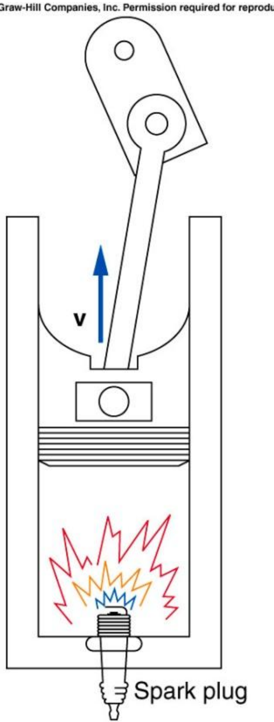
Chapter 11

Heat Engines and The Second Law of Thermodynamics

Heat Engines

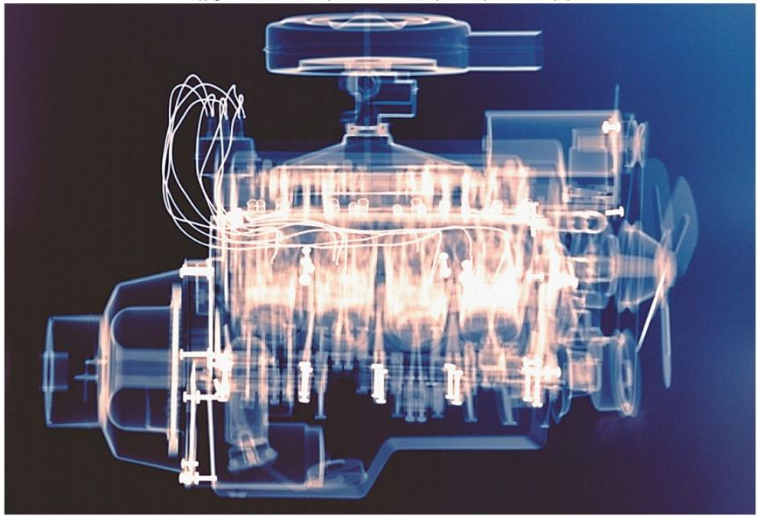
Heat engines use a temperature difference involving a high temperature (T_H) and a low temperature (T_C) to do mechanical work.

- A gasoline engine is a form of a **heat engine**.
  - A spark ignites a mixture of gasoline and air causing a large temperature increase which causes the cylinder to expand.
  - The work done by the gas is transferred to the wheels causing them to rotate.
- Only some of the heat from any heat engine is converted to useful work.
  - Some is released to the environment and can not be used for useful work.



Heat Engines and Energy

1) Any heat engine will require heat input from the high temperature (Q_H), and release heat output at the lower temperature (Q_C).
2) Energy must be conserved in any process:
   - From the first law of thermodynamics, for any engine: $W = Q + \Delta U$
3) Any engine must operate in a cycle. It must repeat a process over and over again.
   - For any complete cycle: $\Delta U = 0$

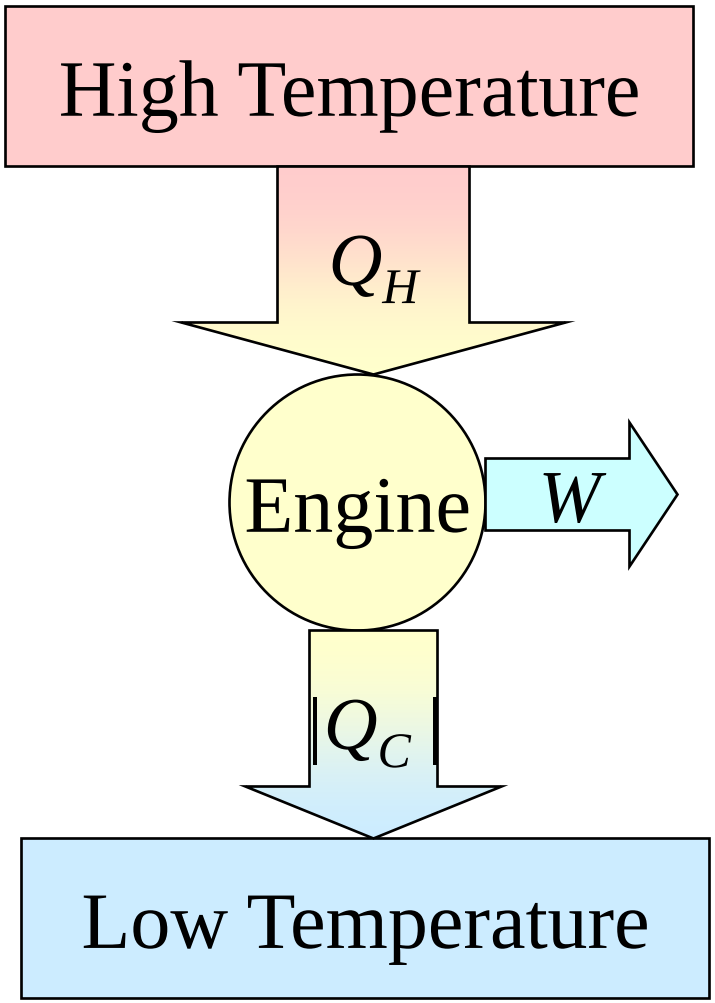


So for any (ideal) engine:

$$W = Q$$

Diagraming Heat Engines and Efficiency

Schematic diagram of energy transfer for a heat engine.



For any engine: $W = Q$, which can be written as:

$$W = Q_H - |Q_C|$$

The efficiency of an engine (e) is defined as the amount of work you get out compared with the heat you put in:

$$e = W/Q_H$$

Interactive Question

Which of the following statements is *not true* about a heat engine?

A) It always operates between a high temperature reservoir and a low temperature reservoir.
B) It operates in a cycle.
C) It can convert all of the input heat to useful work.
D) It conserves energy.
E) It has an efficiency given by the work done divided by the heat supplied.

