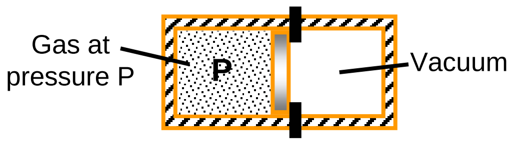
V. The Second Law of Thermodynamics

A. Introduction

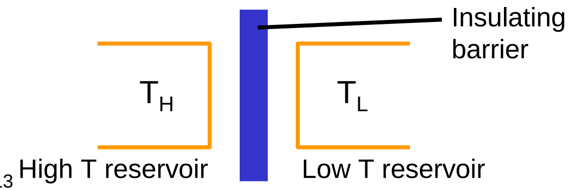
1. The first law: energy is conserved
2. The second law: certain processes do occur and certain processes don't

a. example of a mechanical process (assume adiabatic, piston-cylinder device)



If the pins are removed, our experience tells us which way the piston will move.

b. example of a thermal process



If the barrier is removed, our experience tells us which way heat will flow.

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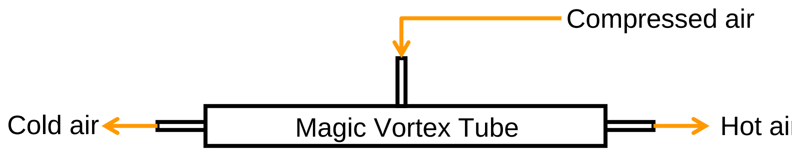
c. example of a less obvious process

It was easy to predict what would happen in the previous two examples, based on our experience. Consider a less obvious example:



How can we use our experience to know whether this process is possible? Is there a way to generalize our experience with simple processes so that we can make decisions about more complex processes?

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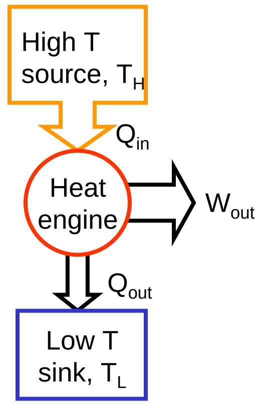
B. Heat Engines

1. Definition of heat engine: a cyclic device that converts heat to work
   a. First Law: energy balance over engine

$$\Delta E = Q - W = 0$$

$$Q_{in} - Q_{out} - W_{out} = 0$$

   b. Examples include the steam power plant, automotive and diesel engines
2. Second Law: is it possible or not? Can Q_{out} be zero? What is the best we can do?



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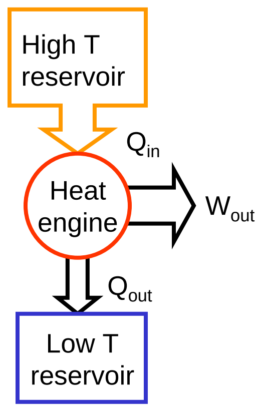
B. Heat Engines

3. Thermal-energy reservoirs: hypothetical closed systems with the following properties
   a. Interact with surroundings only via heat transfer.
   b. Their temperature remains constant and uniform.
   c. Examples: a furnace, the atmosphere, a lake, the ocean, two-phase systems.



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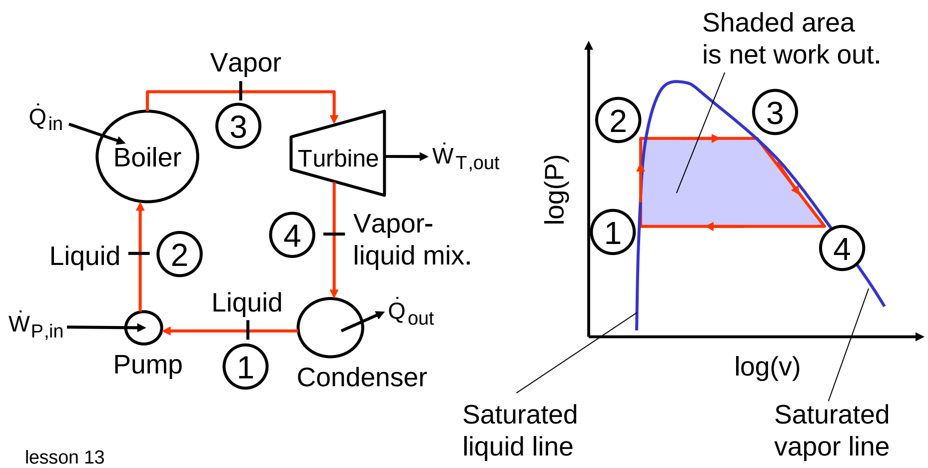
B. Heat Engines

4. A simple steam power cycle (continuous cyclic process)

Simple, ideal vapor power cycle (Rankine cycle, see Ch. 10).



