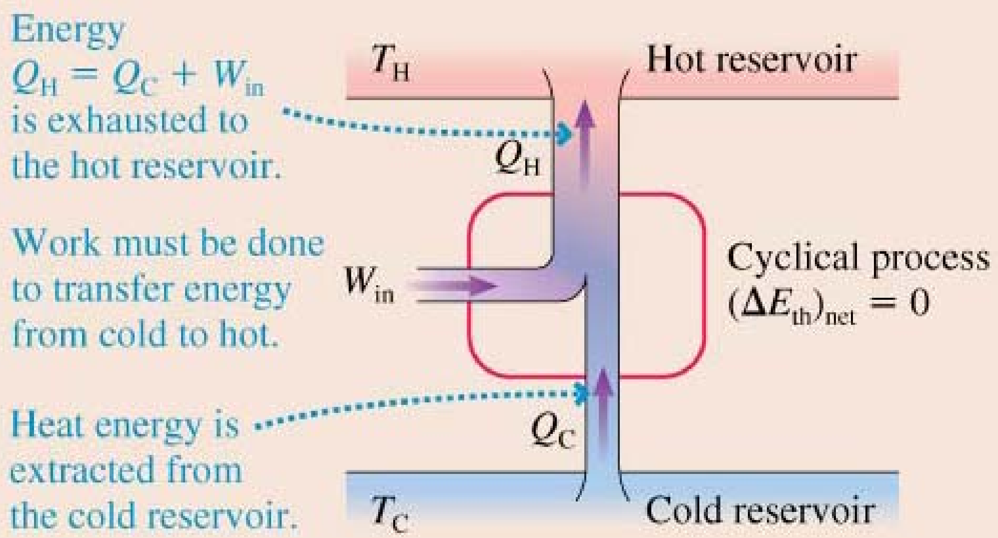
Second-law limit:

$$\eta \leq 1 - \frac{T_C}{T_H}$$

General Principles

Refrigerators

Devices that use work to transfer heat from a colder object to a hotter object.



Coefficient of performance

$$K = \frac{Q_C}{W_{in}} = \frac{\text{what you get}}{\text{what you pay}}$$

Second-law limit:

$$K \le \frac{T_C}{T_H - T_C}$$

Important Concepts

A perfectly reversible engine (a **Carnot engine**) can be operated as either a heat engine or a refrigerator between the same two energy reservoirs by reversing the cycle and with no other changes.

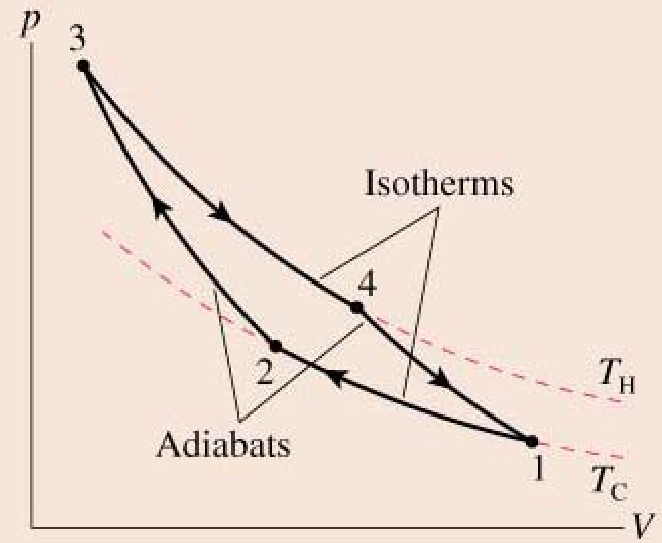
- A **Carnot heat engine** has the maximum possible thermal efficiency of any heat engine operating between T_H and T_C:

$$\eta_{Carnot} = 1 - \frac{T_C}{T_H}$$

- A **Carnot refrigerator** has the maximum possible coefficient of performance of any refrigerator operating between T_H and T_C:

$$K_{Carnot} = \frac{T_C}{T_H - T_C}$$

The Carnot cycle for a gas engine consists of two isothermal processes and two adiabatic processes.



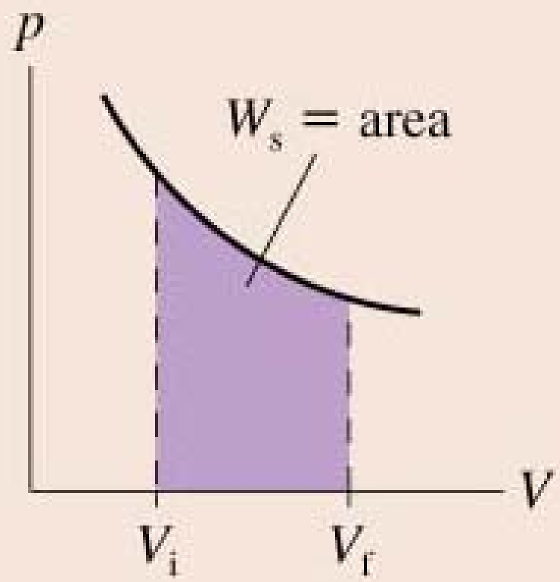
Important Concepts

An energy reservoir is a part of the environment so large in comparison to the system that its temperature doesn't change as the system extracts heat energy from or exhausts heat energy to the reservoir. All heat engines and refrigerators operate between two energy reservoirs at different temperatures T_H and T_C.

Important Concepts

The **work** W_s done *by* the system has the opposite sign to the work done *on* the system.

W_s = area under pV curve



Announcements

- Homework: Ch 17 due today.
  Ch 18 due tomorrow, 9:00 am (extra credit).
  Ch 19 due Monday, 9:00 am (extra credit).
- End-of-semester postings: http://www.wsu.edu/~collins/201/
  Sample final exam, chapter notes, homework.
- Review for final exam, Monday, 11:00-13:00.
- Final exam: Wednesday, Dec. 11, 10:10-13:00.
  You must sit in assigned seat; attendance will be taken.
  Eight problems, equation sheet same as sample exam.
  Not responsible for sections 12.10 and 12.11.

Have a great winter break!