Physics 115
General Physics II

Session 14

Real Cycles
Entropy
Electricity

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Lecture Schedule
(up to exam 2)

21-Apr	Mon	12	Specific Heats, Second Law	18.4-18.6
22-Apr	Tues	13	Entropy	18.7-18.10
24-Apr	Thurs	14	Charges	19.1-19.3
25-Apr	Fri	15	E field	19.4-19.5
28-Apr	Mon	16	Conductors	19.6
29-Apr	Tues	17	Gauss law	19.7
1-May	Thurs	18	Electrical potential	20.1-20.3
2-May	Fri	19	Potential, conductors	20.4
5-May	Mon	20	Capacitors	20.5-20.6
6-May	Tues	21	Current	21.1-21.2
8-May	Thurs	22	Power, Series & Parallel Circuits	21.3-21.4
9-May	**Fri**		**EXAM 2 - Ch. 18,19,20**	

Today

(We're about ½ day behind, will catch up...)

Announcements

- Exam grades are on Catalyst Gradebook now
  - If you wanted to pick up your exam (handout) paper, pls do so today or tomorrow: outside my office (B-303 PAB)
- Clarifications:
  - Only your best 2 out of 3 mid-term exam scores will count
  - Only your best **7*** out of 9 HW scores will count
  - Only your best 10 out of 15 (or more) quizzes will count
    - SO: No makeups/delays/redo's for any of these
  - "Curve" is applied to sums of scores, individual exams do not have letter grades applied

* By popular demand...

Last time

Carnot's theorem

- For any T_H and T_C , maximum efficiency possible is for an engine with all processes reversible
- All reversible engines operating between the same T_H and T_C have the same efficiency ε

Notice: says *nothing* about working fluid, cycle path, etc

- Since ε depends only on T's, Q's must be proportional

$$\varepsilon = 1 - \frac{Q_C}{Q_H} \Rightarrow \boxed{\frac{Q_C}{Q_H} = \frac{T_C}{T_H}} \rightarrow \varepsilon = 1 - \frac{T_C}{T_H}$$

Yet another way to define T : Ratio of exhaust / input Qs

- – Carnot efficiency tell us the maximum work we can get per Joule of energy in:

$$\varepsilon = \frac{W}{Q_H} \rightarrow W = \varepsilon Q_H \rightarrow W_{MAX} = \varepsilon_{MAX} Q_H = \left(1 - \frac{T_C}{T_H}\right) Q_H$$

2^{nd} Law of thermodynamics

- When objects of different T are in thermal contact, *spontaneous* heat flow is only from higher T to lower T only – never the reverse

There are many different ways to say the same thing:

Kelvin's Statement:

No system can absorb heat from a single reservoir and convert it entirely to work without additional net changes in the system or its surroundings.

Clausius' Statement:

A process whose only net result is to absorb heat from a cold reservoir and release the same amount of heat to a hot reservoir is impossible.

Basic idea: of all possible processes that conserve energy, *only some* can actually occur; without external help, heat never flows from cold to hot regions!

Also: cannot reach 100% efficiency in any thermodynamic process

1^{st} law: there is no free lunch! 2^{nd} law: you can't even break even!

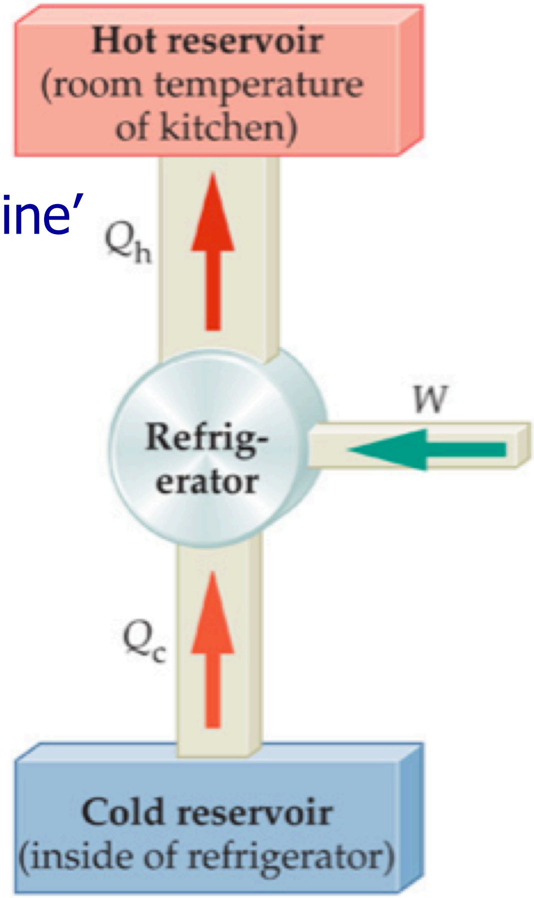
Run a heat engine backwards, and you get...

