CAE 208 / MMAE 320: Thermodynamics

Fall 2023

November 02, 2023

Intro to second law (1)

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ANNOUNCEMENTS

Announcements

- Assignment 7 is due tonight

- Midterm exam 2 is next week (Today’s lecture is the last lecture that will be covered in the exam)

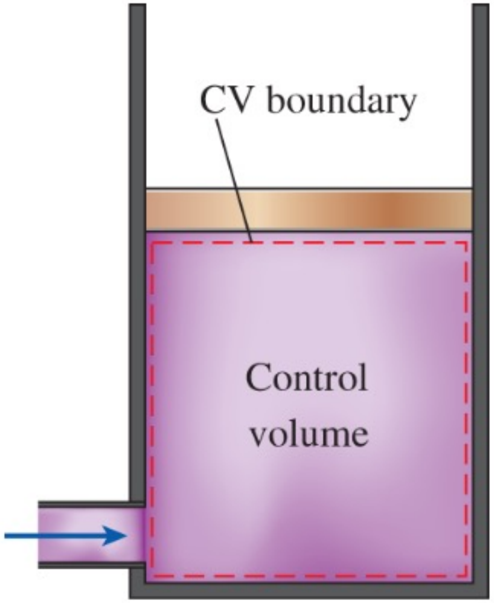
RECAP

Recap

- Let’s look at unsteady flow processes:

$$m_{in} - m_{out} = \Delta m_{system}$$

$$\Delta m_{system} = m_{final} - m_{initial}$$

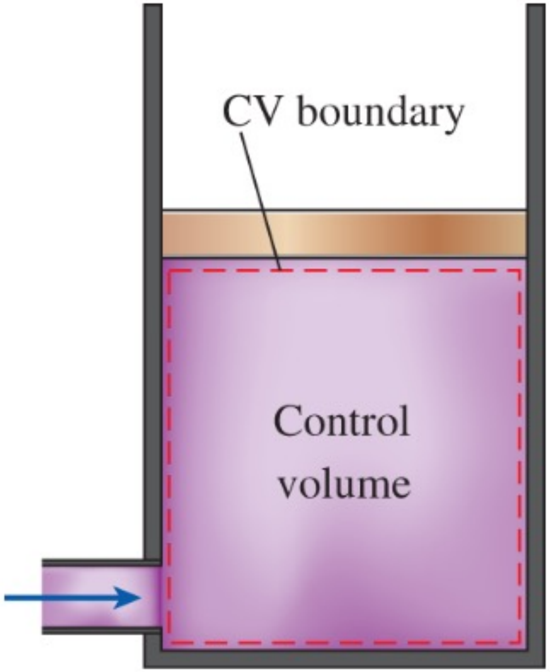


subscripts:
  - ”i” = inlet
  - “e” = exit
  - “1” = initial state
  - “2” = final state

Recap

$$E_{in} - E_{out} = \Delta E_{system}$$

$$(Q_{in} + W_{in} + \sum_{in} m\theta) - (Q_{out} + W_{out} + \sum_{out} m\theta) = (m_2 e_2 - m_1 e_1)_{system}$$



Recap

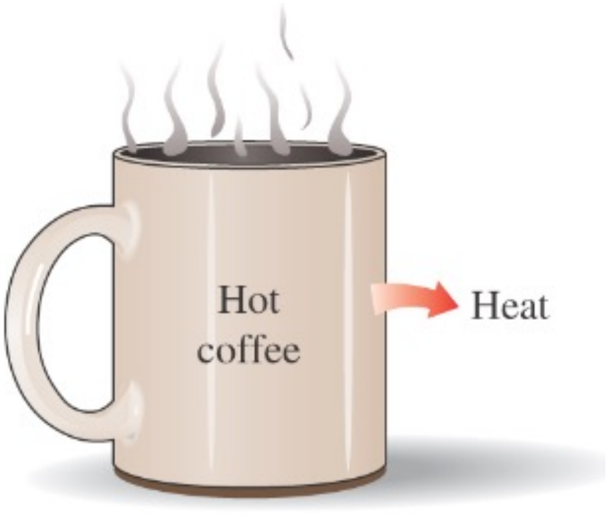
INTRO TO THE SECOND LAW

Intro to the Second Law

- We so far looked at the first law of thermodynamics or the conservation of energy principle

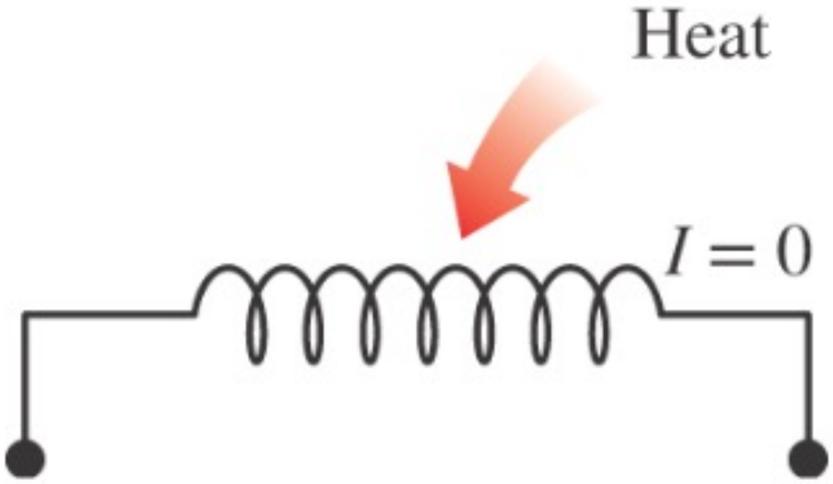
- However, satisfying the first law alone does not ensure that the process will actually take place

- Let’s consider the hot coffee cup



Intro to the Second Law

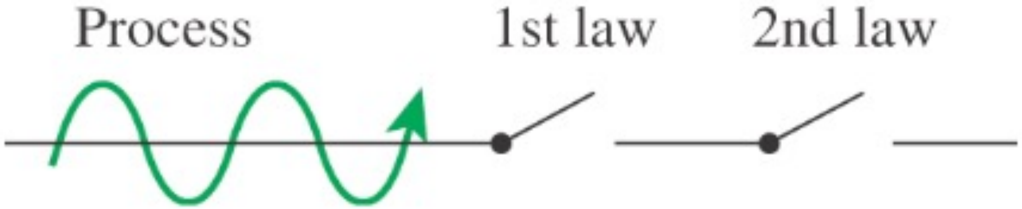
- Let’s look another example:



Intro to the Second Law

- It is clear from these arguments that processes proceed in a certain direction and in the reverse direction

- The first law places no restriction on the direction of a process but satisfying the first law does not ensure that the process can actually occur



Intro to the Second Law

- The inadequacy of the first law to identify whether a process can take place is remedied by introducing another general principle, the second law of thermodynamics (the reverse processes violate the second law of thermodynamics)

- This violation is easily detected with the help of a property called entropy

- A process cannot occur unless it satisfies *both the first and the second laws of thermodynamics*

Intro to the Second Law

- We have *two statements* for the second law
- The use of the second law of thermodynamics is not limited to identifying the direction of processes
- The second law also asserts that energy has quality as well as quantity
- The second law provides the necessary means to determine the quality as well as the degree of degradation of energy during a process
- High temperature energy can be converted to work and thus it has a higher quality than the same amount of energy at a lower temperature

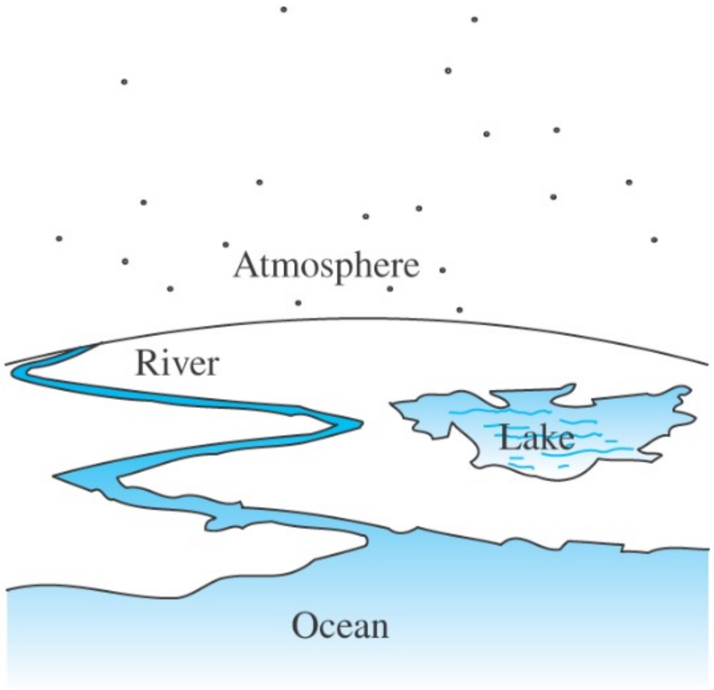
Intro to the Second Law

- The second law determine the theoretical limits for the performance of commonly used engineering systems, such as heat engines and refrigerators as well as predicting the degree of completion of chemical reactions

THERMAL ENERGY RESERVOIRS

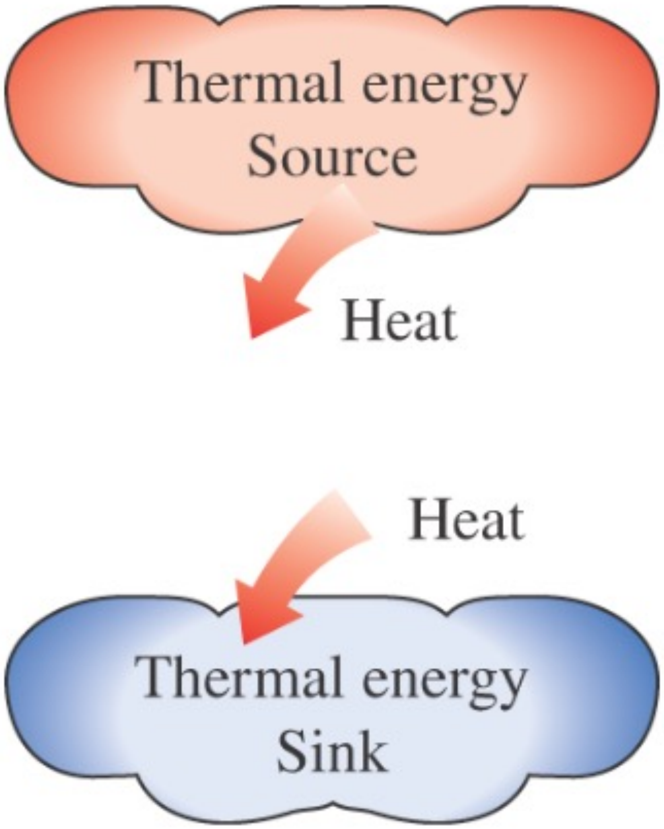
Intro to the Second Law

- We can assume a hypothetical body with a relatively large thermal capacity (mass times specific heat) that can supply or absorb finite amounts of heat without undergoing any change in temperature. Such a body is called a thermal energy reservoir, or just a reservoir.



