Physics 121, April 29, 2008.
The Second Law of Thermodynamics.

http://www.horizons.uc.edu/MasterJuly1998/oncampus.htm

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Physics 121.
April 29, 2008.

- Course Information
- Topics to be discussed today:
  - The Second Law of Thermodynamics
  - Applications of the Second Law - the Carnot Engine
  - Entropy
- The End!

Physics 121.
April 29, 2008.

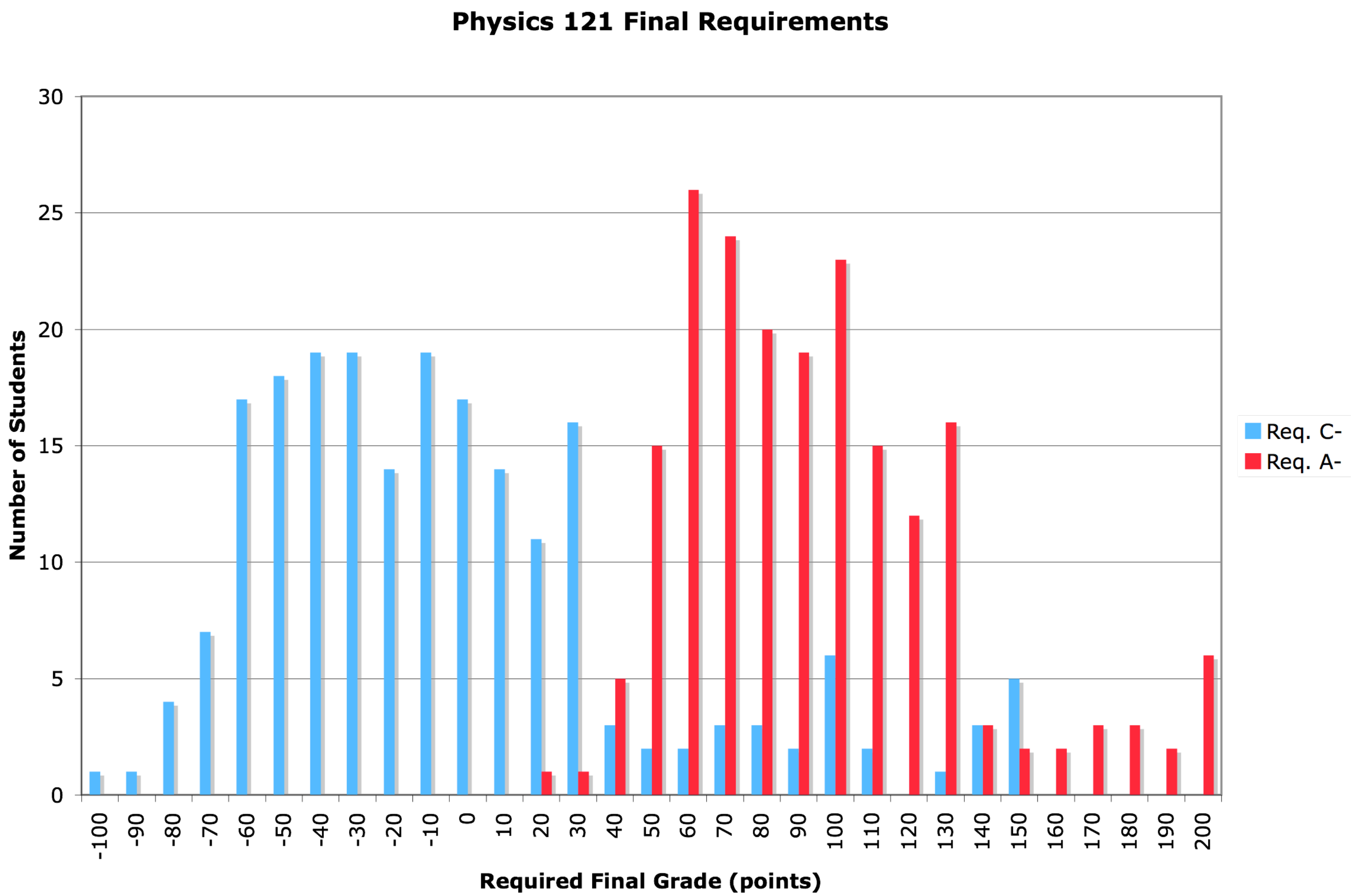
- Homework set # 10 is now available and is due on Wednesday evening, April 30, at 11.30 pm.

- Exam # 3 will be returned in workshops.

- Any complaints about Exam # 3 must be addressed by me; please write down why you feel the exam was not graded properly and hand it to me before next Monday, May 5. I will do the re-grading on Tuesday morning, May 6.

- I have distributed information about the score you need to obtain on the final exam to get a C-, a B-, and an A- in this course.

Physics 121.
Grade Requirements.

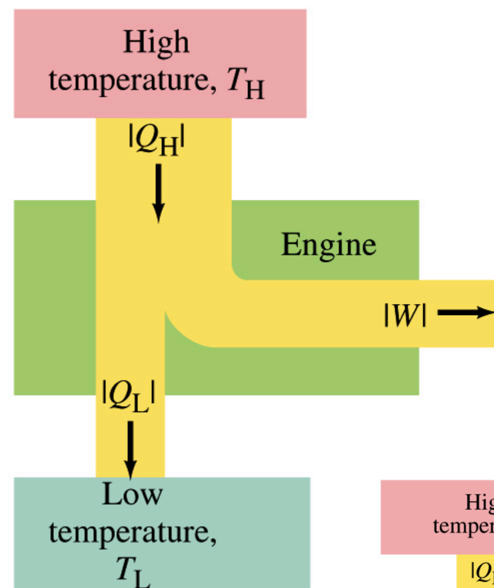


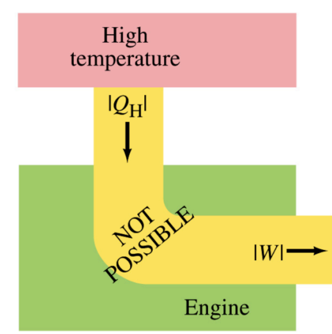
Physics 121.
Final Exam - Details.

