Lecture 9

Topic 3

Second Law of Thermodynamics

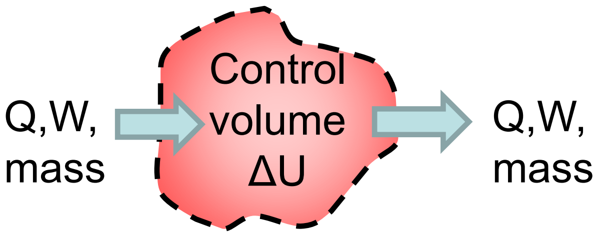
Topics

- **3.1 Definitions and statements of the 2nd Law**

Reading:
Ch 5: 5.1 – 5.3 Borgnakke & Sonntag Ed. 8
Ch 6-1 – 6-4 Cengel & Boles Ed. 5

3.1 Introduction to the Second Law

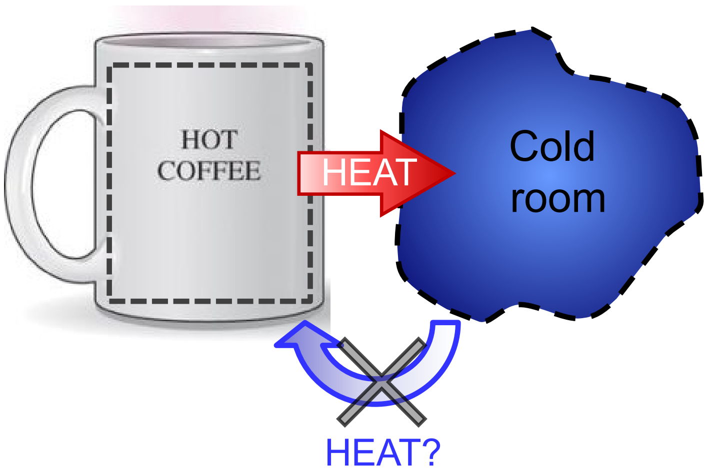
First law of thermodynamics



- Energy balance & conversion.
- Identical quantities of energy are involved during conversion.
  - E.g. W_{in} = 30 kJ can result in Q_{out} = 30 kJ
- No restrictions on the direction of work & heat.

Second law of thermodynamics

- Thermodynamic processes MUST proceed in a certain direction.



- Hot coffee cools as it gives off heat to a cold room.
- Heat will not flow from the cold room to the hot coffee.
  - Hot coffee does not get hotter in a colder environment.

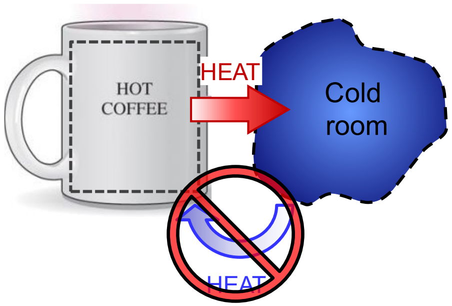
3.1 Introduction to the Second Law

Spontaneous processes

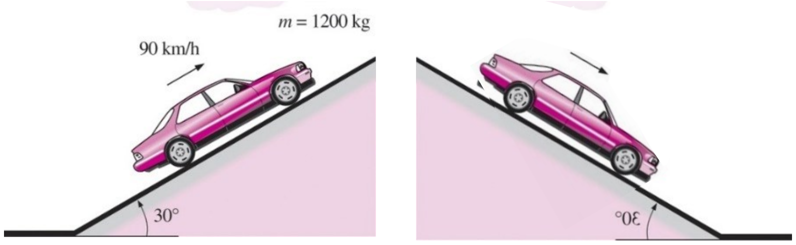
- Processes that can proceed only in a particular direction

<u>Examples</u>:

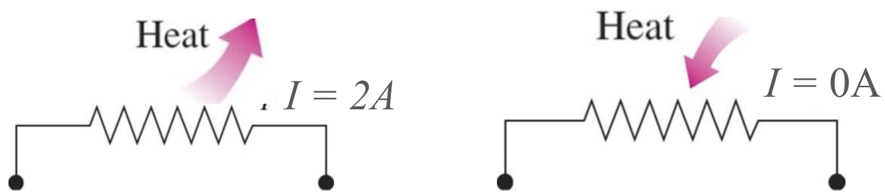
- Hot coffee is not heated by a cold room.



- Fuel is consumed as a car drives up a hill. The car does not refuel as the car coasts down the hill.



- Current running through a resistive wire generates electricity, but also heat. Transferring heat to the wire will not generate electricity.



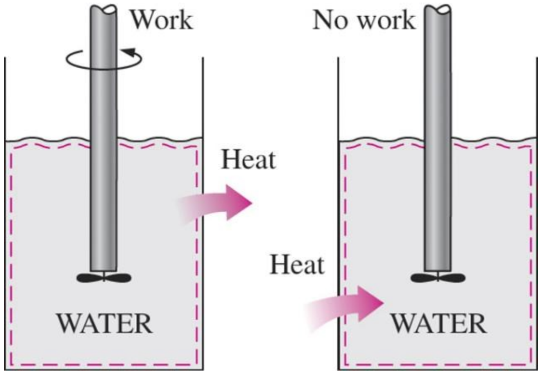
3.1 Introduction to the Second Law

Spontaneous processes

- Processes that can proceed only in a particular direction

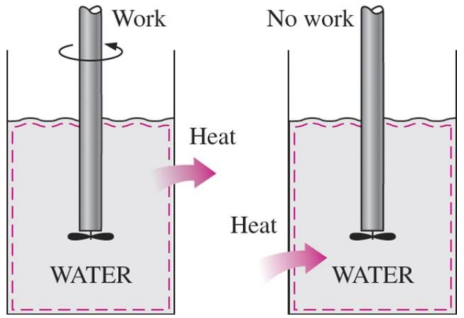
<u>Examples</u>:

- Shaft work can produce heat, but heating a substance by itself cannot generate shaft work.
  - Heat and work are not completely interchangeable forms of energy

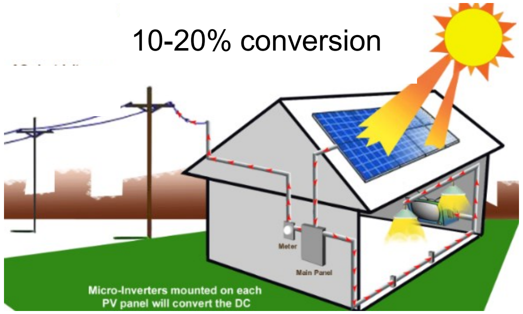


3.1 Introduction to the Second Law

A process will not occur unless it satisfies both the <u>first</u> and the <u>second laws of thermodynamics</u>.



