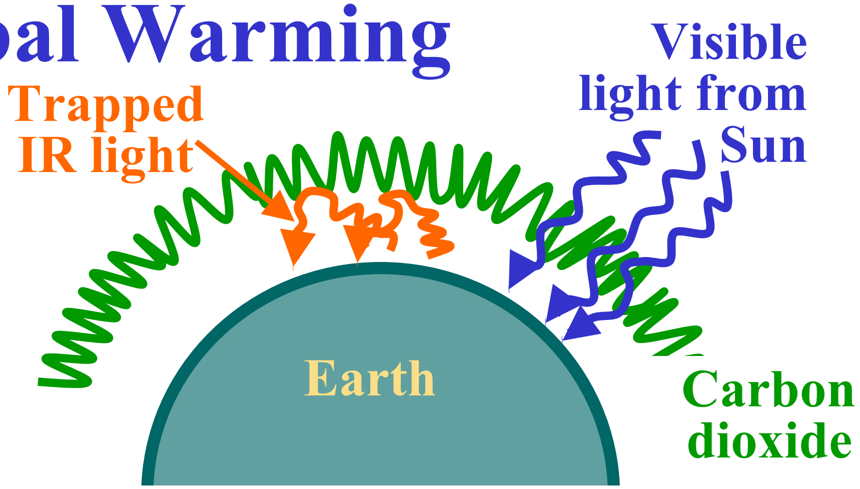
Recap: Greenhouse Effect

- Relies on fact that glass (or plastic) is transparent to visible radiation but **opaque** to infra-red (IR) radiation.
- E,g. Car window closed – visible radiation only transmitted. Car window open – you absorb visible, IR and ultra-violet radiation – get sun burnt!

Greenhouse: Glass traps air (and hence reduces convection). The air is then heated up by solar radiation… Steps:

1. Visible light passes through glass into greenhouse and is absorbed by soil, plants etc. (IR is reflected).
2. Soil heats up and emits IR radiation.
3. IR radiation is reflected back into greenhouse by glass walls and by the roof (its trapped!).
4. Radiation is absorbed by soil etc. and greenhouse heats up (until balanced by conduction loss at wall etc.).
5. Can get very high temperatures inside (on a sunny day) even if cold outside… Open windows to let heat escape (car too!).

Atmosphere: Global Warming



Main “greenhouse” gases

- The CO_2 and H_2O gases in atmosphere are opaque to IR radiation and hence trap heat in lower atmosphere.
- Carbon dioxide (CO_2) and water vapor (H_2O) are in large quantities in the atmosphere.
- CO_2 produced by volcanoes, burning fossil fuels etc. is moderated by plant absorption (and by oceans).
- Rise in CO_2 acts to trap heat which in turn will create more H_2O vapor and problem worsens!
- Produces overall increase in global temperature and much more varied and potentially violent weather.
- Could result on melting polar caps and consequent sea level rise … Also change in salinity can cause deep ocean currents (e.g. Gulf stream) to stop…e.g. causing Europe to **freeze** up in winter.

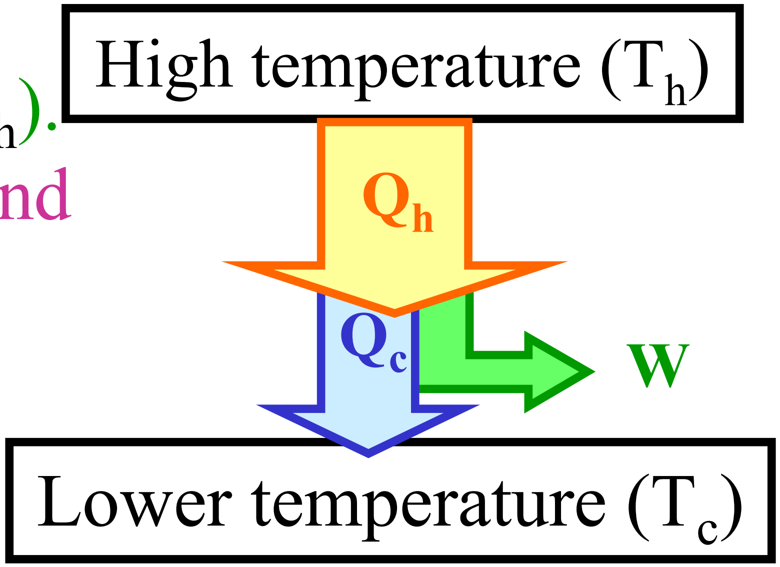
Heat Engines (Chapter 11)

Question: What is a heat engine?

