21-1: Heat Engines and Refrigerators

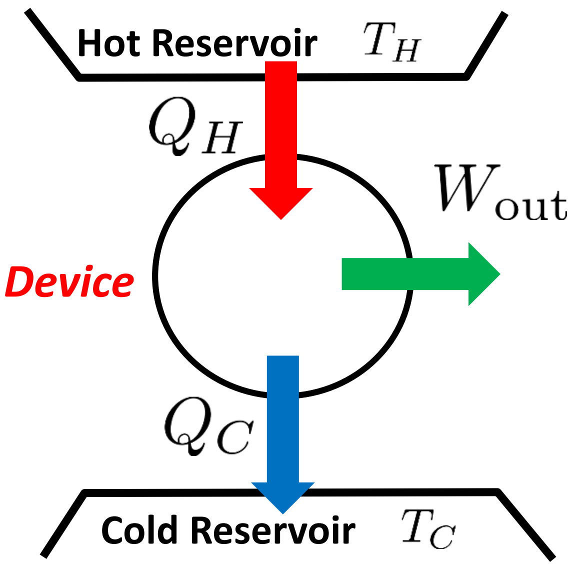
In this chapter, we combine and apply all that we have learned in chapters 18, 19, & 20 to analyze some practical devices that can only be understood through Thermodynamics. ***In fact, this was the historical reason Thermodynamics was invented!***

Heat Engine* is a closed cycle device that extracts useful **work** from **heat** flowing from a **high temperature** reservoir to a **low temperature** reservoir.

Closed cycle means that the system returns to it's initial state

A **Reservoir** is a source or sink of heat that stays at a constant temperature.

Diagram (a little different than text)

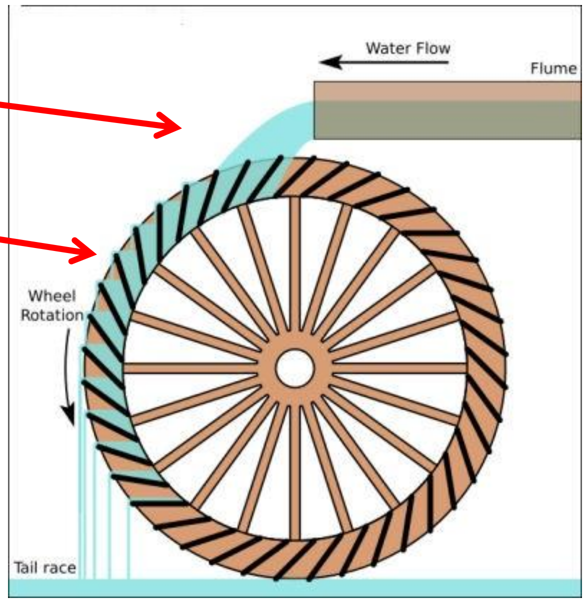


A good mechanical analogy – in action

Water flows downhill under gravity

The wheel extracts some of that energy to do work

This converts gravitational potential energy to work



*This includes a wide array of actual devices: steam engines, internal combustion engines, coal, oil, gas, or nuclear power plants.

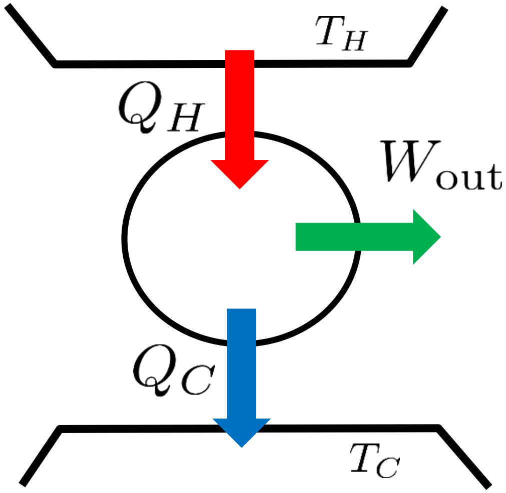
Heat Engine Sign Conventions

Some important sign conventions:

$$Q_H = |\text{heat into the system}| = |Q_{\text{in}}|$$

$$Q_C = |\text{heat out of the system}| = |Q_{\text{out}}|$$

$$W_{\text{out}} = W_s, \text{ work done } \underline{\textbf{by}} \text{ the system on the environment}$$