- <u>First law of thermodynamics</u>: energy balance & conversion.

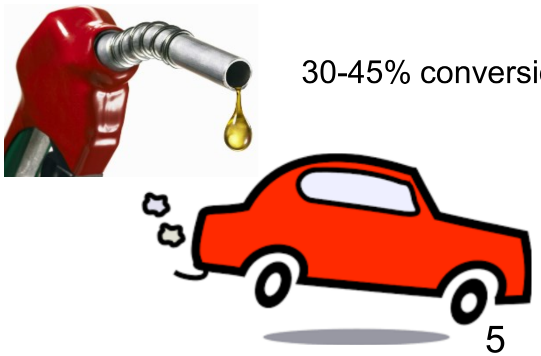


10-20% conversion

- Work can be converted to heat, but heat cannot be completely converted to work.

- During energy conversion, there is often a degradation of the supplied energy into a less “useful” form.

- <u>Second law of thermodynamics</u>: concerned with the direction that processes may take and how much heat can be converted into work.

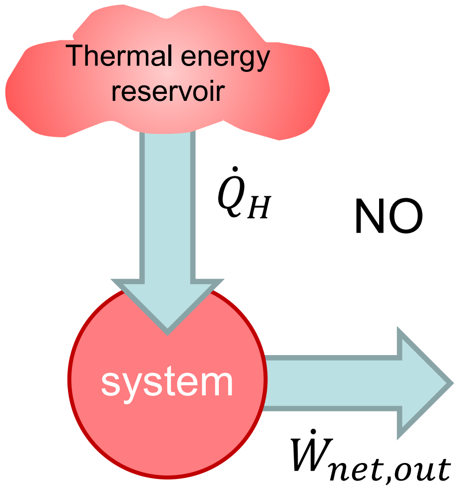


30-45% conversion

3.1.1 2nd Law Definitions & Statements

Kelvin-Planck statement:

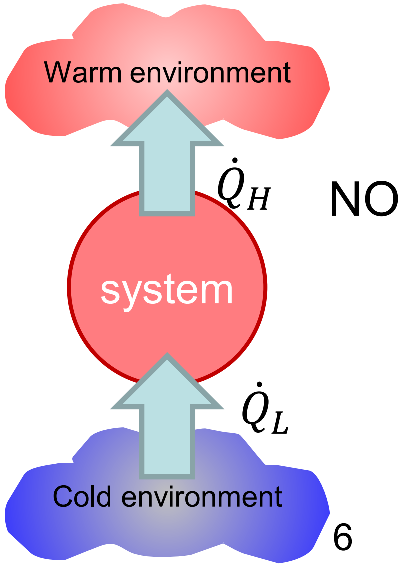
No such device can operate in a cycle that receives heat from a single reservoir to produce work only.



- $Q_{IN} \neq W_{out}$; cannot produce work when exchanging heat with a single reservoir.

Clausius statement:

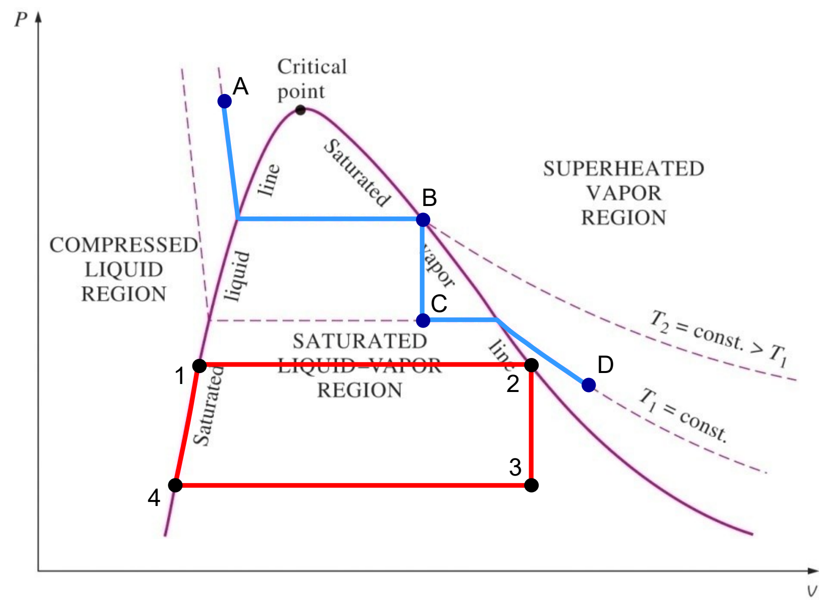
A device cannot operate in a cycle, which produces no effect other than heat transfer from a lower-temperature body to a higher-temperature body.



- Work from the surroundings is needed to force HEAT to flow from lower temperature to higher temperature.