- The final exam will be held on Thursday May 8 between 4 pm and 7 pm in Hubbell. The final exam will cover all the material discussed in the course; there will be NO particular focus on thermodynamics. **NOTE: no error analysis.**
- Extra office hours of the TAs and me will be announced via email later this week.
- The formula sheet to be attached to the final exam will be distributed via email by the end of the weekend, and will also be available on the WEB.
- Please use all the resources at your disposal to prepare for the exam (e.g. the detailed solutions of previous exams, the homework assignments, the study guide, etc.).
- The final exam grades will be distributed via email on Monday May 12.

Second law of thermodynamics.

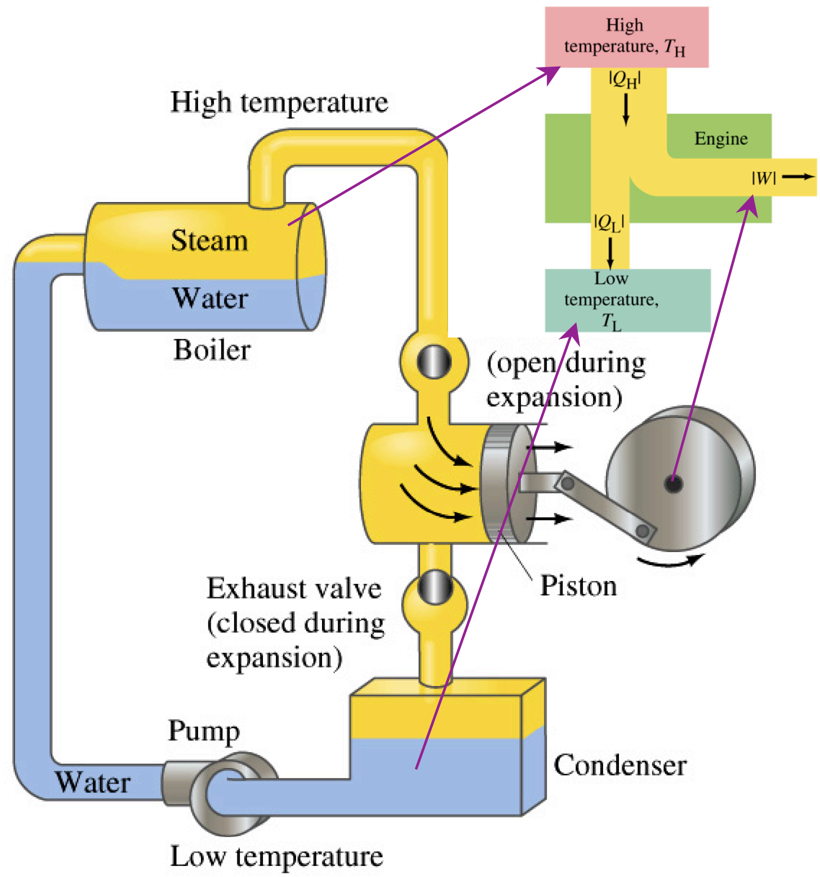
- There are several different forms of the second law of thermodynamics:
    - It is not possible to completely change heat into work with no other change taking place.
    - Heat flows naturally from a hot object to a cold object; heat will not flow spontaneously from a cold object to a hot object.
- Many naturally processes do not violate conservation of energy when executed in reverse, but would violate the second law.





Second law of thermodynamics. Heat engines.

- Most engines rely on a temperature difference to operate.
- Let's understand why:
  - The steam pushes the piston to the right and does work on the piston:
    $$W_{in} = nRT_{in}(1 - V_{in}/V_{out})$$
  - To remove the steam, the piston has to do work on the steam:
    $$W_{out} = nRT_{out}(1 - V_{out}/V_{in})$$
  - If $T_{in} = T_{out}$: $W_{in} + W_{out} = 0$ (no net work is done).
  - In order to do work $T_{in} > T_{out}$ and we must thus cool the steam before compression starts.



