OK, so we ended up last time, we talked about Joule-Thomson expansion, which is an irreversible expansion through a nozzle, through a porous plug, constant enthalpy expansion. And I want to make sure everybody figured out that it really was an irreversible expansion. Anybody have any questions on that, because when we voted, the majority of the class thought it was reversible Yes.

STUDENT: Just a quick question on some of the constraints, like isothermal, isobaric, isovolumetric expansion. For isothermal expansion, that means that delta u does not change, but delta q is equal to delta w?

PROFESSOR BAWENDI: So the question was, for an isothermal expansion, delta u does not change, therefore, dq is equal to dw. The answer is that's true only for an ideal gas. For a real gas, that won't be true. Ideal gas only depends on the temperature, the energy only depends on the temperature. Therefore, if it's isothermal, the energy of the ideal gas doesn't change. For a real gas it depends on more than the temperature

STUDENT: Are there any other constraints similar to that [INAUDIBLE].

PROFESSOR BAWENDI: So, for an ideal gas, the isothermal is the easy one because the energy doesn't change. If you have an isobaric you're going to have to calculate where the energy changes, and that's a calculation that's likely on the homework and very like on an exam as well, too. In fact, we're going to do some of that today, OK, calculate delta u.

Any other questions? Good question.

OK, so we ended up last time showing that for an ideal gas, that there was was a relationship between the heat capacity under constant pressure, and this is the molar heat capacity, that's why we have the bar on top, and the molar heat capacity for constant volume path. They're related through the gas constant.

OK, this is only true for an ideal gas, and we went through that mathematically where the, with a chain rule. And I wanted to do it a different way which is a little bit convoluted, but it introduces the idea of a thermodynamic cycle, and it's something that we're going to use a lot in the class. Because anytime you're working with the function of state, and you're trying to connect two points together in a p-V or a T-V diagram, then it doesn't matter which way you're connecting those two points, as long as you're dealing with state functions it doesn't matter. It only matters if you're looking at the work or the heat right. And so sometimes, when you want to calculate what the energy is at

the endpoint, the path of the experiment that you're doing may not be an easy path to calculate. You may have to find a different path which is an easier one to calculate, and it doesn't matter which path you take, because in the end all you care is what the energy is at the end.

so we're going to use this concept of the path to go from the initial point to the end point. As long as you're dealing with state functions it doesn't matter to get at the same results here.

So we're going to start with a mole of gas, at some pressure, some volume, temperature and some mole so V, doing it per mole, and we're going to do two paths here. We're going to take a constant volume path. So V is constant and we're going to change the pressure to some, a little change in pressure, V is constant here, and then temperatures is also going to change.

So this is a path, which is either a temperature change, with the pressure changes at the same time, going up or down, constant volume. And since the temperature is changing, clearly Cv is going to have something to do with this. So constant volume path, where the temperature is changing.

So somehow this is going to allow us to get Cv. Cv is going to be related to this path. And if I draw a diagram on a T-V diagram of what I'm doing here, so there's temperature axis. There's the volume axis here. I'm starting with some V1 here. And this is going to be here V plus dV. So I'm starting right here. This is my initial point. And the path that I'm describing then, let's assume that we're raising the temperature up is this path right here.

OK, this is my constant volume path going from T to T plus dT. OK, we'll call this 1 here. All right, now I want to make a path where out of that path, C sub p is going to fall out. So that's going to have to be a constant pressure path. Temperature is going to change but pressure is going to be constant.

So what I can do is I can take my initial point here and create a new, different path, where, which is going to be a constant pressure path. So at the end of this path the pressure is constant. The volume is going to change though, to some new volume dV and the temperature is going to change also and I'm going to make it the same endpoint temperature as the endpoint temperature here. And out of this path, since the pressure is constant but the temperature is changing, I'm hoping that C sub p will fall out of that path of that calculation. All right?

This should give us something about C sub p. So this will give us something about C sub v. This will give us something about C sub p. Now these two endpoints here are different. They have a different pressure, a different volume. They do have the same temperature though. So the connection between this endpoint here, and that one here. Same temperature. It's going to be an isothermal path that's going to connect them. So I'm going to connect them in an isothermal way, and as, since I'm dealing with an ideal gas, and as we saw from the first question here, isothermal always means delta u equals zero. So I'm going to write that immediately here, delta u equal zero,

because I know the answer to that path here.