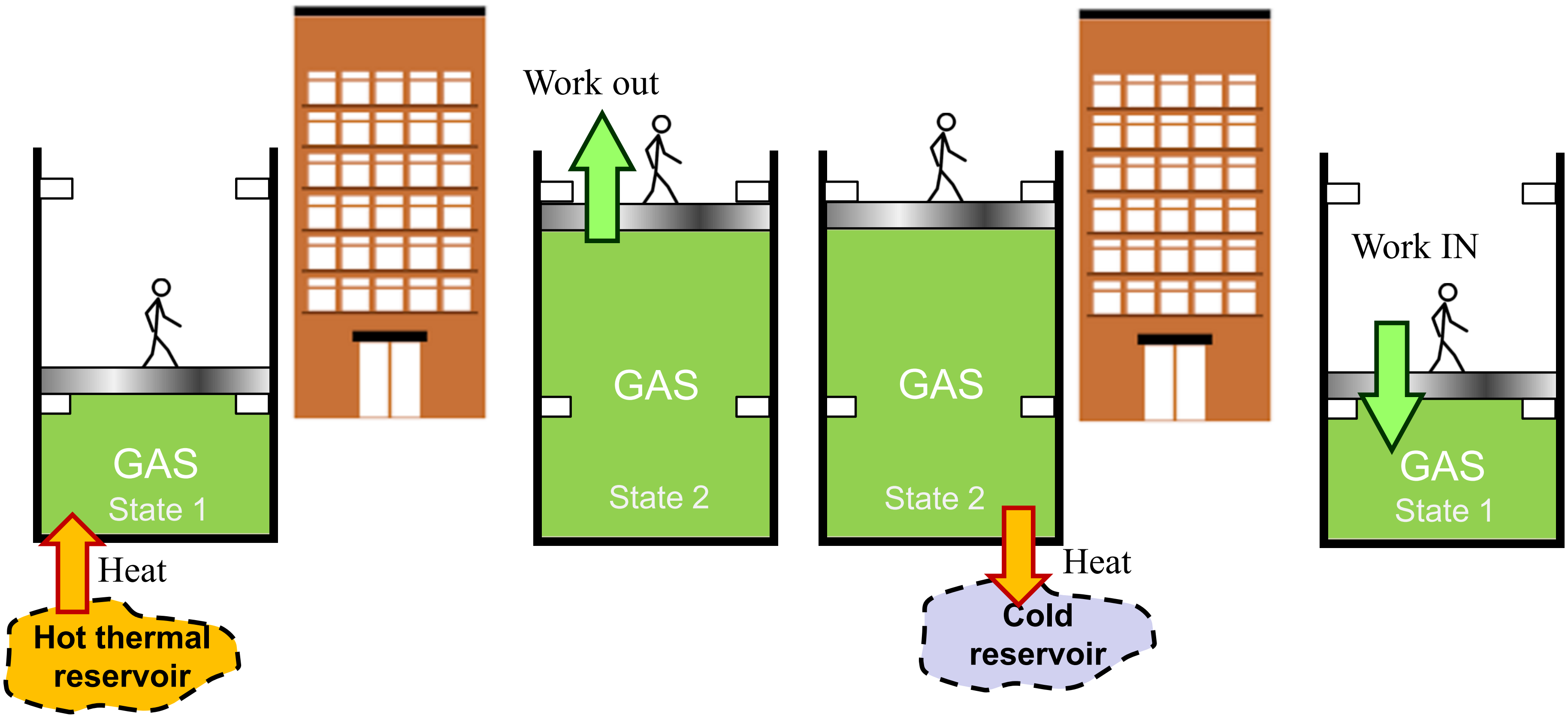
3.1.2 Thermodynamic Cycle

- Consider a thermodynamic cycle to help us understand the 2nd law of thermodynamics.
  - Series of thermodynamic processes which returns the system back to its initial state
  - Recall, lecture 2 (exercise 1.1) – processes on P-v diagram
    - Process A-B-C-D → not a cycle (state D ≠ A)
    - Process 1-2-3-4-1 → thermodynamic cycle – returns to state 1



3.1.2 Thermodynamic Cycle

- Consider a general thermodynamic cycle
  - A series of processes, which returns the system back to its initial state

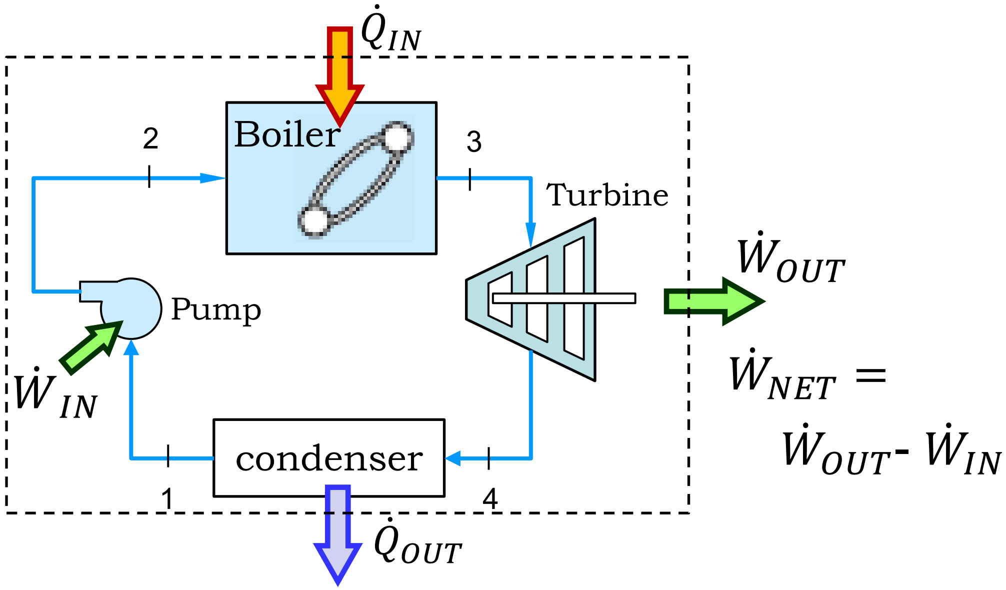


- Heat added to system and gas expands, raising the piston
- Heat removed to system. Gas compresses, lowering the piston

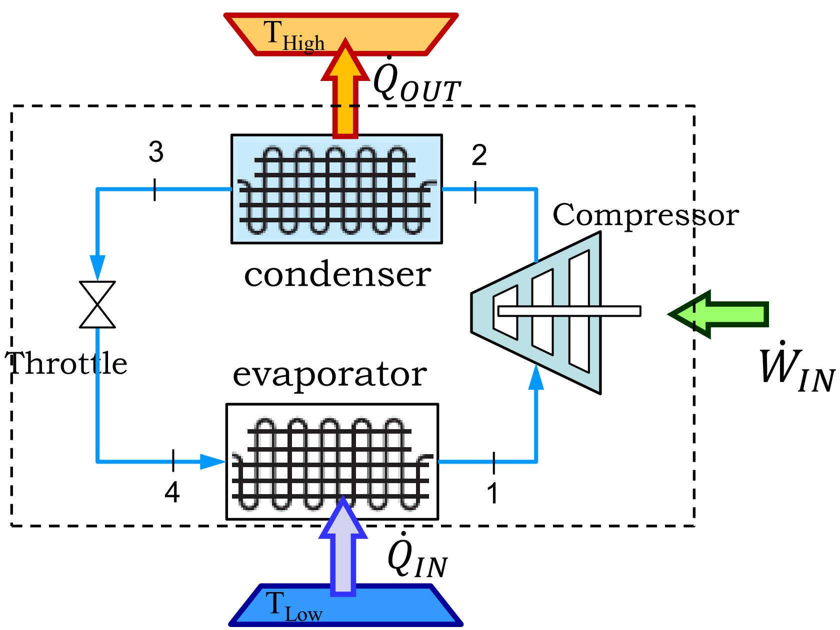
3.1.2 Thermodynamic Cycle

Other Thermodynamic Cycles

- Steam power plant
  - Start from liquid water
  - Goal: produce W_{OUT}
    - P ↑; W_{IN} from pump
    - Q_{IN} within Boiler; T ↑
    - W_{OUT} from Turbine
    - Q_{OUT} in condenser
    - Return to state 1