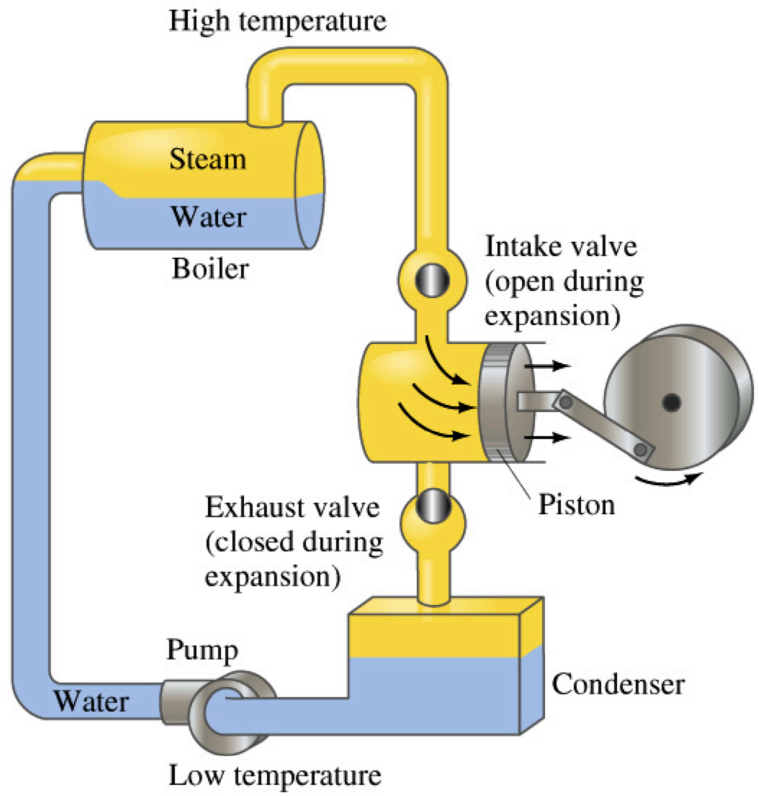
(a) Reciprocating type

Second law of thermodynamics. Heat engines.

- The efficiency of an engine is defined as the ratio of the heat extracted from the hot reservoir and the work done:

$$\text{Efficiency} = |W| / |Q_H|$$

- The work done and the heat extracted are usually measured per engine cycle.
- Because of the second law, no engine can have a 100% efficiency!
- Note: the cost of operation does not only depend on the cost of maintaining the high temperature reservoir, but may also include the cost of maintaining the cold temperature reservoir.

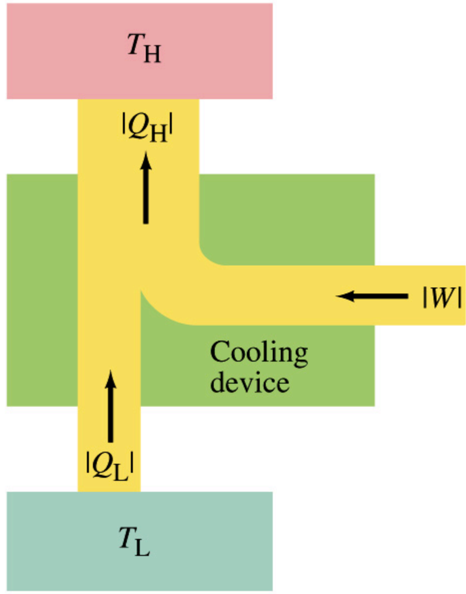


(a) Reciprocating type

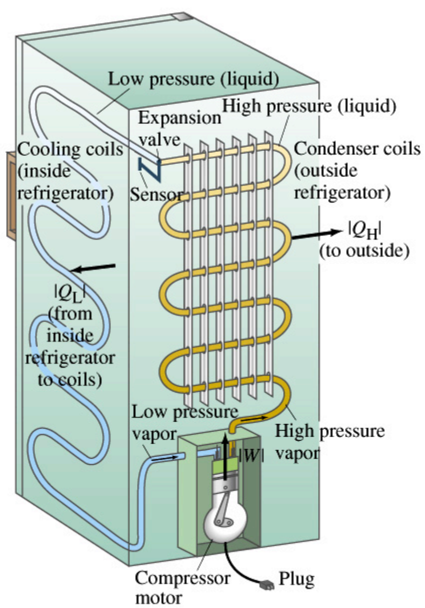
Second law of thermodynamics. Heat pumps.

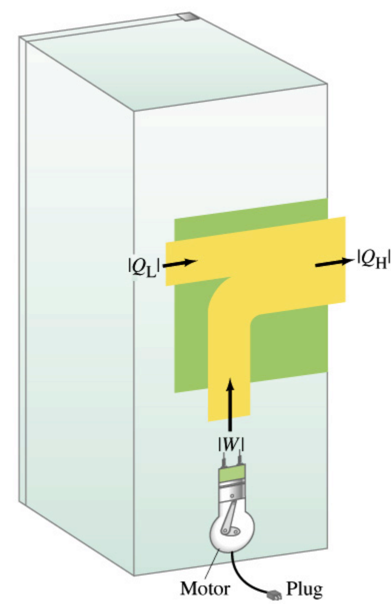
- In many cases (heat engines), the conversion of flow of heat to work is the primary purpose of the engine (e.g. the car engine).
- In many other applications (heat pumps), work is converted to a flow of heat (e.g. air conditioning).
- The performance of a heat pump is usually specified by providing the coefficient of performance K:

$$K = |Q_L| / |W|$$



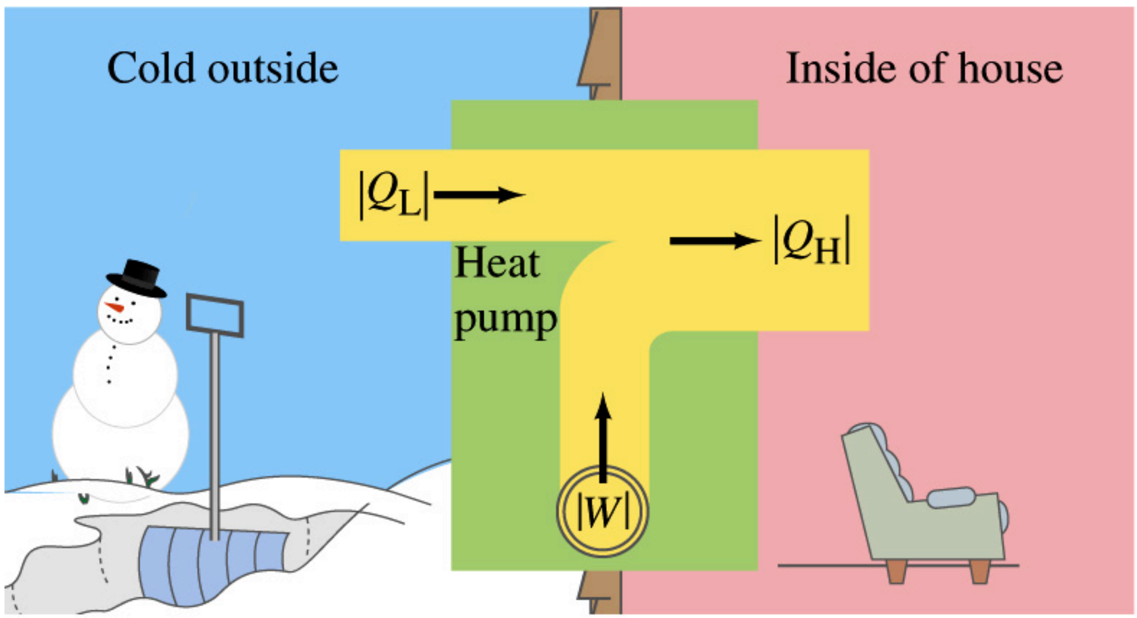
Second law of thermodynamics. Heat pumps.





Note: you can not cool your house by opening the door of your refrigerator!

Second law of thermodynamics. Heat pumps.

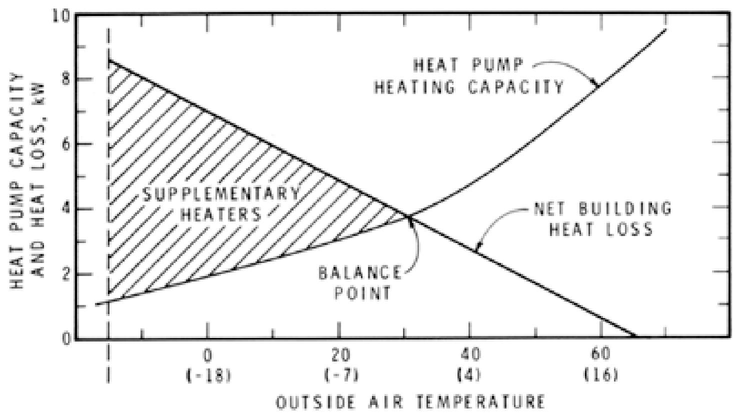


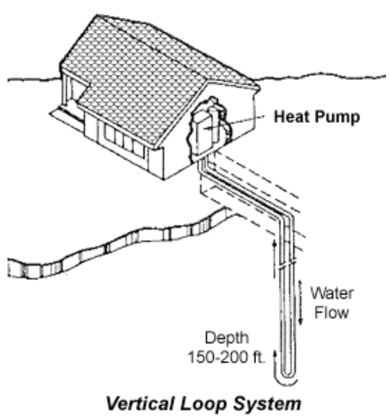
Note: You usually pay for the work done but not for the heat extracted from the outside. You can thus get more energy than what you pay for!

Second law of thermodynamics. Heat pumps.

- Heat pumps:
  - The heat capacity increases with increasing outside temperature.
  - Additional heaters may be required in colder climates.
  - The heat capacity can also be increased by changing the source of heat from the air to the ground.