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5. Energy balance over system (the steam power cycle)

$$\frac{dE}{dt} = \dot{Q}_{in} - \dot{Q}_{out} + \dot{W}_{P,in} - \dot{W}_{T,out} = 0$$

$$\dot{Q}_{in} - \dot{Q}_{out} - \dot{W}_{net,out} = 0 \quad or \quad Q_{in} - Q_{out} - W_{net,out} = 0$$

6. Performance of device

$$Performance = \frac{desired\ result}{required\ input} = \frac{\dot{W}_{T,out} - \dot{W}_{P,in}}{\dot{Q}_{in}}$$ (2-41) (6-3)

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7. The performance of a heat engine is called the thermal efficiency, η_{th}

$$\eta_{th} = \frac{W_{net,out}}{Q_{in}} = \frac{\dot{W}_{net,out}}{\dot{Q}_{in}} \quad (6\text{-}4)$$

$$\eta_{th} = \frac{W_{net,out}}{Q_{in}} = \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}} \quad (6\text{-}5)$$

The performance or efficiency must be determined experimentally. The typical automobile engine has a thermal efficiency of about 25%. This means that 25% of the chemical energy in the gasoline can be converted to mechanical work.

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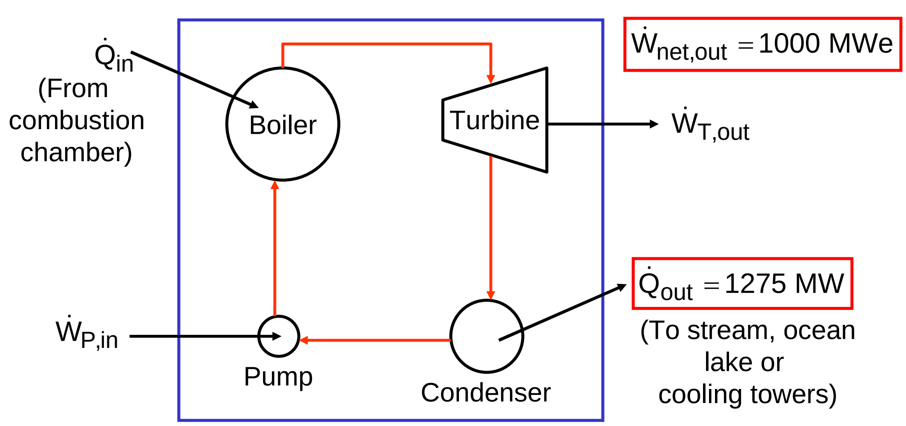
8. Example of a modern, coal-fired steam power plant (1000 MWe)



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8. Example of a modern, coal-fired steam power plant (1000 MWe)

$$\dot{Q}_{in} - \dot{Q}_{out} - \dot{W}_{net,out} = 0$$

$$\therefore \dot{Q}_{in} = \dot{Q}_{out} + \dot{W}_{net,out} = 1275 + 1000 = 2275\ MW$$

$$\eta_{th} = \frac{\dot{W}_{net,out}}{\dot{Q}_{in}} = \frac{1000}{2275} = 0.44$$

$$\eta_{combust} = \frac{\dot{Q}_{in}}{HHV \bullet \dot{m}_{coal}} = \frac{2275}{2500} = 0.91$$

$$\eta_{gen} \cong 1$$

$$\eta_{overall} = \eta_{th}\eta_{combust}\eta_{gen} = \frac{\dot{W}_{net,out}}{HHV \bullet \dot{m}_{coal}} = \frac{1000}{2500} = 0.40 \quad (2\text{-}43)$$

Where HHV is the higher heating value of the coal (MJ/kg, see p. 79) and $\dot{m}_{coal}$ is its mass flow rate (kg/s). Note that $\eta_{gen} \cong 1$.

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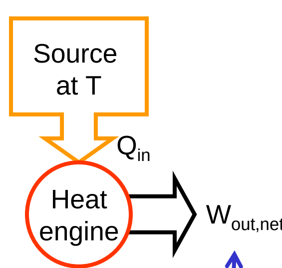
9. The Kelvin-Plank Statement of the Second Law of Thermodynamics

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

What is the best we can do?
Can Q_{out} be zero?

Kelvin-Plank Statement (p. 287):

It is impossible for any process that operates on a cycle to receive heat from a single reservoir and perform a net amount of work on the surroundings.



This means that $W_{out,net} \leq 0$.

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10. A clarifying note on power requirements and efficiencies

If we refer to a 0.25-hp fan, driven by a small electric motor with an efficiency of 54%, does that mean that the fan draws 0.25-hp of electric power or does it draw 0.25/0.54 hp? It turns out that the latter is correct. The motor will draw about 0.5-hp of electric power.