- Refrigeration system
  - Start from sat. vapour
  - Goal: transfer heat from cold to hot reservoir
    - W_{IN} from compressor; T,P ↑
    - Q_{OUT} to high T reservoir
    - Throttle; P,T ↓.
    - Q_{IN} from low T reservoir
    - Return to state 1

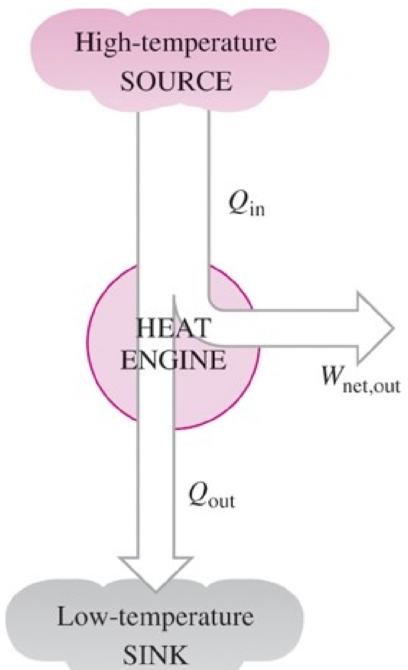


3.1.3 Heat Engine

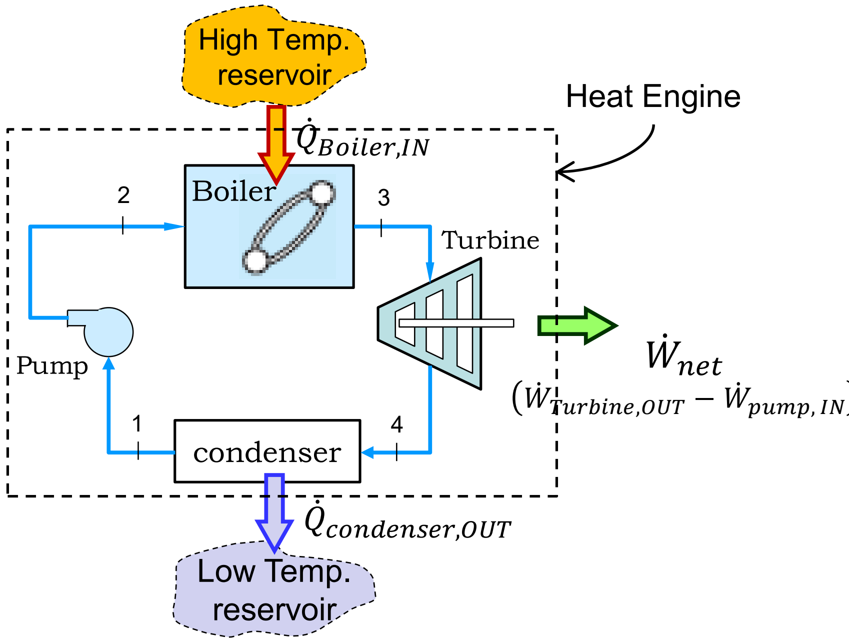
- Aforementioned cycles are representative of a **<u>heat engine</u>** and **<u>heat pump / refrigerator</u>**

<u>Heat Engine</u>

- Net heat transfer (from high T to low T reservoir), producing $W_{NET,OUT}$.
- Fraction of heat is converted to work, while the rest is rejected to a sink



Steam power plant as an example of a heat engine



<u>Heat Engine</u>

1st Law: $\dot{E}_{in} = \dot{E}_{out}$ (steady state)

$$\dot{Q}_{in} = \dot{W}_{OUT} - \dot{Q}_{OUT}$$

3.1.3 Heat Pump & Refrigerators

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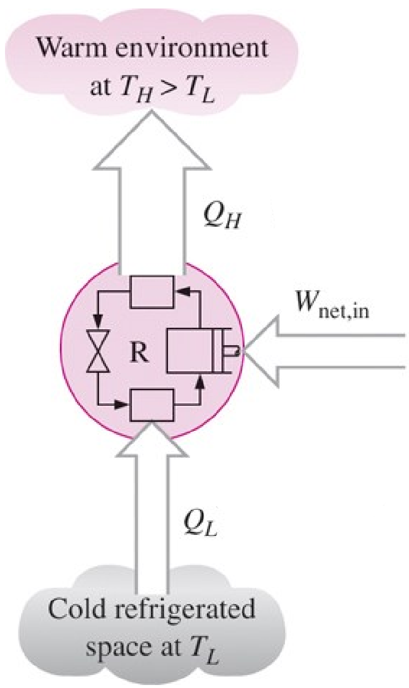
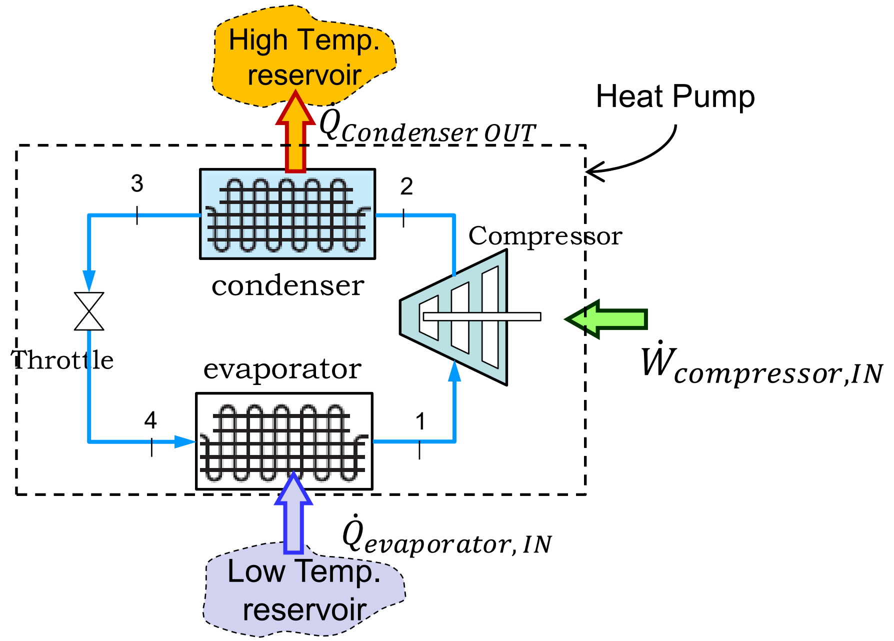
- Aforementioned cycles are representative of a **heat engine** or **heat pump**

