## SPEAKER 0

cool, so that looks like it started. Marvellous. So welcome. This is unit operations, and I see a lot of familiar names and faces from thermodynamics last semester, so hopefully you have an enjoyable time in this class. What we're going to be doing is actually looking at how thermodynamics applies to what engineers do every day, what operations we build, how we purifying mass move energy around. That's going to be our focal point. So I have a probably a five minute overview of how the unit is going to run, and then we'll get into the content and over to the workshop. So the schedule now is everyone part of the teams, the correct teams group and not the old. We don't use this team screwed by now. Hopefully, okay, So in that team's group, once you join in, you're going to be presented with, um, the ability to open the teams group in one note and I'll jump over and show you what that looks like in a minute. But pretty much all of our unit content is in that class. One note. So the units designed in 12 modules, each aligning to one of the weeks of semester. I've modified it quite a bit from last year. So one of the modifications is we only have one assignment ever do on any given week. So if you have a lab assignments do, there's no quiz. If you don't have a lab assignment, do there's definitely wish to do that week. So I put all these up here. All of the assignments do it 11 59 on the relevant Friday. But I'll get into that. I hope no one's actually submitting it at that time. Now, Historically, we've also used this textbook. So Smith, Venice and added, No, sorry, Thurman, Abs, McCabe, Smith and Harry Seventh Edition. So McCabe is we're going to get into what we talked about. Absorption Distillation. McCabe is one of the original authors of Chemical Engineering about 85 90 years ago, and this textbook that we use is the final version before McCain died. Unfortunately, no one's carried that book on, so you can only buy it in print. Now if you're planning to go work as a chemical engineer, I highly highly recommend having that book on your shelf. I cannot put into words how many times alumni will come back and say, You know that McCabe textbook really, really powerful to be able to pull off the shelf for my job. However, I appreciate this 2022 the need to buy a $400 physical textbook that might sit on the shelf someday doesn't really jive with where we're at in education. So for those of you that had me in thermal last year or last semester, I spent the winter holiday writing a reader that corresponds to each of these sections. So it's about 50,000 words, and I've taken all of the examples that we would normally distribute through lecture and embed them as videos within the reader. The hope is all of that content available for you up front. You can have an immersive reader activated. You can have one note translate to different languages as its reading. Hopefully, this will make the content a bit more accessible. However, in 50,000 words, I am no better than most of the students, right. I will make mistakes. So this is a draftee reader. If you notice errors or you're reading along in the textbook and it doesn't make sense, please raise it on the group of teams channel, right? Yeah. Um, okay, So what do the assessments look like? We're going to have six quizzes. They're all designed. They're all available today. You can open all six. There's 60 marks each on the elements, and the content is cumulative through the semester. So when we look back at what's in how our reader sections going So, for instance, this week we should be doing reader sections one and two, if you feel so inclined, This is covering basics of fluid mechanics. So if Jeremy did a really poor job and you're like, this reader is way ahead of where I should be, right, I would strongly encourage going to the textbook. Now, I have three physical copies for students in the library has another three, so they are on campus. If you want to go spend a few hours cross

checking against the textbook. Um, what? You'll notice in this layout, we have a lot of reading up front. So the unit has a tremendous amount of content you're going to need to focus on in the first four weeks of consuming and then pretty much the latter six weeks this semester is all about creating, right. So we're going to try to get most of the core concepts done, and then knock through each of these lab reports and an engineering design report by the end. So the quizzes are intended to kind of make sure we're all tracking on the same page. We've done the reading. We understand how the calculations work pretty much plug and chug formulaic. 70% of the marks are for these four individual labs on now. In previous years, this was always 40% because we had to have a final exam and the students last year said, Look, we learned a lot doing the lab assignments because they are very practical. Here's data from a distillation column. I want you to run it up by hand using Isis and talk about why it deviates very particular engineering about 40% when they're putting in 30 40 hours per assignment way not cool, right? So the only option we had was to kill the final, which we did so in previous years. We have this engineering design report buried within this lab assignments. We've pulled that out now as a separate group based project, but 70% of the marks are coming from the lab assignments, so each of these is not weighted identically because, for instance, heat exchange, you should know more and feel more comfortable with than something mass transfer operation. So our initial lab on heat exchange design will be 185 marks are very last lab, which is AB distortion, the transient mass transfer process. That's probably the hardest thing we're going to do, so that lab only has 95 marks, so they're meant to kind of be equip, liberated with where you should be in the third year, the engineering design report. So I should mention both the for all materials for these lab prompt. And the prompt for the design report is online in one note today. So everything you need to do the unit is already up and running, and you can do it at your own pace. Or you can follow along with the class. In the workshops. I will release what the team assignments for this group project are, but it's a really open ended assignment, right? What we're going to try to do their, um, is say, let's design a system that can deliver 10 Giga litres per year to Broome, right that last for 30 years. So you need to think through what's my energy system? My heat exchange system, mass purification system? And let's bring all of these unit operations together to actually deliver something to the community. Okay, so the criterion references. So because we're doing a lot of engineering writing in this class, we will be evaluating, just like in thermo each of your responses to technical questions using these criterion references. Now that applies to essays that you're given in the quizzes. So a few of the quizzes have essay questions. This will be the criterion reference used to assess them all of the technical questions in the lab and the four technical questions in the group design project. So the point that I would highlight here, not dissimilar to Thermal, is that to go from developing, which considers a good engineer to an outstanding engineer, requires us to understand why the physical processes deviating from theory and to speculate on what are these physical reasons behind that. And that's a really hard intuition to develop. So that's what we're really gunning for in this identical to thermo scientific data presentation and analysis. We have the same tutorials for how to create figures and tables. So if you're not comfortable with that or if you lost marks last semester and still don't understand why, please let me know. We will go through these and make sure you're comfortable with what professional chemical engineering standards look like. And similarly, for spelling and grammar. Grammar Lee inward. And it does half of it for, you know, really no excuse

Report spelling. Okay, so let's get into some of the content from today, actually, before I do what I might put up real quick. Okay, Hopefully. There we go. Okay. So this is when we log into the unit. One note. This is what we should be presented with, right? And what I would recommend is that you launch this from teams and you synchronise it on whatever device or devices you're planning to use most of the time. So the content library, these are all sections that students can only read. You can't write information into these sections. The teacher only. This is for our prep area and the collaboration spaces. What we're going to use for each of these workshops. So what I've done and I have 12 more if I go in here. 12 more workshop prompts, ready to go for workshop one. I've deployed this prompt, and I'll try to do that a day or two ahead of time. And then I'm gonna ask you to working team so either at a table of four or five people or the students online to put them in a breakout room. And once we go through this prompt will have an hour to actually work on that question. And then we'll go team by team and ask you to present. What did your engineering team think about how to answer this question? They're all open ended. They're all incredibly hard. Most of them come from like a research frontier. So insofar as they're really fun questions to try to tackle, um, for the admin. So please take a few minutes here, as I mentioned figure standards again, copies of the criterion references. How do you short cutting inward? Which is great for lab reports accessing uni desk. So anyone that isn't comfortable with it are all of our high isis and multi flash unit desk is probably the easiest way to get in to use that software anytime, anywhere. Um, and then this reader outline we'll take you through for each of the weeks. What's the corresponding class reader content in the textbook now? Something that makes this a little bit unique. Let's see, Amy. Amy, do you mind if I open up yours? Presuming you haven't made any edits to it. Oh, you have. Okay. Okay. So for each of you, when you log in, you'll also see your name and three sections that are only available to you. Right. So the classrooms is just meant to be a general filing folder for whatever you take notes in the workshops or whatnot. The lab assignments contains all of the same prompting information as you would find in this read only lab promise. But you can edit these. So as you're going through them, the ideas you have, the reader, you have the workshops, and you can modify these pages to capture. Well, I'm really comfortable with that question. That should be fine. This one over here? Probably not. I need to focus in on that. And most importantly, each of you has personal copies distributed of the 12 reader section. So as you go through and you say Okay, Zack clearly was writing way too late at night. Way too much coffee. This paragraph makes absolutely no sense. You can flag it and highlighted. You can edit it, add new content, add additional things that make more sense than the way I've explained it again. This is just my take on the content. It differs a bit from the caves. Um, but yeah, so each of you will have access to this. Now, would you look at the content in here? I have written this under the presumption that Jeremy and or Quick Tongue didn't do a perfect job. I don't know if that's a good assumption or not, but I wrote it in a way that if you went through heat and mass transfer or fluids and he said, I'm not totally comfortable with what they've taught me, then this should provide kind of a back end to what are the basic mechanics principles, how we're going to talk about turbulence and we'll get into that today And then, Of course, what are the heat and mass transfer operations that we need to know quite critically. The way this curriculum is designed differs a bit from how heat and masses time. So when we get into things like heat transfer and I'll go through this in more detail, right, we can go through all the basics. But then, how