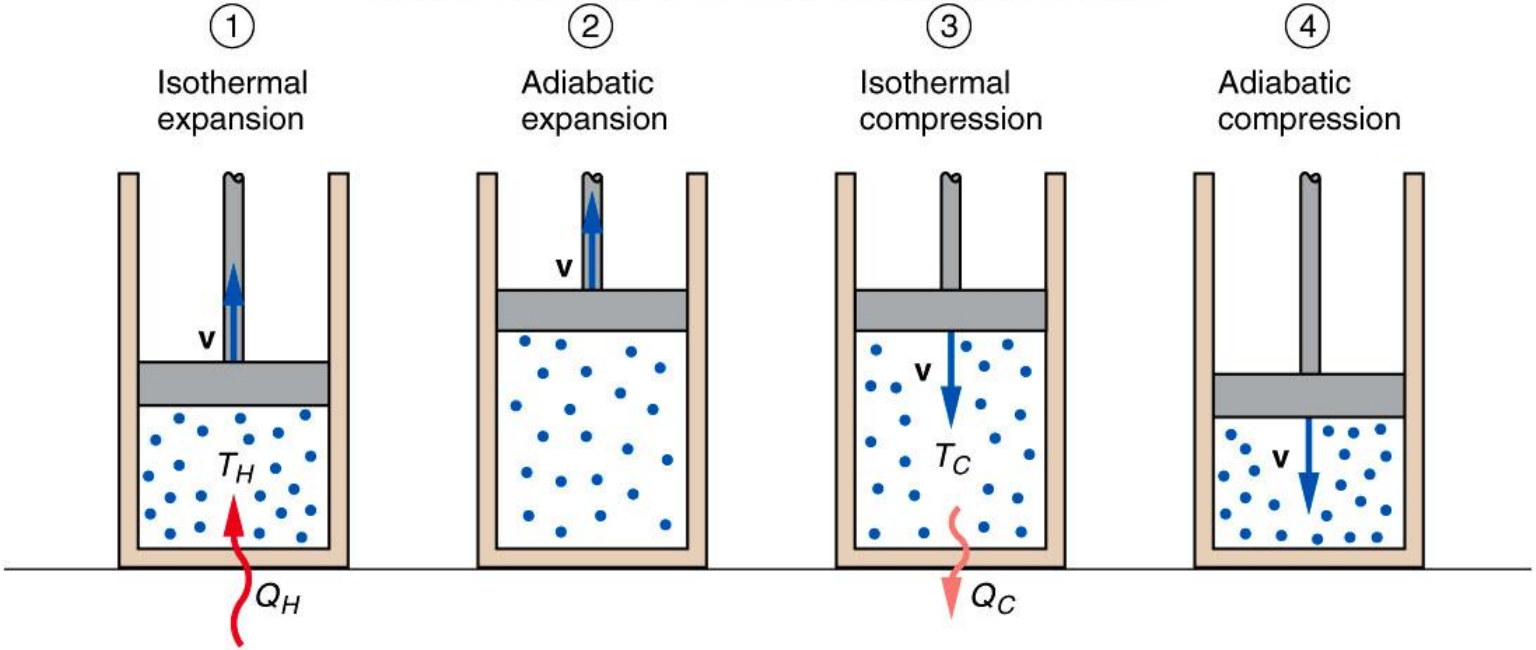
Problem: A heat engine operates at 20% efficiency and does 600 J of work. What is the heat input and output of this engine?

Carnot Engine and the Carnot Cycle

- The efficiency of a typical car engine is less than 30%.
  – This seems to be wasting a lot of energy.
  – What is the best efficiency we could achieve?
  – What factors determine efficiency?
- In the early 19th century Sadi Carnot showed that the best possible theoretical heat engine, an “ideal” engine, would:
  1) run between a hot and cold temperature.
  2) have an efficiency determined only by T_H and T_C.
  3) be completely “reversible” with no friction, etc.
  4) follow a specific cycle, now called the **Carnot Cycle**
- We call such an ideal (not real) engine following this cycle a **Carnot engine**.
  – A Carnot engine is the most efficient possible engine that can run between two temperatures. It is an ideal engine.

The Carnot Cycle

1. Heat flows into cylinder at temperature T_H. The fluid expands isothermally and does work on the piston.
2. The fluid continues to expand, adiabatically.
3. Work is done by the piston on the fluid, which undergoes an isothermal compression.
4. The fluid returns to its initial condition by an adiabatic compression.



Carnot Efficiency

- The efficiency of Carnot's ideal engine is called the **Carnot efficiency** and is given by:

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

- You must use the Kelvin temperature scale in this equation. This is the ***maximum efficiency possible*** for ***<u>any</u>*** heat engine taking in heat from a reservoir at absolute temperature T_H and releasing heat to a reservoir at temperature T_C.
- Even Carnot's ideal engine is less than 100% efficient.

Interactive Question

The significance of a Carnot engine is

A) all automobiles operate on the Carnot cycle.
B) it has the maximum possible efficiency of any engine. operating between the same two temperatures.
C) it violates the second law of thermodynamics.
D) it violates the first law of thermodynamics.
E) it can run at 100% efficiency.

Problem: A steam engine operates at a high temperature of 300 ºC and a low temperature of 100 ºC.

(a) What is the maximum possible efficiency?

(b) If the maximum possible work done by this engine is 50 KJ during each cycle, how much heat does it take in per cycle?

Interactive Question

You are taking bids to have a heat engine built that will operate between 200ºC and 30ºC. Different contractors claim the efficiency of their engines as:

A) 100%
B) 80%
C) 40%
D) 30%
E) 20%

Which contractor would you accept the bid from?

Problem: A 100 hp car operates at 15% efficiency. Assume the engine's water temperature of 85 C is its low temperature and the intake temperature of 500 C is its high temperature.

(a) How much does this efficiency differ from the maximum possible efficiency?

(b) What is the heat input into this engine per hour?

(c) What is the work done by this engine per hour?

(d) What is the heat output per hour?

Second Law of Thermodynamics

- A principle which places limits on the efficiency of heat engines, heat pumps and other devices that transform heat to work and vice versa.
- It can be stated in a number of different ways.
  - We will look at different statements of the law throughout this chapter.
- It is thought to give a direction for time.
- It is can described using a statistical description of a process.
- It is a measure of the amount of disorder of a system.

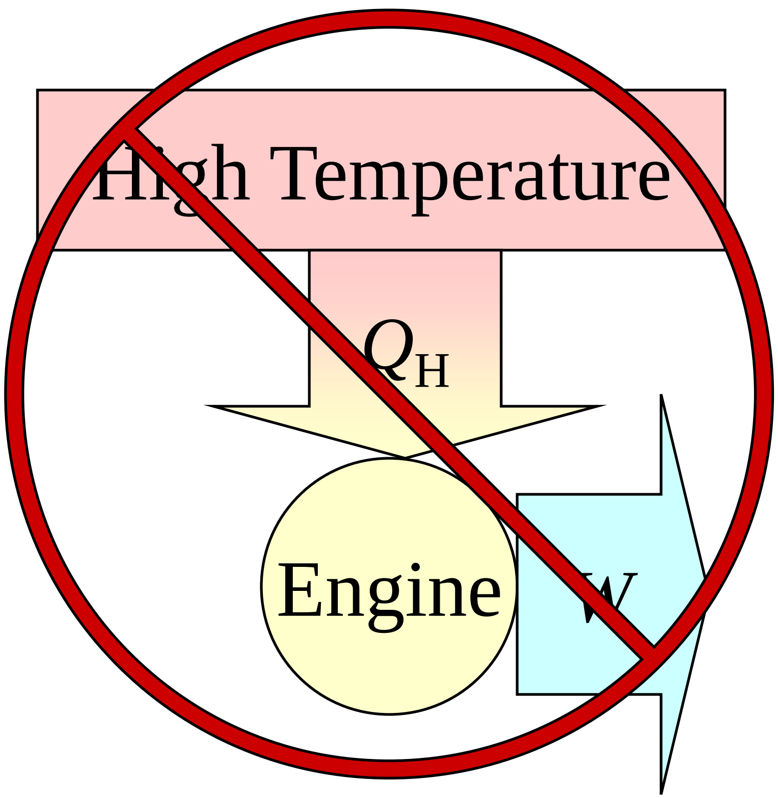
The Laws of Thermodynamics

The British scientist C.P. Snow stated the three laws as:

- Law 1: You cannot win.
  (that is, you cannot get something for nothing, because energy is conserved).
- Law 2: You cannot break even.
  (you cannot return to the same energy state, because there is always an increase in disorder; entropy always increases).
- Law 3: You cannot get out of the game.
  (because absolute zero is unattainable).