Heat Pump & Refrigerators

- Reverse as heat engine
- Cycle that removes HEAT from a low-T body and delivers HEAT to a high-T body
- W_{IN} is required to accomplish such heat transfer



Refrigeration cycle is an example of a heat pump



Heat Pump

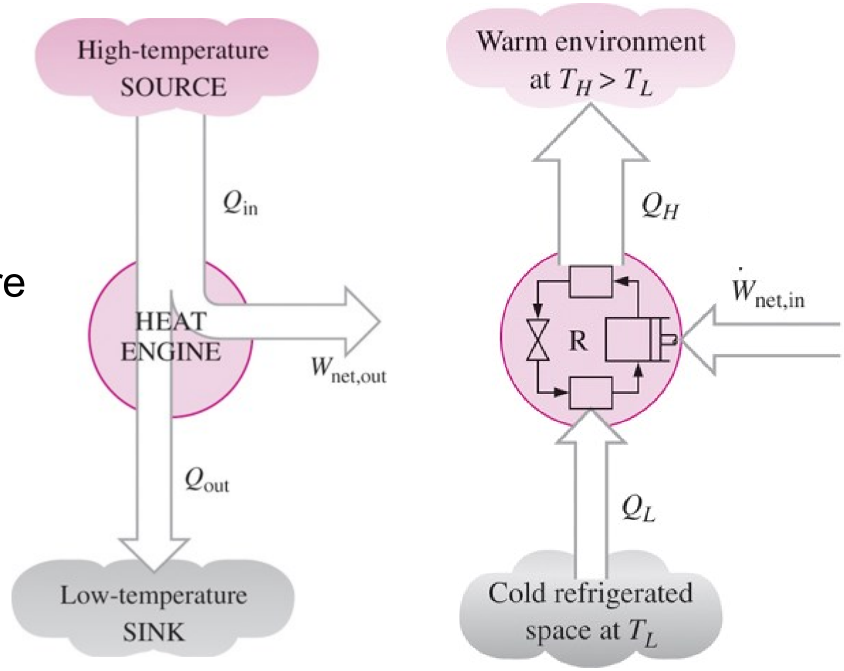
1st Law: $\dot{E}_{in} = \dot{E}_{out}$ (steady state)

$$\dot{Q}_{in} + \dot{W}_{IN} = \dot{Q}_{OUT}$$

3.1.3 Heat Engines & Heat Pump

Heat (thermal) reservoir

- System in equilibrium that can supply/receive finite amounts of heat without any change in system's temperature.
- Large thermal capacity
- Example reservoir (heat engine)
  - High temp. source: Furnace
  - Low temp. sink: Lakes, ocean, atmosphere
- Example reservoir (heat pump)
  - Warm temp.: room, atmosphere
  - Low temp.: refrigerated space, room, atmosphere



Work reservoir

- System in equilibrium that can supply/receive finite amounts of work (adiabatically) without any change in system's pressure.

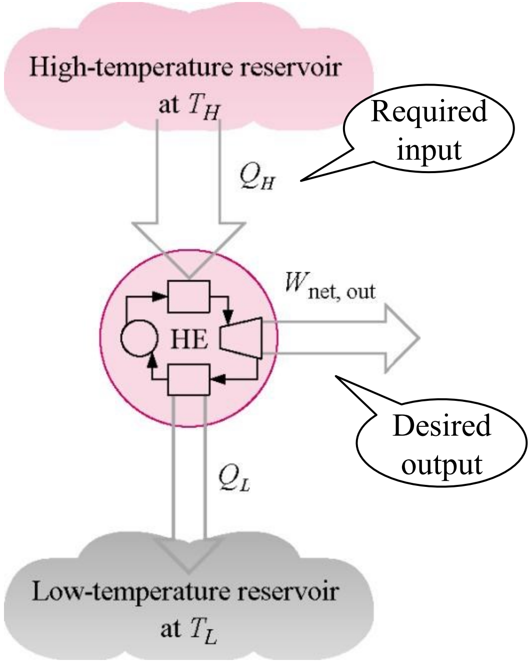
3.1.4 Thermal Efficiency (Heat Engine)

Thermal Efficiency – Measure of performance

$$\eta_{th} = \frac{Desired\ output}{Required\ input} = \frac{What\ you\ get\ out}{What\ you\ put\ in} = \frac{What\ you\ want}{What\ it\ costs}$$

Heat engine

- Desired output: $W_{NET,OUT}$
- Required input: Q_H
- $\eta_{TH} = \frac{W_{NET,OUT}}{Q_H} < 1$



1st Law applied to Heat Engine

- Steady state cycle ($\Delta U = 0$)
- $\dot{E}_{in} = \dot{E}_{OUT}$
- $\dot{Q}_H = \dot{W}_{NET,OUT} + \dot{Q}_L$
- $\eta_{TH} = \dot{W}_{NET,OUT}/\dot{Q}_H \rightarrow (\dot{Q}_H - \dot{Q}_L)/\dot{Q}_H \rightarrow 1 - {}^{\dot{Q}_L}/_{\dot{Q}_H}$

