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Heat Engines, Heat Pumps, and Refrigerators

Getting something useful from heat

(Many slides are from prof. Tom Murphy)

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But First: the Importance of Efficiency

- You almost always waste some of your energy, the amount that you get is determined by the efficiency:
- eff = (useful energy)/(total energy)
- Efficiency is always a number between 0 (all energy wasted) and 1 (no energy wasted) (i.e. 0% to 100%)
- Examples:
  - Electric motors have efficiency around 90% (eff = 0.9)
  - Photosynthesis has about 1% efficiency (eff~0.01)
  - Electric power plants have efficiencies between 25% and 40%
- Increasing efficiency is same as getting more energy!
- Why not increase all efficiencies to 100%?
  - Physics limit for all heat engines: Max eff = $1 - T_C/T_H$

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Heat *can* be useful

- Normally heat is the end-product of the flow/ transformation of energy
  - remember examples from lecture
  - heat regarded as waste: as useless end result
- Sometimes heat is what we *want*, though
  - hot water, cooking, space heating
  - In this case efficiency can be near 100%!
- Heat can *also* be coerced into performing "useful" (e.g., mechanical) work
  - this is called a "heat engine"

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Heat Engine Concept

- Any time a *temperature difference* exists between two bodies, there is a *potential* for *heat flow*
- Examples:
  - heat flows out of a hot pot of soup
  - heat flows into a cold drink
  - heat flows from the hot sand into your feet
- Rate of heat flow depends on nature of contact and *thermal conductivity* of materials
- If we're clever, we can channel some of this flow of energy into mechanical work

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Heat → Work

- We can see examples of heat energy producing other types of energy
  - Air over a hot car roof is lofted, gaining *kinetic energy*
  - That same air also gains *gravitational potential energy*
  - All of our *wind* is driven by temperature differences
  - Our electricity generation depends mostly on temperature *differences*: no steam in turbine would circulate if everything was at the same temperature; however hydroelectric plants don't use temp differences, instead use potential energy

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Power Plant Arrangement

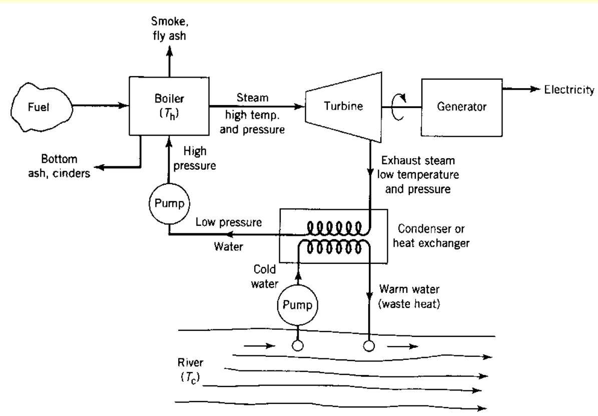

Figure 3.4 A diagram of a fuel-burning electric power plant. Here a river provides cooling water to the condenser, but lake water or a cooling tower could serve the same purpose.

Heat flows from T_h to T_c, turning turbine along the way

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Heat Engine Nomenclature

- The symbols we use to describe the heat engine are:
  - T_h is the temperature of the hot object
  - T_c is the temperature of the cold object
  - $\Delta T = T_h - T_c$ is the temperature *difference*
  - ΔQ_h is the amount of heat that flows out of the hot body
  - ΔQ_c is the amount of heat flowing into the cold body
  - ΔW is the amount of "useful" mechanical work
  - ΔS_h is the change in *entropy* of the hot body
  - ΔS_c is the change in entropy of the cold body
  - ΔS_{tot} is the total change in entropy (entire system)
  - ΔE is the entire amount of energy involved in the flow

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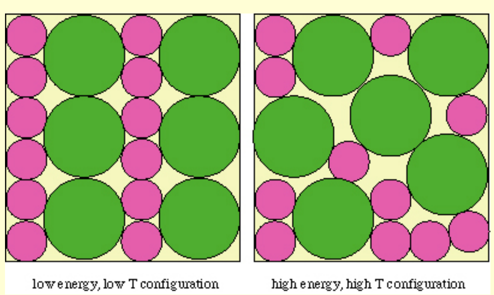
What's this *Entropy* business?