All right, so let's go again what our paths are. Path number 1 I'm going straight up in the V-T diagram. Path number 2 on my diagram it's a reversible, this path number 2, it's a reversible constant pressure path. So I'm going to be keeping the pressure constant, but my volume is going to go up. My temperature is going to go up. Basically I'm putting heat in this system. That's going to be number 2 right here. It's going to be the same temperature as before but the volume is V plus dV now. That's 2, and then, so I'm heating up the system in this path here, and then to connect the 2 endpoints here, I'm going to connect them through a constant temperature path. Basically I'm going to cool down the system so that the -- no, I'm not going to cool down, I'm going to compresses the system back to the smaller volume V1 and the constant temperature conditions.

So that's path number 3 here. And I'm only going to worry about energy in this case here. Because I know energy doesn't care about the path. Energy only cares about where I am on the diagram. And I know energy is related to C_v through $C_v \, dT$ etcetera. So if I worry about energy I have a pretty good chance of extracting out these heat capacities, right, and I don't have to worry about exactly which path and I can really mix things up.

So let's start the process. So the first path then, the first path, constant volume constant V, so I'm going to, again, let's just worry about energy. So du for this first path here, du for path 1, and write dq plus dw what we usually write.

Now it's constant volume when the volume is constant. There's no work being done so I can immediately ignore this dw here. Constant volume $dq = C_v \, dT$. Now it's an ideal gas. So in some sense, I did too much work by writing this, because I knew already $du = C_v \, dT$. I could have written that down immediately, but I just went through the process of writing the first law, what's dw, what dq, $C_v \, dT$, etcetera. I'm just writing what we already know basically.

Let's look at path number 2. Path number 2. OK, let's look at the dw, du again. du for path number 2. dq like the first law down, dq plus dw, then -- what's dq? Well it's a constant pressure path. dq is related to the temperature, the change in temperature. dT through the heat capacity, happens to be constant pressure, so this is exactly what we want. C_p, I forgot to put my little bar on top here because it's per mole $C_p \, dT$ that's my dq here. The path is constant pressure. And then the dw.

Well there's a change now in volume and pressure. So I need, well the pressure is constant, but there's a change in volume. Minus $p \, dV$ is the change, is the work, right? So I can write that down minus $p \, dV$ for that path there. OK, now but it's an ideal gas, so I know something about the relationship between dV and dT, because I've got dT here the dV.

I don't want to have so many variables around. I've got three variables, T, p and V. I know I only need 2, so I can relate dV to dp through the ideal gas law. P dV is equal to R dT. pV = RT for 1 mole, so I just take dV here. dT here because the pressure is constant, so dV is equal to R over p dT. Then pressure is constant. So I can instead of the dV here, I can insert this R over p dT. The p's cancel out, and now I have Cp dT minus R dT.

This is equal to Cp minus R dT. All right, let's complete the cycle now, the path number 3 here. Path number 3 is a constant temperature path, and I already wrote the answer. Constant temperature isothermal delta u is zero. There's no thinking involved. It's one of these things like I mentioned last time, if I tell you delta H in the middle of the night what you say, q Cp for reversible process. Same thing here. isothermal process, what do you say?

Delta u is zero, right? It should be completely second nature. So delta u is zero here. Delta u sub 3 is, for an ideal gas. I gotta put that constraint in there for an ideal gas. Delta u is equal to zero. So now I'm back at the same place. I'm back here right. So path number 1 went from i, let's call this path up here. went to f, and this is how much energy change there was. The sum of path number 2 and path number 3 get me to the same place, so the energy change by going through this time path, this intermediate point here back all the way to final state should be the same the red path.

So what I'm saying is that du through path 1 should be equal to du through path 2 plus du going through path 3. All right, because energy doesn't care about the path. It only cares about the end points.