Intro to the Second Law

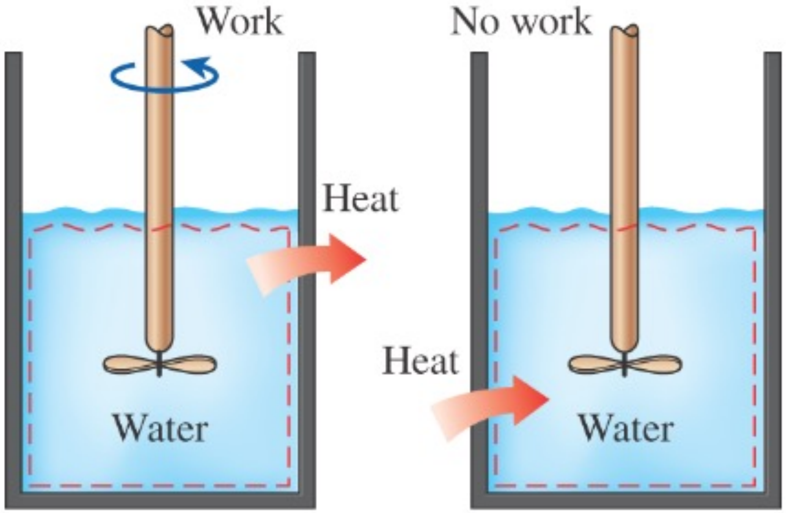
- We can define source and sink:



HEAT ENGINES

Heat Engines

- As we saw, work can be converted to other forms of energy, but converting other forms or energy to work is not that easy (e.g., heat leaving water)
- We can convert work to heat directly and completely but converting heat to work requires the use of some special devices named heat engines



Heat Engines

- Lighting fixtures / Electrical heaters

- Matches / internal combustion engine

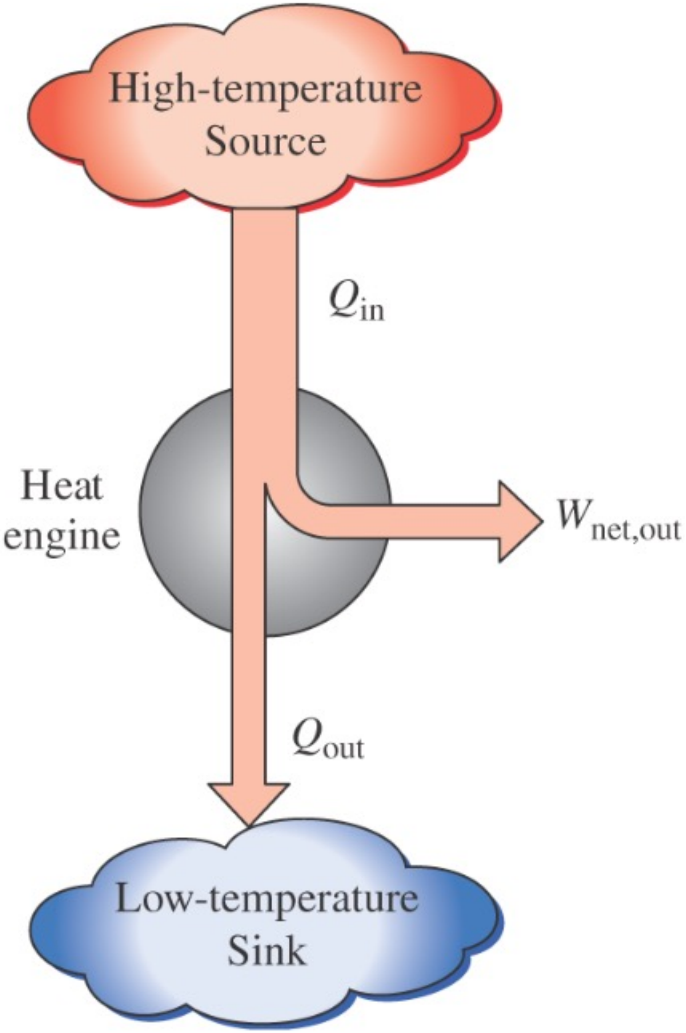
Heat Engines

- Heat engines differ considerably from one another, but all can be characterized by these criteria:
    - They receive heat from a high temperature source (e.g., solar, oil, …)
    - They convert part of this heat to work (usually in the form of a rotating shaft)
    - They reject the remaining waste heat to a low-temperature sink (e.g., the atmosphere, rivers, …)
    - They operate on a cycle

- Heat engines an other cyclic devices usually involve a fluid to and from which heat is transferred while undergoes a cycle. We call the fluid, a working fluid

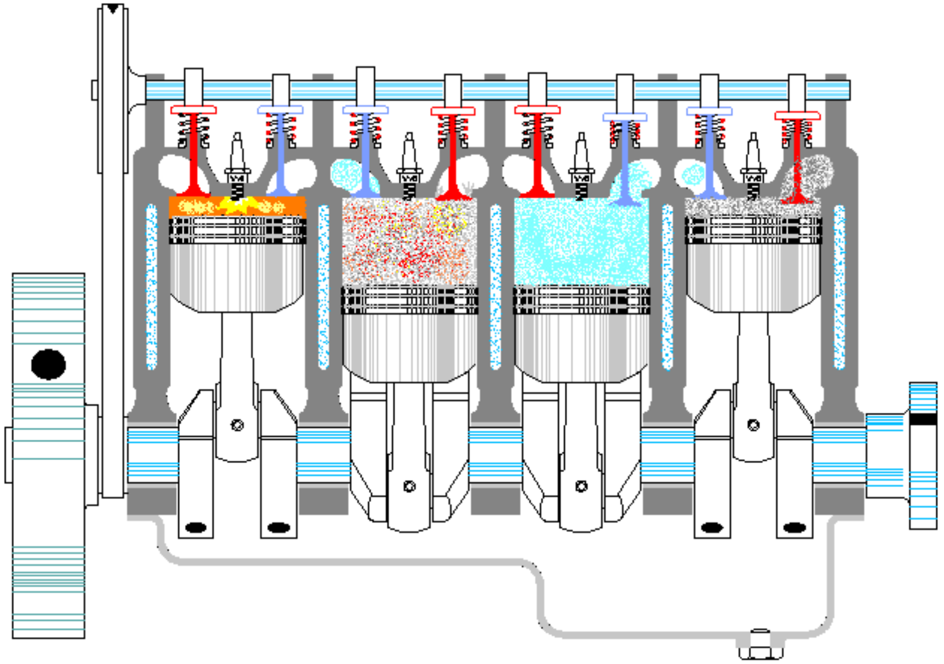
Heat Engines

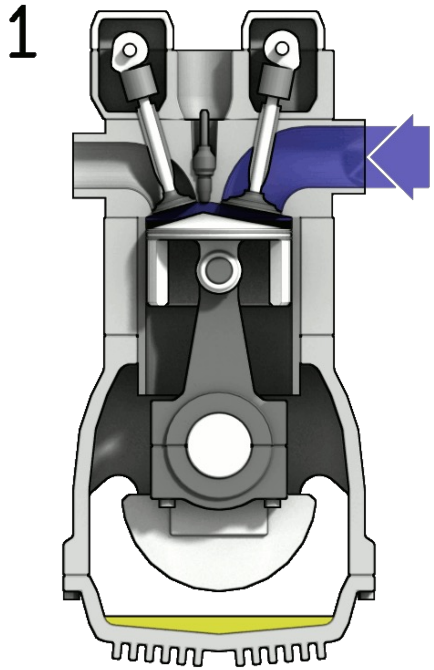
- Heat engines cycles are as following:



Heat Engines

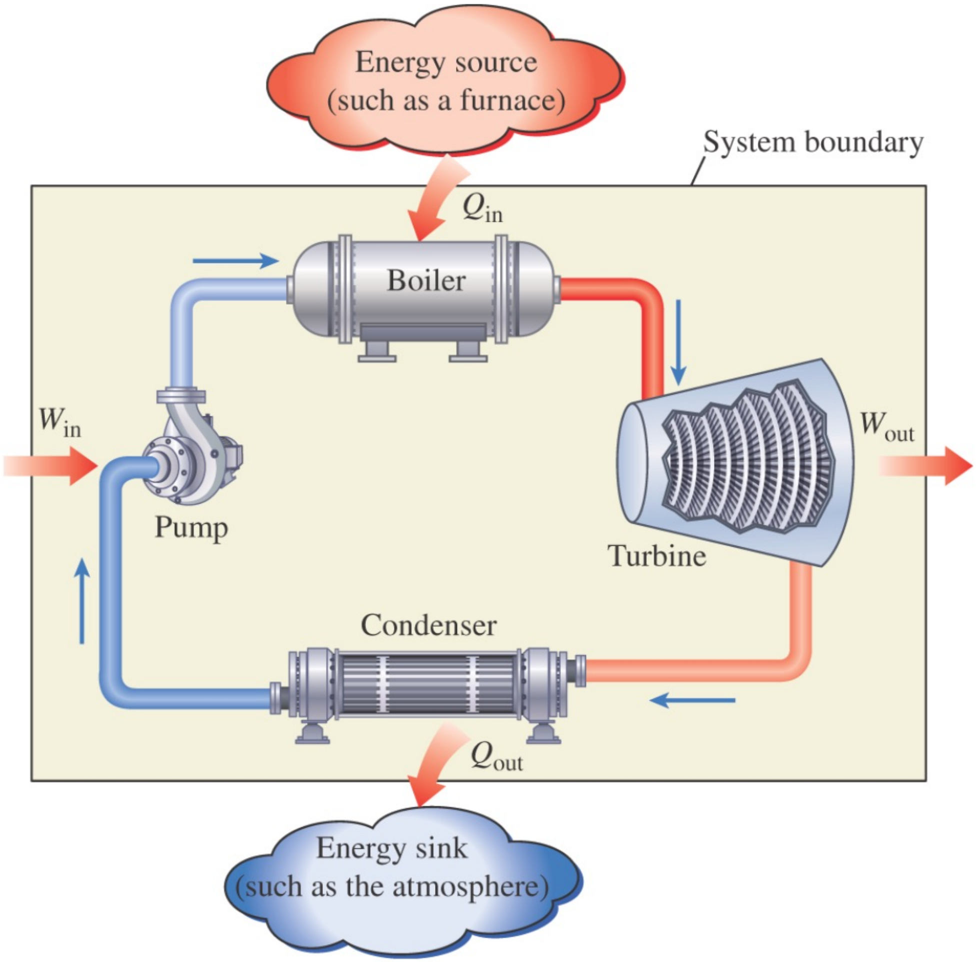
- A lot of times, heat engines are used in a broader sense to consider mechanical engines that do not undergo a complete thermodynamic cycle (e.g., internal combustion engine)





Heat Engines

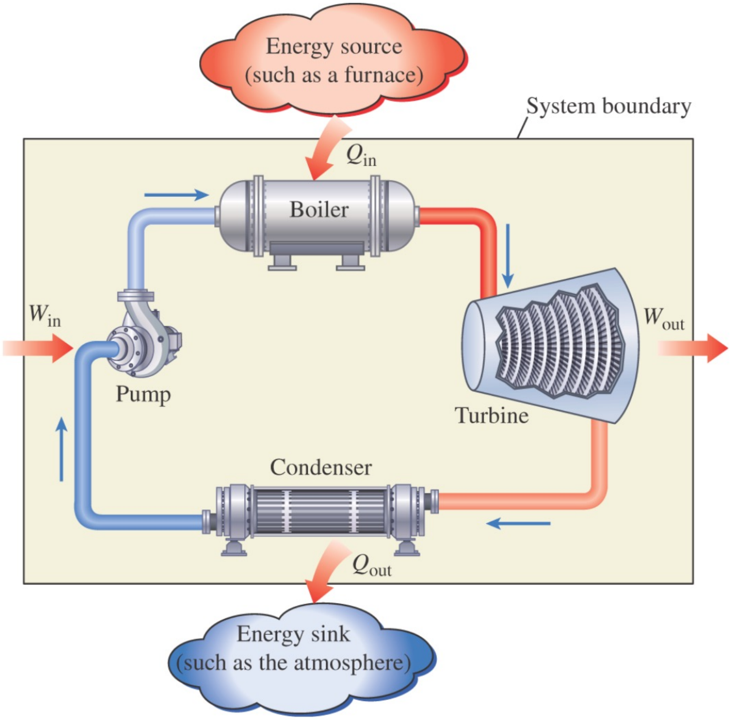
- The best example of a heat engine is the steam power plant:



Heat Engines

- The best example of a heat engine is the steam power plan:

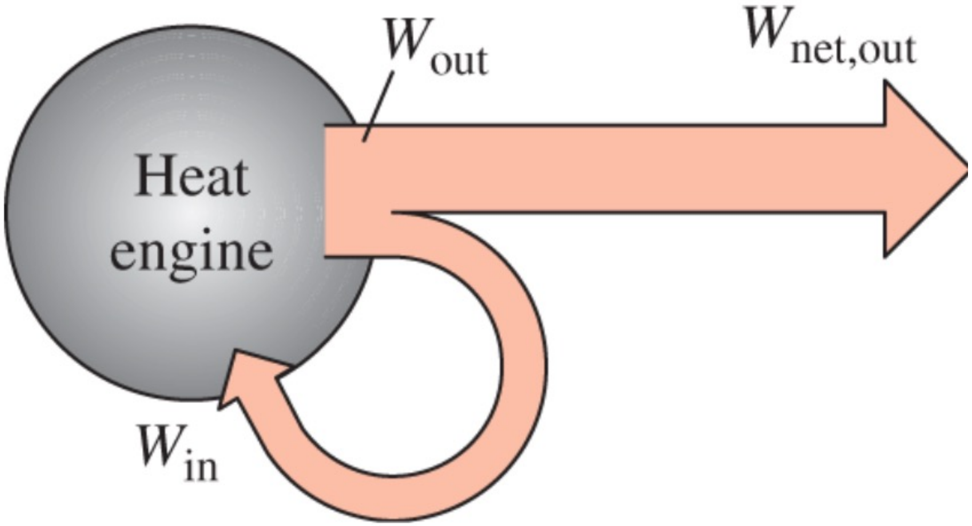
Q_{in} = amount of heat supplied to steam in boiler from a high-temperature source (furnace)
Q_{out} = amount of heat rejected from steam in condenser to a low-temperature sink (the atmosphere, a river, etc.)
W_{out} = amount of work delivered by steam as it expands in turbine
W_{in} = amount of work required to compress water to boiler pressure



Heat Engines

- What's the net work?

$$W_{net,out} = W_{out} - W_{in} \qquad \text{(kJ)}$$



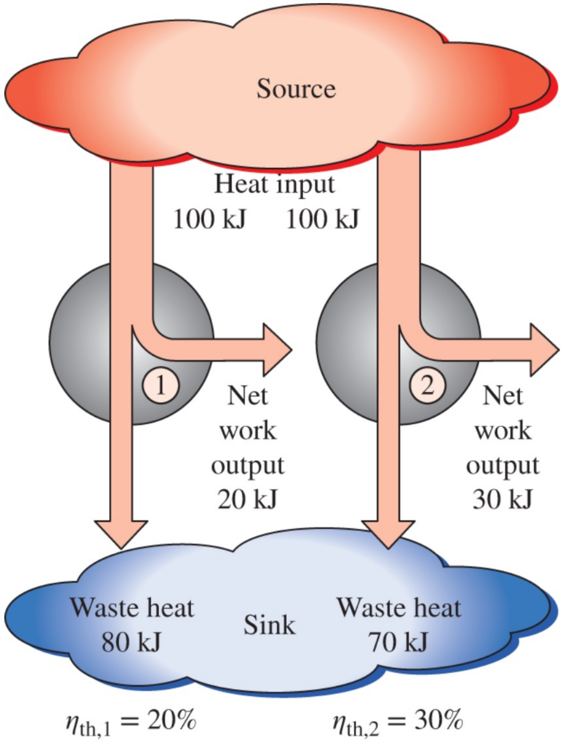
Heat Engines

- Do you remember the relation between work and heat for a cycle?

$$W_{net,out} = Q_{in} - Q_{out}$$

Heat Engines

- The fraction of the heat input that is converted to net work output is a measure of the performance of a heat engine is called the *thermal efficiency*



$$Thermal\ efficiency = \frac{Net\ works\ output}{Total\ heat\ input}$$

Heat Engines

- Thermal efficiency

$$Thermal\ efficiency = \frac{Net\ works\ output}{Total\ heat\ input}$$

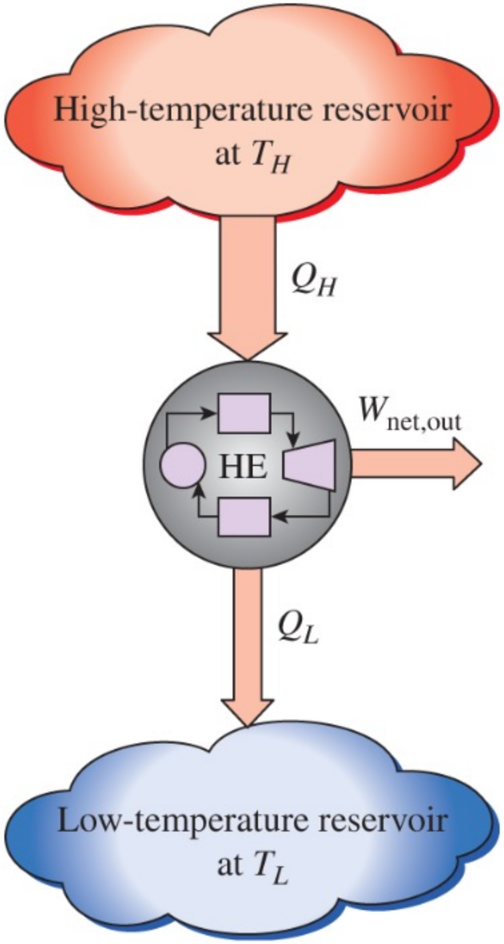
$$\eta_{th} = \frac{W_{net,out}}{Q_{in}} = \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}}$$

Heat Engines

- Cyclic devices (e.g., heat pumps, refrigerators, heat engines) operate between a high temperature medium (or reservoir) and a low temperature medium (or reservoir)
  - ☐ Q_H: Magnitude of heat transfer between the cyclic device and the high-temperature medium at temperature T_H
  - ☐ Q_L: Magnitude of heat transfer between the cyclic device and the low-temperature medium at temperature T_L

Heat Engines

- Using this definition, we can redefine the thermal efficiency:



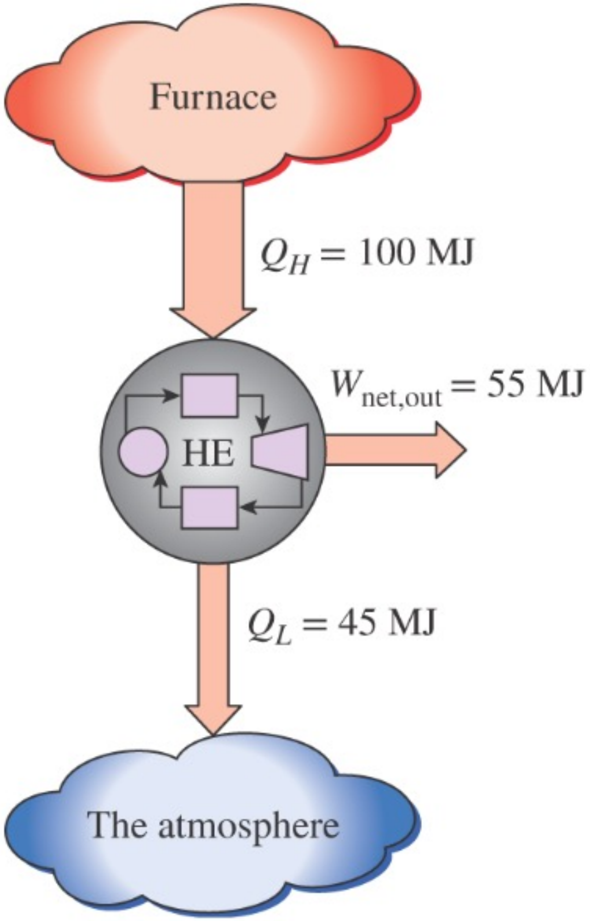
$$W_{net,out} = Q_H - Q_L$$

$$\eta_{th} = \frac{W_{net,out}}{Q_H}$$

$$\eta_{th} = 1 - \frac{Q_L}{Q_H}$$

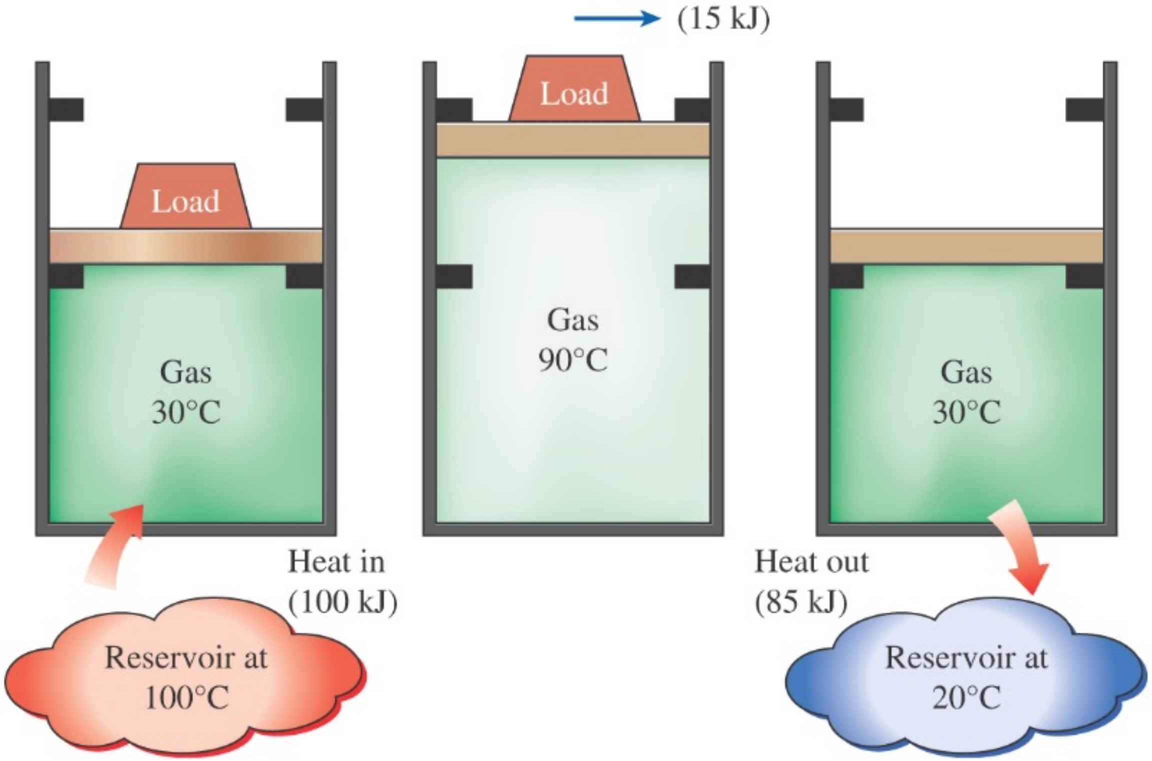
Heat Engines

- Most heat engines reject significant heat to outside



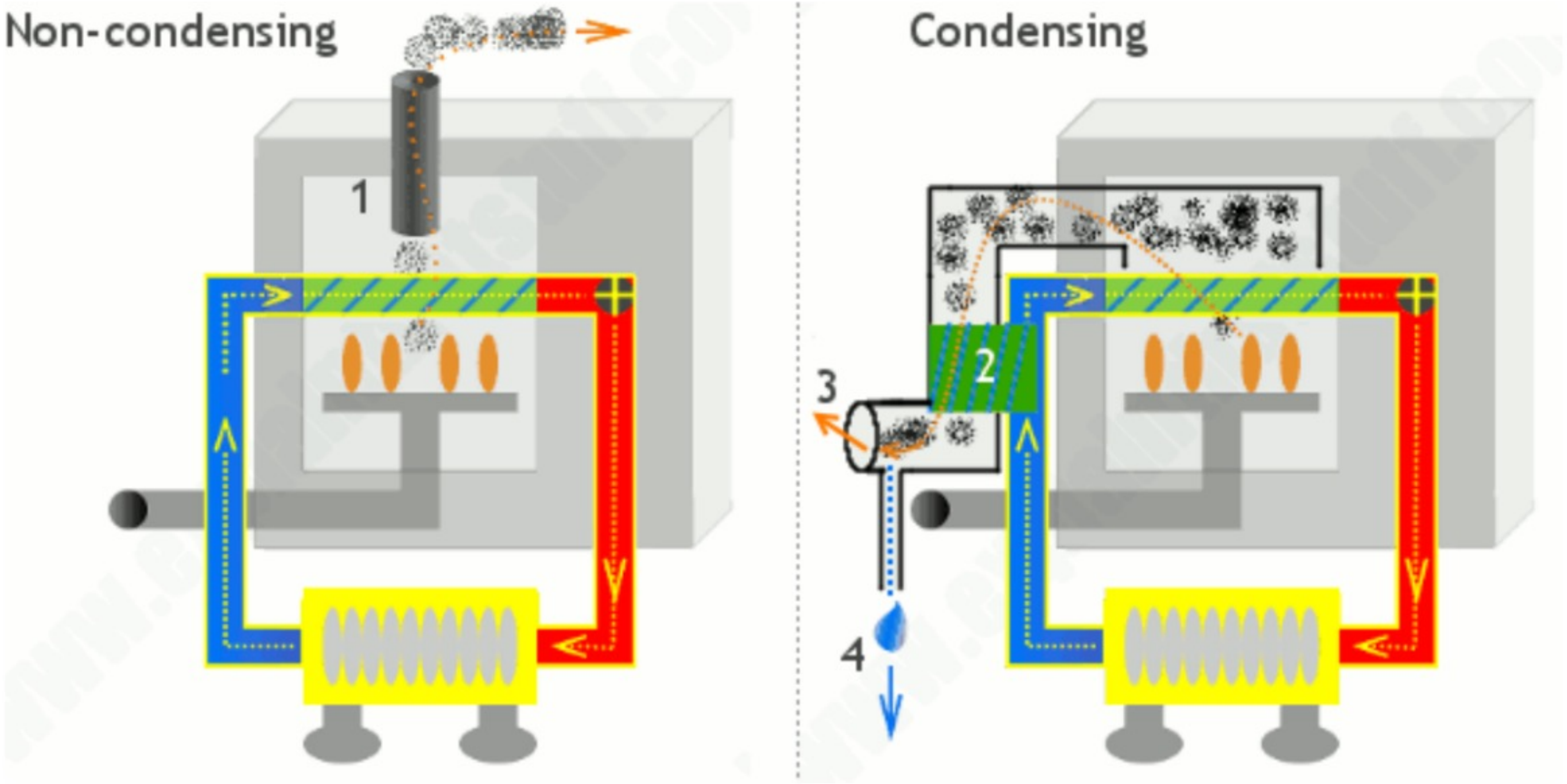
Heat Engines

- Can we save Q_{out}? Unfortunately, no, the cycle has to be completed!



Heat Engines

- We can improve the thermal efficiency:



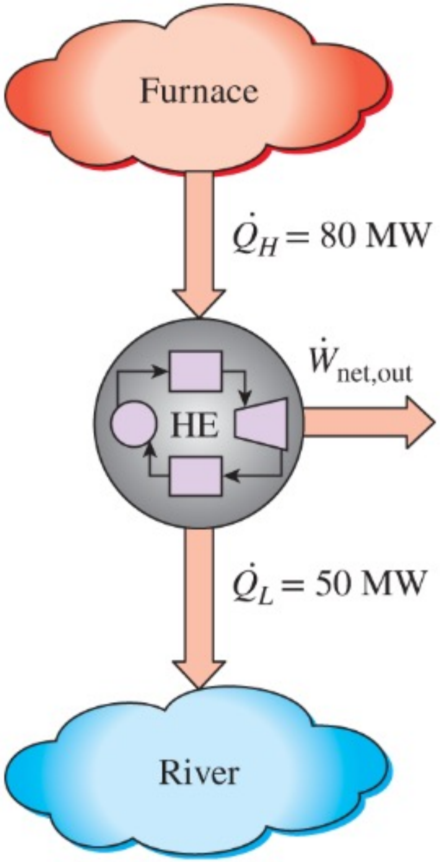
CLASS ACTIVITY

Class Activity

- Heat is transferred to a heat engine from a furnace at a rate of 80 MW. If the rate of waste heat rejection to a nearby river is 50 MW, determine net power output and the thermal efficiency for this heat engine.