2^{nd} Law of Thermodynamics: Kelvin-Planck statement

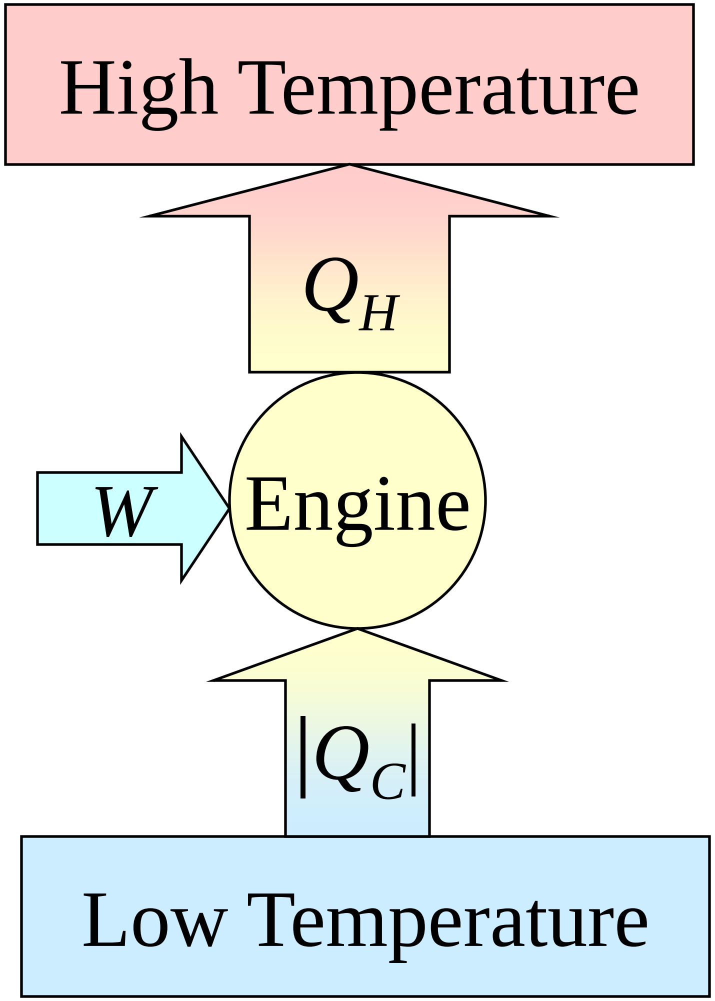
No engine, working in a continuous cycle, can take heat from a reservoir at a single high temperature and convert that heat completely to work.



$$Q_H \neq W$$

This means that no engine can be 100% efficient.

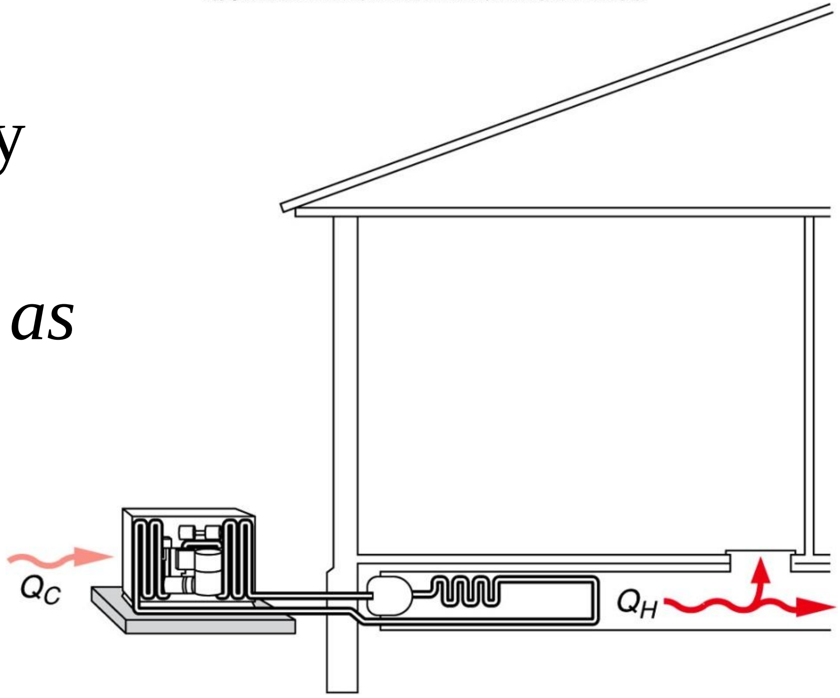
Refrigerators and Heat Pumps



- A refrigerator or heat pump is like an engine run in reverse.
- It takes heat from a cold temperature and makes it colder by doing work and ejecting even more heat.
- From the first law of thermodynamics:

$$|Q_C| + W = |Q_H|$$

- A **heat pump** usually refers to a device that heats a building by pumping heat from the colder outdoors to the warmer interior.
- An electric motor does the work needed to run the pump.
- A refrigerator and an air conditioner work like a heat pump. By doing work, they make a cool area cooler and a warm area warmer..
- We can get a larger amount of heat from the heat pump than by converting the electrical energy directly to heat *(often 2-3 times as much)*.



Interactive Question

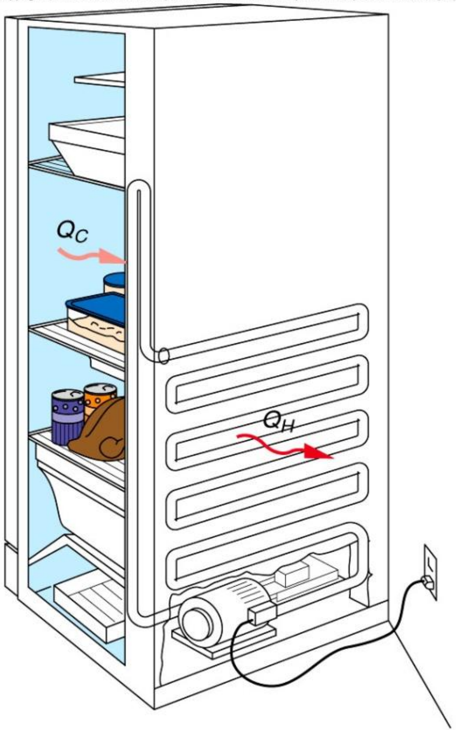
Can you cool your house by plugging in the refrigerator, turning it on, and opening the door?

A) Yes this will work just like an air conditioner.

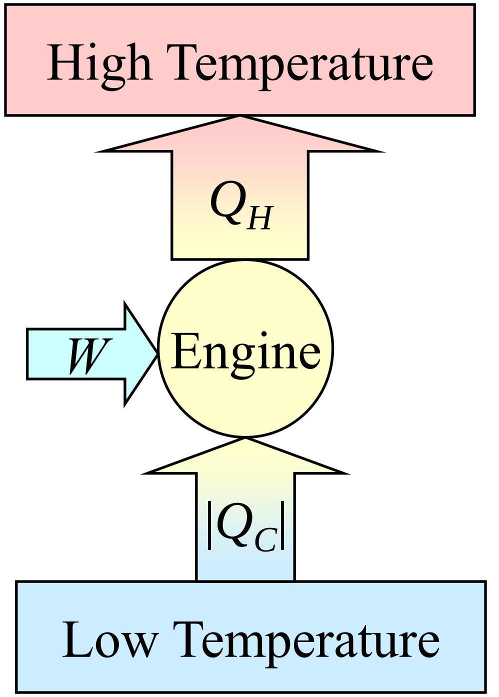
B) Yes, this will work but it will be much more expensive than air conditioning.