Back in Chapter 19, we had:

$$W = \text{work done } \underline{\textbf{on}} \text{ the system by the environment} = -\int PdV$$

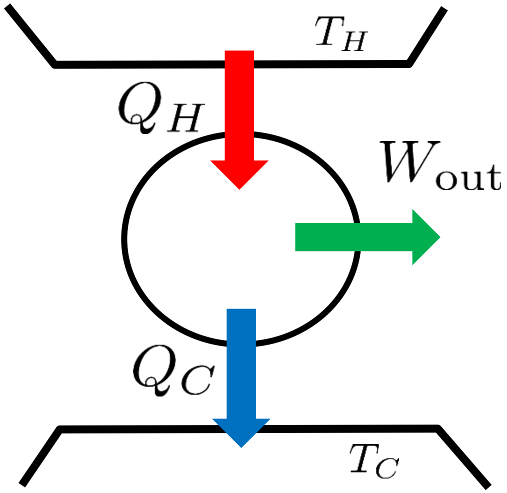
Now, in Chapter 21, it makes more sense to use the work done **by** the system on the environment. **Your author calls this W_s , and W_s = -W. So:**

$$W_s = +\int PdV = +\,(\text{area under the PV curve})$$

So, the First Law can be written in two equivalent ways:

$$\Delta E_{\text{th}} = Q + W \qquad \text{or} \qquad \Delta E_{\text{th}} = Q - W_s$$

Heat Engine Efficiency



Apply the First Law: the easiest way to do this is to say:

Energy into the system **=** **Energy out of the system**

$$Q_H = Q_C + W_{\text{out}}$$

Define: The Engine Efficiency: $$\eta = \frac{\text{energy you get}}{\text{energy you pay for}} = \frac{\text{work output}}{\text{heat input}}$$

So: $$\eta = \frac{W_{\text{out}}}{Q_H} = \frac{Q_H - Q_C}{Q_H} = 1 - \frac{Q_C}{Q_H}$$

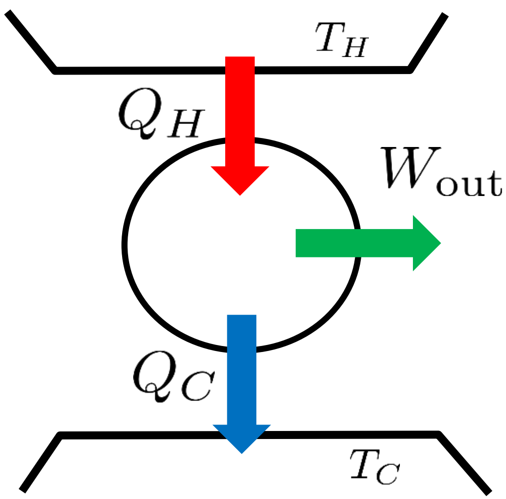
Note: we'll learn how to apply the Second Law to the engine in the next class.

Whiteboard Problem: 21-1

A heat engine extracts 55 kJ of heat from the hot reservoir each cycle and exhausts 40 kJ of heat. Find:

a) **The work done per cycle (LC)**
b) **The thermal efficiency (LC)**

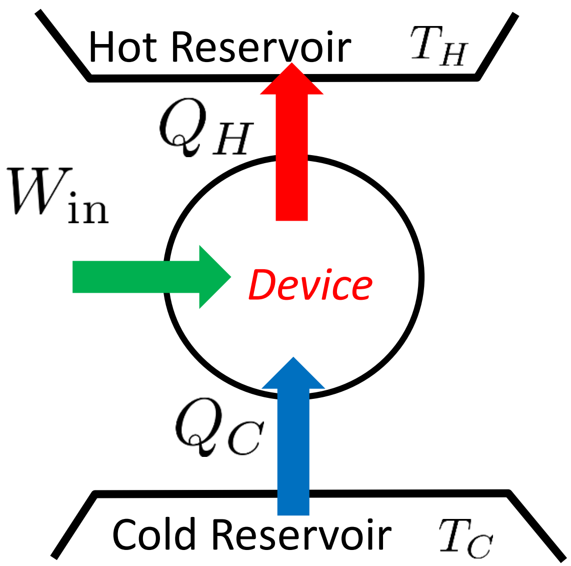
Hint: draw and label a heat engine diagram:



A Refrigerator

Refrigerator is a closed cycle device that does work to move heat from a low temperature reservoir to a high temperature reservoir*

Diagram



Note: Q_C, Q_H, and W_{in} are all positive.