Class Activity

- Solution:



Class Activity

- Solution:

$$\dot{Q}_H = 80\ MW$$

$$\dot{Q}_L = 50\ MW$$

$$\dot{W}_{net} = 80MW - 50\ MW = 30\ MW$$

$$\eta_{th} = \frac{\dot{W}_{net,out}}{\dot{Q}_H} = \frac{30\ MW}{80\ MW} = 0.375$$

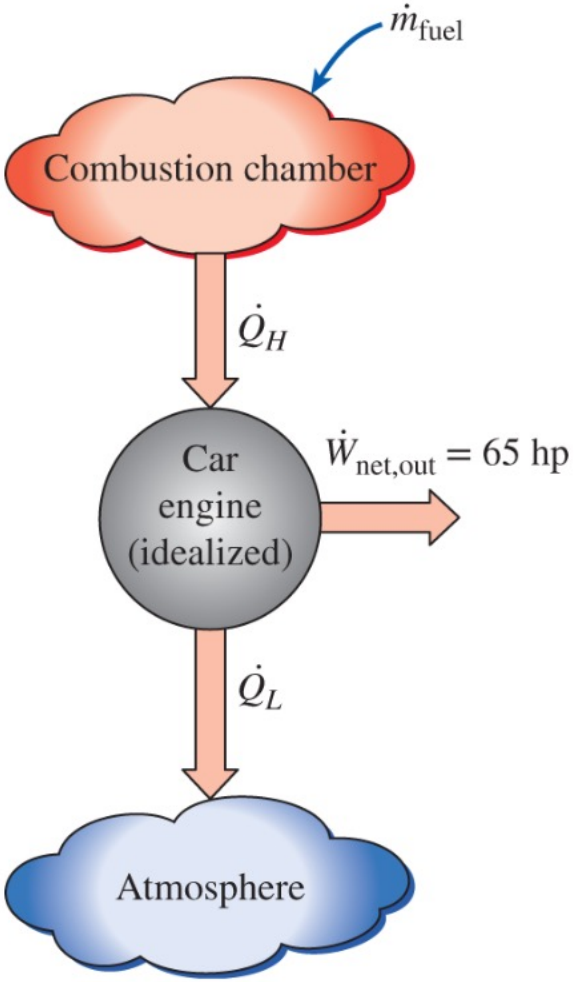
CLASS ACTIVITY

Class Activity

- A car engine with a power output of 65 hp has a thermal efficiency of 24 percent. Determine the fuel consumption rate of this car if the fuel has a heating value of 19,000 Btu/lbm (that is 19,000 Btu of energy is released for each lbm of fuel burned)

Class Activity

- Solution:



$$\dot{Q}_H = \frac{\dot{W}_{net,out}}{\eta_{th}} = \frac{65\ hp}{0.24}\left(\frac{2545\,\frac{Btu}{h}}{1\ hp}\right) = 689{,}270\ Btu/h$$

$$689{,}270\,\frac{Btu}{h} = \dot{m}_{fuel}\times 19{,}000\,\frac{Btu}{lbm}$$

$$\dot{m}_{fuel} = 36.3\,\frac{lbm}{h}$$

Heat Engines

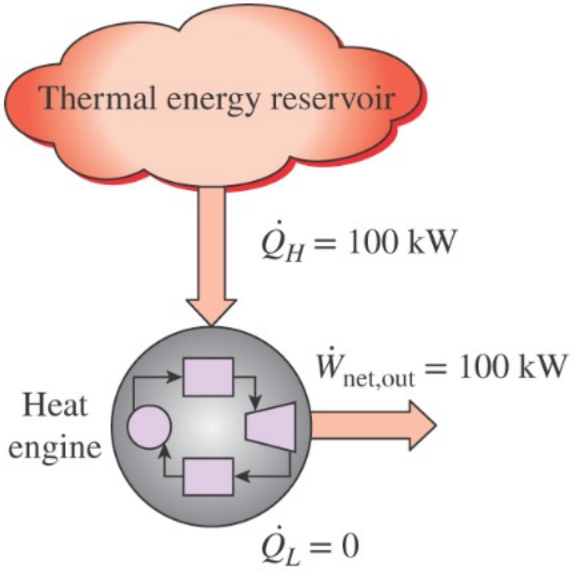
- The Second Law of Thermodynamics: Kelvin-Planck Statement:

It is impossible for any device that operates on a cycle to receive heat from a single reservoir and produce a net amount of work

Heat Engines

- The Second Law of Thermodynamics: Kelvin-Planck Statement can be expressed as:

No heat engine can have a thermal efficiency of 100 percent



Heat Engines

- The Second Law of Thermodynamics: Kelvin-Planck Statement can be expressed as:

For a power plant to operate, the working fluid must exchange heat with the environment as well as the furnace

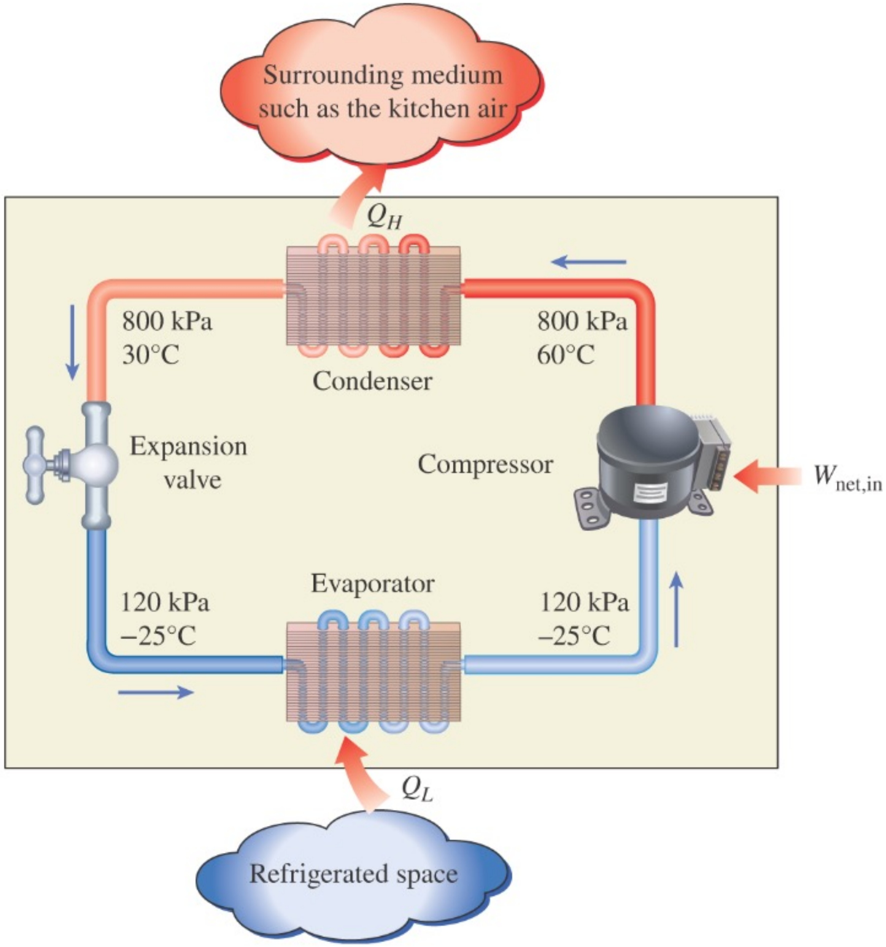
REFRIGERATORS AND HEAT PUMPS

Refrigerators and Heat Pumps

- ***Refrigerators:*** The transfer of heat from a low-temperature medium to a high-temperature one requires special devices called refrigerators
- Refrigerators, like heat engines, are cyclic devices
- The working fluid used in the refrigeration cycle is called a refrigerant

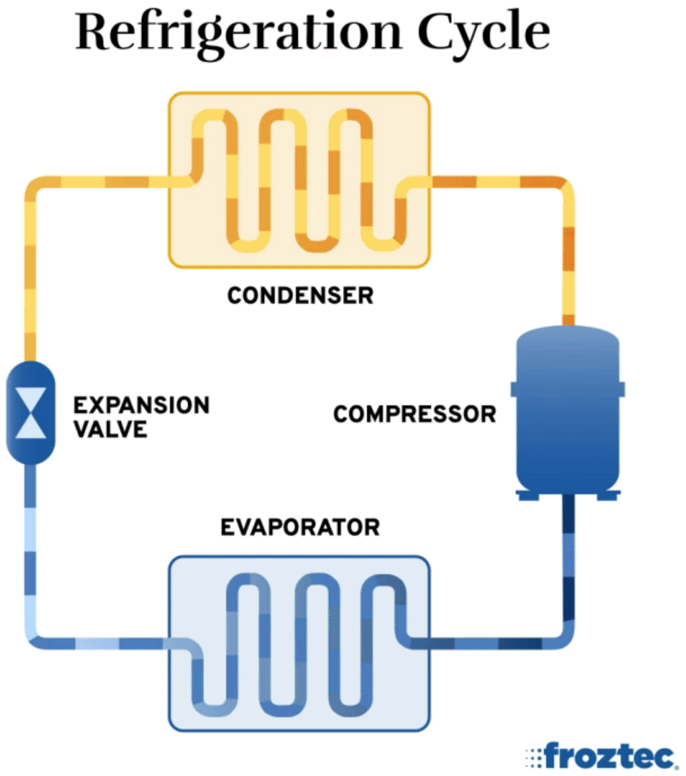
Refrigerators and Heat Pumps

- The most frequently used refrigeration cycle is the vapor-compression refrigeration cycle



Refrigerators and Heat Pumps

- The most frequently used refrigeration cycle is the vapor-compression refrigeration cycle



Refrigerators and Heat Pumps

- The efficiency of a refrigerator is expressed in terms of the coefficient of performance (COP)

- The objective of a refrigerator is to remove heat (Q_L) from the refrigerated space

$$COP_R = \frac{Desired\ output}{Require\ input} = \frac{Q_L}{W_{net,in}}$$

$$COP_R = \frac{Q_L}{Q_H - Q_L} = \frac{1}{\frac{Q_H}{Q_L} - 1}$$

- Can the value of COP_R be greater than unity?