3.1.4 Thermal Efficiency (Heat Pump)

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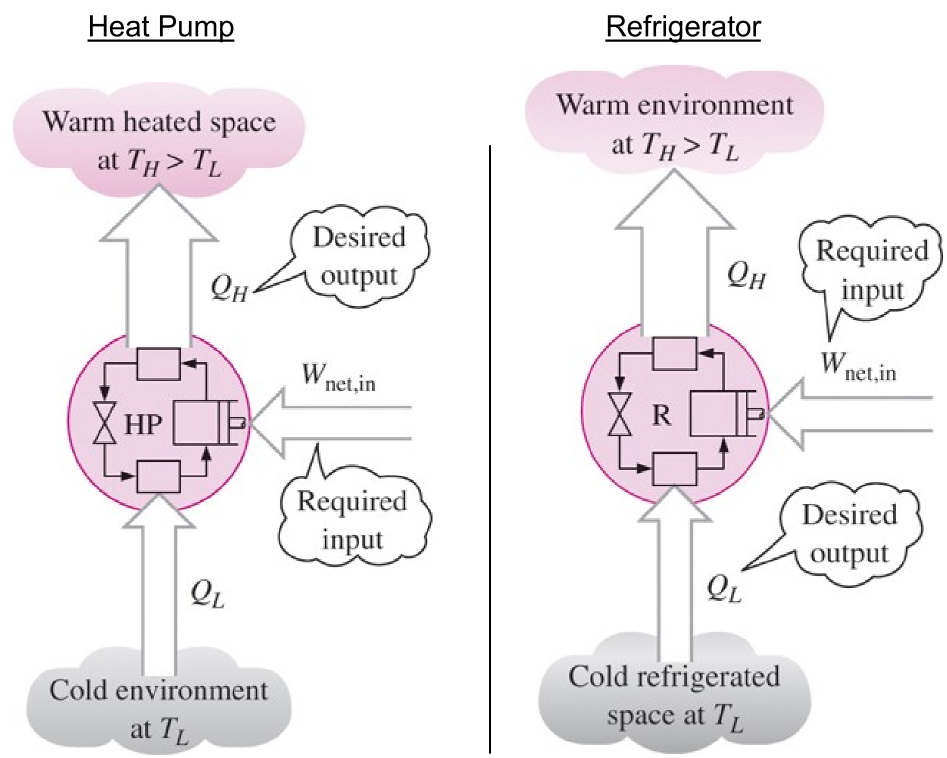
Thermal Efficiency → **Coefficient of Performance**

$$COP = \beta = \frac{Desired\ output}{Required\ input} = \frac{What\ you\ want}{What\ it\ costs}$$



Heat Pump vs. Refrigerator

- Objective of **heat pump:** transfer Q_H to warmer space
  - Desired output: Q_H
- Objective of **refrigerator:** remove Q_L from cooler space
  - Desired output: Q_L
- Required input: W_{in}

3.1.4 Thermal Efficiency (Heat Pump)

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<u>Thermal Efficiency → **Coefficient of Performance**</u>

$$COP = \beta = \frac{Desired\ output}{Required\ input} = \frac{What\ you\ want}{What\ it\ costs}$$

<u>Heat Pump</u>

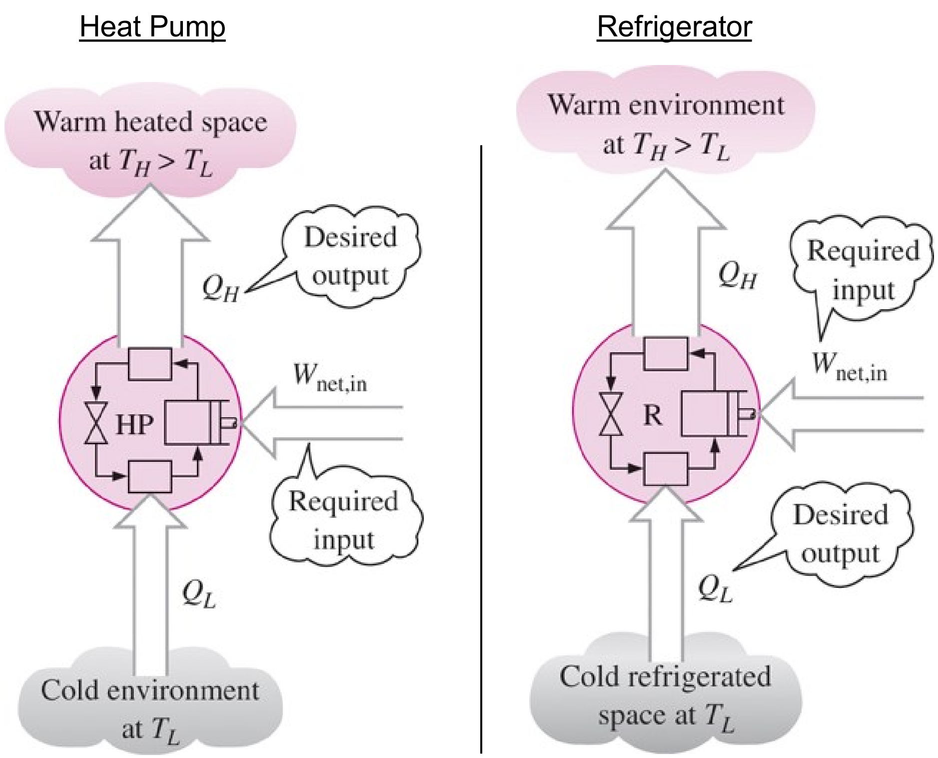
- $COP_{HP} = \frac{\dot{Q}_H}{\dot{W}_{in}} \rightarrow \frac{\dot{Q}_H}{\dot{Q}_H - \dot{Q}_L}$

<u>Refrigerator</u>

- $COP_{R} = \frac{\dot{Q}_L}{\dot{W}_{in}} \rightarrow \frac{\dot{Q}_L}{\dot{Q}_H - \dot{Q}_L}$