OK, so now let's plug what is du through path 1? It's Cp dT and the du through path 2 is Cp minus R dT and then du through path 3 is zero. It's the isothermal process. The dT is cancelled out and voila I have my answer. Cv is equal, oh Cv plus R is equal to Cp whichever way you want to do it, it's a relationship that we had up here that we wanted to prove.

Now, I wanted to go to through this just to go through one cycle quickly because we're going to be doing these all the time, and the importance of the fact that the path doesn't matter, and you can always connect things together in a way, whatever you want. Whatever is the easiest. If you want to calculate a change in delta u. Now if you look at my derivation here, there's one spot where I could have just stopped and proven my point without going through the whole thing.

So if you look at path number 2 here, the constant pressure path du is Cp minus R dT, du is Cp minus r dT for that path. What is du for an ideal gas? It's -- what else do we know that du is always equal to for an ideal gas? Cv dT right. So I could have written right here immediately equals Cv dT, and that was the end of my derivation. I could have done that. It would've been easier, but I wanted to go through the whole path right?

OK, any questions? Cool. All right, so we're going to be doing more thermodynamics processes. We're building up

to entropy and to engines, Carnot cycles, etcetera. And so we need to build our repertoire of knowledge in manipulating these cycles like the one I drew on the board that's hidden now You've already seen the simple process, which is the isothermal process, and you've seen how to functionalize, or what the function is that describes the isothermal expansion.

Let's say we start from some V1 and p1 here, so high pressure, small volume and we end up with a high volume low pressure, under constant temperature condition. So there's some path, isothermal, so T is constant. And we know the functional form for this path, it's the ideal gas law, $pV = RT$, $pV = nRT$. T is constant, so the functional form here is pV is equal to a constant.

All right, or p is equal to a constant divided by volume. If you want to write a function that describes this line here, it's pressure as a function of volume related to each other with this constant. So we know how to do this. So this allows us to calculate all sorts of things to get these functional forms. That's the isotherm here.

We also know how to calculate the work. If it's a reversible process, we know the work is the area under the curve. w reversible. in this case here let's see this is it's a pressure is going down. It's an expansion, so we're doing work against the environment, or to the environment. So work is leaving the system. So minus w reversible is going to be a positive number. V1 to V2 and RT -- you've done this already last time or a couple of times ago and you end up with minus nRT log p2 over p1, OK? So minus w reversible, we're doing work to the environment. This should be a positive number. p2 is less than p1, so p2 over p1 is less than one, log of something less than 1 is negative times negative. So in fact this is indeed a positive number so we didn't make a mistake in our signs.

You always want to check your signs at the and because it's so easy to get the sign wrong, and I was hoping that it was right here because I wasn't sure, but it turned out to be right. Always check your sign at the end.

All right so we know how to do this. Now we are going to do the same thing with a different constraint. Our constraint is going to be an adiabatic expansion or compression. Adiabatic meaning there's no heat involved, and we're going to see how that differs from the isothermal expansion and compression.

OK, so this is the experiment then. We're going to take a piston here which is going to be insulated. It's going to have some volume, temperature to begin with, and then we're going to do something to it. We're going to change the pressure above, right now there's a p external, which is equal to p on the inside. OK, we're going to do this reversibly, which means we're going to slowly change the external pressure very, very slightly at a time, so that at every point we're basically in equilibrium, until the pressure reaches a new smaller pressure p2.

So that's going to results in an expansion where the new volume new temperature new pressure and an external pressure, which is p2 which is a smaller pressure. It's really important that this, that you remember that this is the

reversible case. We're going to also look at the irreversible case briefly. So on the p-V diagram, then, there's a V1 here a V2 here, a p1 here a p2 here. This V2 is going to be different than this one here. A priori we don't know what it is. We don't know if it's bigger or smaller. We kind of feel like it's going to be different because it's a different constraint. This is isothermal. This is adiabatic, there's no heat.

So there's going to be a line that's going to connect the initial point to the final point, and that line mathematically is not going to be the same as this one here. And our job is to find out what is the mathematical description of this path, this line in p-V's case that connects these two point.