Refrigerators and Heat Pumps

- *Heat pumps* are in the news right now:

Department of Energy

President Biden Invokes Defense Production Act to Accelerate Domestic Manufacturing of Clean Energy

JUNE 6, 2022

- **Heat Pumps** – Our nation's buildings, homes, offices, schools, hospitals, military bases, and other critical facilities drive more than 40% of all U.S. energy consumption. To reduce the amount of energy needed in our buildings, leading to less reliance by the U.S. and allies on adversaries such as Russia for oil and gas, heat pumps are an important solution. Their use by the U.S. and allies can shrink Russian revenue for war and reduce climate instability. However, currently, U.S. HVAC manufacturers are not producing heat pumps at the rate needed. The Biden-Harris Administration can help American manufacturing expand and expedite the installation of heat pumps in homes and residential buildings by qualified building professionals.

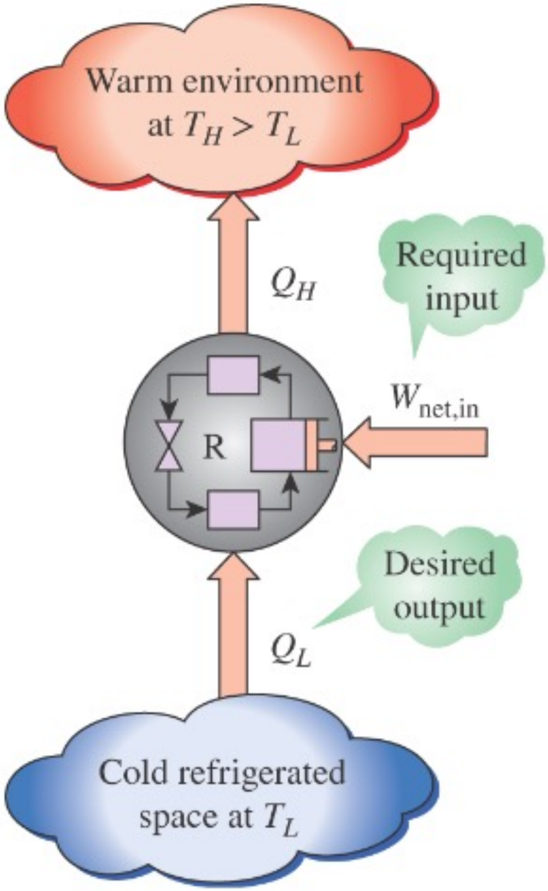
Refrigerators and Heat Pumps

- ***Heat Pumps:*** The objective of a heat pump is to supply heat Q_H into the warmer space

$$COP_{HP} = \frac{Desired\ output}{Require\ input} = \frac{Q_H}{W_{net,in}}$$

$$COP_{HP} = \frac{Desired\ output}{Require\ input} = \frac{Q_H}{Q_H - Q_L}$$

$$COP_{HP} = COP_R + 1$$

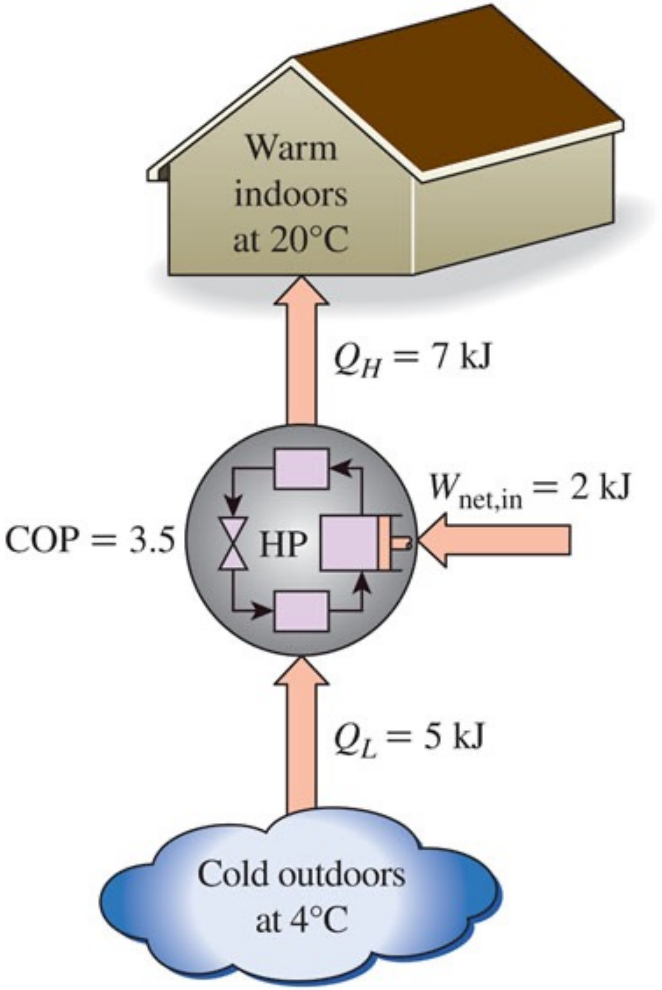


Refrigerators and Heat Pumps

- ***Heat Pumps:*** The objective of a heat pump is to supply heat Q_H into the warmer space
  - ☐ For fixed values of Q_L and Q_H can the value of COP_{HP} be lower than unity?
  - ☐ What does COP_{HP} represent?

Refrigerators and Heat Pumps

- ***Heat Pumps:*** The objective of a heat pump is to maintain a heated space at high temperature. This is accomplished by absorbing heat from a low-temperature source, such as well water or cold outside air in winter and supplying this heat to the high-temperature medium as a house:



Refrigerators and Heat Pumps

- Performance of refrigerators, air conditioners, and heat pumps:
  - ❑ Most heat pumps have a seasonally averaged COP of 2 to 3
  - ❑ Most existing heat pumps use the cold outside air as the heat source in winter (air-source HP)
  - ❑ In cold climates their efficiency drops considerably when temperatures are below the freezing point
  - ❑ In such cases, geothermal (ground-source) HP that use the ground as the heat source can be used
  - ❑ Such heat pumps are more expensive to install, but they are also more efficient

Refrigerators and Heat Pumps

- Performance of refrigerators, air conditioners, and heat pumps:
  - ☐ Air conditioners are basically refrigerators whose refrigerated space is a room or a building instead of the food compartment
  - ☐ The COP of a refrigerator decreases with decreasing refrigeration temperature
  - ☐ It is not economical to refrigerate to a lower temperature than needed

Refrigerators and Heat Pumps

- Energy efficiency rating (EER): The amount of heat removed from the cooled space in Btu’s for 1 W h (watthour) of electricity consumed

$$EER = 3.412\ COP_R$$

CLASS ACTIVITY

Class Activity

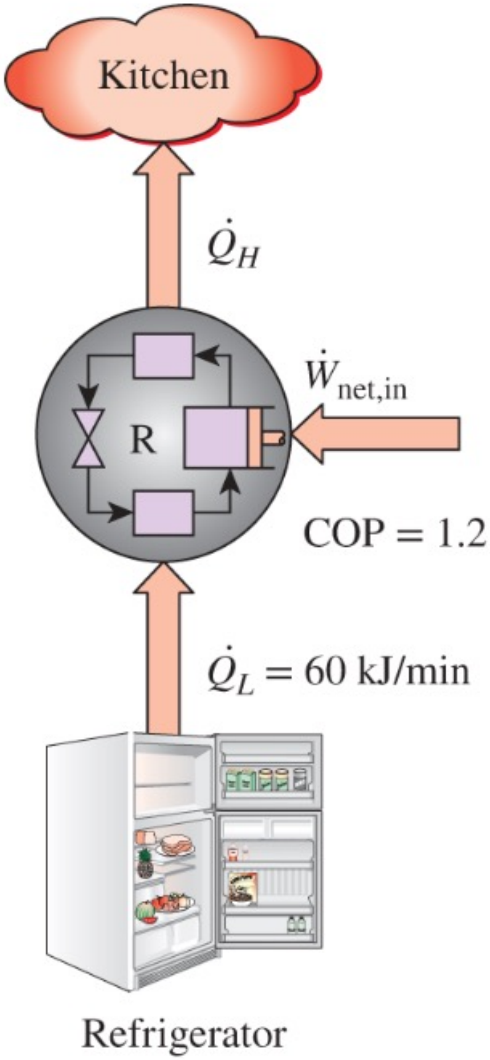
- The household refrigerator with a COP of 1.2 removes heat from the refrigerated space a rate of 60 kJ/min. Determine:
  a) The electric power consumed by the refrigerator
  b) The rate of heat transfer to the kitchen air

Class Activity

- **Solution:**

$$\dot{W}_{net,in} = \frac{\dot{Q}_L}{COP_R} = \frac{60\ kJ/min}{1.2} = 50\frac{kJ}{min} = 0.833\ kW$$

$$\dot{Q}_H = \dot{Q}_L + \dot{W}_{net,in} = 60 + 50 = 110\ kJ/min$$



CLASS ACTIVITY

Class Activity

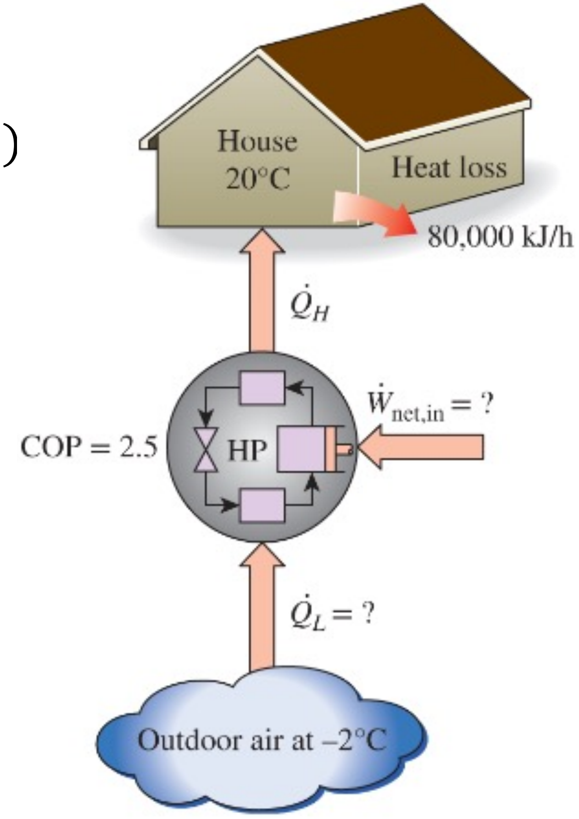
- A heat pump is used to meet the heating requirements of a house and maintain it at 20 °C. On a day when the outdoor air temperature drops to -2°C, the house is estimated to lose heat at a rate of 80,000 kJ/h. If the heat pump under these conditions has a COP of 2.5, determine
  a) The power consumed by heat pump
  b) The rate at which heat is absorbed from the cold outdoor air