Answer: A device that takes in energy from a warm source and converts a fraction of the thermal energy into mechanical energy (i.e. work).

- Heat engines are essential for our everyday life:
  - Steam engine (power stations)
  - Internal combustion engine (automobiles)
  - Jet engine (aircraft transportation)
  - Rocket motor (spacecraft)
  - Nuclear power / solar power / geothermal…
- Heat engines convert thermal energy into mechanical energy. But not all of the energy can be converted to perform useful work.

- A quantity of heat (Q_h) is taken from high temperature reservoir (T_h).
- Some is converted into work (W) and the rest of the heat (Q_c) is released into lower temperature sink (T_c).
- The high temperature reservoir is heated e.g. by fuel combustion, nuclear reactions, solar radiation.


High temperature (T_h)

Lower temperature (T_c)

- The lower temperature sink carries off waste heat that is not used for conversion into work (dumped into the environment).

  Example: Hot car exhausts, power station cooling towers, cooling fins /radiators…

  Qu: Why don’t we use the “waste” heat to do more work?

  Answer: Fundamental physical laws governing conversion of heat to work that require a fraction of heat from source to be rejected at a cooler temperature than source!
- This means heat engines **can never be 100% efficient**!

Efficiency of a Heat Engine

$$\text{Efficiency (e)} = \frac{\text{Work done}}{\text{Heat input into system}} = \left(\frac{W}{Q_h}\right)$$

W = Work done by engine on its surroundings (+ve)

Q_h = Quantity of heat taken from source to perform work.

- Engines usually function in **cycles** where the engine repeats the same process over and over.
- Efficiency is computed using the heat and work values for one (or several) complete cycles.
- Example: A heat engine takes 1500 J of energy from a high temperature source in each cycle and does 300 J of work in each cycle.

$$e = \frac{W}{Q_h} = \frac{300}{1500} = 0.2 \text{ or } 20\,\%$$

$Q_h = 1500$ J

$W = 300$ J

Result: Not very efficient (1200 J of energy lost) but this is typical of many engines.

Internal Energy (ΔU)

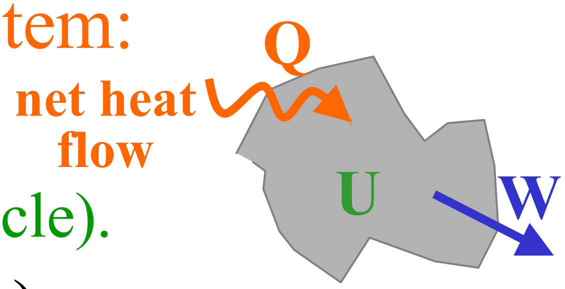
- As an engine returns to its initial state at the end of each cycle, its internal energy remains unchanged.

  i.e. the change in internal energy (ΔU) over one cycle is zero.

  $$\text{or} \quad \Delta U = 0$$

- However, the first law of thermodynamics states that the change in internal energy of a system equals the amount of heat added minus the work done by the system:

  $$\Delta U = Q_{net} - W_{out}$$



- For a heat engine ΔU = 0 (over 1 complete cycle).

  $$\text{Thus:} \; W = Q_{net} \quad \text{or} \quad W = (Q_{hot} - Q_{cold})$$

- Work done in one cycle equals the net heat flow into and out of engine (conservation of energy).