And again, I want to stress this is a reversible path. If it was non-reversible, I would be allowed to put an initial point and a final point, but I wouldn't be allowed to put a path between them like this, connecting them together. Because if it's irreversible, it's very likely that I don't know what the pressure inside the system is doing while this is happening. It could be very chaotic. The pressure could not be, might not even be constant throughout the system. It could have eddies and all sorts of things. So for an irreversible process, I wouldn't really be allowed to put a path there. I can do that because it's reversible, and I can get a functional form out.

What we're going to find in this process is that the functional form from this is that p is related to the volume through a constant, but instead of being V to the first power as it was for the isothermal, it's now a V to some constant gamma. What we're going to find is that gamma is greater than 1. And if gamma is greater than 1, and you're changing the pressure to the same final point, what we're going to find then is the volume that you go to is going to be a smaller volume than for the isothermal.

We're going to go through these points, so don't worry about getting at all straight right now. All right, so let's do this. Let's try to show this. Let's try to show that in fact this is the right functional form, that pV to the gamma is equal to constant is the right form that describes the path in an adiabatic expansion or compression.

So let's do the experiment. Let's write everything that we know down. This is where, the way that we should start every problem set or ever problem. It's writing everything we know and what it means. OK, so adiabatic. All the words mean things mathematically. Adiabatic means dq equals zero. Let's write that down. dq equals zero. Reversible. Reversible means that if I looked at dw it's minus p reversible. It's minus p external dV, that's what it is, but in the reversible process p external is equal to p.

That's the only time you can set p external equal to p is if it's reversible. So this is the external pressure. This is the internal pressure of the system. You can only do this because it's reversible. What else do I know? It's an ideal gas. So I can write du is Cv dT and pV is equal to RT. OK. So what else can I write? Well from the first law, du is equal to dq plus dw, and I wrote down everything I knew at the beginning here. I wrote dq equals zero I wrote what dw was.

So du is just minus p dV. Now from the ideal gas, I have another expression for du, C_v dT. So now I have two expressions for du. That's a good thing, because I can them equal to each other. So if you get these two guys together you get C_v dT is minus p dV. So we're connecting temperature and changes in temperature and changes in volume together.

OK, now we don't really want this p here. This is going to be a function, I only need two variables, and here I've got three variables down. So I know p is going to be a function of T and V, and I know how to relate p to T and V because I know the ideal gas law.

So instead of p, here I'm going to put nRT over V. or RT over V bar. So now, this expression becomes C_v dT over T is equal to minus R dV over V. And I also did a little bit of rearrangement. Yes?

STUDENT: [INAUDIBLE]

PROFESSOR BAWENDI: Well, let's see. du is, for an ideal gas, it's always equal to C_v dT. Constant volume process tells you that if you have a constant volume, then dq is C_v dT. This is what the constant volume path tells you, that you can equate C_v dT with dq. The ideal gas tells you that this is always true here. It's an ideal gas in adiabatic expansion dq is equal to zero. Adiabatic expansion means you can't use this. dq is zero. The that is adiabatic. It's not constant volume. You're allowed C_v comes out here for this adiabatic expansion, which is not a constant volume only because this is always true for an ideal gas.

We didn't use a constraint that V is constant. Just use this as an ideal gas here. OK, so we've got dT here dV here. We want to get rid of derivatives. We want to integrate. So let's take the integral of both sides, going from the initial point to the final point. We've got C_v integral from T1 to T2, dT over T is equal to minus R from V1 to V2 dV over V. OK, we do take that integral, and that leads us to C_v log of T2 over T1 is equal to minus R log of V2 over V1, and now we know how to rearrange this, because the C_v times a log of T2 over T1 is the same thing as the log of T2 over T1 to the C_v power, right.

So by rearranging these expression of the logs here, this is the same thing is writing log T2 over T1 to the C_v power is equal to log of V1 over V2 to the R power. And I've reversed the fraction here because of the negative sign here. OK, get rid of the logs, and you get that T2 over T1 is equal to V1 over V2 to the R over C_v by taking this C_v and bringing it on the other side here.

OK, so now we've got the initial and final points, a relationship between the temperature and volume for the initial and final points. Eventually that's not what we want. Eventually we want the same relationship in the pressure and volume. We want a relationship in p-V space, not in T-V space. So we're going to have to do something about

that. But first, it turns out that now we have this R over Cv. and remember, we have this relationship between R Cv and Cp here, which is going to be interesting. So let's get rid of R in this expression here.

