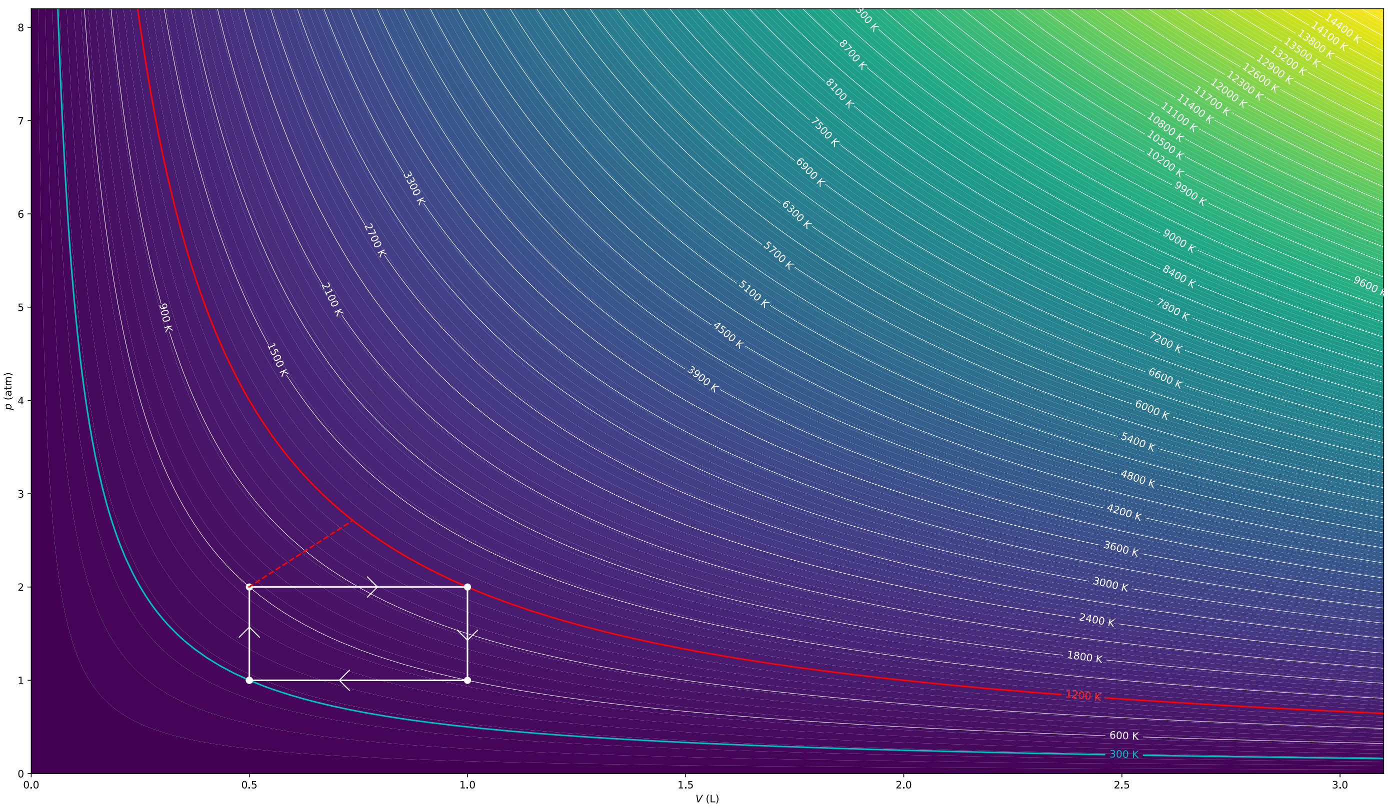
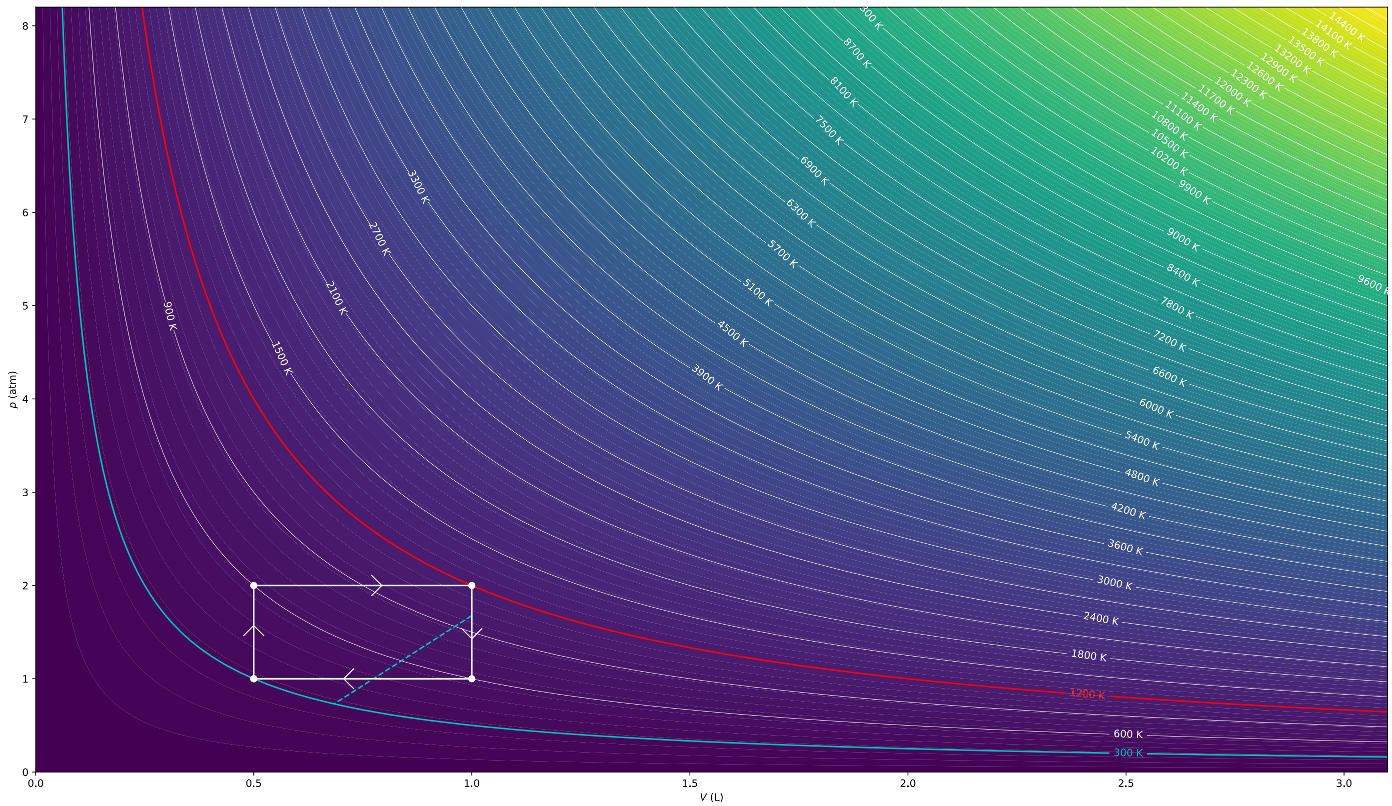
We saw in A gas heat engine, continued that our rectangular cycle in a pV diagram had an efficiency of 15%, where the Carnot efficiency was 75%. You worked (in Heat in a gas heat engine) on a triangular cycle, which did better, but was still far from ideal (i.e. Carnot). So how can we design an engine that can approach the Carnot efficiency, and why do our simple engines work so poorly?