- Entropy is a measure of disorder (and actually quantifiable on an atom-by-atom basis)
  - Ice has low entropy, liquid water has more, steam has a lot



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The Laws of Thermodynamics

1. Energy is conserved
2. Total system entropy, S, can never decrease

$$\Delta S_{tot} >= 0$$

3. As the temperature goes to zero, the entropy approaches a constant value—this value is zero for a perfect crystal lattice

- The concept of the "total system" is very important: entropy can decrease locally, but it must increase elsewhere by *at least* as much
  - no energy flows into or out of the "total system": if it does, there's more to the system than you thought

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Quantifying heat energy

- We've already seen many examples of quantifying heat
  - 1 Calorie is the heat energy associated with raising 1 kg (1 liter) of water 1 ºC
  - In general, $\Delta Q = c_p m \Delta T$, where c_p is the heat capacity
- We need to also point out that a change in heat energy accompanies a change in entropy:

$$\Delta Q = T\Delta S$$

- Adding heat increases entropy
  - more energy goes into random motions→more randomness (entropy)

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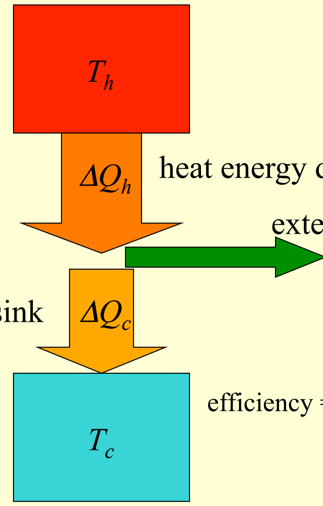
How much work can be extracted from heat?

Hot *source* of energy



heat energy delivered from source

externally delivered work:

$\Delta W = \Delta Q_h - \Delta Q_c$

conservation of energy

heat energy delivered to sink

Cold *sink* of energy

$$\text{efficiency} = \frac{\Delta W}{\Delta Q_h} = \frac{\text{work done}}{\text{heat supplied}}$$

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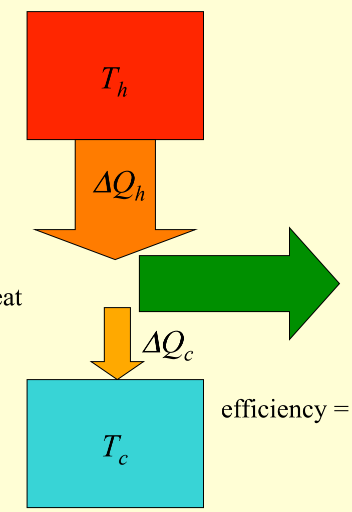
Let's crank up the efficiency

Let's extract a lot of work, and deliver very little heat to the sink



In fact, let's demand 100% efficiency by sending *no* heat to the sink: all converted to useful work

$\Delta W = \Delta Q_h - \Delta Q_c$

$$\text{efficiency} = \frac{\Delta W}{\Delta Q_h} = \frac{\text{work done}}{\text{heat supplied}}$$

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Not so fast…

- The second law of thermodynamics imposes a constraint on this reckless attitude: **total entropy must never decrease**
- The entropy of the source goes down (heat extracted), and the entropy of the sink goes up (heat added): remember that $\Delta Q = T\Delta S$
  - The gain in entropy in the sink must *at least* balance the loss of entropy in the source

$$\Delta S_{tot} = \Delta S_h + \Delta S_c = -\Delta Q_h/T_h + \Delta Q_c/T_c \geq 0$$

$\Delta Q_c \geq (T_c/T_h)\Delta Q_h$ sets a minimum on ΔQ_c

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What does this entropy limit mean?

- $\Delta W = \Delta Q_h - \Delta Q_c$, so ΔW can only be as big as the minimum ΔQ_c will allow

$$\Delta W_{max} = \Delta Q_h - \Delta Q_{c,min} = \Delta Q_h - \Delta Q_h(T_c/T_h) = \Delta Q_h(1 - T_c/T_h)$$

- So the maximum efficiency is:

maximum efficiency $= \Delta W_{max}/\Delta Q_h = (1 - T_c/T_h) = (T_h - T_c)/T_h$

this and similar formulas *must* have the temperature in Kelvin

(THIS IS CALLED THE CARNOT EFFICIENCY

$$\text{Carnot Eff} = (T_h - T_c)/T_h$$

$$= 1 - T_h/T_c$$

- So perfect efficiency is only possible if T_c is zero (in ºK)
  - In general, this is not true
- As $T_c \rightarrow T_h$, the efficiency drops to zero: no work can be extracted; there must be a temperature DIFFERENCE

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Examples of Maximum Efficiency