C) No, this won’t work because the engine will burn out.

D) No this won’t work because the refrigerator outputs more heat than it cools.

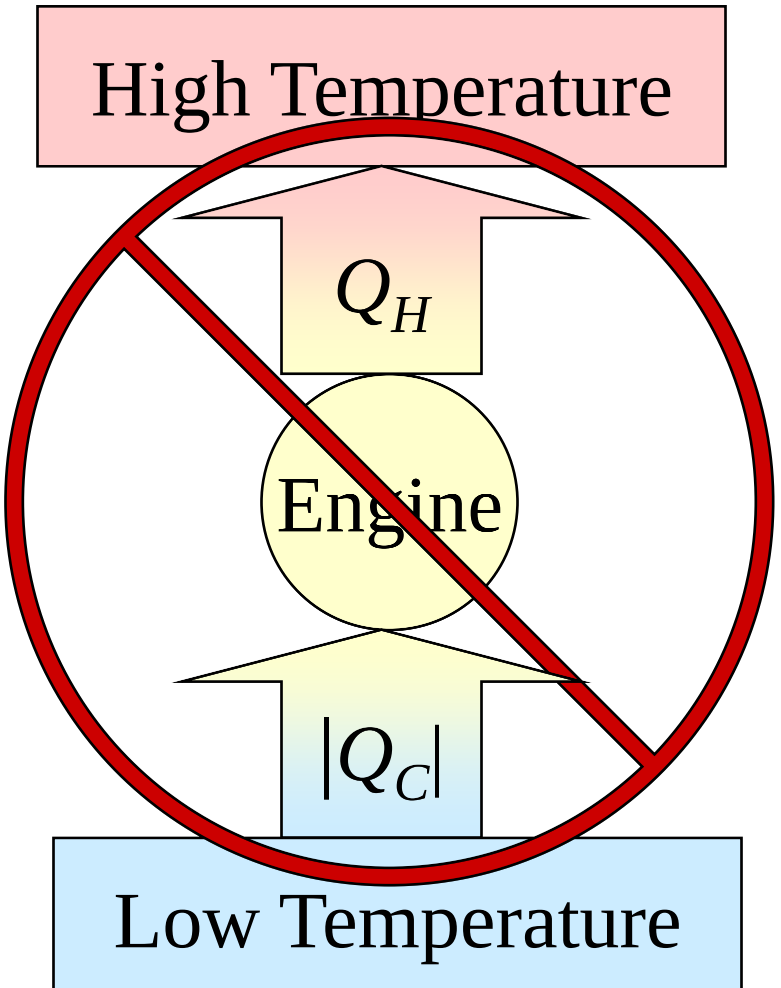


Problem: A heat pump uses removes 400 J of heat from a low temperature environment by doing 250 J of work in each cycle. How much heat is delivered to a high temperature reservoir per cycle?



2nd Law of Thermodynamics: Clausius statement

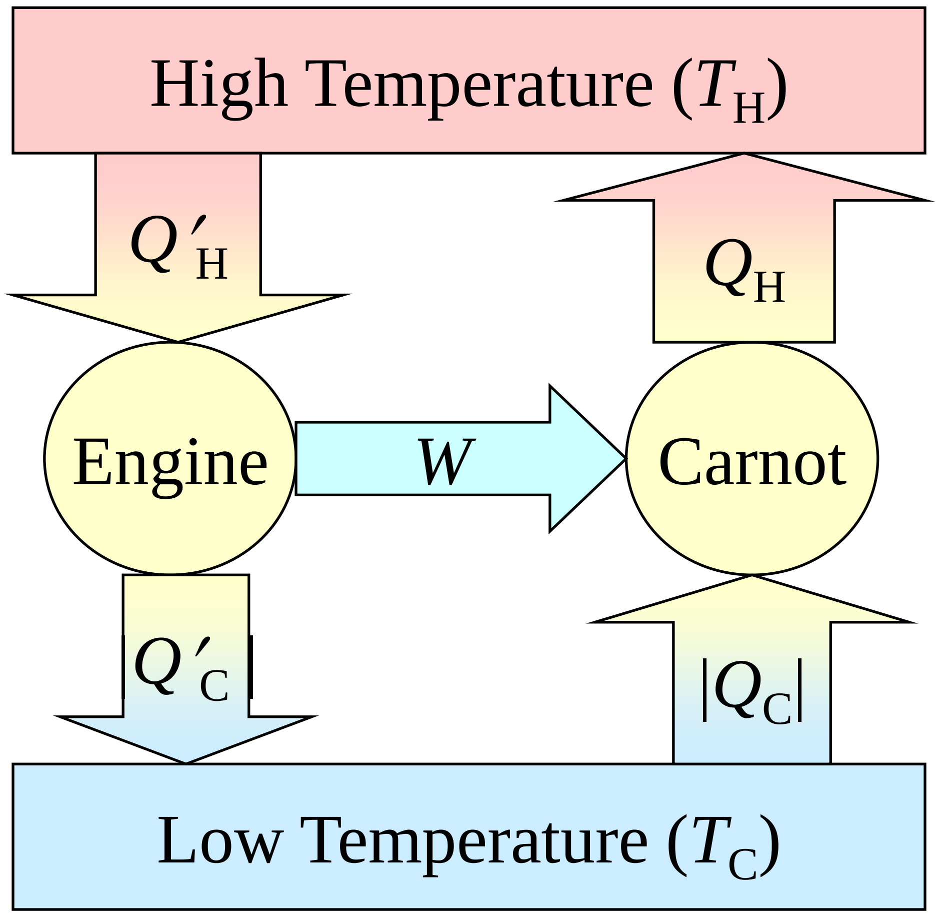
Heat will not flow from a colder body to a hotter body unless some other process is also involved.