- Engine efficiency: $\mathbf{e = \frac{W}{Q_h} = \frac{Q_h - Q_c}{Q_h}}$ or $\mathbf{e = \left(1 - \frac{Q_c}{Q_h}\right) \times 100\ \%}$

Carnot Engine

- Sadie Carnot, France (early 19th century) developed an ideal heat engine (i.e. engine operation completely reversible).
- Carnot reasoned that greatest efficiency of a heat engine is given by taking in all of the input heat at a single high temperature and releasing **all** the unused heat at a single low temperature.
- This is analogous to a water wheel operation.
- Carnot determined that in an ideal heat engine the ratio of two energy terms is identical to the ratio of temperatures:

$$\frac{Q_{cold}}{Q_{hot}} = \frac{T_{cold}}{T_{hot}}$$ where **T** is in **Kelvin**

- The efficiency of an ideal (Carnot) engine is:

$$e_c = \left(1 - \frac{Q_c}{Q_h}\right) \quad \text{or} \quad e_c = \left(1 - \frac{T_c}{T_h}\right)$$

Carnot Engine

Results:

- The Carnot efficiency is the maximum possible efficiency for a heat engine.
- Remarkably, the efficiency only depends on the temperatures of the two reservoirs between which the heat engine operates!
- To obtain high engine efficiency it is therefore essential to operate with a large temperature difference as possible.

Consequences:

- Only a heat engine whose cold reservoir was at zero Kelvin or whose hot reservoir was infinite could operate at a 100 % efficiency.

Example: Maximum efficiency of a coal-fired power station?

- Carnot efficiency:

$$e_c = \left(1 - \frac{300}{823}\right) = 0.64$$

$T_{hot} = 550\ ^{o}C\ (823\ K)$
$T_{cold} = 27\ ^{o}C\ (300\ K)$

or $e_c = 64\ \%$

- Thus, 36% of heat is wasted by rejecting it through the large cooling towers into surrounding atmosphere.
- This represents maximum possible efficiency for this temperature difference.
- In practice the real efficiency is **somewhat lower**.
- Practical considerations:
  - limit maximum temperature (metal softening)
  - minimum temperature limited by nearby lake or river temperature.

Second Law of Thermodynamics

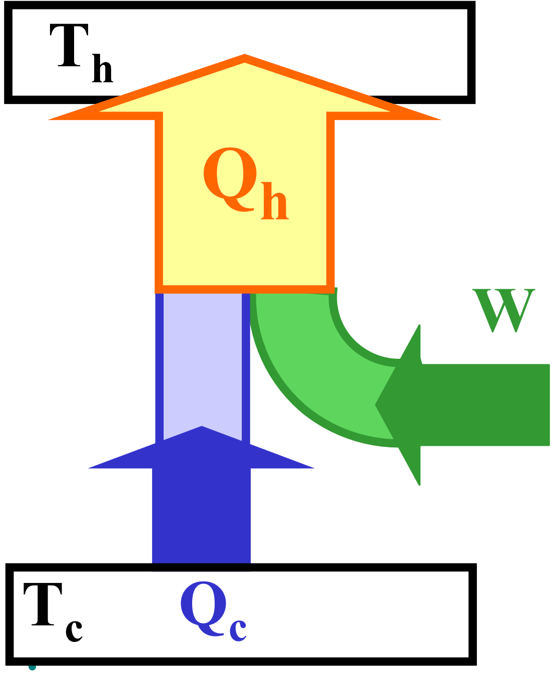
- Developed by Lord Kelvin, U.K. (19th century) – based on Carnot's work.

❖ **No engine, working in a continuous cycle, can take heat from a reservoir at a single temperature and convert it ALL to work.**

- This is a re-statement that no engine is 100 % efficient.
- The 2nd law also shows that no engine can have a greater efficiency than a Carnot engine operating between two given temperatures.
- Thus, a heat engine with an efficiency greater than Carnot engine (for that temperature difference) would violate 2nd law of thermodynamics.
- The 2nd law is a natural law (not derived from mathematics). It cannot be proven but in time has shown itself to be an accurate statement on heat transfer, heat engines and heat pumps.

Heat Pumps (Refrigerators)

- A refrigerator is a heat engine running in **reverse.**
- A refrigerator keeps food cold by pumping heat out of its colder interior into the warmer room.
- A refrigerator warms the room **considerably**.