First Law Balance: **Energy In = Energy Out**

$$W_{\text{in}} + Q_C = Q_H$$

Define: **Coefficient of Performance, K**:

$$K = \frac{\text{energy removed}}{\text{energy you pay for}}$$

So:

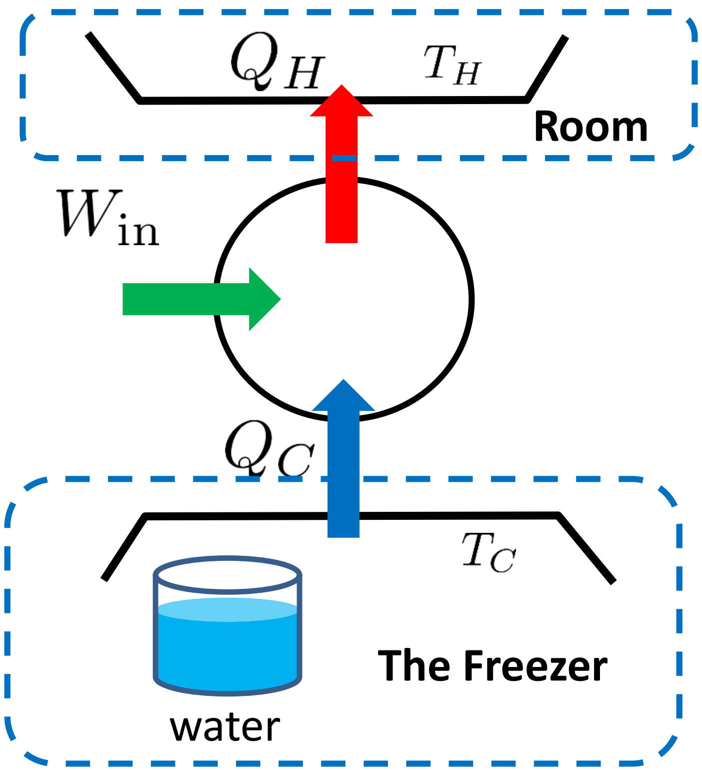
$$K = \frac{Q_C}{W_{\text{in}}} = \frac{Q_C}{Q_H - Q_C}$$

***Note:** left alone, heat won't go from cold to hot. Here, you must do work to *"push the heat uphill" – very much like you have to pump water uphill.*

Whiteboard Problem: 21-2

(a good review problem; you'll need stuff from chapters 18 & 19)

100 mL of water at 15°C is placed in the freezer compartment of a refrigerator that has a coefficient of performance of 4.0. **How much heat energy is exhausted into the room as the water is changed to ice at -15°C?** **(LC)**



Hint: Draw a good refrigerator diagram:

c_w = 4186 J/kg°C

c_i = 2090 J/kg°C

L_f (water) = 3.33 X 10^5 J/kg

Density of water = 1000 kg/m^3

A very practical HW Problem: 21-47

47 ‖ A heat engine running backward is called a refrigerator if its purpose is to extract heat from a cold reservoir. The same engine running backward is called a *heat pump* if its purpose is to exhaust warm air into the hot reservoir. Heat pumps are widely used for home heating. You can think of a heat pump as a refrigerator that is cooling the already cold outdoors and, with its exhaust heat Q_H, warming the indoors. Perhaps this seems a little silly, but consider the following. Electricity can be directly used to heat a home by passing an electric current through a heating coil. This is a direct, 100% conversion of work to heat. That is, 15 kW of electric power (generated by doing work at the rate of 15 kJ/s at the power plant) produces heat energy inside the home at a rate of 15 kJ/s. Suppose that the neighbor's home has a heat pump with a coefficient of performance of 5.0, a realistic value. Note that "what you get" with a heat pump is heat delivered, Q_H, so a heat pump's coefficient of performance is defined as $K = Q_H/W_{in}$.

a. How much electric power (in kW) does the heat pump use to deliver 15 kJ/s of heat energy to the house?

b. An average price for electricity is about 40 MJ per dollar. A furnace or heat pump will run typically 250 hours per month during the winter. What does one month's heating cost in the home with a 15 kW electric heater and in the home of the neighbor who uses a heat pump?