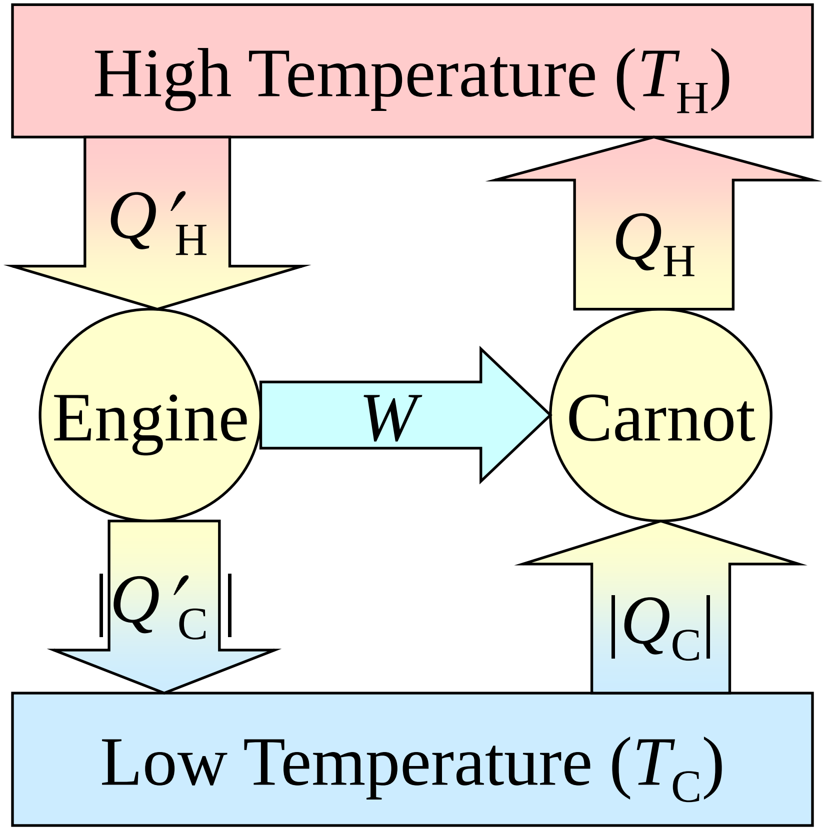


$$Q_H \neq |Q_C|$$

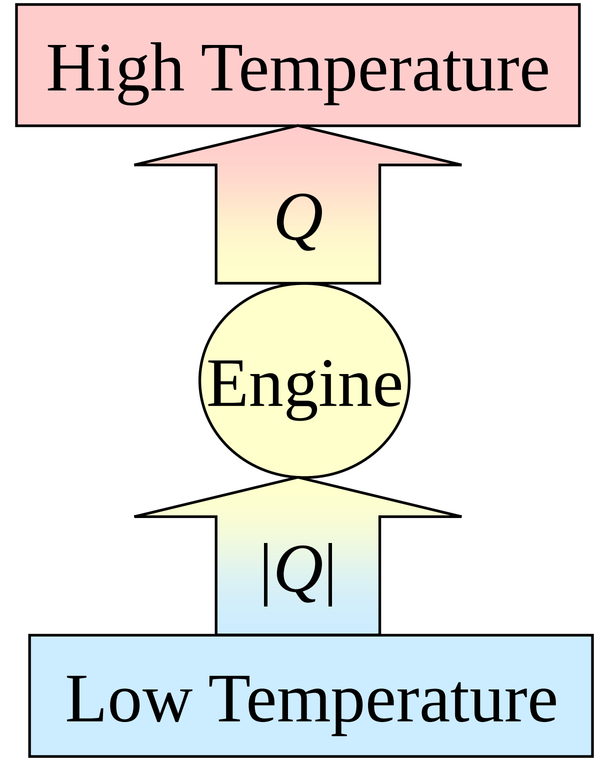
Proof of Carnot's Theorem

Pretend there is an engine with a better efficiency. We'll connect this "better" engine to a Carnot engine running backwards as a Carnot refrigerator. The work output of the "better" engine is the work input to the Carnot refrigerator.





which can be drawn as:



From 1st Law: $W = |Q_H| - |Q_C|$

$$W = |Q'_H| - |Q'_C|$$

So:

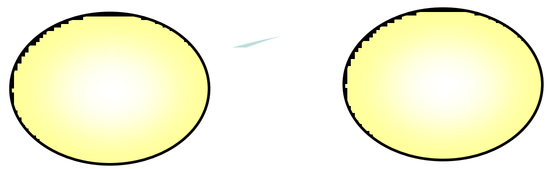
$$|Q'_H| - |Q'_C| = |Q_H| - |Q_C|$$

$$|Q_H| - |Q'_H| = |Q_C| - |Q'_C|$$

But this drawing violates the 2nd law. So our assumption about a "better" engine must be wrong. That is, there is no engine more efficient than a Carnot engine.

Reversible and Irreversible Processes

Reversible processes are those that can proceed through very small steps so that the system is always at equilibrium.



What prevents the eggs from coming back together? Energy would still be conserved… The 2nd law of Thermodynamics prevents this. Let's look at the 2nd law in terms of a new entity called "entropy."

What is Required for Reversible Processes?

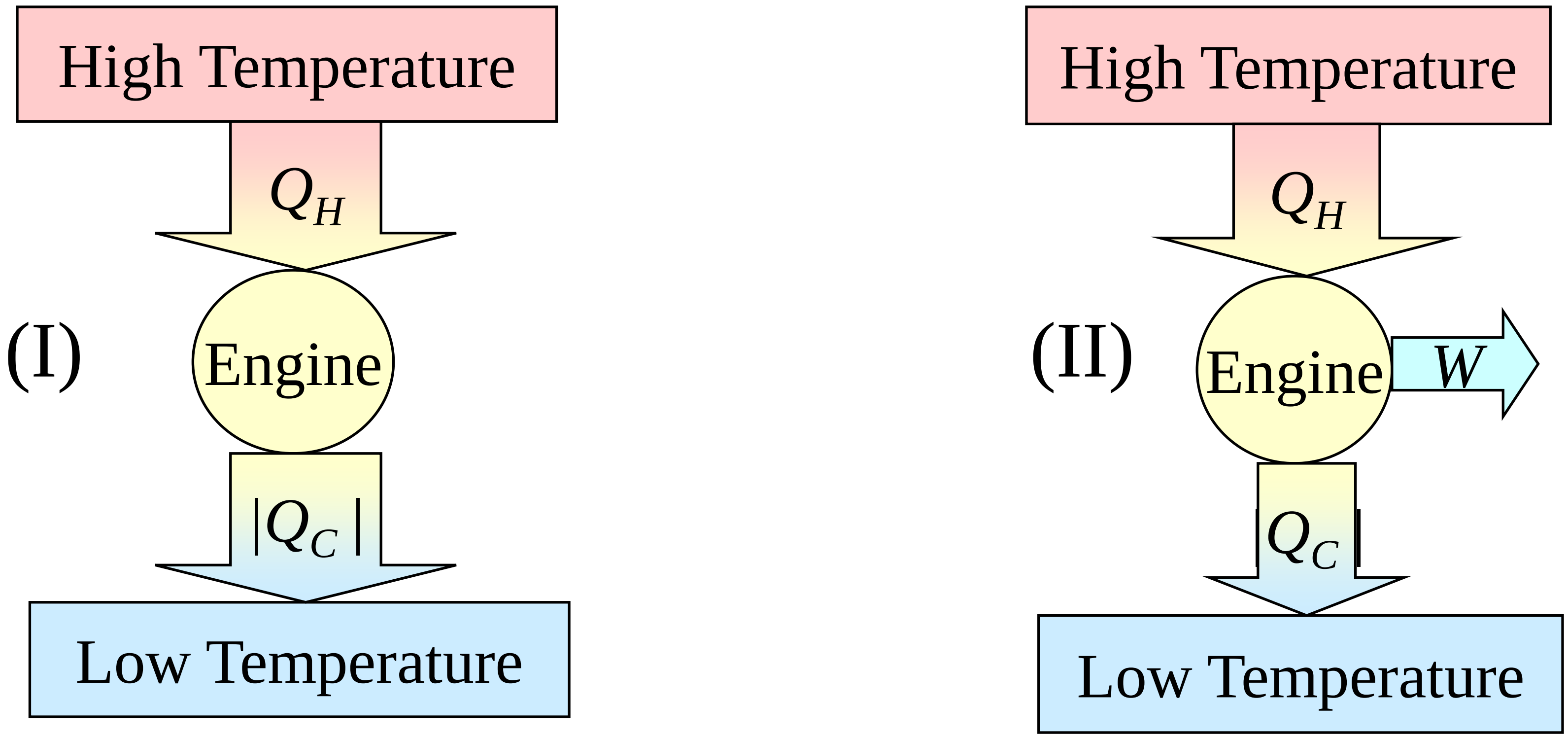
- A real reversible process must always be at equilibrium.
  - No real processes of change are reversible
- We can approximate processes as reversible, just as we approximated processes with no friction or air resistance, for instance.
- The “ideal” Carnot engine is reversible.