- Refrigerator = heat engine in reverse
  - Move heat from cold to hot location
  - Bad news: To do this must do work **on** the 'engine'
    - Must exhaust more heat than we removed
  - Energy conservation: $Q_H = Q_C + W_{IN}$
  - Good news: can be very efficient
  - For refrigerators (heat pumps), what matters is

    heat removed vs work done
    - Carnot efficiency is not relevant
    - But Carnot Q / T relationship still applies:

$$Carnot: \frac{Q_C}{Q_H} = \frac{T_C}{T_H} \rightarrow W = Q_H - Q_C = Q_H\left(1 - \frac{Q_C}{Q_H}\right) = Q_H\left(1 - \frac{T_C}{T_H}\right)$$

  - Benefit/cost = (Heat removed from T_C) / W
    - Define 'coefficient of performance' : $COP = Q_C / W_{IN}$



Refrigerator

- Example:

We want T_C =5 C =278 K, and T_H =room temp = 293 K

Refrigerator walls leak in 100 J/sec (100W) from room

What is the minimum possible power the refrigerator motor must supply?

$$\frac{Q_C}{Q_H}=\frac{T_C}{T_H}\rightarrow Q_H=Q_C\frac{T_H}{T_C}\rightarrow W_{MIN}=Q_H\left(1-\frac{T_C}{T_H}\right)=Q_C\left(\frac{T_H}{T_C}-1\right)$$

We must remove $Q_C=100J$ each second, so in one second

$$W_{MIN}=100J\left[\left(\frac{293K}{278K}\right)-1\right]=105.3J\rightarrow W_{MIN,per\sec}=5.3J\quad(5.3W)$$

That's for an ideal, *reversible* Carnot refrigerator

Reality: Typical home refrigerator has COP = 4 $\boxed{COP=Q_C/W_{IN}}$

So power required W= Q_C / COP = 100W/4 = 25W

Notice: not much work is required to push Q backwards

Entropy

- From Carnot's theorem we get

$$\frac{Q_C}{Q_H} = \frac{T_C}{T_H} \rightarrow \frac{Q_C}{T_C} = \frac{Q_H}{T_H} \Rightarrow \boxed{\frac{Q_T}{T} = const,} \text{ for ideal, reversible Carnot engine}$$

- Rudolf Clausius (Germany, 1865): define a new thermodynamic state variable – *entropy* S

$$\Delta S = \frac{\Delta Q_T}{T}, \quad \Delta Q_T = \text{heat transferred at temperature T}$$

  - This is change in entropy for heat transferred reversibly at T
  - Entropy increases for Q > 0 → heat *into* system, decreases for Q < 0 → heat *removed from* system
  - How to apply to a real, irreversible processes?
    - S is a state variable: for a reversible process with same initial and final states, ΔS will be the same

Entropy change in cyclic engines

- For an ideal, reversible heat engine,

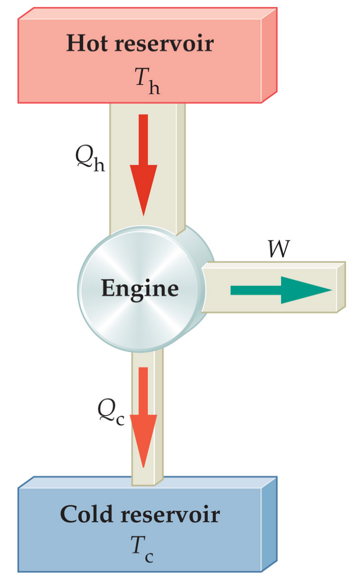
$$\Delta S_H = -\frac{\Delta Q_H}{T_H}, \quad -\Delta Q_H = \text{heat } \textit{taken} \text{ from hot reservoir}$$

Entropy change of hot reservoir

$$\Delta S_C = \frac{\Delta Q_C}{T_C}, \quad +\Delta Q_C = \text{heat } \textit{added} \text{ to cold reservoir}$$