many of you are comfortable with the muscle number of correlations? A little bit? Yeah, Quite comfortable. Okay, so we're going to go through Probably. I think it's about 14 or 15 different muscle correlations for heat transfer and corollary Sherwood correlations for mass transfer. And that's the basis that McCabe's curriculum is developed on. So there is a bit more than what should have been taught in heat and mass, but it should act as a revision. All right, so mm. Oh, that's not good. Yeah, our books. So I want to go through probably about 10 or 15 minutes. Just highlighting what are the kind of core concepts from fluid that we're gonna need for the discussion today? Of course, the first and foremost is appreciating that whenever we're under a body of fluid, we have a hydrostatic head associated with that. So very simply rho GH density of the fluid g, the gravitational acceleration of Earth and H the height of that food. So the deeper I am in this column, right as I go down in the Zet absence deeper we go, the higher the pressure. And this should obviously be a very comfortable point from fluids. But it will start to play up in particular in our workshop activity this week and next week, a kind of correlation and one of the points the reader teases in. And a few calculations that you have to do for the first quiz next week is using the idea of a hydrostatic head difference between two points to measure the pressure. So if I have something like a flowing fluid, then I can deploy these so called nanometers to actually measure the difference in pressure. Or if I know the difference in pressure, I can measure the velocity at which I'm travelling. So the same principle is used for aeroplanes, for instance, to measure their their pressures externally or their velocities externally. So what we're relating here is this difference in pressure between P A and P V. Across the phenomenon in a gravitational field to the difference in density and R M is the actual reading that the engineer takes. So the difference in height between the same fluid at two different points impression. So ground shouldn't be new for anyone, I hope. Cool. Um, so this concept of fluid had the workshop challenge for today Is talking about the deepwater horizon at Macondo. You're old enough to remember the deepwater horizon, baby. Okay, I feel like ancient history. So, um so So I got to work on a part of the deepwater prizing problem, and we ended up running a consortium in working for about 10 years afterward trying to solve some of the uncertainties. Interestingly, our friends from environmental engineering, who were the original first responders onto the scene trying to model what was happening under the ocean, said, Well, okay, we've measured the density of the oil that was spilling out. We've taken it to a lab in environmental engineering lab. We measured the density. They assume that density would be identical to what was under 1300 metres of water. How does that sound like a good idea to chemical engineers? Probably not. So in fact, half of the US government's response plans were based on that assumption because they were all written and led by environmental engineers. So the concept of thermodynamic equilibrium and the fact that under high pressure I can drive more gas into a liquid phase and, as a consequence, drop its density by 2030%. They didn't have a chemical engineer in the room, and that's part of the reason that the response plans weren't didn't go very well. So this concept of making sure we understand how system pressure is changing with Roger Ph or Rogue Delta Z is quite critical now, once fluid started to motion. So the workshop question I want to put up today is around trying to figure out whether those little oil droplets that were created at the site of the blowout so 1300 some metres underwater, whether those little oil droplets are gonna go up or they're gonna go out or some combination of the two just because they are more or less dense than water does not mean they'll rise in the

open ocean. So as we start thinking about fluids in motion, then one of the the key concepts that goes through both the reader and the quiz for week or the week after week to quiz is looking at relating a sheer field. So sheer stressed how how much force pushing across the fluid relating to how it's going to share. So the velocity achieved in the fluid during share, which is dictated by its viscosity mu. So in general, most of the time in engineering labs will work with Newtonian fluids like water. So the harder I push on the fluid, the more well it deforms constantly. So the harder I pushed the more deformation, I guess, however, some fluids and like crude oil in this example, when it's saturated with methane, right, the harder I push on the fluid, the easier it is to continue moving it. So if I'm thinking about rising oil droplets in the open ocean, well, the faster they go, the faster they can go, the easier it is for them to go because they can deform in time. And this would be an example of something like a big implants, because I put so much pressure on it to move the oil in the first place. But then I would see an arc coming across here that the Earth are are going up. So, um similar to this dilated. Yeah, well, so now the background that's going to come into this workshop question is around. Fluid turbulence. So tell me what Jeremy shared with you about the nature of turbulence. Feel like comfortable with ways. Turbulence? Yeah. Thanks for everything. It makes everything difficult. Okay, It does. It really does. Why does it make everything different? Very complicated. Mhm. It is now. I tend to think so. I spent years trying to better understand turbulence, right years and years and years. I think it's usually talk poorly, right? It is. It's a complex concept, but it's not hard to get depending on how you look at it. And if you think of it in terms of initially, you have some river that's flowing at a constant velocity, perfectly laminar. Everything's calm. The second I start to push a bit too hard on that because the fluid is in compressible, all of us and all of the momentum. Energy is not directed during in the flow of the river, so I would tend to use a metaphor like trying to pack people onto a tram and telling them to run inside the tram body to body from one end to the other, right? The bigger the fire or the emergency, or the reason that they have to run, the more chaotic it's going to get. And they're going to push left and right to try to get from one end to the tram to the other, as opposed to a calm, even file line. So when people then in that metaphor, start pushing left and right, and the way I refrain is we start getting the creation of these turbulent Eddies. And that turbulent eddy itself is what we used to characterise the amount of turbulent energy in the system. Mhm. Now the interesting. And I don't know. Has anyone ever heard of the energy cascade from fluids? Is that a thing that Jeremy did? What do you know about the energy cascade and energy like that? The Eddie's getting smaller.

SPEAKER 1
Okay, they get sick.

SPEAKER 0
Yes. So think of the metaphor of this tram, right? And let's imagine that everyone on the tram is the exact same size and weight except one big wrestler due to the back end. Who wants to go from that side to the front? Really, really fast. Well, if he starts turbulent Lee pushing everyone around going left, right and centre. People around him in that process are going to respond. They're going to have to push left her right or they're going to push back. So in that way, if you have a very large Eddie, you have a response of these other Eddies around that will start. Being created to this

flow is the process by which a turbulent stream is going to take its momentum, energy and ultimately, divorce that into heat energy by the creation of these subsequently smaller and smaller and smaller Eddies. Now the rub here for the workshop questions. If you have small oil droplets rising in the open ocean, then by and large, the ocean current itself is static, right? Maybe it's a point, oh, 5.1 metres a second huge debts, but it's not flowing really fast. So for the oil droplets that are flowing up towards the surface, these are the droplets themselves are what's creating turbulent motion, right? So I have a droplet interacting with water and around that I have the creation of these smaller and smaller Eddies. Now, if these Eddies contact something another fluid or another oil droplet below. They can start to act as a sheer force on the surface of that fluid. Coming back to this diagram, they're creating a sheer stress when they bang left or right on this train car, right? So as soon as they collide with something, that's a sheer stress in a different direction to flow itself. So this is the concept, then, that we're going to take forward into the workshop question now an interesting point, and I don't know if we would have covered this. But these Eddies get smaller and smaller and smaller until they can't, and the size of which they can't get smaller is dictated by the amount of energy they have in the first place. So if I have a highly highly turbulent system, I can create Eddies on a micron light scale. If I have a mildly turbulent system, I can only create pretty big Eddie's. That's the smallest they're going to get. And Kabul. Gaurav was a Russian physicist in 1948 proposed relationship governing exactly how small can these cities get. And so this is what it's called now, the common ground late scale relating to the Kine Matic viscosity of the fluid so functionally, How easy does it deform per density and or on the energy of the turbulence, kinetic energy in the system. So how much energy is trapped up in that momentum? So something, and this won't be relevant to our workshop. But it's very relevant to the first quiz and some of the reading. If I then have a fluid flowing against wall. So pretty much all of our unit operations from heat transfer to mass transfer, I'm thinking about fluids. Interacting with the wall at some solid is what's going to govern the transition of energy and mass across the system, which means that having a no slip condition at the wall means I have to start thinking about boundary layers right now. Fluids would have gone into the idea of this turbulent boundary layer, but what we're also going to see is we get into have mass transfer and heat transfer is I can have thermal boundary layers and mass boundary layers. So the fact that I have a more stagnant portion of fluid from fluid mechanics means that the heat transfer characteristics here change, as do the mass transfer characteristic. So my wall is absorbing molecules out of the bulk or it's transferring heat. Have to help for this boundary layer. When I think about comparing fluid theory to what I actually get inflammatory, and I point this out up front because traditionally I don't think boundary layers are covered very well here. This is one of the main reasons that all of your unit operations data is going to deviate from theory because theory does not build in boundary layers, right, you can. But all of our basic theory doesn't. The trick is knowing we're trying to intuit. Where is the boundary layer that's causing the deviation from what I measured and what I predict so well so we can have boundary layers and laminar systems. We would tend not to use that in unit operations. Laminar systems flow slowly, right and slow. Systems don't make enough money. So if we're trying to build an engineering system that's robust and cost effective, we want turbulent flow 99.9% of the time, so in that if I have a turbulent system, then I will split this boundary layer right so as it starts to be the boundary layer on set as I increase the turbulence in the system. I have a