http://irc.nrc-cnrc.gc.ca/cbd/cbd195e.html

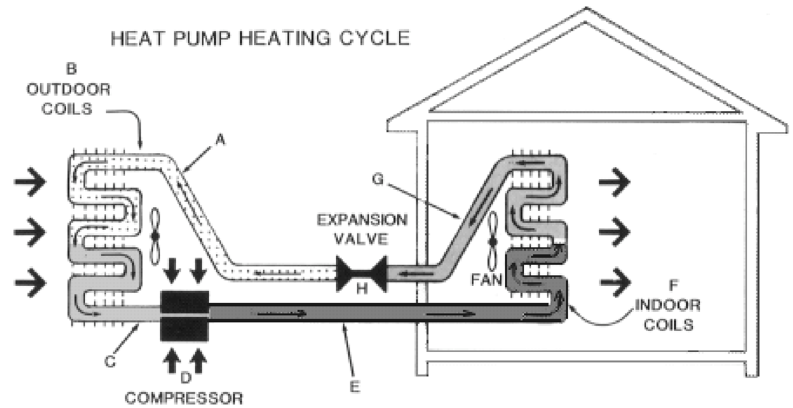


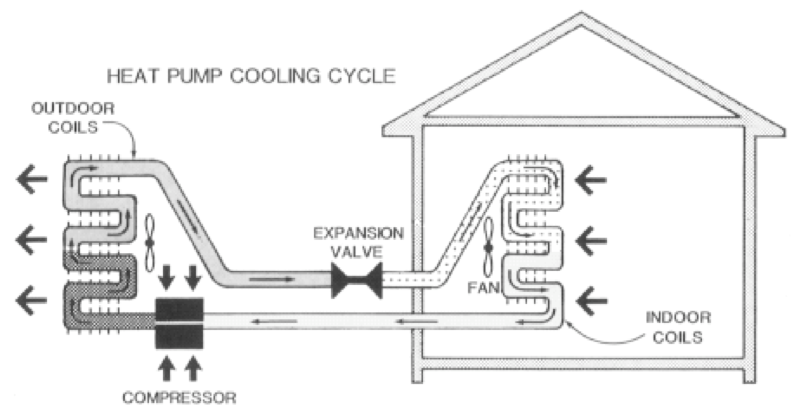


http://www.bchydro.com/powersmart/elibrary/elibrary685.html

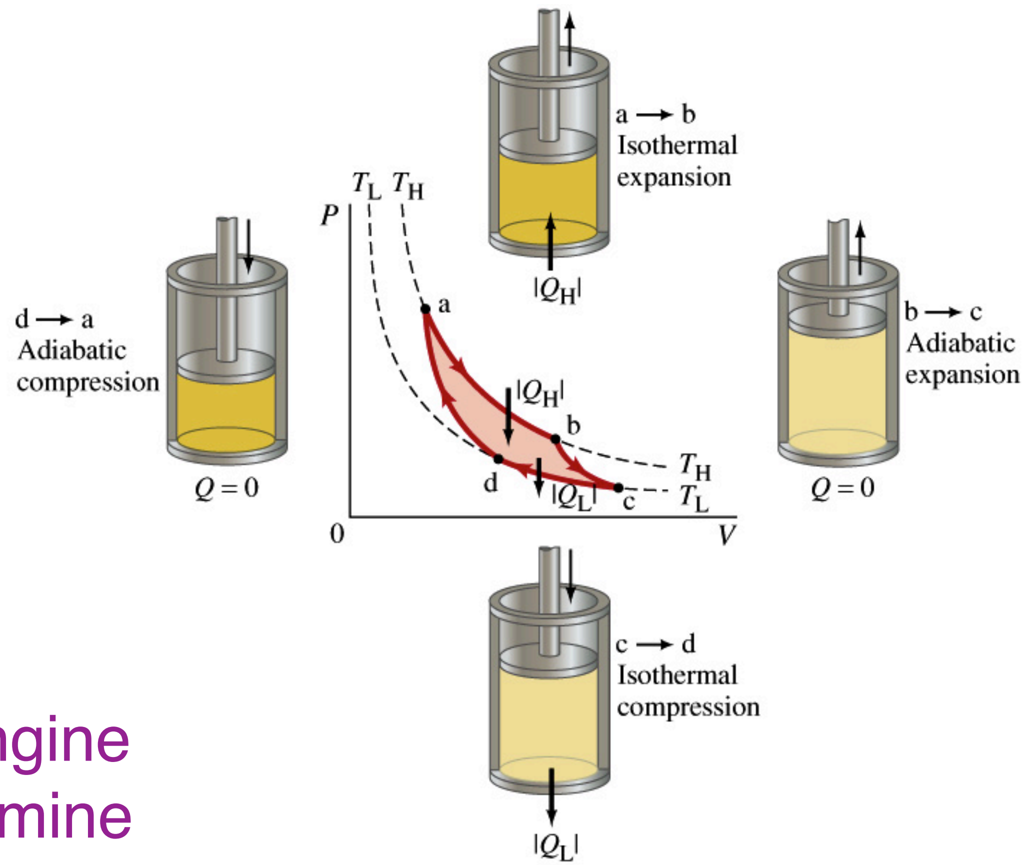
Second law of thermodynamics.
Heat pumps.

- Heat pumps:
  - Heaters in the winter: take heat from the outside to the inside.
  - Air conditioners in the summer: take heat from the inside to the outside.





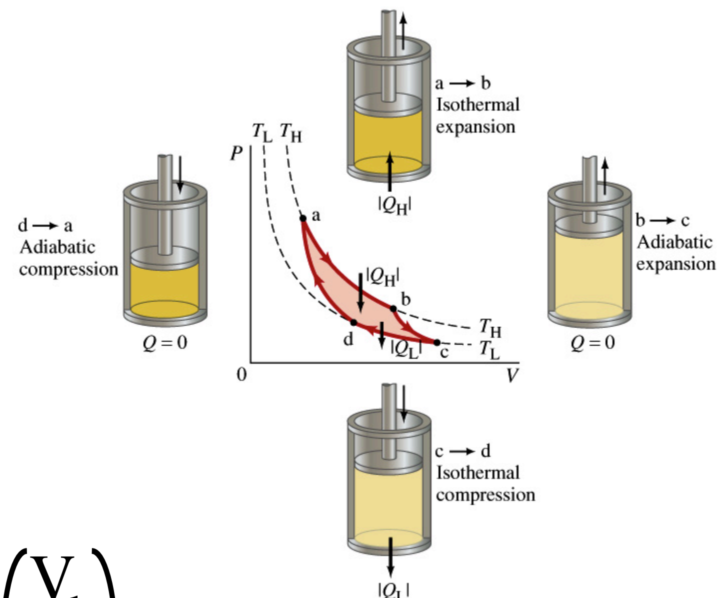
Second Law of Thermodynamics. The Carnot Cycle.



A "perfect" engine used to determine the limits on efficiency.

Second Law of Thermodynamics. The Carnot Cycle.