Note You can watch this ten-minute video to get an idea of what this lecture looks like. It was a practice video from when I first taught this content with this animation. You can also download the python code that I used to create these figures (and interactively make little lines).

Rectangle engine To start with, let's consider how our rectangle engine will operate in practice. I'll draw a picture here with a high temperature of 1200 K, and a low temperature of 300 K, running over the same pressure and volume ranges as we used in class.



Here is a picture of the rectangle cycle, where I have included in red and blue the hot and cold temperatures. Since this is a heat engine, we assume that all the energy comes from the hot bath (at red) while the system is being heated. The gas is being heated during the first and second stages of the process. But you can see that the temperature of the gas is way lower than the temperature of the reservoir, so the heating process is *extremely* irreversible. When we found the maximum efficiency, we saw that it happened when the Second Law inequality was an equality, which means when the engine is reversible. So fundamentally, the issue with our rectangle engine is that it requires an irreversible transfer of energy by heating from something that is much hotter to something that is much colder.

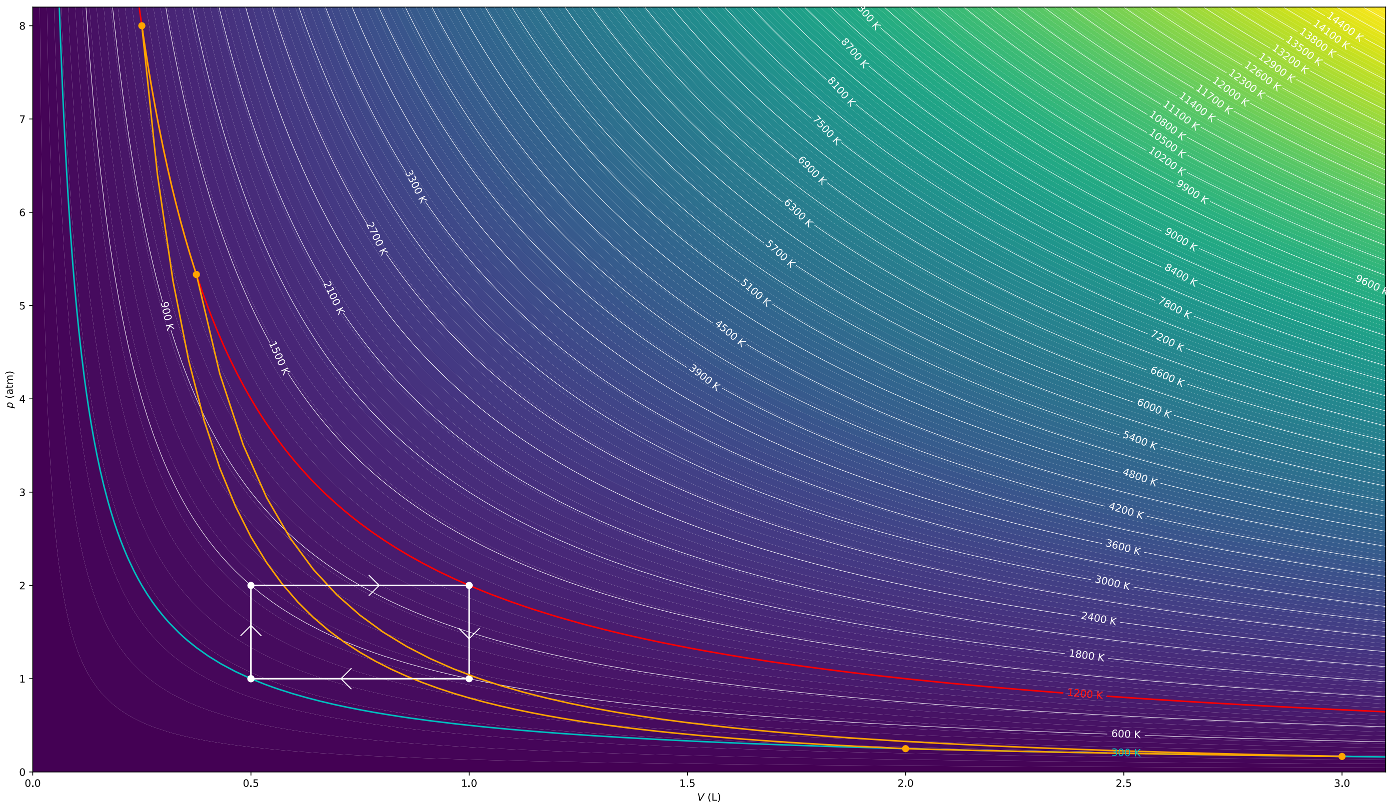


By the same token, on the third and fourth steps, when the gas is being cooled, the gas is heating its environment which is way cooler than the gas is, so again, we have a very irreversible process.

Carnot cycle So the challenge is to figure out how to create a reversible heat engine. This means that the only scenario where we can transfer energy by heating is if the gas is at the same temperature as the hot bath or the cold bath. That allows us to move along the red and blue isotherms. But how can you change the temperature of a gas from 300 K to 1200 K without heating it?! This is confusing, and is made more confusing by the English language. We use the same verb "to heat" to mean *raise the temperature* and *transfer energy spontaneously from something warmer to something colder* . In Physics we try (but don't always succeed) to always use the verb *to heat* to mean the latter, a spontaneous transfer of energy.

A short aside You might wonder based on my above definition of *to heat*, how can we heat the gas when it is at the same temperature as the hot bath? The answer is that we think of the gas as having an *infinitesimally* lower temperature than the hot bath, so the energy will spontaneously tranfer, but could be essentially reversed by making the gas infinitesimally hotter than the hot bath.

Okay, but now we still need to figure out how to raise (or lower) the temperature of a gas without heating it. Based on the equation of state $U = \frac{3}{2}k_BT$ you can see that we need to increase the energy of the gas without heating. The other option is to do work on the gas to raise its temperature *without any transfer of energy by heating.* We do this by insulating the gas from its environment, which is what we call an **adiabatic process**. We can compress the gas adiabatically to raise its temperature, and we can allow it to expand adiabatically in order to lower its temperature. On the pV diagram this will look like:



This diagram is hard to draw, and most humans draw it quite poorly. An easier way to draw the Carnot cycle would be with a TS diagram, with temperature on the horizontal axis and entropy on the vertical axis.

In your small groups, sketch a Carnot engine on a TS diagram.