bifurcation, so I have a pseudo turbulent boundary layer on top, and I can see these small Eddies flowing around this energy cascade being created. Then what's called have what's called a buffer layer that sits is like an intermediate kind of a lubricating layer before I get to a final, viscous sub layer. Now the trick here is that this viscous sub layer still behaves as though it's liable. So in a highly turbulent system, 90 some percent of my boundary layer has fluid turbulence in it, meaning the fluid I'm going from left to right across the screen. The fluids not all going from left to right as soon as I have turbulence in this, the fluids going toward the wall away from the wall against the direction of flow. It's going everywhere. But as soon as I hit that visit sub layer right on the point of contact with the wall, I still have a laminar behaviour so I can approximate what will be relevant to your lab exercises if I'm either in Lamott er well, if I'm in laminar flow, I can use the blouse. Easiest solution. So the thickness of the total boundary layer hydro dynamically delta on X the distance or the cross section of low distance is related to the Reynolds number at the point of contact with the wall. If I'm in a turbulent system, it's not an exact solution. But I can approximate it here. Um, 0.385 on that Reynolds number to the power of point to. So this allows me to think about how does the boundary layer evolve as a function of X as I go from contact with the wall through the end of the pipe? This is how long or the thickness of the boundary line. I can actually plot this out. Oh. Mm. So that that boundary layer example is one of the reasons that you're going to see data deviating from reality. If you put that into a lab report to say okay, we think or I think lab reports for individual. I think that this we're getting boundary layers. You need to tell me where you think they're forming and use these kind of calculations to be able to inform. Well, it's reasonable. At this entry length, we'll get to the next slide that I have a boundary layer this thick that's now inhibiting heat or mass transfer, which is why I see a degradation in performance relative to what I should. The other major reason that built operations deviate from theory. It's because engineers don't allow enough time for what we call entrance or establishment of flow. So the nature of that boundary layer I go back to this I can imagine either laminar or turbulent layers will continue growing, growing, growing with time, right? Neither the lousiest solution or this turbulent approximation. These don't end right. It's continuously with Reynolds numbers. So in theory they should grow Delta Great infinity as I go along that axis of flow. But at some point, if I'm in a cylindrical pipe, the two boundary layers are going to contact each other. And when they do, I get the best out what we call fully established flow so I can see on the left if I begin perfectly uniform prosection. These dashed lines indicate the growth of my boundary layer, and this would be for a lamb in our system until I get a perfect problem in a laminar flow is actually the meeting of the two boundary layers or all sides of the boundary layers as opposed to a natural phenomenon. Now I raise this because in most of our unit operations that we're going to work on and a surprisingly concerning Lee large number in industry the point at which we take measurements or the point at which we expect the unit operation to do something for us, must be after we have fully established flow were fully developed flow. So if I'm in turbulent flow that's going to be about 50 pipe diameters and found in laminar flow. It should be 100 meaning if I start taking measurements here before I have fully established flow, I'm going to get massively fluctuating readings, and I have no way to determine whether those readings are accurate. I have to be in fully astound the flow that, for my measurement principles, mass flow pressure temperature to actually mean something. No, If I'm let's imagine, we have a heat transfer operation. So if I take a tube and I then turn a 90 degree

angle on that tube right the second that that tube turns 90 degrees, I don't have fully established flow anymore, right? Which means I need to wait another 50 pipe diameters to have fully established flow, at which point all of my muscle number, correlations and in mass transit will be sure would correlations. All of my engineering correlative abilities are based on having this fully established flow. So if I have a unit operation, that's about the volume of this table area. How on earth am I going to get fully established flow going back and forth across that thing? I'm not right. So this is another massive source of deviation between theory and reality. Mm. So I'll finish up here before we go on to the This is a fun video remaining Melbourne looking at boundary layers evolving as the fluid turbulence continues increasing up and up and up, we can see our Reynolds number here on the bottom. We're still a relatively laminar flow. We'll cross over 1002nd, but I can actually see from this fluorescent dye. I can see the nature of these Eddies in this energy cascade, the really phenomenal video, and it's an open access article so you can go to this link if you want to download. Mm right. You can actually see the correlation to having that that stagnant layer, which is shown in bright white right, that pseudo laminar layer sitting underneath this establishing turbulent back there. Now, if I have an object inflow, right, so Jeremy's unit would be focusing most on things flowing through objects. But what if I have objects in my flow channel? That's going to be where unit operations takes over? Well, if I have something that's very clearly aligned to the fluid streamlines like a flat plate sitting in the middle of flow, I don't really get a whole lot of deviation around it, Right? Flu is going to split. I might have a little bit of recirculation on the back end, but otherwise it's fine. But if I turn this 90 degrees as the other bookend condition, I have massive wake shedding after this. Now, these both of these principles of thinking about the boundary layers themselves and the energy cascades created from one fluid impacting on another are critical for this workshop because they dictate how quickly or easily oil droplets can rise or move about the open ocean. Okay, so I will jump across now. This still works. Yes. Okay, two, scroll up. So in this collaboration space and I'll come to the students online, and we'll put you in a group here in a minute. Um, everyone should be able to open your one note either on a phone or computer and see this prompt. Now, what I'll ask you to do is if you're in person, especially these two back tables split up a little bit. Way too many people on the team. There won't be any fun, but there are more tables in the back. So let's try to say like, four or five people protein. So everyone has a chance to actually do some engineering work here. And if you right click, you can say new page. Right? So once you have your teams put together, you can say a new page and give your team of fund or your page and fun Team name, right. My team oil droplets. Please make sure that you put your names at the top of the page you create, so we know who's on what team doing what works. And then what we can do is at the end of the hour, will come back. Alaska to nominate one percenter protein and over the course of 12 weeks, mix it up so I don't see the same people presenting every time and come up and give it two or three minute summary of what your team found. So what's on the table for research? Everything right? Google Scholar. Don't USE ENGINEERING TOOLBOX It's a crap reference. It's a horrible right. It's not a real reference. There's no data behind, right? You can't tell me who took the date or what it means. Not engineering toolbox, but anything from Google Scholar Web science one search even Wikipedia in most cases will be sufficient. So let's go through the prompt then. So in the deepwater horizon for those that, um, I won't give a long introduction if you bring it. But it was a blowout in the summer of 2010, when a

bps deepwater drilling rigs in the Gulf of Mexico so waste too much time. So when you're drilling for oil and gas, right, the drill bit itself has to be. The pressure applied to the drill bit has to be equally grated against the substance you're drilling into. So if its poorest media, it's gonna be like a dry kitchen sponge but saturated with something of interest. So you're dry. Kitchen sponge is saturated with air dropped into water is saturated with water Well, in most oil and gas applications, you have a combination of oil and gas in the interstitial space of the sponge, meaning as you drill in, you have two, very finally, Aquila break the pressure on the head of the drill bit against the response from the fluid in this interstitial space. Now, if you've made the assumption that it's pure oil and you hit a massive gas pocket, that drill is going to kick right. Or conversely, if you've been drilling through gas and you hit oil whole 100% oil in this space, um, it's going to hit a lot of resistance and effectively. This is what happened as the deepwater drilling campaign was underway, which then, because the drill bit was connected, um, to a gas or an oil and gas extraction system, allow those reservoir fluids to flow through. Now they tried a few different things to stop this, So this is an image of it was taken by a subsidy. R. O V. There were a number of attempts tried to hide it to quell this. And I can talk about that later. If you're interested. That's That's what I had gotten into, um, but effectively, it took them like, six weeks. And none of these attempts were really effect. Nothing worked. They tried to dump the whole world golf balls on it literally. They tried to pulverise car tyres and pressurise them and dump car tyres on top. That didn't work. Um, they tried to put a case on or something about half the size of the zone. A cap on top of this thing. Well, it filled up with gas, and it's buoyant in water with 20 ships on top of the ocean surface. So that was a bad idea. So BP was convulsing, trying to come up with every idea, but it could Ultimately, the only solution was to drill parallel wells around us to take the pressure off the drill. Well, fractured. Now, the question that we raised then is that when this first happened right, you had these sub c r. A V is floating around from news media to BP and the US government videotaping all of this oil that was flowing out of the cut stacks of the part that actually was chopped off or cut in the process. But that was what, some 12, 1300 metres underwater. So they're all up on the ocean surface saying, Okay, where is the oil going to go? You're releasing? What is it? 800,000, 700,000 gallons. Something like this. So you have a lot of 700,000 tonnes? Was the upper limit of the estimate. So you have a lot of oil that's entering the Gulf of Mexico. The next question, where is it going to end up? And this was the engineering question of the day so that the previous work that was drawn in came from researchers at the University of Hawaii, and what they had looked at is naturally occurring hydrocarbon seats. So if you go to pretty much any deep water environments on the planet, if there are oil and gas reservoirs beneath it, these will naturally seep out droplets of oil and bubbles of gas over time through millennium. And in fact, of that 700,000 gallons that was spilled into for 700,000 tonnes spilled into the Gulf about a third of that naturally seeps into the Gulf every year. Very strange that we don't think of our aquatic environments is one that naturally the reservoirs will contaminate. But if you have a massive release all at once, then most of your ecosystems, both from the deep water and shallow shallow end are going to be at risk. So in studying these seeps from Hawaii, what they observed is, Well, look, there's enough material, so a large volume of material. But it's not uncommon that having these buoyant particles, they will lift all of the water around it up in form of a nearly vertical plume. But then other folks said, Okay, that's fair if you're under 300 metres of water, which most of these plumes studies have