Interactive Question

Which of the following is a reversible process?

A) A glass vase falls on the floor and shatters.
B) Ice is taken from the freezer and melts.
C) Air flows into a chamber that initially contained a vacuum.
D) None of the above.

Interactive Question



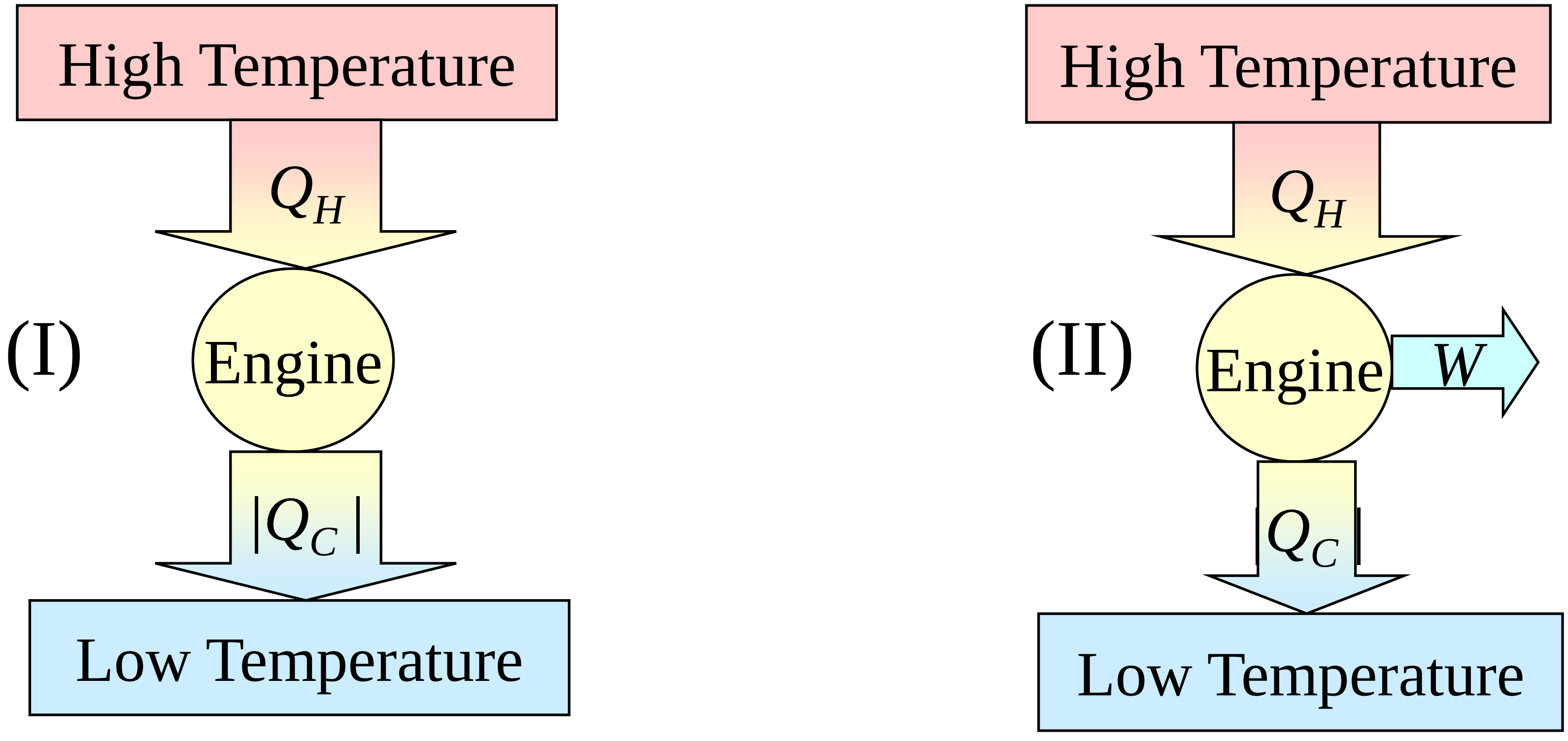
Which process is possible:

A) I

B) II

C) I and II

D) Neither I nor II



High Temperature
Q_H
(I)
Engine
$|Q_C|$
Low Temperature
High Temperature
Q_H
(II)
Engine
W
$|Q_C|$
Low Temperature

Entropy

- Entropy is sometimes defined as ***a measure of the disorder of the system***.
- The entropy of a system increases any time the disorder or randomness of the system increases.
- Entropy remains constant in reversible processes but increases in irreversible processes.

2nd Law of Thermodynamics: Entropy Statement

The entropy of an isolated system can only increase or remain constant. Its entropy can never decrease.

- For an isolated system, entropy remains constant in reversible processes but increases in irreversible processes.
- An increase in entropy means an increase in randomness, or a decrease in order. Disorder increases in any real spontaneous process.
- In any process we lose some ability to do useful work because the randomness has increased.
- The entropy of a system can decrease if it interacts with the environment whose entropy is increased, so that the entropy of the system plus the environment increases.
- The universe is an isolated system, so in any process the entropy of the universe increases.

Interactive Question

The entropy of the universe

A) is always decreasing.
B) is conserved.
C) is impossible to calculate.
D) can only increase or remain constant.

Interactive Question

When you clean up your room the order of the room increases. Does this violate the 2^{nd} law of thermodynamics?

A) Yes, the second law is a general principle by can be violated.
B) Yes, the second law doesn't apply to things like this.
C) No, the room only looks more ordered but it really isn't.
D) No, the order of the room increases, but the disorder of other things increases more.

The previous interactive question illustrates an important principle:

- Any time the entropy of something decreases (its order is increased), it means that the entropy of the environment had to increase more, so that the total entropy of the universe increases.
- It takes input energy or work to decrease the entropy of a system.
  - It takes work to clean your room or build a house and increased entropy of your biological system.
  - It takes input energy from the sun for biological systems to decrease their entropy. The sun’s entropy increases more.

Interactive Question

Which of the following is *not* a proper statement of the 2^{nd} law of thermodynamics?

A) Entropy increases in any irreversible process and is constant in a reversible process.
B) No engine can take heat from a single reservoir and convert it all to work.
C) Heat will not flow from a hotter to a colder body unless some other effect is involved.
D) Heat will not flow from a colder to a hotter body unless some other effect is involved.

The Statistical View of Entropy

Example: Roll Two Dice

Macrostates	Microstates	Num	Prob
2	(1,1)	1	1/36
3	(1,2) (2,1)	2	1/18
4	(1,3) (2,2) (3,1)	3	1/12
5	(1,4) (2,3) (3,2) (4,1)	4	1/9
6	(1,5) (2,4) (3,3) (4,2) (5,1)	5	5/36
7	(1,6) (2,5) (3,4) (4,3) (5,2) (6,1)	6	1/6
8	(2,6) (3,5) (4,4) (5,4) (6,2)	5	5/36
9	(3,6) (4,5) (5,4) (6,3)	4	1/9
10	(4,6) (5,5) (6,4)	3	1/12
11	(5,6) (6,5)	2	1/18
12	(6,6)	1	1/36

All microstates are equally probable. All macrostates are not.