Class Activity

- **Solution:**

$$\dot{W}_{net,in} = \frac{\dot{Q}_H}{COP_{HP}} = \frac{80{,}000\ kJ/h}{2.5} = 32{,}000\ kJ/h\ (8.9\ kW)$$

$$\dot{Q}_L = \dot{Q}_L - \dot{W}_{net,in} = (80{,}000 - 32{,}000)\frac{kJ}{h} = 48{,}000\frac{kj}{h}$$



Refrigerators and Heat Pumps

- The Second Law of Thermodynamics: Clasius Statement

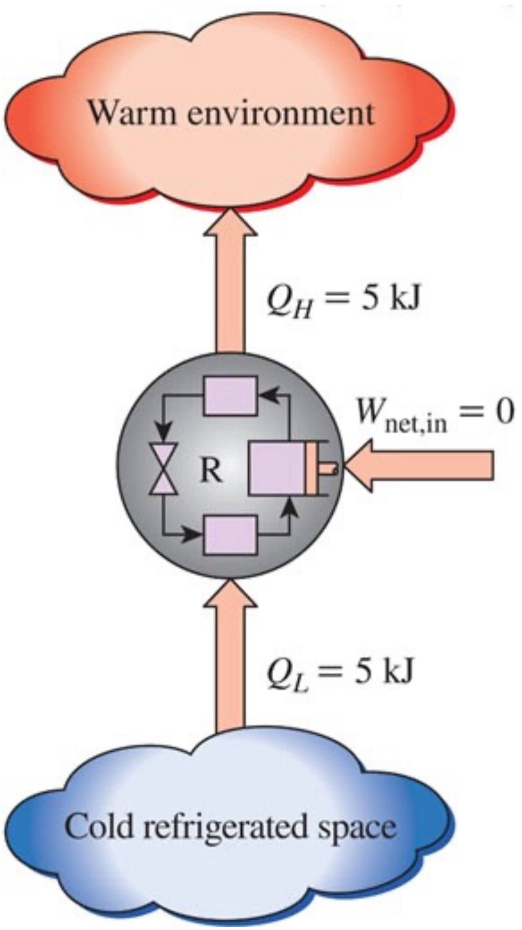
It is impossible to construct a device that operates in a cycle and produces no effect other than the transfer of heat from a lower-temperature body to a higher-temperature body.

Refrigerators and Heat Pumps

- The Second Law of Thermodynamics: Clasius Statement
  - ❑ It states that a refrigerator cannot operate unless its compressor is driven by an external power source, such as an electric motor
  - ❑ This way, the net effect on the surroundings involves the consumption of some energy in the form of work, in addition to the transfer of heat from a colder body to a warmer one
  - ❑ To date, no experiment has been conducted that contradicts the second law, and this should be taken as sufficient proof of its validity

Refrigerators and Heat Pumps

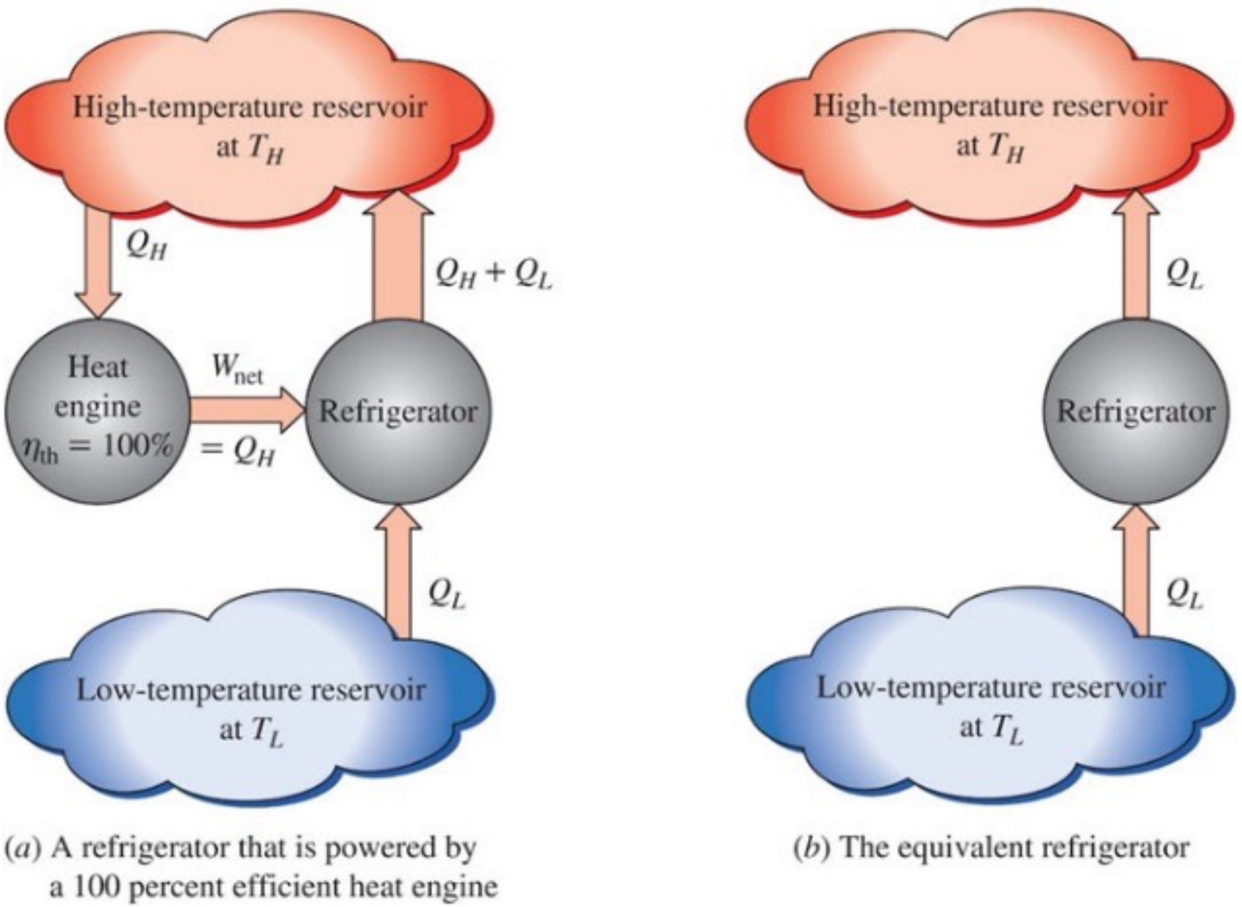
- The Second Law of Thermodynamics: Clasius Statement



A refrigerator that violates the Clausius statement of the second law.

Refrigerators and Heat Pumps

- Equivalence of the Two Statements



(*a*) A refrigerator that is powered by a 100 percent efficient heat engine

(*b*) The equivalent refrigerator

Proof that the violation of the Kelvin–Planck statement leads to the violation of the Clausius statement.

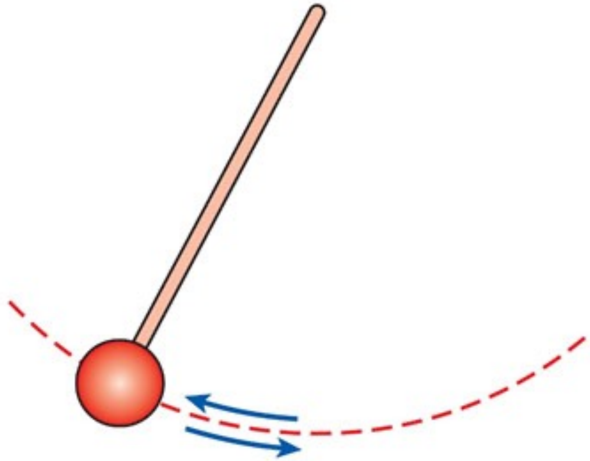
Refrigerators and Heat Pumps

- Equivalence of the Two Statements
  - ❑ The Kelvin–Planck and the Clausius statements are equivalent in their consequences, and either statement can be used as the expression of the second law of thermodynamics
  - ❑ Any device that violates the Kelvin–Planck statement also violates the Clausius statement, and vice versa

REVERSIBLE AND IRREVERSIBLE PROCESSES

Reversible and Irreversible Processes

- ***Reversible process:*** A process that can be reversed without leaving any trace on the surroundings
- ***Irreversible process:*** A process that is not reversible
- All the processes occurring in nature are irreversible


(*a*) Frictionless pendulum


(*b*) Quasi-equilibrium expansion and compression of a gas

Reversible and Irreversible Processes

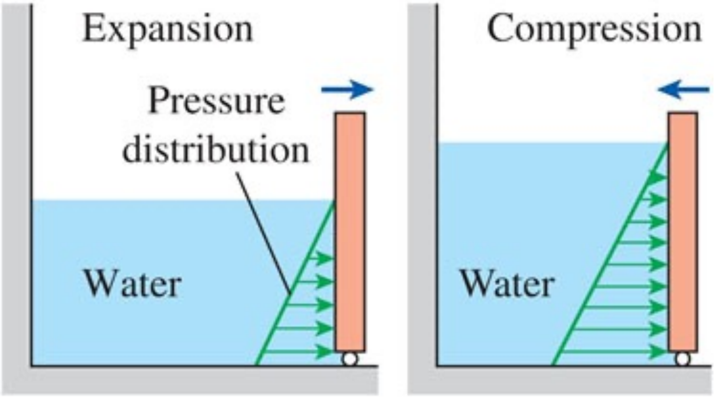
- Why are we interested in reversible processes?
  1) They are easy to analyze
  2) They serve as idealized models (theoretical limits) to which actual processes can be compared.