Entropy change of cold reservoir

$$\Delta S_{TOTAL} = -\frac{\Delta Q_H}{T_H} + \frac{\Delta Q_C}{T_C} = 0 \quad \text{because } \frac{Q_C}{T_C} = \frac{Q_H}{T_H} \quad \text{(Carnot)}$$



- So entropy of system + reservoirs does not change
- In any real engine, $\frac{Q_C}{T_C} > \frac{Q_H}{T_H}$ so $\Delta S_{TOTAL} = -\frac{\Delta Q_H}{T_H} + \frac{\Delta Q_C}{T_C} > 0$
- Conclusion: Entropy of (system + surroundings)* always increases when any irreversible process occurs

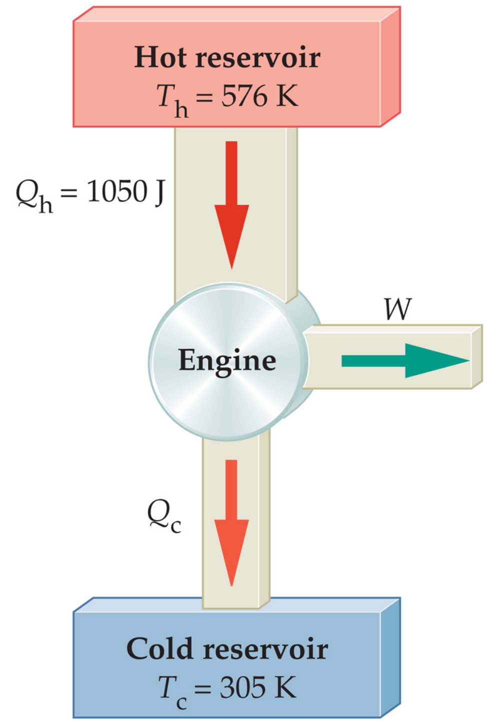
  * = the Universe

Example: ideal heat engine operation

- Heat engine operates between 576 K and 305 K
- 1050 J is taken from the hot reservoir
- So

$$\varepsilon = \left(1 - \frac{T_C}{T_H}\right) = \left(1 - \frac{305}{576}\right) = 0.47$$

$$\varepsilon = W / Q_H \rightarrow W = \varepsilon Q_H = 494J$$



- Entropy changes:

$$\Delta S_H = -\frac{1050J}{576K} = -1.82J / K$$

$$\Delta S_C = \frac{(Q_H - W)}{T_C} = \frac{(1050J - 494J)}{305K} = +1.82J / K$$

$$\Delta S_{TOTAL} = -\frac{\Delta Q}{T_H} + \frac{\Delta Q}{T_C} = 0$$

Entropy of Universe is unchanged

Irreversible process example

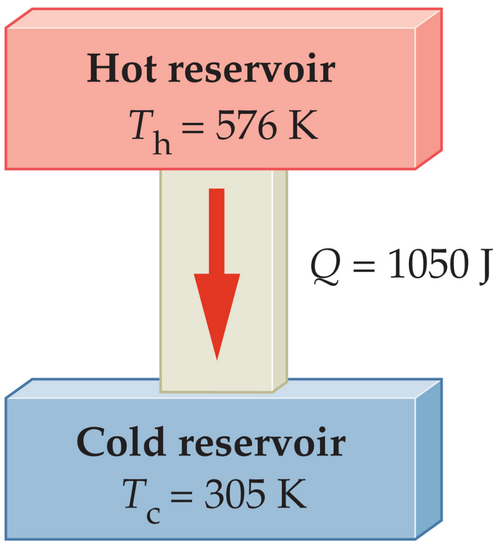
- Move 1050J from hot to cold reservoirs
  - example: cold object comes to equilibrium temperature with room, by losing 1050 J of heat

Now

$$\Delta S_H = -\frac{1050J}{576K} = -1.82J/K$$

$$\Delta S_C = \frac{(Q_H)}{T_C} = \frac{(1050J)}{305K} = +3.44J/K$$

$$\Delta S_{TOTAL} = +1.62J/K$$



Entropy of Universe had to increase:

there was no W to subtract in Q_C !