done in this case were under 1213 100 metres of water because it came from two locations. Now, in that instance, you're releasing oil with such a high degree of turbulence that by the time it contacts the water column, it's like a freight train running into a 20 ft thick brick wall. Huge momentum impact, which is going to mean what can be pulverised. Well, the water is the wall, so it's going to absolutely pulverise the oil and gas particles that are being contacted. So then there was a competing theory that offered Okay, you're going to actually get very, very, very small, like very small width of a human hair, gas bubbles and oil drop. And if you do, then if you're over 1000 metres into the water column, you get these stratification layers, meaning you have density differences that will set up. So, um, at 999 metres, the Gulf Mexico might have a density. Use 10 30 kilogrammes per cubic metre, but at 1000 and one metres, it has a density of 10 50. So for things to cross that density barrier, that stratification barrier take a higher degree of buoyancy. So this was the debate, right? Because if if these oil droplets end up small and they're entrained in stratification layers, they're not going to surface at the site of the deepwater prison. They're not even in a surface in New Orleans. They're going to surface in Florida and Mexico, environments that are not used to dealing with oil where New Orleans is so for the clean up and remediation crews. Where is the oil going to go? And the first question is, how small are these drops? It's going to be so the workshop question that we want to put up as we've been trying to figure out. And this this was dated back to like November of 2010 was an actual question. And this 700,000 tonnes is going to require a massive cleanup effort. Where do you put your resources and why? That's the engineering question, right? So if I have large droplets on the order of, say, 102 100 my problems, they go straight up to the servants. I can put a buoy around them. I can put a chemical field in place and collect them on the ocean surface. If I get below 100 microns, these things are going to fan outward. We're going to show up on the Mexican coastline Floridian, Alabama and a bit further to the Caribbean. And turns out the people that actually did this answer other alone. But mm, the modelling after the fact to figure out why I was really, really fun. So as we're getting into this, um first workshop. I will shut up here and I'll stop the recording and hand it over to the wall in one hour. What I'd like your team to work on and you're going to need to go into the literature into Google Scholar and try to figure out what a how do I predict droplet sizes in a dispersing system. And what do I need to think about in terms of heat transfer and mass transfer at the deepwater ocean, Deep ocean water will be about four C. Oil's coming out at about 70 or 80. Um, I also the oil is infused with method. Ocean water doesn't have a lot of methane in it, So the second of those oil droplets contact water. Methane will begin dissolving into the water phase denuded or strips the oil droplets of their methane. And these considerations together can lead you to a point of predicting. Will these droplets rise immediately, or will they fanned out in the stratification? Okay, so I will stop the recording there if you're able and at least in the back to tables to split up and draw those tables in from behind you, so 4 to 5 people per group and we will reconvene at 22 to, and I'll come around and say hi to every table and answer any questions we have. Okay. Thank you. Okay. So for the online team, let me just real quick. I'm going to stop the recording, so

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that summary of the content for today. So very, very brief and we'll get kicked straight into the workshop project. Okay, Perfect. So welcome to workshop Week two. Now, as we mentioned in the beginning, right, This is meant to be a revision largely what

you've done from thermodynamics and fluid mechanics. I'm not going to spend too much time on the backgrounds of fluid or fluids. Sections two and three of the rear are written with the perspective that perhaps very made didn't do a perfect job, and no lecturer does. So it's also written a way of what I think about fluids. Sections two and three are what I think of in the context of thermodynamics needed operations, so it might be a little bit of a different angle. So if we pick up with the where fluids would leave off with the Bernoulli equation, right and who wants to volunteer? What are the assumptions required to empower the Bernoulli equation? There a couple critical ones who wants to volunteer one 11 oclock laminar flow that's absolutely got one of three. We can't just use the Bernoulli equation serving in Iraq. You go to the hospital, the doctor says, Okay, I'm gonna do a manual ventilation. I'm going to use the Bernoulli equation to figure out how hard to squeeze us. You're going to be like No, no, no. It's kinda late me with the Bernoulli equation, right? Why? This flow must be in compressible. So as soon as we start to have compressible flow, meaning if we have too much mass of our compressible gas accumulate in one area, the pressure starts to go up and so we can get fluctuations in terms of pulses flow through that mass. And the third and final is where do I see a time derivative in the Bernoulli equation? I don't. So it is steady state flow. It's steady state in compressible land. Now, this is a critical thing to point out right, because when we start thinking about our unit operations, every single unit operation is based on stuff moving. If I could put it in a tank and lock it, it's not really going to be a very good unit operation, because I can't pass material continuously to it. So I have to think about fluid flow. Now, one of the points that we're going to start getting into is when you use Aspen, isis or Aspen absorption. Those all contained relatively simplistic models from how they close a momentum balance. So if they're in the simplistic of the terms, they'll use Bernoulli. But if they're in a compressible flow or a transient pseudo transient flow, they're going to apply pressure drop models to capture this wall. Friction term. All right, so when we think about our pressure difference from PHP be a height difference, Zita has it be velocity differences. What usually care about you so you can use a B. And we have this hug turn here for what work we're adding into the system and a loss term Ape Sabbath for what we're losing now. What fluids would have taught you is that that H sub f is always fluid friction against the wall, right cylindrical flow channel ducted flow. I'm losing energy because my fluid is combating. With wolves cannot move. That's cool. We can go into in section three and four. We get into How do we estimate this h seven n? We can use semi empirical correlations. We can use a moody diagram to look it up, but when I want to get into today is what happens when my fluid is losing energy because it slams against another fluid. So that can be water or an Aquarius fluid combating against a hydrocarbon fluid, a vapour contacting the oil or the acquis phase. And so this is going to take us into a deeper exploration of the deep water prizes. So when I open a tool like Aspen, hi, this is what it's thinking is how many phases do I have? Water, gas, oil, Right? And what does that flow pattern look like? Because every time I have interface, I lose energy now, one point to make. And and this is a formalism, more of McCabe than it would have been your fluid dynamics curriculum. But we can take this h seven, right? Just a generic fluid friction loss. Not necessarily the wall. It would consider accumulation of wall friction inter facial friction. So gas, oil, gas, water and any type of fitting that my fluid is going to flow across. So if I'm going to put some kind of fluid across an expansion valve or for those that took Thermo last semester and orifice, right, well, as soon as I do that I need to account for the frictional loss from that orifice, and so I can go to tables that

are in that reader and look up. What is an appropriate case of each case for the type of, Or if it's the type of valve the type of pipe bend that I have, and I can pull them into this model to directly estimate what that HC Beth is going to look like. So this should mostly be revisions. Where unit operations takes off is when we start thinking okay, I don't really care about fluid combating with the wall. What happens to find an object in Florida? So I have some kind of submerged object we use the sphere. Is that the simplest benchmark? But if I have fluid of any kind flowing around that well, now, my entire scenario has been inverted on me. And how do I think about momentum loss, heat transfer, mass transfer to and from the sphere, So there are a couple important points to make here. The first is that when we think about fluid shear, stress hitting the wall, Jeremy would have spent a lot of time banging on about viscosity insurers stress, right? Those are his two favourite turns. Well, I have the same effect of share stress when I have fluid approaching this sphere, right? The fluid in the front is slamming into the front of the sphere. Exact same type of shear stresses fluid hitting the wall right, going back to last week, that analogy of having a football player run through train car filled with people the same thing. But what happens if one of those people is immovable right now? We're going to have a lot of shear stress now, the way that we when we talk about sheer Spence, engineers typically mean against the pipe wall. So if we're thinking about something inside the flow, then we would typically call it drag. So the drag coefficient gives me a balance of effectively. How much stress is applied to the front of the objects of the force of the flow on the area that's projected against the momentum of the fluid coming in. So it's telling me how much energy I'm burning at the contact point of this submerged object. Now, why do we care? But when we get into the second and the fourth Labs These are based around unit operations where I have a cylinder filled with some kind of hundreds, thousands of objects of interest. And I'm going to use those objects as a vehicle to transfer mass, either to the objects themselves. In the case of absorption, um, or to a flu encoding the object in the presence of gas in the, uh, time for ab absorption. So I need to think about the drag coefficient. Right? And I can estimate this if I'm an in turbulent flow. Hopefully I am. I can estimate this as a precaution. Haliti to the Reynolds number. So the reader is going to go into more detail around the physics behind this. But as long as we're comfortable with the concept that fluid snacking the front of an object is kind of the same as it hitting the pipe wall, then I can start to think about well, if I have some unit operation filled with my little objects right and I'm going to pass a fluid, could be liquid could be made across this thing to the mass transfer operation. I really, really need to know how much energy. What's that frictional loss going to be across this bed and it could be a million objects are in this bed. Well, I don't have a correlation with that easily, right? So we can go to the Kozeny Carman equation. This blue portion is what happens, and we can actually get to cause any carbon through fundamental theory. It's a little bit of empirical correction, but it's from a first principles. Derivation. And then if I think about what happens when I velocity of stuff around, my bed is really, really fast, I get into a kinetic law. So this is the bird plumber relation. You're going to learn a lot more about this in in 30 18. But what you need to know for here is that effectively, we don't really care about the book hand limits of the Kozeny Carman for laminar flow or the bird plumber for turbulent. We put them together and call it the arrogant equation. Right? So if I'm in really laminar flow really, really low Reynolds number, this blue portion accounts for 99.9% of the contribution of Delta P. I mean really high Reynolds number. This thing goes down towards zero and this accounts for 99.9% so