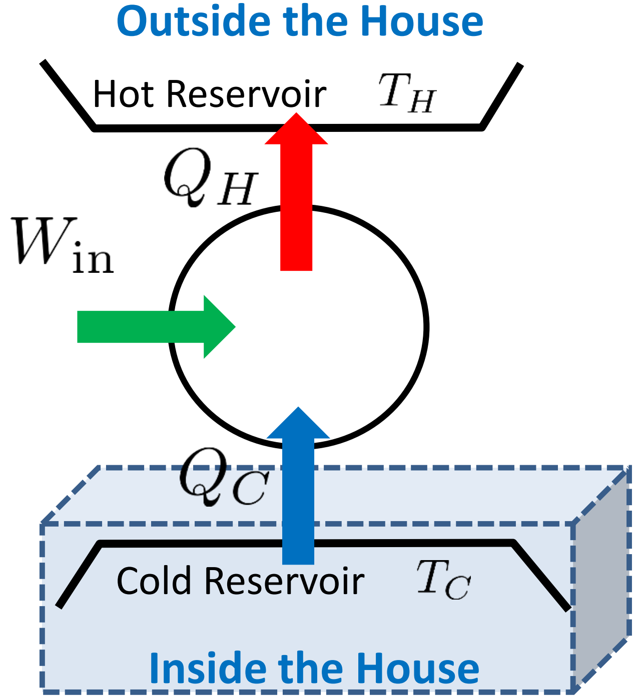
You're going to do this problem for homework, but we should talk about it since you likely have one of these devices in your house.

It can be used as an air conditioner in the summer and to heat your house in the winter!

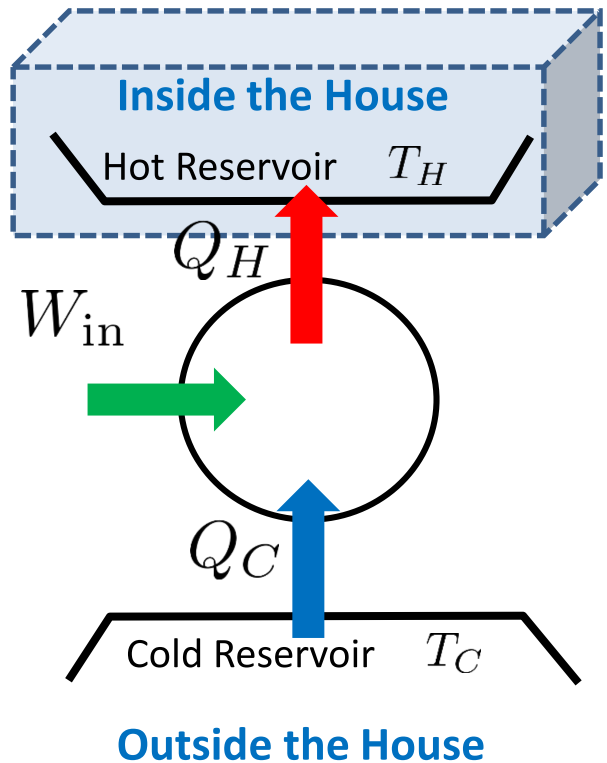
How can it do both?

An Air Conditioner and a Heat Pump

Air Conditioner
(like a refrigerator)



Heat Pump



What's the difference?

The air conditioner moves heat from the cold inside to the warm outside, just like a refrigerator, but the heat pump moves heat from the cold outside to the warm inside. In this sense, the heat pump is air conditioning the outside.