- Step 1: a to b.
  - The gas is in contact with a heat bath at temperature T_H and weight is removed from the piston.
  - The gas expands, while maintaining a constant temperature (the change in the internal energy is thus equal to 0 J).
  - Using the first law of thermodynamics we see that

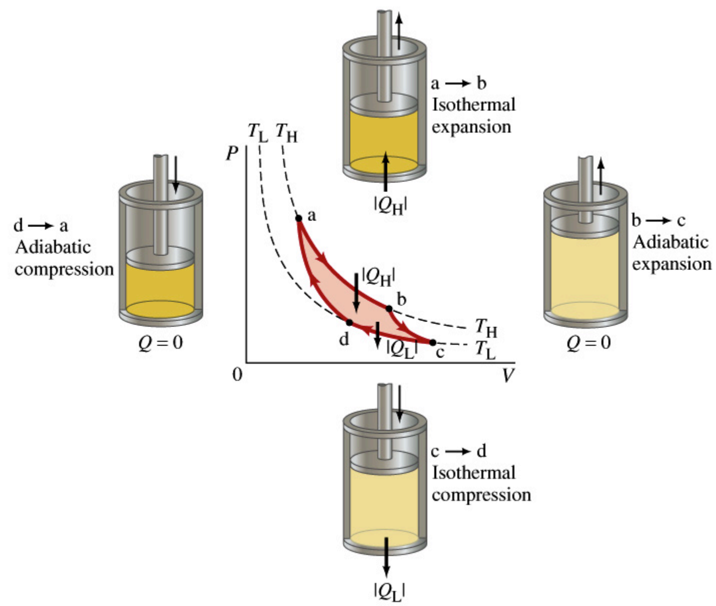


$$\left|Q_H\right| = \left|W_H\right| = n\,R\,T_H \ln\left(\frac{V_b}{V_a}\right)$$

Second Law of Thermodynamics. The Carnot Cycle.

- Step 2: b to c.
  - The gas is isolated from the environment and some more weight is removed from the piston.
  - The gas expands and during the adiabatic expansion, the temperature of the gas will decrease.
  - For adiabatic expansion pV^{γ} is constant, and we can thus related state b to state c:

$$T_H V_b^{\gamma-1} = T_C V_c^{\gamma-1}$$



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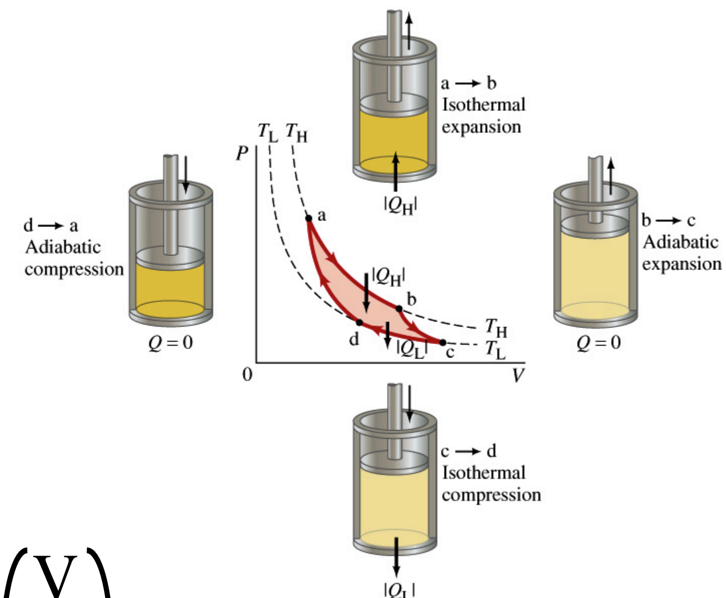
Second Law of Thermodynamics. The Carnot Cycle.

- Step 3: c to d.
  - The gas is in contact with a heat bath at temperature T_C and weight is added to the piston.
  - The gas is compressed, while maintaining a constant temperature (the change in the internal energy is thus equal to 0 J).
  - Using the first law of thermodynamics we see that

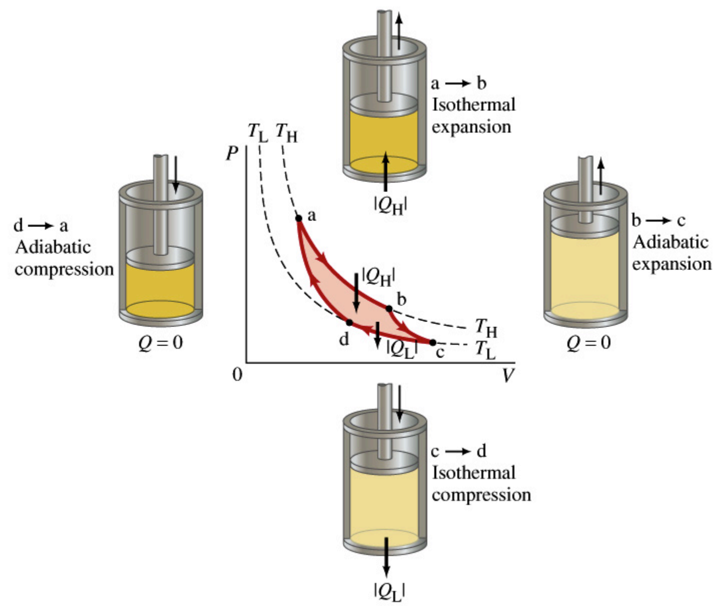


$$\left| Q_c \right| = \left| W_c \right| = n\,R\,T_C \ln\left(\frac{V_c}{V_d}\right)$$

Second Law of Thermodynamics. The Carnot Cycle.