effectively it can put them together as one operating equation. And these are examples of the types of things I could fill this bed with. The very simplest are the ratchet brains. So these are little hollow cylinders, right? And they might be the size of your fingernail, and we're going to fill a bed up with about 100,000 of these, coat them in water and pass a co two rich gas across the CO two prefers to be in water. These things create a lot of inter facial area boom. We get a mass transfer operation, right? That's one of the things we'll be doing with absorption and to use something like the the urban equation. I really only need to know a few things about the bed, and this is why we like it. I need to know what is the generic size of the stuff that I've put in decent P. So an average diameter krasic and what's the Spirit City? So if I have an absolute sphere, right, like in my previous example, that it would be one. But as I start to come into more cylindrical systems, or in particular, natural systems like using Micah or sand. I can get really low spirits cities, meaning I have a very high surface area to volume ratio that tends to be really good for mass transfer operations. So when I put these things into a bed, what it will start look like I can imagine that the lowest velocity of whatever is flowing across this now, in this example, I'm using gas, but it could very well be liquid. Um, if I have almost no velocity, then whatever I've put in that bed is going to pack all the way down to the bottom. Well, I'm flowing some fluid up from the bottom of it. Eventually, the momentum of that fluid is going to start rattling the bed right, and it will start increasing its height. This point that that happens is called fluid isation. And the idea is that I effectively have enough velocity in my fluid phase that I have lifted a portion of those solids that are in the bad up. And that's good for me, right? Because the higher that bed is, the more pathways I have between all these submerged objects, the better the mass transfer. I don't get local depletion of mass or energy, and I can keep going to hire the fluid velocity the higher the bed will get. And the more turbulent it will eventually be the point where suspending is dense, right, solid in error or in a fluid of interest. So the point about fluid isation here, this is we're going to come back to this when we do lab two and land for The only thing you really need to take away is the use of the bird funding equation and understanding that if I haven't activated for ab or ab absorption, I can tend to get better outcomes as I cross this minimum fluid isation velocity. So I'm starting to lift the bed up and get a little more air inside or fluid inside, and I get a much better inter facial area as I go above that fluid isation point. The terminal aspect of fluid isation is when I have so much velocity. But I start chucking this stuff out the top of the bed. The bed is depleting in its solids. With time, this would be called a conveying that right, so have to supply fresh materials from the bottom. And I'm conveying spent materials at the top very rare scenario and that the final point then as an engineer, if we think about this urban equation, alright lets us relate the pressure loss similar to the Bernoulli equation. But let's me relate the pressure loss across some two phase bed. That's a very, uh, the extension from the British because I now have two phases to consider, at least. But across this toothpaste bed, I can rearrange this thing to solve for Well, what is this velocity visa not them required? In order to achieve that minimum point of fluid isation, I can rearrange if I have very small particles. I'm going to tease out the Cassini Carman equation that very large particles at a very high Reynolds number. I'll use the bird plumber. But I can solve either of these for that minimum velocity, which the forces in the bed are balanced and I will start to see the bed particles lifting up. And this is one example of an industrial bed. Pregnancy will have some poor section in here. I'm filling that patent material distributing gas from beneath, and I

use a little bubble plates. So as the gas pressures up the bubble capital open release the gas and the bubble that falls down. So it's a way for me to evenly distribute some fluid of interest through the bed. And then as it comes up here, I would take the gas off the top ones. It's been cleaned, so these are the take home messages from Sections three and four of the reader. Again, most of it should be revision. I'm hoping Jeremy did a good job. What are the things that I liked you to call out if you're seeing, I think material in sections two through four of this re difference really, really, really new. You feel like you should have learned in fluids. But you didn't. Please just highlight it. And when we come back to the end of semester and I'll ask you for some feedback on the reader and how sitting with the rest of the classes let me know, right, So we know what to kind of tease into and how to to adapt fluids as it were. So, um, I will shut up now 15 minutes as problems. The reminders for this week. So the reader. We front loaded a lot of the reading. So if you can crash through the end of section four by the weekend, what that will set you up is basically we're going to do one section a week from here on in right now. The transition most of the times but actually working on engineering problems and not reading readers and taking quizzes because this should be a year three times. Uh huh, Who is one is due this Friday, So I set it by the end of day. I hope that's not an imposition to anyone. I really hope you're not submitting at 11 59 PM That would be That would be really unfortunate. Please feel free to submit early. Um, this quiz again should mostly be a freebie, I would expect, because you should be pretty comfortable with the thermos and the fluids aspects of it. Once we get into Quiz three and forward, it will start to pick up a lot of new content, be a bit more difficult, and for anyone either listening to the recording or here. If you don't already have access to the class. One note, let me know straight away because that will start to become an imposition in coming weeks. All right, do we have any questions that you'd like me to go through from the reader? The assignment, the quizzes? Anything? No question explaining. Perfect. Everyone's on the Saturday cool. All right. What I will do is I'll put up the prompt for this week, so drop this at it. Had a bit of a strange time sinking all this. Now with this. Believe that section. But I come into work shop, too. Yeah, so I'll ask each table. And I think most tables are reasonably well sized, like I want to break in half. It's more fun, but we'll ask each table to to prepare their discussion on this following last week. But what I've done is to put in here a bit of theory for you around. Well, how do we determine droplet sizes if I'm just And this is not just for oil in water or something like this? This is a generic physics screen work for how we predict the dispersion of one compressible or valuable phase inside of another. Typically, we relate these these droplet sizes or these dispersion particle sizes to some character of turbulence, so the best practise would be the turbulence, kinetic energy. Sure, Jeremy's hit that point multiple times. That is a very hard quantity to get out experimentally if you don't have a computer. So in in olden days we would try to relate it to something like the Reynolds and we're Weber numbers or some combination of the two now in the actual deepwater horizon, for the question that we raised last week was, Where are the oil drop that's going to go right? Are they gonna go? If they're really big, they're going to go straight up to the top of the ocean, and we need to clean it up. Their huge implications for the safety of the 21 shifts that we're responding because you have B text compounds of benzine talks between Xiling and I'm missing one, but you have really dangerous carcinogenic compounds in the oil. You also need to worry about the HSC of the workers who were actively cleaning it up. And there were a number of lawsuits at BP for that. But more

concerning Lee. If you have really small droplets and you don't know right, that's the caveat is. If you know you have small droplets, that's fine. But if you don't know you have small droplets. Then these things can atomize and they can go out of the stratification layers and service hundreds or thousands of miles away. So what? Actually not? Well, a lot of the early work that went in So from May 2010 on forward, probably for a year or two, was claiming that actually, no, you're not going to get small droplets. All of that deep, 700,000 tonnes of oil is going to go straight up to the top done. And that was really convenient for being breakfast. I said, Okay. Our liability, which ended up to be about $65 billion is limited to this 10 square mile area. Cool. We can control that. We're done with liability. And there were those of us saying, Yeah, yeah, you're not going to get like an eight millimetre droplet. It's just not physical, right? For those of us that do this kind of work day in, day out for decades, you can't And in fact, I remember standing at a conference in Houston doing Q and A with this audience member from M. I. T. Is in order, and I was getting a little bit irritated, and it had been a really late 1994. So I wasn't well rested non. And I said, Look, if Jesus himself reappeared and said, I'm going to make an eight millimetre droplet the gods of physics to be like nothing not going to happen. How can you proclaim on a $60 billion liability that you can make a drum? Jesus himself couldn't if he tried. That argument works in America. So all of that to say, well, when we really get down to the physics and and some of the group's last week pulled up the German So, um, deter crowds carrying alone Simone pesh The Germans built a rig about the size of this room to study exactly how these would disperse when they're at high pressure. With all this dissolved gas turns out, you know, they're not going to disperse these eight millimetre. Drop it or nothing just took us 10 years to prove it. So well, that was going on BP and a couple of its technology companies and then said, Okay, well, we don't We're saying that these droplets are going to be big. But let's be honest, we don't know that, right? We're engineers. And the reason I use this problem as an example is virtually everyone working on it was an engineer. If you weren't an engineer, you had no place in any of this conversation. So this is what happens when all of the engineering disciplines get together and start a screaming match about how to help people, right? It doesn't always go. And the point that I make is that as chemical engineers, you have some really unique perspectives that need to come to the table there. So BP said Okay, we're going to assume these are big drops. But what if we're wrong? What's our contingency? We do not want, um, oil that we can't control surfacing elsewhere. So then came the idea. Well, what if we use soaps? Right, So subsea dispersants. All these are right. If you've seen people use, like dawn or Palmolive district, urgent to clean, uh, waterfowl that are covered in oil. It's pretty common image. Well, those same detergent technologies can be turned up quite quite aggressively, and so you can make this kind of super soap as it were, that when it finds an interface between water and oil, it cleans, too. Now, in doing so, it drops the tension between water and oil, allowing a little bit of momentum to slice the oil droplet in half. So if you were initially going to have, say, one millimetre droplets now you're going to have, like, 50 micron drop or 20 or 30 micron droplet and for reference frame the width of a human hair is about 35 microns. So the results of all this, the effect of adding these dispersants in was to decrease the water oil invitation potential, meaning if we know we have a constant momentum coming out of that spill or that deepwater beliefs than for that constant turbulence, kinetic energy. We can make that energy do more work if we drop the innovation attention. So for the same amount of energy, it can destroy more and