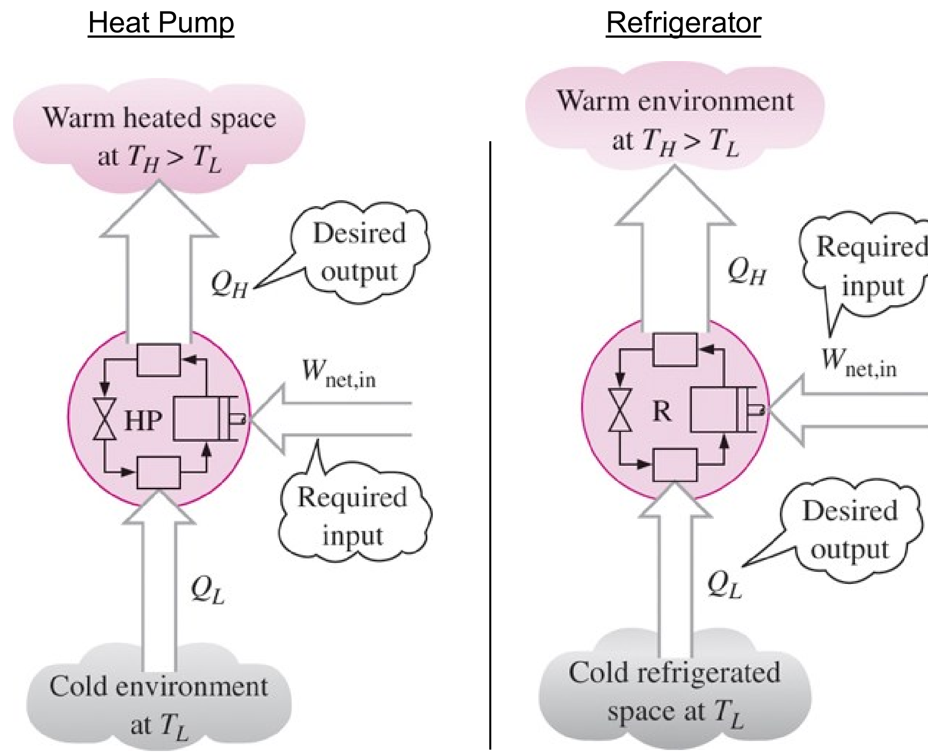
- Under same T_H & T_L, COP_{HP} and COP_R are related by

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



3.1.4 Thermal Efficiency (Heat Pump)

Can reverse air conditioner to heat indoors (cold fluid exchanges heat with outside). AC acts as a heat pump.



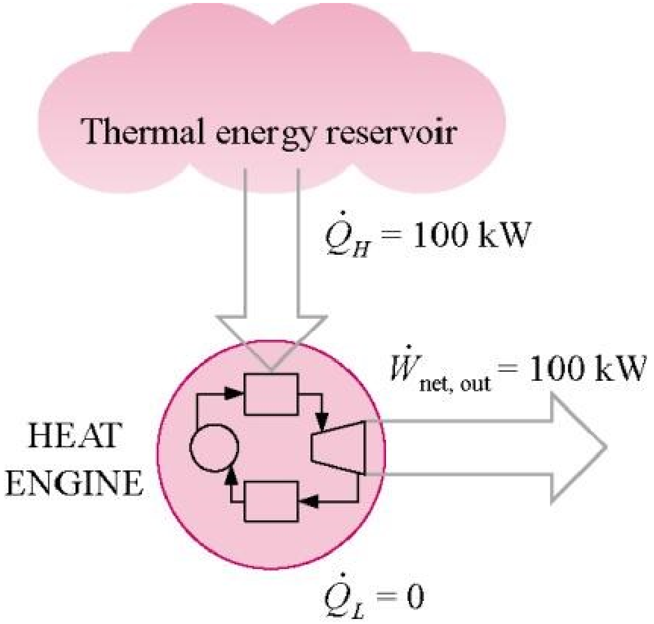
3.1.5 Revisiting Second Law Statements

- Revisit 2nd law statements with respect to heat engines and heat pumps

Kelvin-Planck statement

No such device can operate on a cycle that receives heat from a single reservoir and directly produces net work.

- Heat engine cannot produce $W_{NET,OUT}$ while exchanging heat with a single reservoir only
- I.e. maximum possible efficiency is less than 100%.



Heat engine violating the Kelvin-Planck statement.

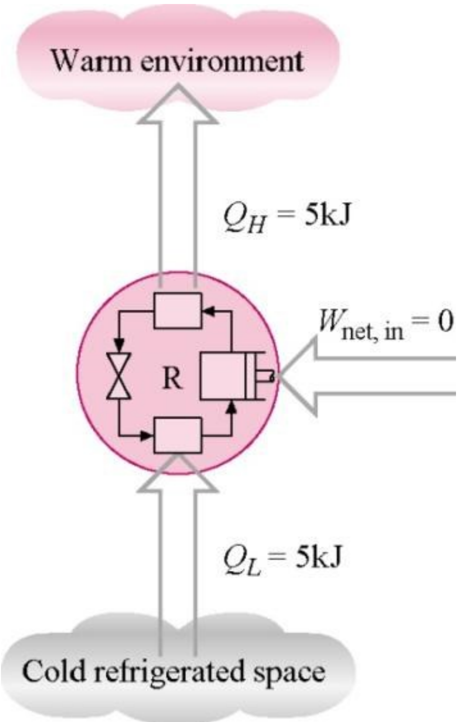
3.1.5 Revisiting Second Law Statements

- Revisit 2nd law statements with respect to heat engines and heat pumps

Clausius statement

No such device can operate in a cycle to produces no effect other than heat transfer from a lower-temperature body to a higher-temperature body.

- Work from surroundings is required to transfer heat from a low-temperature medium to a high-temperature medium.
- $\boldsymbol{COP} < \infty$