$$\Delta S_{TOTAL} = -\frac{\Delta Q_H}{T_H} + \frac{\Delta Q_C}{T_C} > 0$$

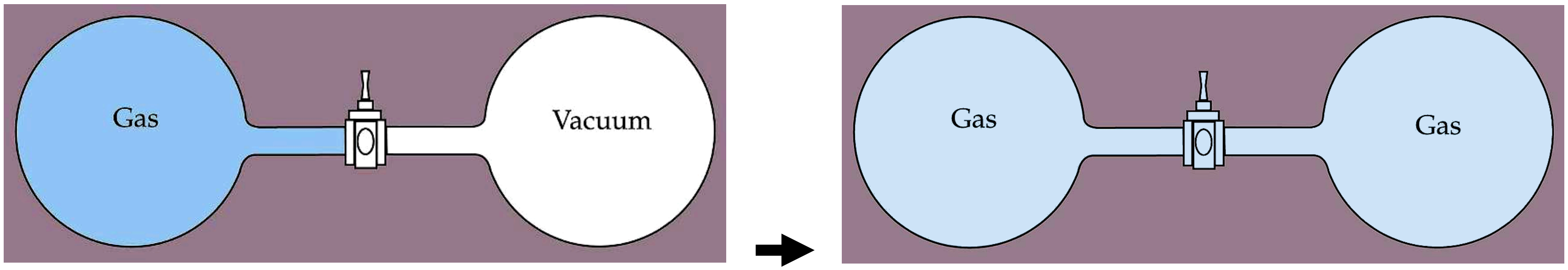
Increased entropy = Increased disorder

- Difference between reversible engine and irreversible process with same T's = work obtained from engine
  - For irreversible process, ΔS_{UNIV} was +1.62 J/K
  - For reversible engine, W = 494 J
    - This is exactly the Q that is "wasted" in irreversible process
    - Notice: $\frac{W}{T_C} = \frac{494J}{305K} = 1.62J/K \quad \Rightarrow W = \Delta S_{UNIV}$
    - The extra energy exhausted at $T_C \rightarrow \Delta S_{UNIV} > 0$
    - "Opportunity lost" – Q could have become work
- In general: entropy increase signals increased disorder
  - Salt and pepper in separate shakers vs mixed salt and pepper
    - It takes work to regain the order
  - Heat separated into H and C reservoirs, vs at equilibrium T
    - It takes work to push the Q back to higher T

Entropy, disorder, "the arrow of time"

- 2nd Law says "*spontaneous* heat flow is from higher T to lower T only – never the reverse"
- Physical processes proceed "naturally" from order to greater disorder, never the reverse
  - Another expression of the 2nd Law of thermodynamics
- Deep thought:
  - Most basic physics processes are in principle "Time symmetric"
    - They can play equally well backwards as forwards
      - Example: billiard balls colliding
    - In Relativity, time is just another dimension, like x, y, z
  - To us, time seems only to move forward
  - Explanation: probability, not physical law
    - There are many more ways to be disorderly than orderly
      - Example: sox neatly folded in drawer, vs strewn in room

Entropy and Probability



Consider free* expansion of a gas, from an initial volume $\mathbf{V}_1$ to a final volume $\mathbf{V}_2 = 2\mathbf{V}_1$. (*no work done by gas)

"It Can Be Shown": The entropy change of the universe for this process given by:

$$\boxed{\Delta S = nR\ln\frac{V_2}{V_1} = nR\ln 2}$$

Why can't the gas spontaneously go back into its original volume? (Would not violate the 1st law: there is no energy change involved.)

Answer: such a contraction is **extremely improbable**.

Free expansion: probability

Suppose the gas consisted of only N=10 molecules

What is the probability that the process will reverse itself, and all 10 molecules will happen to be back in the left-hand flask, at any given instant?

Ludwig Boltzmann connected entropy and probability

$$p(1\text{ molecule}) = \frac{1}{2}$$

$$p(10\text{ molecules}) = \left[p(1\text{ molecule})\right]^{10} = \left(\frac{1}{2}\right)^{10} = \frac{1}{1024}$$

$$\text{In general: } p = \left(\frac{V_2}{V_1}\right)^N \qquad \ln p = N \ln \frac{V_2}{V_1} = \boxed{n N_A \ln \frac{V_2}{V_1}}$$

$$\Delta S = \boxed{nR \ln \frac{V_2}{V_1}} \rightarrow \Delta S = \frac{R}{N_A} \ln p = k \ln p \qquad \boxed{\Delta S = k \ln p}$$

Quiz 8

- The air in this room is uniformly distributed – air pressure is the same everywhere.

What physical principle assures us the air will not suddenly collect in one corner of the room, leaving us gasping in a vacuum?

A. Conservation of energy
B. Conservation of matter
C. Bernoulli's principle
D. 2nd Law of thermodynamics