more droplets into these smaller versions. So the question that we want to ask them we're subsidy dispersants the right choice, why or why not? And raised? This is a really hard engineering question, right? And there's still billions of dollars of liability that had not been resolved around the choices that were made. When you start doing your research and teams, you will find I was part of a group that argued quite aggressively for 10 years. No, they were not the right choice. And I love surfactant chemistry, right? But that's my whole research. Then I think dispersants are wicked cool from a science perspective, there was absolutely no justification to use them in my But BP did right, and Halliburton made a truckload tonnes and tonnes and tonnes of this dispersion and, to put it in perspective, a thimble full. If you were to shoot like at a bar, a symbol full of this dispersant that would kill you. So imagine what happens when you dump 100,000 litres of that into the Golden Banks. No one's eating fish from the Gulf for a decade. Mhm. So this is one of the examples of what happens when then the engineers get together and they panic. They panicked because the environmentalists don't know what the chemists know that don't know what the mechanical engineers no, and no one's willing to really call the boundary where their disciplinary knowledge ends, but it turns out things like dispersed, dispersing and dispersants. This is pure chemical engineering. Everyone in the room that made these decisions that wasn't a chemical engineer should have excused themselves hours beforehand. So there are counter arguments on both sides of this line. What I would like you to do in teams and we will come back a hard stop at one thirties or friends from law to have another panic attack at 1 30. I want to hear from each of your groups. Why, from a technical engineering framework. Why would you have added dispersants or not? I'll give you one hint. A counter argument for their used is that if we cannot bound the risk of uncontrolled release and migration of oil, it is far better. The devil, you know, right to inject a toxic dispersants, then risk that, say all of that oil is going to surface on the beaches of Cuba, Right? Not knowing where it goes can be a much higher risk than causing an intermediate evil Today. That was one of the counter arguments, so I'll hand it over to please make sure that the only thing I'll ask is when you come back make sure your arguments are technical as technical as you feel comfort. Okay, I'll put everyone in online in a breakout room, and then I'll come around to each of the tables and see how you're going.

SPEAKER 0

perfect. It's just started. And there's a live transcript on the side. Uh, if you'd like to either see the words or have it translated on the fly, So welcome to Workshop three. Uh, So there are a few reminders to go through an admin before we get started with the Summit of Content for the week. Um, so this week corresponds to Sections five and six in the reader. And as I was mentioning before we started class, uh, Section five should be a bit of four and five together. Should be a bit of a refresher. He transferred, however, if you're taking it concurrently, but hopefully these sections should be sufficient to backfill the knowledge that you're going to need if you do find as we get into the lab exercises. If you find deficits in the reader, please take a moment and make a note of that so you can point those out to me as we go through semester and we can improve it in future years. Now Quiz number two. This will cover fluid mechanics and and some of the heat transfer content that will be due by this Friday at 23 59 so hopefully you're welcome and encouraged to submit it beforehand. Um, but I'll come back next week and we'll start looking at some of those summited quiz outcomes and identifying if there are some gaps and deficits that we need to fill. Um, I do want to raise, and I'll put this as a an open question for

folks that you can use the meeting chat to talk about the best alternatives now that we're getting into some new content for the rest of the semester. What I'd like to do is open a one to our kind of open consultation session at some point during the week, um, so far classes meeting Wednesday afternoon. My thought and I specifically want to make sure this is time for folks who are working, so hopefully we can do. Probably not early morning. If you've done fluid mechanics with Jeremy, it sounds like, but maybe something later in the afternoon after most most folks could get out of work at least for half an hour or an hour of it. So those that can't join us in class are able to, um, are able to attend. So given or at least able to ask questions. So given that our lectures will be Wednesday afternoon, my inclination would be to look at either Monday or Friday late afternoon, say another 3 to 5 or 2 to 4 or something like that. So if you could use the meeting chat to please let me know what afternoons of the week would work best for all of you. I'll take a scroll through that and then send out a booking here through the team's channel. So the final note is that laboratory report number one will be due next week, Friday. So if you haven't already looked at that lab prompt. Please, please, please take a moment. It should take maybe 2030 minutes to read through again. For those that did Thermo, this lab will be a significant refresher reason. The same equipment. We're just looking at some new engineering questions and dimensions to go into, um so, in particular, some of those lab problems That would be good to get a really good correct on that over the weekend. About half the lab you should be able to do quite quite easily if you've done lab number two from Thermal last semester and it kind of gets you started. But I would expect it will probably take about 10 to 15 hours to do the lab questions that are branching out from there where we're analysing, uh, comparing the heat transfer system to what ISIS might predict and then trying to extrapolate to an industry scale. So it does. There are some challenging questions toward the end that you appreciate. Uh, so for this week, the Summit of Content and this will be the first of two, uh, kind of introductory summit of workshop lectures across Sections five and six of the reader. Uh, we'll be getting into the unique heat transfer concepts that we need to know, uh and then next week, looking at some design of shell and tube heat exchangers and some of the logistics around that. So the first and foremost is that when we talked in the last few lectures around a boundary layer that can emerge hydro dynamically. And of course, we then saw whenever we're going to change the flow, this could be a turn of a quarter or an obstruction or something like that. We absolutely want to have at least 50 diameters worth of entrance length before we have fully established flow in laminar systems. And that's for that hydrodynamic boundary layer from both sides of the pipe to meet each other. Um, so we turned off transcription. I'll go ahead and start transcription again, just for those who might be joining or seeing this after the fact. That way, it's all saved for them. Um, so the same phenomenon that gives rise to that 50 diameters of entrance length to achieve fully established phone lamb eater systems and 100 diameters of entrance length and turbulent systems. We can imagine that in that hydrodynamic boundary layer because we have different velocities. We have different shear stress profiles, so the further we go toward the wall, the fluids under more stress. Well, if we think back to thermodynamics right, the more pressure that we put systems under or fluids under, We know that there are thermo physical properties are going to change, and so in the same way, we can start to get the sensitivities of the thermo physical properties because of this hydrodynamic boundary later. Now, what that gives rise to is a thermal boundary layer, so we can imagine if we look at this diagram. On the right

hand side, I can see a thermal boundary layer right where the temperature gradient so that the T equals T infinity On the right hand side means that that that interface shares the temperature of the bulk or infinite fluid. But inside of that, we have a temperature gradient between the edge of that thermal boundary layer and wolf. And this gradient goes with things like the heat capacity and the viscosity of the fluid have easily Those Eddies can dissipate, um, fluid momentum into heat, thus contributing to the heat activity. Um, and the US coppers Sorry. Another viscosity the thermal conductivity of the fluid itself. So inside these boundary layers, because we tend to see laminar flow, we have the same kind of conduction concern so that the ability for that near stagnant fluid to conduct heat across it as it reaches that wall. Now the Crandall number is what we'll use to characterise the thickness, the ratio between the hydrodynamic and the boundary layers. So if the Crandall number is equal to one and this panel number is defined by the heat capacity, viscosity and thermal conductivity, when that Crandall number equals one. It means that the A and B profiles on the right hand side are identical to one another. Now, if the panel number is greater than one, meaning we have an emphasis on momentum diffuse city over thermal diffuse city than it means my thermal boundary layer will be thinner. So when I'm thinking about a unit operation and heat transfer, I then need to take a moment to think about. Well, I have this probably some kind of core conviction inside of whatever flow channel I have if I have a heat transfer operation. But I probably also have a bit of conduction as these thermal boundary layers established at the wall, right? It's not conviction all the way up to that wall interface. I have a combination of convection and conduction in the fluid, and then I conduct heat across the wall and then into whatever outer fluid is encapsulating that heat transfer operation. Uh, well, skip this line. So, uh, this is a representation of what that might look like. If I'm, for instance, I'm using one warm fluid to heat another cool fluid. I need to, of course, think about conduction across the wall that you would have learned about heat and mass transfer. But I also have to bring in the background knowledge of fluid mechanics and think about conduction through the boundary layers before convicting out into the fluid itself. Now there's a special condition, and I would encourage everyone to spend a few minutes and the reader focusing on log mean averages and log mean diameters. There is a very specific set of cases in which we need to think about either the log mean diameter of the wall, and that's for a wall that's very, very thick relative to the Flow Channel or a log mean temperature driving force that will come into in the next lecture, relevant to a shell and tube heat exchanger, for instance. Now I invoke a log mean definition. For instance, I have a 10 inch thick pipe wall and a one inch diameter flow channel, so in the pipe wall itself is multiple integers of the flow channel that's moving through it. Then I need to think about a log mean difference in that invokes because the temperature gradient through the wall becomes so significant relative to the temperature gradients, either on the external or internal fluids. So the definition of the log mean diameter here is shown, and the reader breaks down the calculation basis for both logmein diameters and lobbying driving forces. So, in our definitions, then of the product number, we appreciate that I need to balance this ability for the fluid to disperse momentum energy into heat with the heat exchange properties of the fluid itself, right and something like a shell and tube heat exchanger or a plate type heat exchanger. And the way that we would then go about characterising. The average heat transfer effectiveness is what's known as a new cell number correlation. Now, hopefully, you should have seen it a bit of this in heat and mass transferred. Uh, my understanding is that we probably do more