Entropy, Thermodynamics, and Statistics

- The second law of thermodynamics simply says that events with very low probabilities will not happen.
- Macro-states with few micro-states will not occur.
- There is a precise mathematical description of the 2^{nd} law of thermodynamics in terms of entropy which states that everything moves towards the more probable state.

An example of probabilities:

- If you flip a properly weighted coin ten times could you get 6 or more tails?
  - Yes, there is a 38% probability that will happen.
- If you flip a properly weighted coin 10,000 times could you get 6000 or more tails?
  - No, there is only a 8.7 10^{-88} % probability that will happen.)
  - This can’t happen in the history of the universe. (There are only 10^{17} s since the universe began.)
- As you flip a coin more times, the answer will get closer to the average; the most random possible answer.
- The 2nd law of thermodynamics states that over time with lots of molecules everything moves to the state that is most probable. This is the most disordered, or random, state. It is the state with the highest entropy

Problem: Three students have designed an engine that operates between 300 K and 500 K. Which of these engines is possible?

Engine	Q_H	Q_C	W
1)	250 J	-140 J	110 J
2)	250 J	-170 J	90 J
3)	250 J	-160 J	90 J

Review of Three Laws of Thermodynamics

0. **Zeroth law:** If two objects have the same temperature as a third object, then they have the same temperature as each other.
1. **First law:** $W = Q + \Delta U$

   In any cyclic process, $W = Q = Q_H - |Q_C|$
2. **Second law:** Entropy remains constant in a reversible process and increases in any irreversible process, (which describes any spontaneous process). The second law can also be stated as heat doesn't spontaneously flow from a lower temperature to a higher temperature, or no engine can be 100% efficient.

Interactive Question

A heat engine that in each cycle does positive work and rejects heat, with no heat input, would violate:

A) The zeroth law of thermodynamics
B) The first law of thermodynamics
C) The second law of thermodynamics
D) None of the above

Interactive Question

A heat engine absorbs heat from a reservoir and does an equivalent amount of work, with no other changes. This engine violates:

A) The zeroth law of thermodynamics
B) The first law of thermodynamics
C) The second law of thermodynamics
D) None of the above

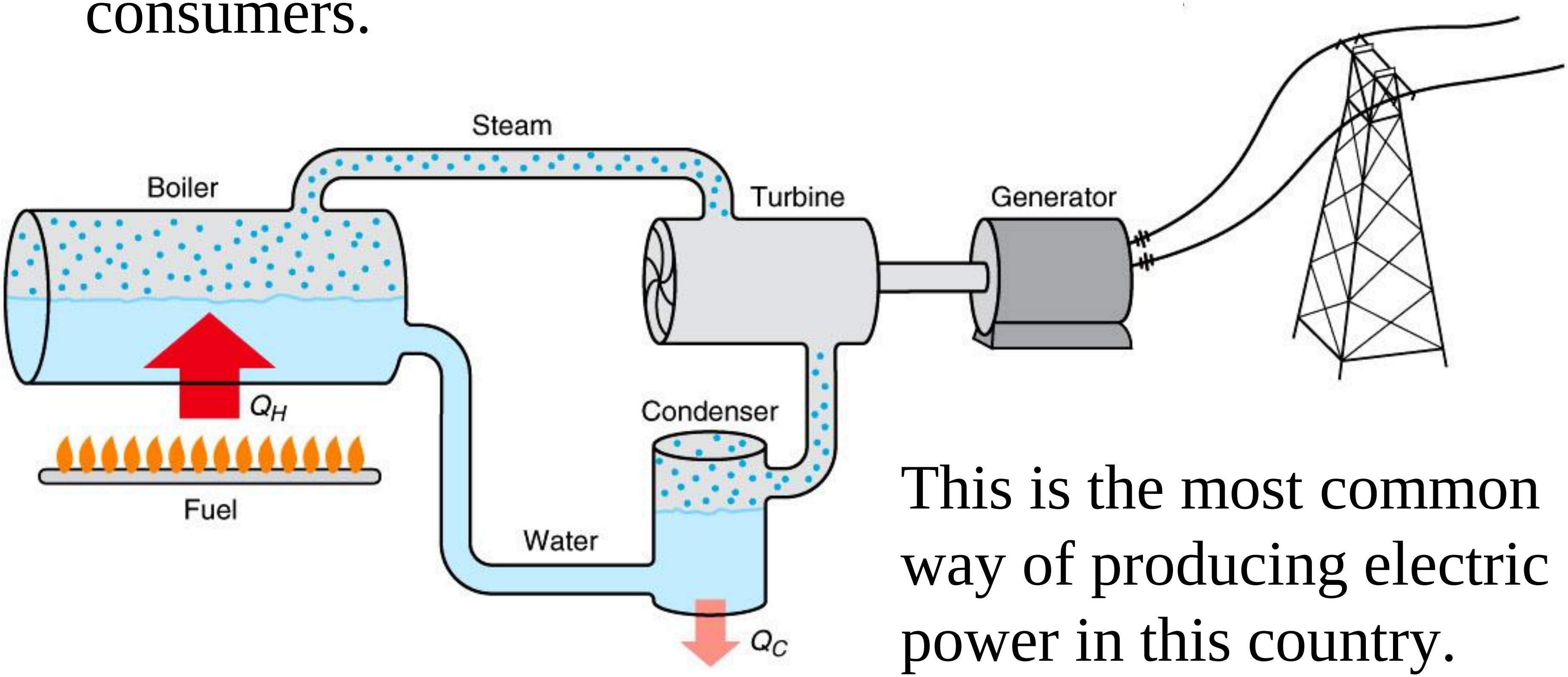
Interactive Question

A cyclic process that transfers heat from a high temperature reservoir to a low temperature reservoir with no other changes would violate:

A) The zeroth law of thermodynamics
B) The first law of thermodynamics
C) The second law of thermodynamics
D) None of the above