- Step 4: d to a.
  - The gas is isolated from the environment and some more weight is added to the piston.
  - The gas is compressed and during the adiabatic compression, the temperature of the gas will increase.
  - For adiabatic expansion pV^{γ} is constant, and we can thus related state b to state c:

$$T_H V_a^{\gamma-1} = T_C V_d^{\gamma-1}$$



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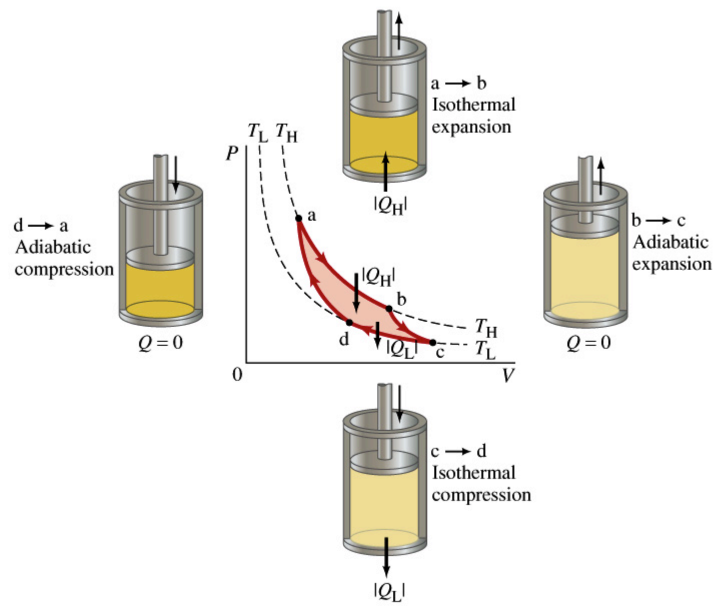
Second Law of Thermodynamics. The Carnot Cycle.

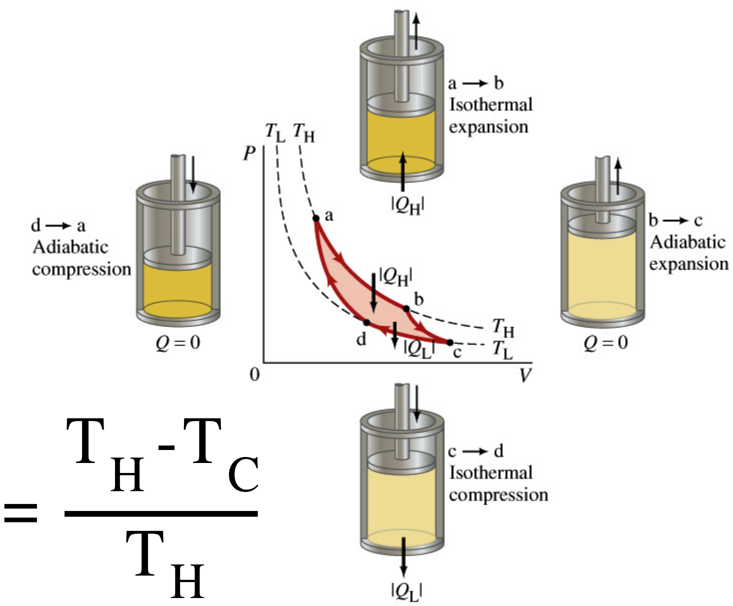
- The adiabatic expansion and compression steps can be used to show that $V_b/V_a = V_c/V_d$.
- This relation between the volumes is very useful since it allows us to determine the ratio of the heat flows:

$$\frac{|Q_H|}{|Q_C|} = \frac{T_H \ln\left(\frac{V_b}{V_a}\right)}{T_C \ln\left(\frac{V_c}{V_d}\right)} = \frac{T_H}{T_C}$$



Second Law of Thermodynamics. The Carnot Cycle.

- The efficiency of the Carnot cycle can now be determined.
- Note that the work done by the Carnot engine is the difference between the heat extracted from the hot reservoir and the heat dumped in the cold reservoir:



$$e = \frac{|Q_H| - |Q_C|}{|Q_H|} = 1 - \frac{T_C}{T_H} = \frac{T_H - T_C}{T_H}$$

Second Law of Thermodynamics.
The Carnot Cycle.

- If we look at the efficiency of the Carnot cycle:

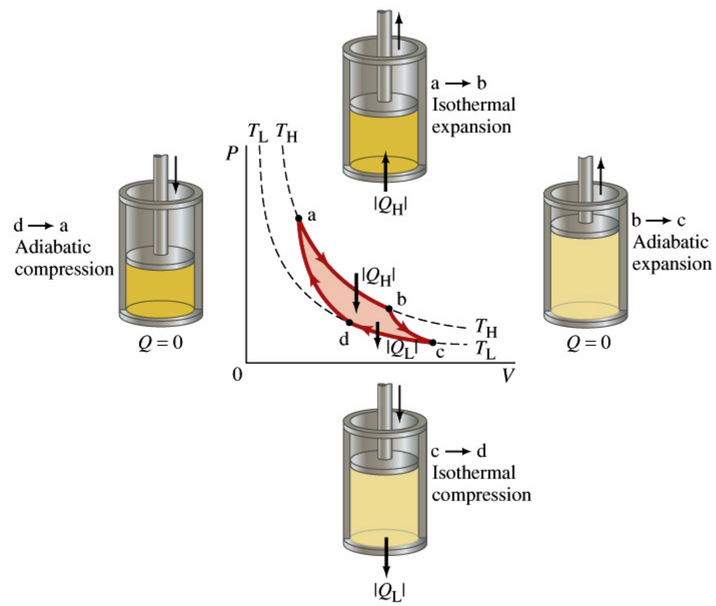
$$e = \frac{\left|Q_H\right| - \left|Q_C\right|}{\left|Q_H\right|} = 1 - \frac{T_C}{T_H} = \frac{T_H - T_C}{T_H}$$

  you see that the efficiency improves when the temperature difference between the hot and the cold bath increases. This is why it sometimes pays to increase the cooling of your engine!