Nestle correlations in this class than any other, but it's really important that everyone spent a few minutes getting comfortable with What is this new muscle correlation and how do I weaponise it? And the reason why is that alongside the host of muscle correlations will look at for heat transfer operations, there is a parallel of Sherwood correlations that we will look at for all mass transfer operations at Steady State, So it's really critical that we're all comfortable with how these are used. So if I look at the one of the simplest muscle correlations and of course, the muscle number being dimension list is our ratio of convective to conductive heat transfer. So it gives me an idea of how to balance these across the conductor conviction in the bulk conduction through the boundary layer wall and outer boundary layer and conviction again into the secondary bulk. So I can bound each side of the pipe and think about an average conductive heat or convicted heat transfer coefficient. So H seven x that binds both that volumetric flow where the momentum flow and he transferred as well as the boundary layer itself. So the nacelle correlation itself I've highlighted here in blue and specifically, what we would typically say is this inner portion where I can see muscle being equal 2.332 times the cubic root of the Crandall number and the square root of the Reynolds of the local rounds number. Now, this is for the special case of flow across a flat plain, so we tend not to see this very often, and we'll look at pipe flow correlations in a minute. But what this lets me do is if I know the rental them the Reynolds number and the preamble number. And I can see on the right hand side we've expanded those out. So what do I need to know? The average velocity? Uh, something about the viscosity which you can see actually almost cancels out. But not quite. But something about the viscosity density, thermal conductivity, he capacity. So these are all thermodynamic quantities, right? This muscle number? Then let me calculate the H seven x Deon Kay. So again, K is showing up as a thermo physical property. So if I know the diameter of the Flow Channel, I can use this muscle correlation to plot the overall convective heat transfer coefficient inside or outside as a function of distance, effectively letting me plot that right hand diagram of the thermal and hydro dynamic boundary layers. Uh, if I then span across the whole plate, I can get a laminar flow coefficient for correlation show on the bottom. Here. What's probably more relevant, these correlations on this page. So for a laminar flow in a pipe or duct itself, representing a bounding condition. I have this muscle correlation which we can see is a limiting value ends at about 3.66. So we tend to see muscle numbers very, very low When we're in laminar flow. All I need to be able to calculate this average heat transfer coefficient, uh, is knowledge of the Crandall Reynolds and geometry of the system. But most of the time we as engineers will be operating in turbulent flow. And so there are two relevant correlations. One is the data's Bulger correlation. So this is a muscle correlation shown here. Now this takes the same general form and were in fact going to see this form emerged over and over in our different mass and heat transfer applications. But I have some semi empirical coefficients multiplying a Reynolds number two of power and a panel number two power right. If they could be a route power a 2nd, 3rd, 4th through or they might be a positive power. Now this this is relevant Adidas Boulder correlations relevant when the fluid includes its end value so prattled to the end. If I'm heating a fluid and this point forward if I'm cooling at its 0.0.3, Um and then, alternatively, I can for turbulent flow. Use the cedar. Take correlation so I can see here I have a similar definition and empowers raised, but I'm including this Visa VI. Uh, so this is giving me a correction factor for the fluid viscosity and how it might change across this temperature landscape so I can see the definition of the show here. I'm taking a

relative viscosity to that of water. Now, this would be very useful, for instance, either laminar or turbulent flow. If I was trying to characterise the inside of the heat transfer pipe so of the fluid that I'm either using to heat or or that I'm actively heating how is that heat transfer coefficient going to change? But what about if I'm flowing fluid across the outside of set of pipes? Uh, this might be, for instance, if you have a reverse cycle air con on your house or place of living, you can go out back and see all these tubes with the fan blowing across it. So that is using a natural convection or forced convection, depending from the natural, relatively stable air temperature across this to bundle to act as an infinite heat sink. Now, in that case, if I have external flow, as would be the case in my household air conditioner, I need to think about a different type of, um, heat transfer correlation. So we'll use something that's resembling a vessel correlation, as we can see here. But it's not, quite, uh, direct in its use of the Reynolds number or the panel number. I can see how this is multiplied a bit differently, But again, I still need to know. You know what that fluid velocity will be on the outside of the the two bundle, as well as the thermal physical properties that I get from something like multi flash Now. Interestingly, if we think about fluid dynamics or fluid mechanics, and in some of the dynamics around submerged objects that we talked about last week, I can also imagine if I have flow coming across a to bundle. Well, I'm going to have these Eddies. If the flow is turbulent, we hope that it would be for effectiveness. Then I'm going to have these Eddies that show up downstream of the two bundle right and what these will represent, um, is a an inefficiency in the process of he transferred. So in fact, what I can do is start plotting On the right hand side is this, uh Y axis is a new cell number calculation as a function of the angle with which that external fluid is coming across the tube bundle. And so I can see when I start to get a direct angle. So a 90 degree angle or around around there about I see that the optimal set of heat transfer conditions the highest muscle number that will allow me to get a very effective heat transfer. Whereas if I'm coming from an angle of attack of just under the two bundle, I tend to see the poorest performance. So this is the basis for a lot of modern engineering. I can think about either forest conviction in this case. If I put a fan on that that back end he transferred to the air conditioner. But I can also think about natural convection, right? If you're in a windy city or a place with a lot of freshwater or saltwater currents coming through, then it's entirely reasonable. If you don't have a huge temperature change to think about using the natural conviction of the Earth as a cooling or mechanism to drive conviction across these services. Uh, now, in this case, when I think about natural conviction, I start to have if I picture on the right hand side this this set of two bundles that I'm going to have some kind of buoyancy effect, right? Airflow entering the very bottom of the tube bundle is going to have a very different experience to air coming across the top. And so in that case, I have the warm air that comes in the bottom that will buoyant. We move upward in addition to having airflow or water flow across the top of it. And so I have to bring both of these dimensions together and the solution approach that we use it still in muscle correlation. But instead of Reynolds number, I need to have the grass off number, and this allows me to think a bit about fluid buoyancy relative to the fluid momentum itself. And I can look in this this table and this is also replicated in the reader. And so you can say, Well, what are the A. We're sorry to be an end coefficients for this muscle correlation. I can find them here on the table and this tells me the range of products of grass off and Crandall numbers that would be relevant. So do that calculation. First, find the right orientations or plates or tubes upward or downward. Uh, make sure that the correlations valid and then pull

the BNN numbers. That would be irrelevant. Right? And I should reinforce all of this, then is I would go back to the definition of the muscle number. Once I do that calculation, I can go back to the fundamental definition of the muscle number, as we might show here, right? And as long as I know d. So the diameter flow or a approximate diameter float and the thermal conductivity of the fluid K. Once I know the Nestle number, I can calculate the convicted, the transfer coefficient h so last, but not least in a bit of a taster for what we're going to get into next week. Then we're going to start thinking about different types of heat exchangers. So I'll start by outlining just a few general general high level types. So the first is a shell into, uh, the basic concept here is that I have one heating or fluid to be heating to be heated. Sorry, that will enter on the left side of this, um, cylindrical type. Peter, I can have different orientations, but cylindrical is the most common, and it will be distributed run across these tubes that are laid throughout the centre of it before being warmed in the tubes before collecting on an exit channel and exiting through the top of the apparatus. What I will then do is on the shell science. If I have all these individual two bundles running through the length of the cylinder on the shell side, I can take warm steam or superheated steam and pass it through as a second eight exchange medium. The features of something like this if I use superheated steam that I'm going to have a temperature difference as the steam exchanges its energy with whatever is in the tube side or if I'm in a condensing system, we remember that anything that boils or condenses will be at a constant temperature. So what we're showing in this right hand plot is the example of condensing steam that will be a solid line on the top. So a constant temperature vapour and the warming fluids so is that enters on the left side of a very large temperature driving force for heat transferred and is it exits on the warm side? I have a very small temperature driving tools so I can see that in playing with the types of heat exchange media, Um, I can even think about reorienting the flow as we'll talk about a minute, and this starts to give me as the engineer more control over exactly how much heat is added or the ability to design or modify and change when you start to get fouling into that system. Now on the bottom is a much simpler and more common type of heat transfer device called a double pipe or equivalently pipe and pipe heat exchanger. And the idea is that I can have an infinitely long pipe or however long it needs to be. It can have curls in it, although I need to think about flow reestablishment before I get a steady state heat transferred. But if I imagine this for a minute, a straight pipe containing some fluid that I need to heed. Well, it would stand quite logical that I'm going to put a jacket around it containing a warmer fluid of interest or cooler fluid. If I'm trying to cool it down, um, and that I would run this either in the same direction as the current or parallel or purpose Sorry and the same direction of the current or against the current flowing inside. Now, if I'm in a parallel flow, meaning the jacketed heat transfer fluid is flowing in the same direction as the internal pipe, I can see when we begin the heat transfer process, just like in the shell, and to have a very large temperature driving force approach temperature. And when I exit that double pipe, I have a very small temperature approach. Now we'll get into next week's workshop that the challenge there is around, um, the effectiveness of the heat transfer. So the larger the driving force, the more energy I can offload or take on in either flu. So once I get to the very end of that heat transfer process, I tend to see very poor efficiency, so that next marginal metre of double pipe heat exchanger isn't gonna buy me all that much, whereas in a counter current flu. So this would mean, perhaps, that the central pipe is flowing in this direction and I have an external current flowing around