So R over Cv, R is Cp minus Cv. We proved that first thing this morning, divided by Cv so this is Cp over Cv minus 1 and because I know the answer of this whole thing here, I'm going to call this thing here, Cp over Cv. I'm going to call it gamma. Because I know the answer, right. I know the answer. I'm going to call this gamma. By definition I'm going to define gamma by Cp over Cv by definition.

OK, so that means that this is really instead of R over Cv. it's really gamma minus one. So now I've got this gamma placed in there, gamma minus 1, so I've ben feeling a little bit better. I've gotten V to the gamma power almost to the gamma power, it's minus 1 here. But it's almost right and I'm looking for something like this here, V to the gamma power pV to the gamma power is a constant to describe that line. So I just got to get rid of the temperature now. Somehow I've gotta get rid of the temperature and make it pressure instead.

OK, so let's -- let me get rid of this here, let's use the ideal gas law to get rid of the temperature. So we have T is pV over R. So now if I look at my V1 over V2 to the gamma minus 1, that's T2 over T1. I'll replace the ideal gas law for those two T's. That p2 V2 over R, and then I have p1 V1 over R, the R's cancel out.

Well let's see, there's a V1 over V2 to the gamma minus 1. There's a V1 over V2 here or V2 over V1. That's going to get rid of this minus 1 here. Then I'm going to get, be left with a p2 over p1. So this guy here gets rid of this, and I have my answer as V1 over V2 to the gamma power is equal to p2 over p1. Or I can re-write this as p1, V1 to the gamma is equal to p2 V2 to the gamma. That means that p1 and -- where I am, the point number 1 and point number 2 were completely arbitrary. They happen to be on the path. So any point I pick on that path will be equal to p1, V1 to the gamma.

So if I take p times V to the gamma, anywhere on the path, it's going to be equal to the same relation from my first point. This is going to be true for any point on the path. As long as I'm on the path, pV to the gamma will be whatever it was for the first point, which is going to be some sort of constant.

All right, so I've proven my point. I've proven what I was trying to do, which was to show that on this adiabat, everywhere on the adiabat, if you take a functional form that relates p and V together, it's going to have this relationship with gamma as related to the heat capacities. Gamma is Cp over Cv. OK, now there's more we can say because we know that's Cp is related to Cv through this R here, and R is a positive number. So Cp is always bigger than Cv.

In fact, if it's an ideal gas Cv and Cp are well defined numbers, it turns out. If you have a monotomic ideal gas, OK, so an atomic version, not a molecular ideal gas, then it turns out that Cv is equal to 3/2 R, and therefore, Cp

which is just R plus this is five halves R, which means that gamma for a mono atomic ideal gas is 5/3. So if you have a gas of argon atoms, you know what gamma is.

This is something that you're going to prove in statistical mechanics, and so we're not going to worry about where this comes from. We're just going to take it for granted. All right, so gamma is for ideal gas, is bigger than one. In fact we have a number for it if it's an atomic ideal gas. So what it means then is if I look at if this relationship here, gamma is bigger than 1, so gamma something bigger than 1 minus 1. This is, so this is positive here. It's positive. So if I have an expansion where V2 is greater than V1, so V2 is greater than V1, so this is a number which is less than one, then I expect then T2 is going to be less and T1, T2 is less than T1.

OK, I have this number here to a power, which is positive, a positive power. And its number is less than one. This is going to give me something which is less than one. So T2 is less than T1, and I have a cooling of a gas. So whenever you have an adiabatic expansion, the temperature cools, it gets colder. It gets colder, and if I look at my graph here, then if the volume of the expansion, if the temperature of the adiabatic expansion was colder, that means that -- this is the wrong graph here. If I want to compare it with the isothermal expansion, which is sitting here.

All right, so gamma, the gas is cooling so V2 is going to be less than it what would be if the temperature kept constant. So finally, on the same graph, I put down what an isothermal expansion would be, if my final pressure is the same pressure, my volume for an isothermal expansion will be bigger than for an adiabatic expansion.