- A pump (electric motor) does work on the "heat engine" causing heat to be removed from the lower temperature reservoir and deposited in the higher temperature reservoir.
- In doing so a **greater amount of heat** (Q_h) is **released** in the upper reservoir than taken from the lower reservoir.
- This does not violate laws of thermodynamics or conservation of energy (as diagram shows).

i.e. $\Delta U = 0$ and $\boxed{Q_h = Q_c + W}$ (work done **ON** system)

Clausius Statement of 2^{nd} Law of Thermodynamics

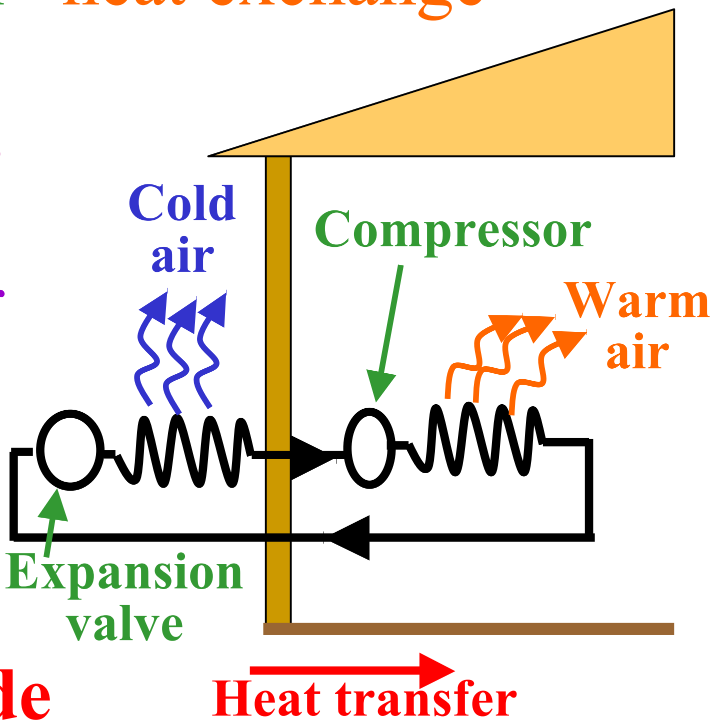
- **Heat will not flow from a cooler body to a hotter one unless another process (e.g. work) is involved.**

- Heat pumps are remarkable devices as the amount of heat transferred (pumped "uphill") can **far exceed** the work input (as $Q_h = W + Q_c$).
- Heat pumps can therefore deliver quantities of heat that are **several times** the amount of electric energy supplied as work!
- Coefficient of performance (COP) is ratio of heat delivered (Q_h) divided by work input (W):

$$\mathbf{COP} = \frac{Q_h}{W} = \frac{T_h}{T_h - T_c} \qquad \text{(T is in Kelvin)}$$

- The COP is therefore higher when T_h and T_c are similar (i.e. ΔT is not large.)
- If ($T_h - T_c$) is large requires more work to pump heat "uphill" to the hot reservoir. (Heat pumps are not good in Utah.)

- A heat pump uses two sets of coils for “heat exchange” between outside and inside air.
- Inside: Electric motor compresses gas raising temperature and pressure.
- Gas then condenses in heat exchanger giving off heat to inside room.
- Outside: liquid vaporizes as it passes through an expansion valve and takes in heat from surrounding air.



Net result: Cool outside, warm inside
(a refrigerator uses the same mechanism).

- If outside air temperature is too low (i.e. COP low) then we can use ground temperature at a few meters depth (or a river) for the cold reservoir to improve COP.
- Heat pumps can also be used as air conditioners in summer (more complex arrangement).
- COP is typically 3 for a practical system (i.e. 3 times more heat transferred than work done).

Power Plants

- Excluding hydroelectric and wind power, most electricity is generated from thermal power sources that use heat engines.

  Fossil fuel: power plant operates at high temperature (~ 500 to 600 ºC) with the lower temperature, below 100 ºC.

- Typical efficiency ~ 40 to 50 %. (So at best ~ 50% of fuel energy is lost to environment).
- Waste heat can be used for "space heat" (or agriculture) but not often as power stations distant from cities. (CO_2 waste).

  Nuclear power: less efficient ~ 30 to 40% (as upper temperature lower). No CO_2 emission but dangerous, long-lived, radioactive waste instead!

  Geothermal power: much less efficient as temperature difference smaller (typically 20 to 25 % efficient, $\Delta T \sim 150$ ºC) but clean and free!

  Ocean currents: temperature difference only ~ 20 ºC. Results in very low efficiency (~ 7 %), but clean and free!