We have covered a number of concepts in thermodynamics, and I wanted to step back and take a perspective on how what we have learned can place fundamental limits on what is possible, and can guide us as we consider solutions to contemporary challenges.

First Law Energy conservation places a fundamental limit on what we can do with energy. We use energy flow diagrams to view this limit.

Second Law We talked about irreversible processes, and how the Second Law places another limit on what is possible. This is extremely powerful, but can also be confusing (and misapplied!) because entropy can be confusing.

Multiplicity We learned a statistical interpretation of entropy. This interpretation often not very productive (because we cannot compute the multiplicity), but it can give us an intuitive sense of entropy, and can also lead to powerful and simple predictions. For instance, using an information-theoretic definition of entropy one can predict the minimum amount of heat generated (and work done) when doing bitwise operations on a computer!

$\Delta S = \frac{Q}{T}$ We learned the relationship between heat and entropy, which gives us a more powerful tool for applying the Second Law, and a way to check against some misinterpretations.

$T = 1/\frac{dS}{dU}$ We defined the temperature in terms of entropy.

Carnot efficiency We applied the Second Law to heat engines, to find that efficiency $\leq 1 - \frac{T_C}{T_H}$.

Gas heat engine We looked at how compute the efficiency of a gas heat engine, and learned the equations of state of an ideal gas:

$$U = \frac{3}{2} N k_B T \tag{1}$$

$$pV = N k_B T \tag{2}$$

We also applied the First Law to this problem, recognizing that the change in the energy of a system must equal the net energy added to the system:

$$\Delta U = Q + W \tag{3}$$

0.0.1 Additional applications...

Challenge: the transition to electric cars An important advantage of electric cars is that conversion of electrical to mechanical energy can in principle be done with no energy wasted as heat. This enables regenerative braking, and in principle makes the electric cars more energy efficient, since the electric power plant can use a higher T_H, a lower T_C and more efficient cycle than the portable internal combustion engine.

In theory electrical power can and is generated from renewable sources, but in practice any additional power drawn on the grid must come from fossil fuels, so transitioning from gasoline to electric cars does not transition away from fossil fuels, until most of our electric power comes from renewable sources.

Challenge: Computing generates waste heat The global CO_2 footprint of computing is now greater than that of the aviation industry.

- There is a fundamental limit on the energy required to operate an AND or an OR gate.
- One could harvest waste heat from a data center... but not for generating power.