So when I expand this gas adiabatically and it cools down, why do you think it might cool down? It cools down because I'm doing work through the environment, but the energy has to go somewhere, right? There's an interplay between the energy inside the gas which is the heat energy which is allowing me to do all that work to be outside, and so I'm using up some of the energy that's inside the gas to do the work on the outside.

And here, in an isothermal expansion, The bath is putting back the energy that the gas is expanding or using to expand, and so the energy is flowing back into the gas through the environment in the isothermal expansion. In the opposite case, if you have a compression, then it's the opposite of expansion. Compression you're expected to heat up, right? So in the compression, you're going to have V2 is less than V1. So that T2 is going to be greater than T1.

That's going to be your heating up of the gas. And that really is the bicycle pump. That example I gave last time with the bicycle pump was not quite the right example. But this time this really is the bicycle pump. That you're pushing really hard on it. So you start with the bicycle pump at one bar, let's say, right? And you compress the air in the bicycle pump.

You do it so quickly that the heat flow between the inside of the bicycle pump and the outside is too slow compared to the speed at which you compress. But you don't compress it so quickly that you're not in there reversible process so you compress that if you were to feel the temperature of the air and you can feel it through the nozzle gives you an idea of the temperature of the air inside your bicycle pump. You'll feel that it's warmer. You've just done an adiabatic compression of the ideal gas, you can pretend there is an ideal gas. And that gives rise to the heating that you can actually measure.

OK, any questions on this part here. All right, so we've just gone through the reversible adiabatic, and I'm not going to do this in detail, but I want to go through the irreversible adiabatic fairly quickly, and see where the difference is here.

OK, so now we're going to do the same kind of experiment, but irreversibly. An irreversible adiabatic. OK, so the experiment is going to be to take my cylinder now, and the external pressure and the internal pressure are not going to be in equilibrium with each other during the process. I'm going to start with my cylinder here, I'm going to put little pegs here so it doesn't fly up. There's going to be some external pressure.

I'm going to set that equal to p2. There is going to be an internal pressure where p1 is less than p2 and there's V1 and T1 here. The whole thing is going to be insulated. Then I'm going to release these little pegs here and my piston is going to shoot up now because p2 is less than p1. So p2 is less than p1, the external pressures is less than the internal pressure. So it's going to shoot up until the internal pressure and the external pressure are in equilibrium. So they're both p2. external is p2 and I have p2, V2, T2, on the other side.

OK, so in my diagram now, I have p1, V1 for my gas. p2, V2 for my gas, so I know that I'm starting here and I know that I'm ending here, but I can't connect this path here. I don't know how to do that. It's an irreversible expansion. I don't know what the pressure is doing in there, doing that expansion. It could be quite chaotic. It could be non-spacially constant.

OK, so but you still know a number of things. We're now going to be able to write you know dw is minus p dV, but we're still going to be able to write a bunch of things. We're still going to be able to write that it's an adiabat so that dq equals zero. We're still going to be able to write dw instead of pV where p is the internal pressure. dw now is actually much easier. It's minus p external. Well p external is actually p2, so that makes it actually easier. dV we're still going to write that it's an ideal gas. So du is still going to be equal to Cv dT, and we're still going to be able to use the first law, all these things don't matter where the path is. Still know that du is dq plus dw. dq is zero. dw is minus p2 dV.

So this is what we know, just like what we wrote there. We write what we know. I'm not going to turn the crank here. I'm going to give you the answer. OK, you use the ideal gas law, etc., then you get a relationship that

connects the pressure and the temperature, like here we got a relationship that connected the temperatures and the volumes together. You can get a relationship that connects the temperature so this is T2 times Cv plus R is equal to T1 on Cv plus p2 over p1 times R.

This is going to be the connect, what connects the pressures and the temperature. And p2 is less than p1, so this number right here is less than 1. So and Cv plus R, Cv plus something less than R, so T1 better be bigger than T2. OK, so T2 is less than T1. Same qualitative result as before. You have an expansion. It's and adiabatic expansion. You get a cooling of the gas. OK?