- A coal fire burning at 825 ºK delivers heat energy to a reservoir at 300 ºK
  - max efficiency is (825 – 300)/825 = 525/825 = 64%
  - this power station can not possibly achieve a higher efficiency based on these temperatures
- A car engine running at 400 ºK delivers heat energy to the ambient 290 ºK air
  - max efficiency is (400 – 290)/400 = 110/400 = 27.5%
  - not too far from reality

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Example efficiencies of power plants

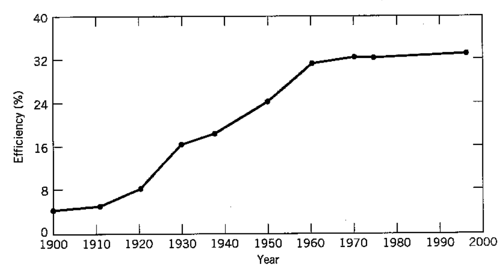

Figure 3.5 Typical efficiency of an electric power plant for converting chemical energy in the fuel into electric energy. The best new plants now achieve nearly 40%. (*Source:* Delbert W. Devins, *Energy: Its Physical Impact on the Environment*, John Wiley and Sons, New York, 1982; and U. S. Energy Information Administration, *Electric Power Annual*, 1996, Volume I.)

Power plants these days (almost all of which are heat-engines) typically get no better than 33% overall efficiency

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Types of heat engines

- External combustion engine
- Internal combustion engine (gas/diesel)
- Gas turbine (aka jet engine)
- rocket

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What to do with the waste heat (ΔQ_c)?

- One option: use it for space-heating locally (called co-generation)

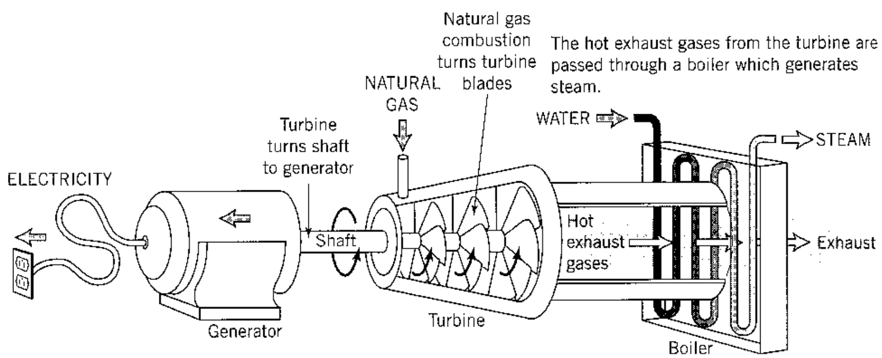

Figure 3.13 A small cogeneration plant that uses the combustion of natural gas to drive a gas turbine coupled to an electric generator. The hot exhaust gases boil water to steam for use in space heating and cooling. (*Source*: Exxon Corporation.)

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Overall efficiency greatly enhanced by cogeneration

Table 3.1 Cogeneration Plant, University of Colorado, Boulder

Fuel	Natural gas
Engine	2 Mitsubishi industrial gas turbines
Generating capacity	32 MW_e
Capital investment	$41,000,000
Construction started	1990
System lifetime	40 to 50 years
Estimated payback time	15 years
Average exported electric power	8 MW_e
Cost of electricity produced	$0.024/kWh
Price of electricity sold	$0.047/kWh
Annual income from electricity sales	$1,600,000
Cost of electricity from public utility	$0.068/kWh
Efficiency for producing electricity	34%
Overall efficiency	70%

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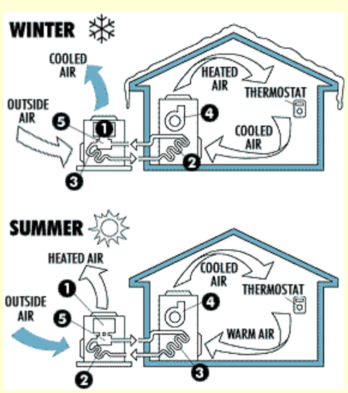
Heat Pumps



Heat Pumps provide a means to very efficiently move heat around, and work both in the winter and the summer

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Heat Pump Diagram

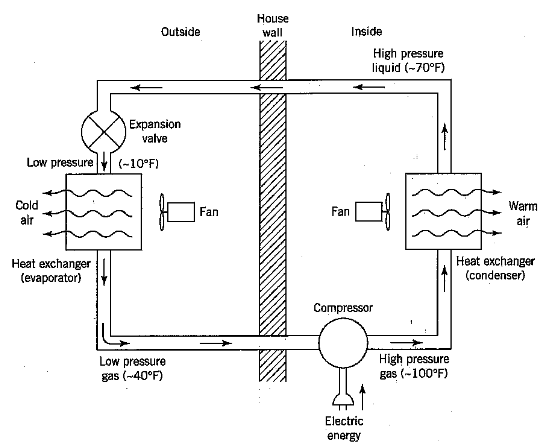

Figure 3.12 An electrically driven heat pump using Freon as a working fluid. In principle, the system becomes an air conditioner if the fluid flow direction is reversed. In practice, the reversal of function is more complex.

