Yesterday we introduced the concept of direction caused by irreversibilities. This led to the notion that real processes are inherently inefficient.

→ Kelvin-Planck Statement: “It is impossible to build an engine that will operate in a cycle (i.e. continuously) that will provide no effect except the raising of a weight & cooling of a single thermal reservoir.”

Thermal reservoir: infinite temperature source, provides thermal energy $Q@$ a constant temperature during the process under consideration: lakes, rivers, atmosphere, buildings.

For this system to work we have to add a cold reservoir, otherwise there is no temperature gradient for heat to flow.

Remember what Sadi Carnot said: $\eta = \frac{W_{\text{net}}}{Q_{\text{in}}} < \text{Efficient}$

How would we define the thermal efficiency of the cycle above?

thermal efficiency: Ratio of the desired output (what you want) to the required input (what you paid):

\[ \eta = \frac{W}{Q} < \frac{\text{what you want}}{\text{what you paid}} \]

Always \( \eta < 1 \)

Therefore $W < Q@\text{in}$, so $\Delta q_{\text{out}} = -W < \text{Cold reservoir must exist.}$
Similarly \( N = \frac{Q_{\text{in}} - Q_{\text{out}}}{Q_{\text{in}}} \) or \( N = 1 - \frac{Q_{\text{out}}}{Q_{\text{in}}} \) for a heat engine.

This means that the efficiency of a heat engine also depends on the heat transfer into and out of the system. What controls heat transfer? Temperature difference.

\[ N_{\text{max, heat engine}} = \frac{Q_{\text{in}} - Q_{\text{out}}}{Q_{\text{in}}} \rightarrow \frac{Q_{\text{hot}} - Q_{\text{cold}}}{Q_{\text{hot}}} \rightarrow \frac{T_{\text{hot}} - T_{\text{cold}}}{T_{\text{HTT}}} \]

\[ N_{\text{max}} = N_{\text{Carnot}} = 1 - \frac{T_{\text{cold}}}{T_{\text{HTT}}} \]

Does it matter which temperature scale we use here? Yes!! You need to use an absolute temperature scale for the Carnot engine.

This is the maximum possible efficiency for a heat engine, i.e., there are no irreversibilities (other than heat) affecting the engine, so a Carnot engine or device is reversible.
Example: 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 the net power output, the thermal efficiency, and the minimum temperature of the furnace for this to be possible.

\[
\eta_{th} = \frac{W_{out}}{Q_{in}} = \frac{Q_{in} - Q_{out}}{Q_{in}} = \frac{130\text{ MW}}{80\text{ MW}} = 0.625 \text{ or } 62.5\%
\]

How do we find minimum \(T_f\)? Cannot

\[
\eta_{Carnot} = 1 - \frac{T_c}{T_f} \Rightarrow 0.375 = 1 - \frac{300}{T_f} \Rightarrow T_f = \frac{300}{0.625} \Rightarrow T_f = 480\text{ K}
\]

What if I turned my heat engine around?

I could use this to cool a space like a refrigerator.

How would I define the efficiency of this? \(\eta_{ideal} = \frac{W_{out}}{W_{in}} = \frac{Q_{in} - Q_{out}}{Q_{in}}\)

This is called the Coefficient of Performance (COP) for a refrigerator:

\[
\text{COP} = \frac{Q_{out}}{W_{in}} = \frac{Q_{in} - Q_{out}}{Q_{in}} \Rightarrow \frac{T_c}{T_h - T_c}
\]
Can I do something with this system besides cool a space down? = refrigeration = Yes! I can use it to heat up a space. This is called a heat pump - takes heat from colder temperature & moves it to a higher temperature.

Example: A heat pump is maintaining a house @ 20°C. On a cold day the air temperature drops to -2°C & the house is estimated to loose heat at a rate of 80,000 kJ.

If the heat pump has a COP of 2.5 under these conditions, find a) power required to drive pump B) the amount of heat extracted from the outdoor air

\[ Q_c = 80,000 \text{kJ} \]

\[ W_{in} = \frac{Q_c}{\text{COP}} = \frac{80,000}{2.5} = 32,000 \text{kJ} \text{ or } 8.9 \text{ kW} \]

How much heat came from the outside air?

Energy Balance: IN=OUT \[ Q_c + W_{in} = Q_h \]

\[ \Rightarrow Q_c = 80,000 \text{kJ} - 32,000 \text{kJ} \Rightarrow Q_c = 48,000 \text{kJ} \]

So we are only paying for 32,000 kJ! If we used electric base boards our electric bill would be 2.5 times higher!