- Some processes are more irreversible than others

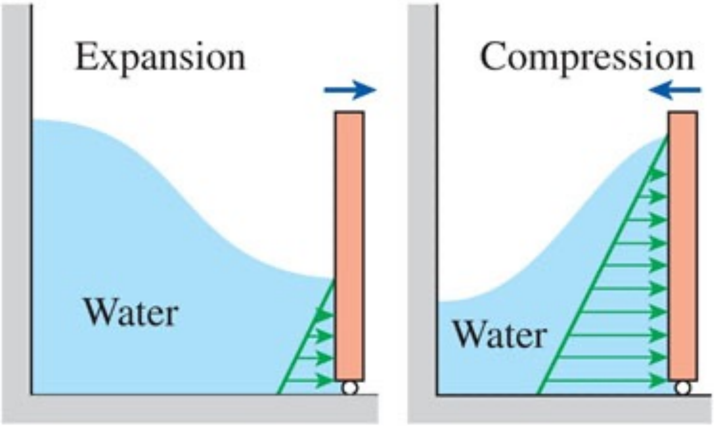
- We try to approximate reversible processes

Reversible and Irreversible Processes

- Reversible processes deliver the most and consume the least work



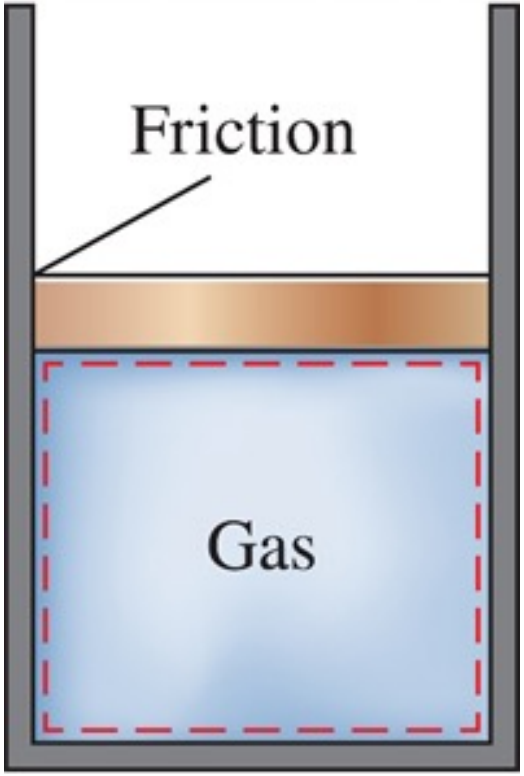
(*a*) Slow (reversible) process

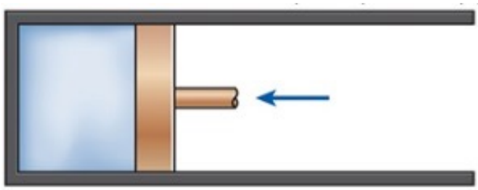


(*b*) Fast (irreversible) process

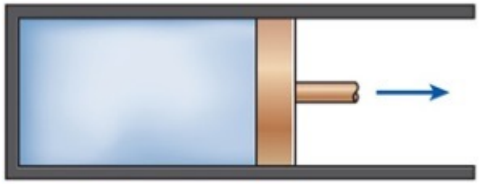
Reversible and Irreversible Processes

- The factors that cause a process to be irreversible are called irreversibilities





(*a*) Fast compression



(*b*) Fast expansion

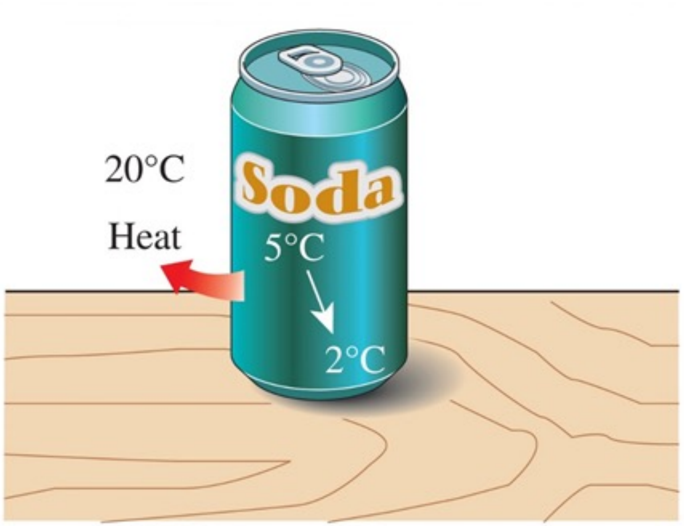
(*c*) Unrestrained expansion

Reversible and Irreversible Processes

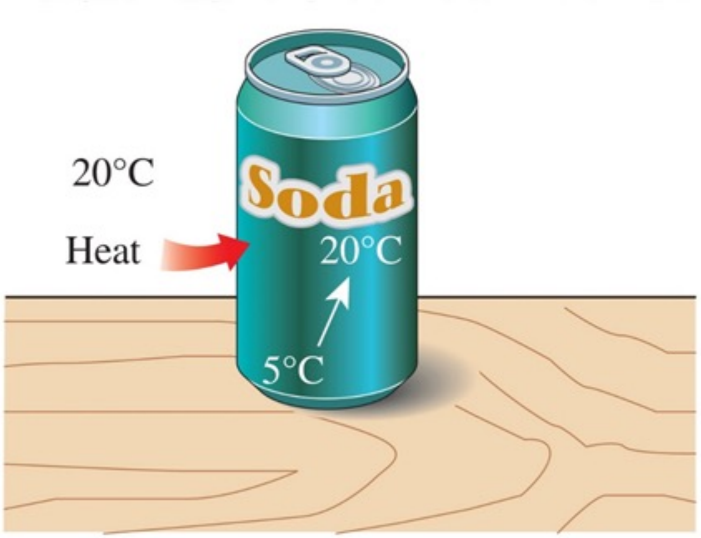
- Irreversibilities includes friction, unrestrained expansion, mixing of two fluids, heat transfer across a finite temperature difference, electric resistance, inelastic deformation of solids, and chemical reactions
- The presence of any of these effects renders a process irreversible

Reversible and Irreversible Processes

- Heat transfer through a temperature difference is irreversible
- The reverse process is impossible



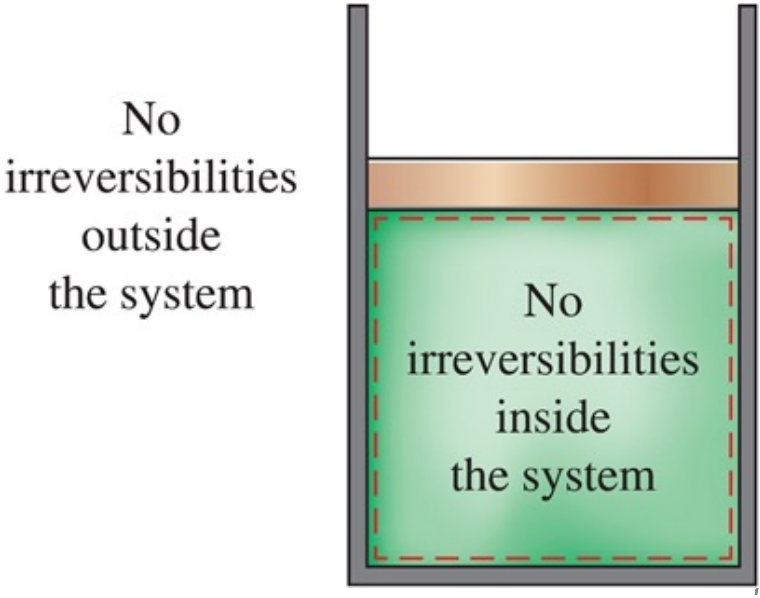
(*b*) An impossible heat transfer process



(*a*) An irreversible heat transfer process

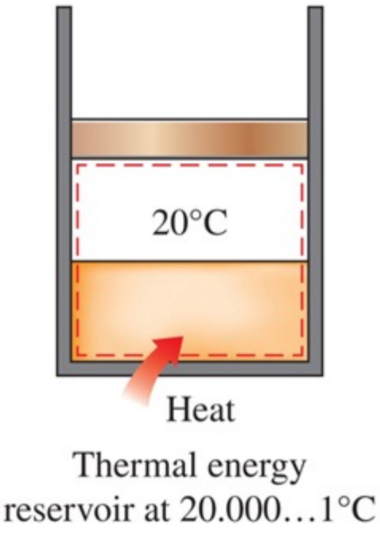
Reversible and Irreversible Processes

- Internally and Externally Reversible Processes:
  - Internally reversible process: If no irreversibilities occur within the boundaries of the system during the process (e.g., a quasi-equilibrium process)
  - Externally reversible: If no irreversibilities occur outside the system boundaries (e.g., heat transfer between reservoir and a system)

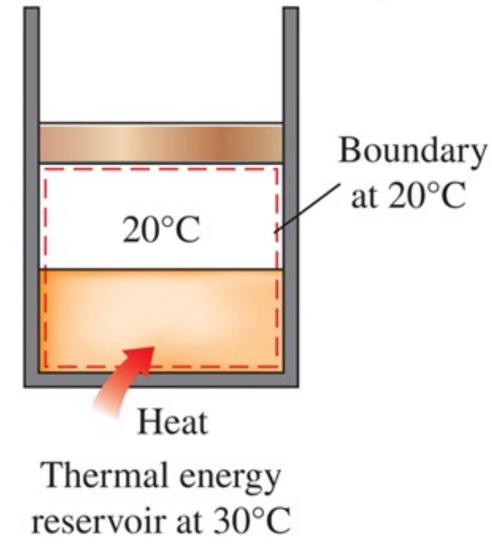


Reversible and Irreversible Processes

- Internally and Externally Reversible Processes:
  - ❑ Totally reversible process: It involves no irreversibilities within the system or its surroundings
  - ❑ A totally reversible process involves no heat transfer through a finite temperature difference, no nonquasi-equilibrium changes, and no friction or other dissipative effects.



(*a*) Totally reversible



(*b*) Internally reversible