Now here's a question for you guys, which we're going to vote on, so you better start thinking about it. Is the temperature T2 in this process smaller or larger than if I were to do the process reversibly with the same endpoint pressure. So now, instead of having p external equals to p2 here, I put p1 and I let this whole thing go reversibly. And I compare T2 irreversible to T2 reversible.

They're both less than T1. They're supposed, there's a cooling happening in both cases. One is going to be colder than the other, maybe. Maybe they're going to be the same. I don't know. I'm going to let you try to figure that out qualitatively without doing any math.

See if you can figure it out. OK, so which is colder? I'm going to let you think about it for about thirty seconds or so. You can talk to each other if you don't, can't figure it out.

All right, let's take a vote. How many people say that T2 irreversible is colder than T2 reversible? One, two, don't be shy, three four, anybody else, five. OK, I've got five votes here. Professor Nelson?

PROFESSOR NELSON: Oh, I'm abstaining. PROFESSOR BAWENDI: You're abstaining, OK, good choice. OK, what about T1 cooler than T2? OK, I've got a lot of votes here. So the majority of the people, so this is much bigger than five. OK. So remember last time the majority was wrong, right? The majority was wrong last time. That doesn't mean that the majority is wrong here. It could be right. Let me give you another piece of information here that you already know. Minus w irreversible, this is the work which is done to the environment by the system, minus w irreversible is always smaller than minus w reversible. You learned that a little while ago.

OK, so this is a little hint. Let's vote again. Let's think about it for ten seconds why this could be interesting and relevant, and I want to ask if anybody changed their mind. Anybody change their mind, change their vote? Yes You want to change your vote? To which one?

STUDENT: From T2 reversible is greater than T2 irreversible, saying that T2 reversible is [UNINTELLIGIBLE].

PROFESSOR BAWENDI: So the question then, which one is colder?

STUDENT: T2 reversible should be colder.

PROFESSOR BAWENDI: T2 irreversible should be colder?

STUDENT: Yes.

PROFESSOR BAWENDI: All right. OK. I'm going to keep you there then, the majority. Yes?

STUDENT: I'm switching to [INAUDIBLE].

PROFESSOR BAWENDI: You're switching this way here? So now we have six here. Anybody else want to switch?

All right, let's take the example of, the extreme example, let's go to the extreme example where p external is really small. And I have this adiabatic expansion where p external is really small. it's kind of like the Joule expansion, an ideal gas.

What happened to the temperature in a Joule expansion in ideal gas? Anybody remember? Anybody remember? Joule expansion, this is where we proved that delta u was only dependent on temperature. Bob Field taught that lecture. Nobody remembers? Well, all right, delta u is equal to zero for that. What happened to the temperature in that expansion? It's an adiabatic expansion.

Well, we'll revisit that. Let me ask you another question here. So w, the work is less for the irreversible process than the reversible process. There's less work done to the outside. So there's less energy expanded by the system. The energy expanded by the system is smaller for the irreversible process. It's not doing as much work. It's not pressing against as much pressure. Right? p external equals p2 is less than p external equals p internal.

So it doesn't have to do as much work. It doesn't have to expend as much energy, therefore, the majority in this case is right. The temperature is not going to cool as much for the irreversible process. The reversible process is going to be colder because it has to expend more energy. It's going to have a higher pressure. The pressure is going to decrease along the way, but it's going to have to do more work because of this right here. So the majority in this case is right. Now the Joule expansion, the temperature doesn't change, T equals zero. eta sub J, the Joule coefficient for an ideal gas, is equal to zero and eta sub J was dT/dV under constant energy.

All right, any questions? Yes?

STUDENT: [INAUDIBLE].

PROFESSOR BAWENDI: The only -- a priori, that's true. But it's hard to imagine an irreversible compression the way we can just imagine an irreversible expansion. You have to do it awfully fast to get your irreversible

compression. I don't know how to do it really. I think it's, but it's more complicated, but you're basically right, basically right.

That's why we always talk about irreversible expansion, because it's easy to write down an irreversible expansion. A compression is a little bit more complicated. Any other questions?

OK, great. Monday Professor Nelson who is sitting here will be taking over for a few weeks and then you'll see me again after that.