Ideal Gas Engines and Refrigerators

Many actual devices use a working fluid that goes through a phase change (e.g. the steam engine). Here we want to study something simpler: engines and refrigerators where the fluid is always in the gas phase that we can treat as an ideal gas. **ideal gas**. **Your author summarizes our knowledge about ideal gases in Tables 21.1 & 2:**

TABLE 21.1 Summary of ideal-gas processes

Process	Gas law	Work W_s	Heat Q	Thermal energy
Isochoric	$p_i/T_i = p_f/T_f$	0	$nC_V\,\Delta T$	$\Delta E_{th} = Q$
Isobaric	$V_i/T_i = V_f/T_f$	$p\,\Delta V$	$nC_P\,\Delta T$	$\Delta E_{th} = Q - W_s$
Isothermal	$p_iV_i = p_fV_f$	$nRT\ln(V_f/V_i)$	$Q = W_s$	$\Delta E_{th} = 0$
		$pV\ln(V_f/V_i)$		
Adiabatic	$p_iV_i^{\gamma} = p_fV_f^{\gamma}$	$(p_fV_f - p_iV_i)/(1-\gamma)$	0	$\Delta E_{th} = -W_s$
	$T_iV_i^{\gamma-1} = T_fV_f^{\gamma-1}$	$-nC_V\,\Delta T$		
Any	$p_iV_i/T_i = p_fV_f/T_f$	area under curve		$\Delta E_{th} = nC_V\,\Delta T$

TABLE 21.2 Properties of monatomic and diatomic gases

	Monatomic	Diatomic
E_{th}	$\frac{3}{2}nRT$	$\frac{5}{2}nRT$
C_V	$\frac{3}{2}R$	$\frac{5}{2}R$
C_P	$\frac{5}{2}R$	$\frac{7}{2}R$
$\gamma = \frac{C_P}{C_V}$	$\frac{5}{3} = 1.67$	$\frac{7}{5} = 1.40$

Some Notes:

There is only one gas law: $PV = nRT$ or $PV = Nk_BT$

In all of these equations, your author is using the **work done by the system**:

$$W_s = +\int_i^f PdV$$

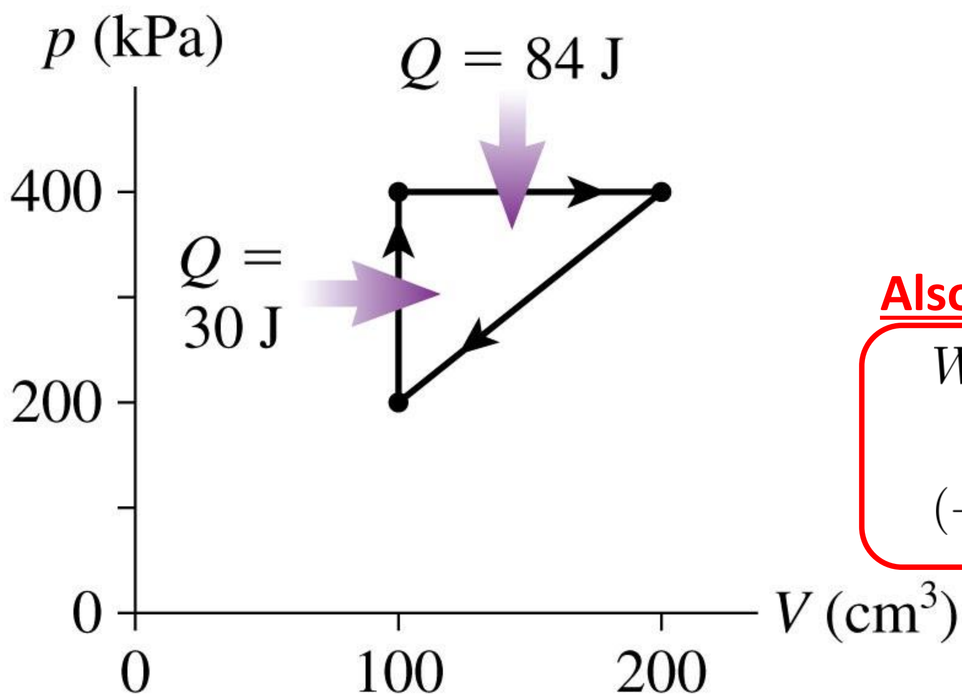
Whiteboard Problem: 21-3

The figure below shows the PV diagram for a heat engine cycle.

What are:

a) **The output work, W_{out}, and the heat exhausted to the cold reservoir?** (LC, enter W_{out})

b) **The thermal efficiency?** (LC)



Some Hints:

What do the arrows for the Q's mean?

That's heat coming into the system – usually we have to figure this out – next class.

Also: (*this is really important*)

$$W_{out} = W_s \text{ (for the cycle)}$$

$$= \text{area bounded by the cycle}$$

(+ for clockwise; - for counterclockwise)