- Carnot's theorem tells us that no real engine can have an efficiency more than that of the Carnot engine.

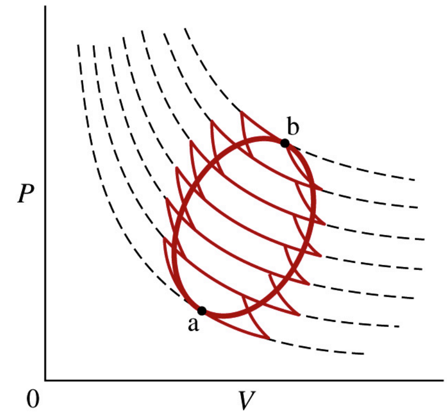
Second Law of Thermodynamics. The Carnot Cycle.

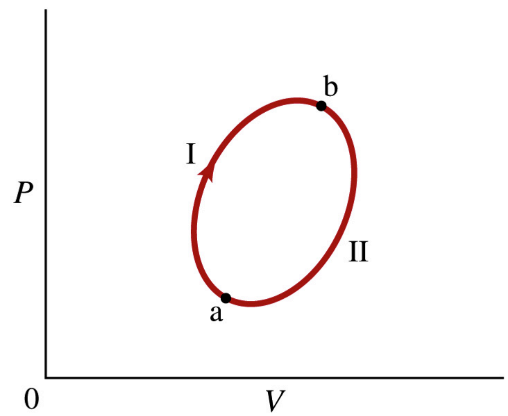
- The Carnot cycle is an example of a reversible process, which is a process that can be done in reverse.
- A reversible process requires that any changes are made infinitely slowly.
- Real processes are not reversible due to for example friction , turbulence in the gas, etc.



Entropy.

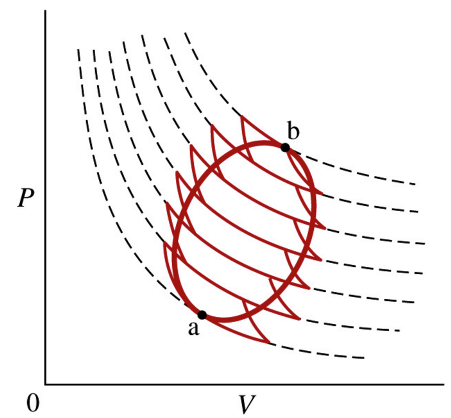
- Our study of the Carnot cycle showed that $Q_H/T_H + Q_L/T_L = 0$.
- Since any reversible cycle can be approximated by a series of Carnot cycles, we expect that the integral of dQ/T along the closed path of the cycle is 0 J.
- One consequence is that the integral of dQ/T between a and b is independent of the path.
- The quantity dQ/T is called the entropy dS.
- The entropy difference between a and b is thus path independent, and entropy is a state variable.

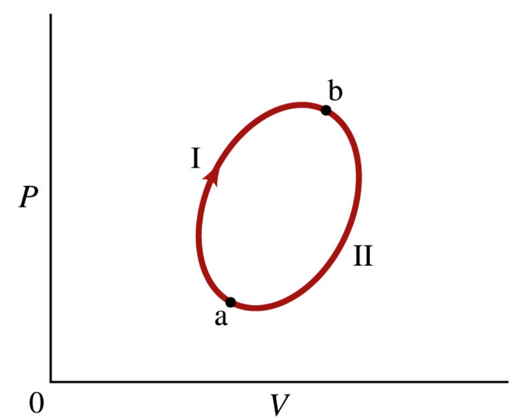




Entropy.

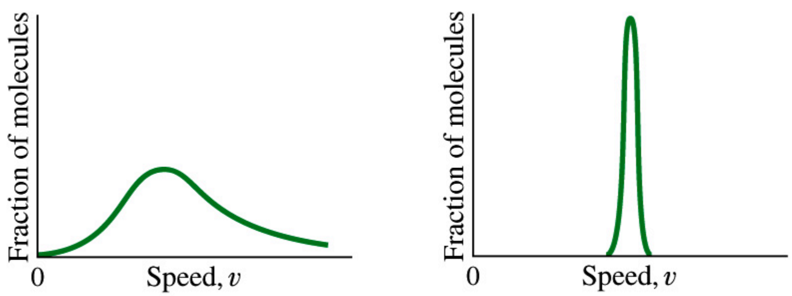
- Entropy is a state variable, but Q and W are not state variables since they depend on the path used to get from a to b.
- For a reversible process, the change in the entropy of the engine is opposite to the change in entropy of the environment that provides the heat required (or absorbs the heat generated). The net change in the total entropy is thus 0 J/K.
- For an irreversible process, the net change in the total entropy will be larger than 0 J/K.





Entropy and the Second Law of Thermodynamics.

- We can express the second law of thermodynamic can be expressed in terms of entropy:
  - The entropy of an isolated system will never decrease. It either stays the same (reversible process) or increases (irreversible process).
  - Natural processes tend to move toward a state of greater disorder.



(a) (b)

Physics 121.
Do you violate the second law?

- During the past 4 months, your brain hopefully has absorbed much of what I have covered, and concepts associated with mechanics should be in a much more ordered state in your brain on May 8 compared to their order on January 17.

- Do you violate the second law by going from disorder to order?

- Not if you include the disorder you dumped into your environment due to sweating over the exams and homework assignments. If you include that disorder, this course has a resulted in a greater disorder in our Universe (since clearly the impact of Physics 121 is irreversible).

Physics 121. The End.
You are free (and so am I)!