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Heat Pumps and Refrigerators: Thermodynamics

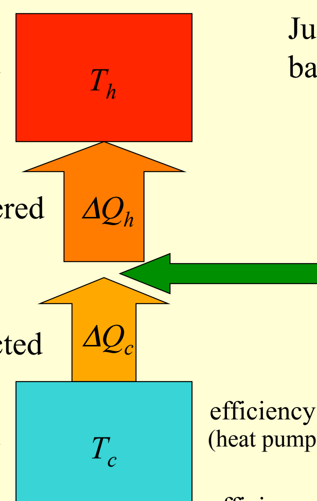
Just a heat engine run backwards…

Hot entity (indoor air)

heat energy delivered

heat energy extracted

Cold entity (outside air or refrigerator)



delivered work:

$\Delta W = \Delta Q_h - \Delta Q_c$

conservation of energy

efficiency (heat pump) $= \dfrac{\Delta Q_h}{\Delta W} = \dfrac{\text{heat delivered}}{\text{work done}}$

efficiency (refrigerator) $= \dfrac{\Delta Q_c}{\Delta W} = \dfrac{\text{heat extracted}}{\text{work done}}$

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Heat Pump/Refrigerator Efficiencies

- Can work through same sort of logic as before to see that:
  - heat pump efficiency is: $T_h/(T_h - T_c) = T_h/\Delta T$ in ºK
  - refrigerator efficiency is: $T_c/(T_h - T_c) = T_c/\Delta T$ in ºK
- Note that heat pumps and refrigerators are most efficient for small temperature differences
  - hard on heat pumps in very cold climates
  - hard on refrigerators in hot settings

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Example Efficiencies

- A heat pump maintaining 20 ºC when it is –5 ºC outside has a maximum possible efficiency of:

  293/25 = 11.72
  - note that this means you can get almost 12 times the heat energy than you are supplying in the form of work!
  - this factor is called the C.O.P. (coefficient of performance)
- A freezer maintaining –5 ºC in a 20 ºC room has a maximum possible efficiency of:

  268/25 = 10.72
  - called EER (energy efficiency ratio)

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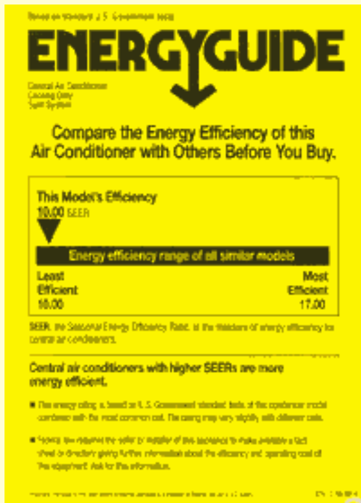
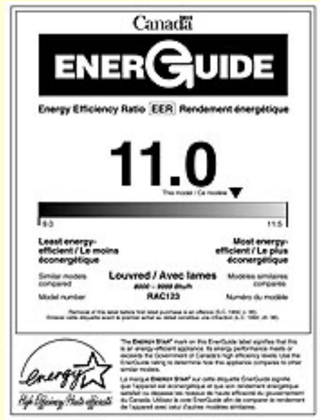
Example Labels (U.S. & Canada)





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Participation Question (write on piece of paper with name and hand in)

1. A windmill puts out 1000 Watts of electrical power. It is used to run a motor at 90% efficiency which lifts an elevator system which has 80% efficiency? How much energy is finally given to lifting after 10 seconds of operating?

- A. 7200 Joules
- B. 10000 Joules
- C. 720 Watts
- D. None of the above
- E. Can't be calculated from these numbers

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Participation Question (write on piece of paper with name and hand in)

1. If you open the door of your refrigerator and leave it open, the kitchen will

A. Slowly cool down
B. Slowly heat up
C. Stay the same temperature
D. Can't say from this info; depends upon EER