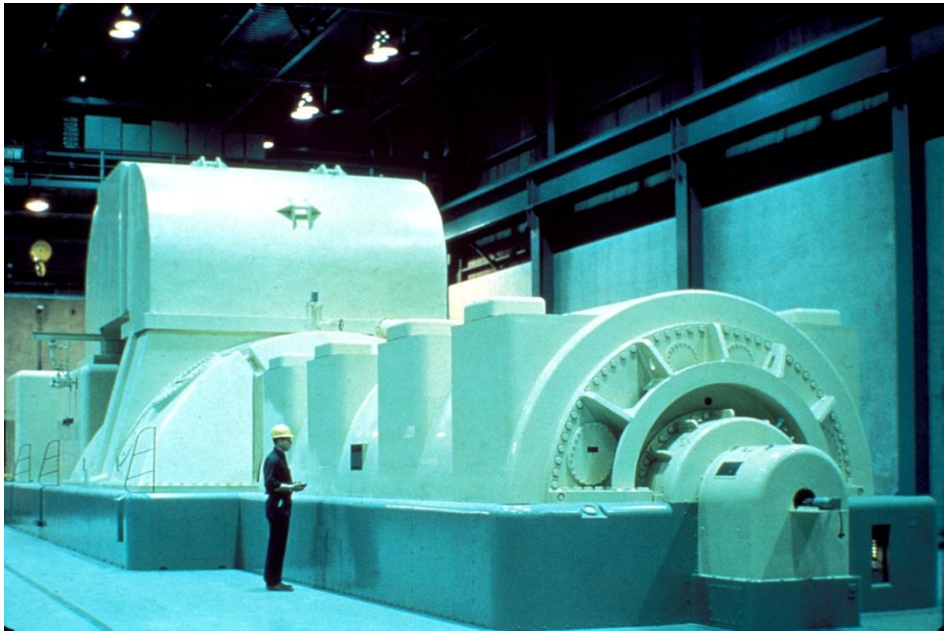
Thermal-Electric Power Plant

1. Fossil fuel (coal, oil, natural gas) is burned to release heat that causes the temperature of water and steam to increase.
2. Hot steam is run through a turbine (a heat engine) that turns a shaft connected to an electric generator.
3. Electricity is transmitted through power lines to consumers.



This is the most common way of producing electric power in this country.

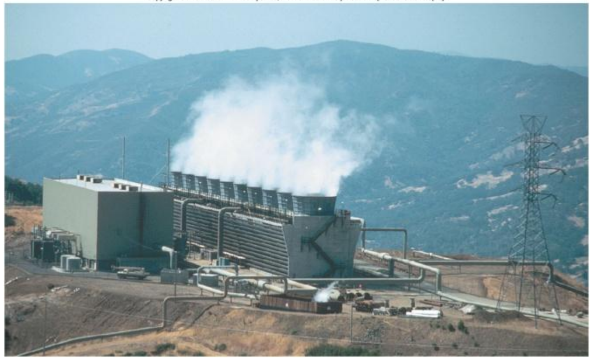
- Because the steam turbine is a heat engine, its efficiency is limited by the second law of thermodynamics.
  - Any real engine involves irreversible processes and so must fall short of the ideal completely reversible Carnot engine.
  - A steam turbine comes closer to the ideal than the highly turbulent internal-combustion engine.
- The maximum possible efficiency is dictated by the temperature difference between the hot and cold reservoirs.
  - Heating the steam to as high a temperature as possible is advantageous.
  - The exhaust temperature is near the boiling point of water, where the steam condenses to water.



- Only about half the thermal energy released in burning coal or oil is converted to mechanical work or electrical energy.
  - The rest is released into the environment at temperatures too low for running heat engines.
  - Cooling towers transfer this waste heat into the atmosphere
  - …or heated water is released into a river (though this is not done much anymore due to environmental damage.)

Alternatives to Fossil Fuels: All Heat Engines

- Nuclear power plants
  - Lower thermal efficiencies
  - More heat released into environment
  - No carbon dioxide and other greenhouse gases released
  - Nuclear waste must be processed and disposed of
- Geothermal Energy
  - Heat from the interior of the earth, such as hot springs and geysers.
  - Water temperature not hot enough to yield a high efficiency
- Direct Sun
  - Warm ocean currents
  - Solar collectors



Interactive Question

Which of the following sources of electric power is *not* an example of a heat engine?

A) Fossil fuels
B) Geothermal
C) Wind energy
D) Solar collectors
E) More than one of the above

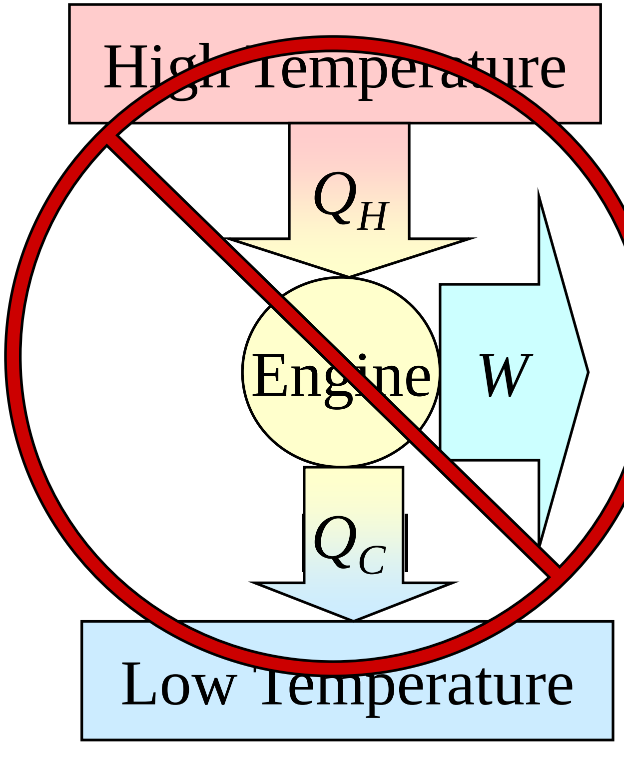
High-Grade and Low-Grade Heat

- The temperature difference between the hot and cold reservoir determines the maximum possible efficiency.
- **High-grade heat** is heat at temperatures around 500°C or higher, and is more useful than heat at lower temperatures.
- **Low-grade heat**, around 100°C or lower, can produce work but with considerably lower efficiency.
  - Low-grade heat is better used for purposes like heating buildings.
  - Much low-grade heat, such as the low-temperature heat released from power plants, goes to waste because it is not economical to transport it to where it might be utilized.
- Although it is difficult to transport heat from one place to another, electrical energy is easily transported.

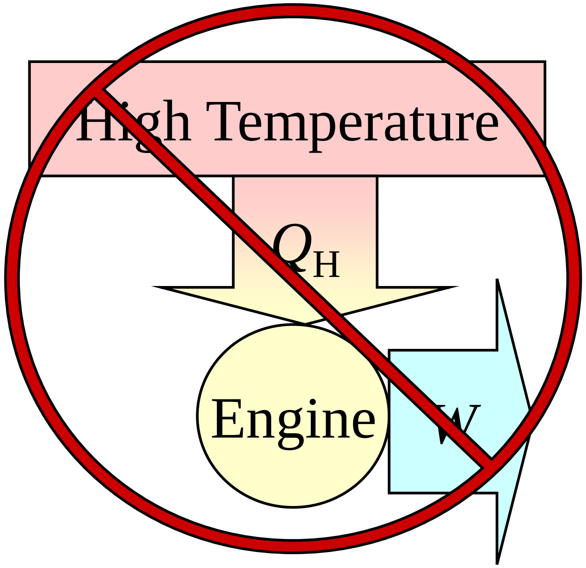
Perpetual Motion

There are claims of machines that produce more energy than they consume, or that never run out of energy. Such machines are not possible and are called **perpetual motion machines**.

A perpetual-motion machine of the first kind would violate the 1st law of thermodynamics. It puts out more energy as work or heat than it takes in.



A perpetual-motion machine of the second kind would violate the 2nd law of thermodynamics. It claims to take heat from a single temperature reservoir and convert it completely to work, or claims an efficiency higher than the Carnot efficiency.



If someone offers to generate electricity by running a water wheel with water drained from the bottom of a pond returning to the top of the pond, don't buy it.