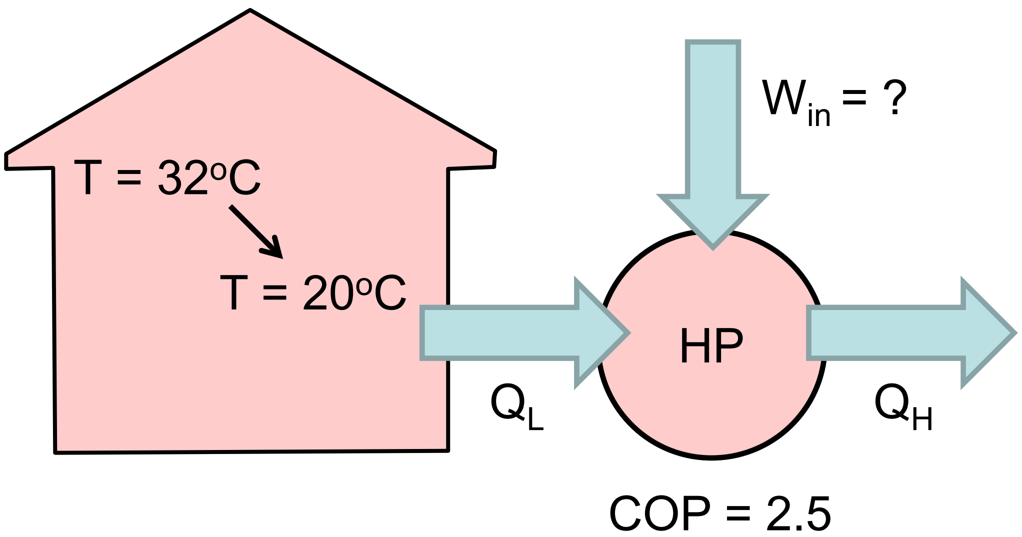
Heat pump violating the Clausius statement.

3.1.6 Example

Example 3.1

When a tenant returns to their well-sealed house on a hot summer day, the house air is 32°C. The air conditioner is turned on, cooling the house air to 20°C in 15 min. If the COP of the air conditioner system is 2.5, determine the power drawn by the AC. Assume the entire mass within the house is equivalent to 100kg of air for which the air can be treated as an ideal gas with constant specific heats $C_V = 0.72$ kJ/kgK

Solution:

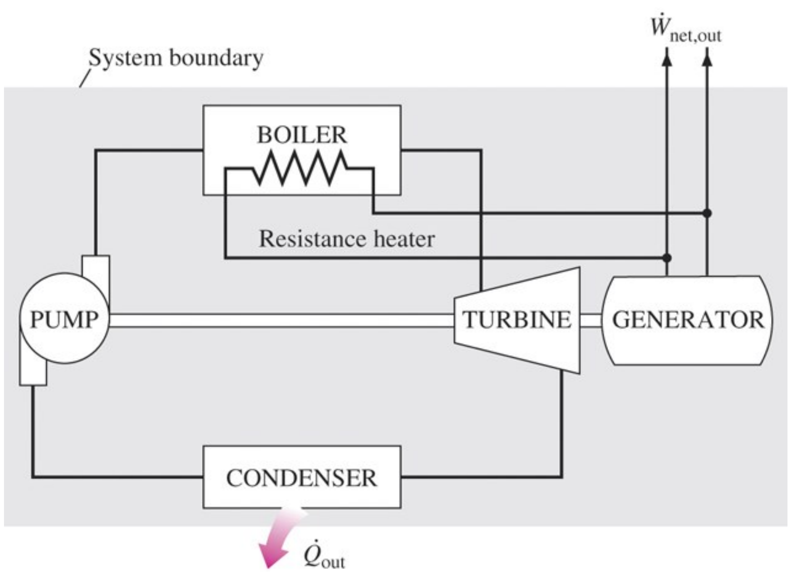


Ans: 0.384 kW

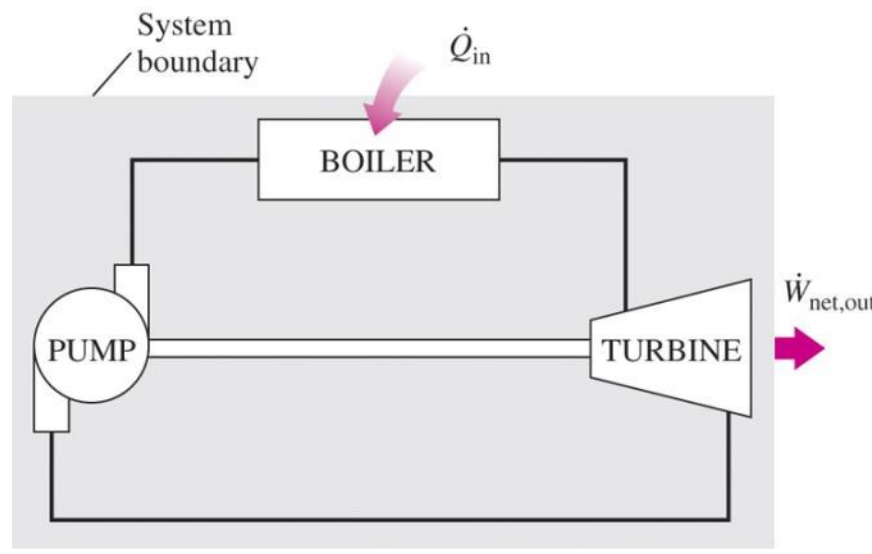
3.1.7 Perpetual-Motion Machines

Perpetual-Motion Machines

- Device violating the 1st or 2nd law of thermodynamics.
- Perpetual-motion machine of the first kind: violates 1st law.
- Perpetual-motion machine of the second kind: violates 2nd law.



PMM of the first kind. No energy input.

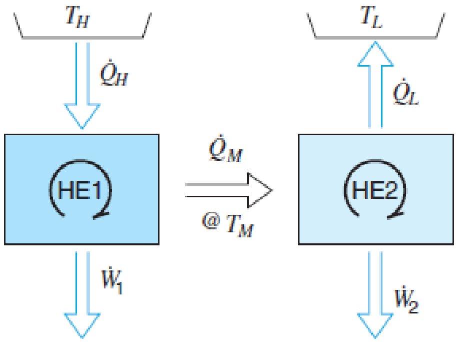


PMM of the second kind. $Q_{IN} = W_{OUT}$; $\eta_{TH} = 100\%$.

3.1.8 Exercises

Exercise 3.1:

A combination of two heat engines is shown. Find the overall thermal efficiency as a function of the two individual efficiencies.



[ans: $\eta_{TH,overall} = (\dot{W}_1 + \dot{W}_2)/\dot{Q}_H$]

Exercise 3.2:

A refrigerator removes 1.5 kJ from the cold space using 1kJ work input. How much energy goes into the kitchen and what is the coefficient of performance?

[ans: Q_H = 2.5 kJ, COP_R = 1.5]

Exercise 3.3:

A window air-conditioner unit is placed in an apartment and tested in cooling mode using 750 W of electric power with COP of 1.75. What is the cooling power capacity?

[ans: $\dot{Q}_L$ = 1313 W]