it in the opposite direction. There, I see a much more consistent, uh, he transferred the driving force at the beginning and the end of the internal pipe. So we'll be getting into more specifics next week. In particular, I encourage everyone to make sure you take a few minutes to focus on the shell and tube heat exchange systems and the natural conviction, uh, and forced conviction that will apply to the laboratory. One prompt. And, uh, yeah, I haven't seen any comments come up in the meeting. Chat around what the best time for an open consultation session is. So if you have one, please add it in. Otherwise I'll put a poll out to the glass later this afternoon. Okay, so I will stop sharing that and stop the recording, and we'll get into the workshop prompt for today.

SPEAKER 0

Okay, so the recording and transcriptions now started. And when we finish these slides, I'll go ahead and stop the recording. So the workshop prompt that we do together won't be recorded. That will just be you all, Um, as we go ahead and get started here, I just wanted to kind of comment. We are seeing a bit of a fall off and participation. Um, so I was It was really pleased in the first few weeks and will be backed in person together, most certainly next week. But in particular, I'm keen to see how the different type of hybrid student led workshop activities function as we go from majority in person to a hybrid of in person, online to a teams based experience and back. Um, and I am quite concerned when I see something like 1/5 or sixth of the class president. Um, one of the reasons that we took the time to put the reader together for this year is that you shouldn't need to feel as though you have to be 100% up to date in the reader or the textbook to get value out of these workshops, right in particular. This is meant to be practical engineering experience for you all to have the opportunity to practise your engineering skills. So not participating in the workshop is simply not getting practical experience that we're here to facilitate. So I'd like to encourage, particularly those who are watching this online later on and watching the recording of this workshop. Please try as best as possible to participate in the sections or the sessions that we put together. Otherwise it's going to be difficult, um, to have the intuition to know how to put together those lab reports and how to put together the Design Project report. That's all based in this kind of practical experience that we have so some reminders for this week. So we have this week kind of brings us to the end of that what I called early on this front loading period of workload in the unit. So we did a lot of reading up front. This week brings us to Reader section seven. Um, I am interested in connecting with you all and getting feedback on the reader what you liked what perhaps was a bit confusing, what we need to revisit for next year um, but we will be relying less on the reader moving forward. And I would assume probably a couple hours of reading. Maybe three hours of reading a fortnight from here on out will be sufficient. Because now, for the next eight weeks, a majority of our time is going to be focused on these laboratory design project reports. Which brings me to the second point. So our lab, one report which is on refrigeration but really focusing on the heat transfer components is due this Friday. Um, as with most other submissions, I think we set the deadline at 11. Or 23 59. So the end of day Friday. But I encourage everyone not to wait until that point. Please feel previous event whenever you're you're happy with the report, um, similarly to the thermodynamics reports and and the lab exercises there. Most of these questions I don't require a substantial amount of overthinking, right when we look at each of the lab problems, the latter 20 to 30% of the marks are intended to be for highly technical questions that might push you a little bit. Um, that might require

you to do some out of the box thinking, but that 1st 60 to 70% of the questions these should be pretty straightforward, particularly in lab one. Once we get into the next couple labs, um, we'll start to see quite a bit of new content emerge. And and at that point, it might be a bit more abstract and how to approach the questions. But for now, we would hope that everyone's had a pretty smooth time on this live report. As with every year, our policy is to mark these within 10 working days as per university policy. And I don't think we've missed that deadline in two years of classwork. Um, so we will have these reports marked and back to you before the lab to submissions are due. However, it will not be in one week. Right. So we have, I think, two weeks between this submission and the next lab submission. My goal is to try to have everything done before the next week of that lab submission. So probably 7 to 8 total days, as opposed to 10 working days, um, which should give you enough time for those really high level points of feedback and critiques to take them on board for the lab to report. Okay, Um and then finally, thank you all for voting on the open consultation hours. I put a note on teams and LMS around this. I do appreciate that. Not everyone voted for Monday afternoon, and then not everyone can make that, um, tyranny of the majority in a democracy. Right? So what I would say is, for those who cannot make either the workshop or the open consultation section recessions, please. If you want a private consultation with myself with the facilitators or want to schedule an ad hoc like a just a working evening, something like this let me know. And I'm happy to try to set that up. Okay, so in this this week's workshop, we just want to summarise about six units or extended unit operations that are based on heat transfer. And these are common applications for the chemical engineer. The first of these is Eric Gold Exchange. So, as I mentioned in last week's workshop, you know, in in 50 to 80 years ago, we would oftentimes find chemical or mechanical engineers that would use, um would tend to to go from one working fluid to another throughout the unit operations process. So it would not be common in olden days to think about using, uh, naturally occurring thermal reservoirs like that air cooled heat exchanges or water heated or water cooled systems, Um, as the primary means, simply because there's not quite as much control over the built environment as there is over the engineered environment. Uh, that, I think, quite is changing very rapidly, uh, in part due to climate change and concerns around emissions profiles. But also in the past 50 years, we've started to get a better sense for how you know oceanic ecological land based environments change in response to using them, uh, in in a way of of a unit operation. So, really, a classical example of this came in the 19 seventies, when the US was in the heat of building all of its nuclear power plants. Right, So very, very topical for Australia today. And the main concern in the seventies from the environmental community in the States was not so much around the nuclear aspect of the power plant. And I appreciate, you know, in modern times we see a lot of pushback against nuclear due to concerns of radio activity and lots of containment and such. But in fact, in the 19 seventies, the main concern was around dumping hot water or warm water into precious ecosystems. So if you were to build a land based nuclear plant, probably putting it in the middle of the U. S. Where there's not going to be a huge amount of tectonic activity, well, that plan is going to take effectively. Warm out water, right? Once it's, it's passed through steam heat exchange systems, and it's been put through multiple, um, secondary and tertiary heat exchangers to eat as much energy as possible. You're still dumping water that's either 30 or 40 C into a river or an environment that naturally operates between 18 and 20. So there is quite a significant pushback to Well, you're changing the environment of this ecology by

increasing or modifying its temperature. So that was kind of the initial reaction back in the seventies that we saw two using natural thermal reservoirs for unit operations. Uh, now right in the line, and we're going to get to this very, very acutely in the workshop today. But now I think that the concern around climate change and emissions far overwhelms what the environmental community 40 50 years ago was concerned about in the way of water or temperature calibration. The one very common application of these air cooled heat exchange. Right. And the idea is that if I look at the heat exchanger in my refrigerator or that which we're working on in the laboratory, um, you know, I'm using laboratory air or, in the case of my home refrigerator, the home air or the air conditioner and reverse cycle system of using the outside air as an infinite reservoir to heat and cool so often times. And you can see this. If you have a reverse cycle in your home, you can see these large blades and a found system that's sitting on top of that heat exchange. So this is using forest errors of circulation environment, and we can see in this limit right. We have a muscle correlation specifically designed. We're specifically tailored for fan forced external air, so we need to be moving between three and six metres per second to use it, and we would find that in most cases right, we can see these correction factors shown on the table on the side. In most cases, we're looking at Reynolds numbers on the order of 201,000 somewhere in that bracket, um, and so we would expect that by and large, we can deliver quite an extended heat exchange from this type of network. Now in general, these types of heat exchangers both in that example and that which we use in the lab is based around that in the shell and tube system, and in most cases, and especially organising the workshop today, we would be using a shell and tube system without necessarily augmenting the phase of the heat exchange or the working fluid. However, there are quite a few applications in which I want to use the shell and tube heat exchanger or something similar to handle either the condensation of a warm vapour or the boiling of a cooler liquid. So one of the first examples of this we'll talk about as a condenser. So what happens if I take my shell and tube heat exchanger here? I can see it's configured on the left in a single pass side by saying liquid, and I'm simply going to use this liquid in its cooler state to condense steam entering at this port F on the top right, and that port F will then allow the the steamed flow in condensed due to heat exchange with this cooler liquid flowing through both weirs and through the the tube side and exiting that is a condensate. Now, when we go from a single phase two, a multi phase heat exchanger like this, one of the key aspects that must be varied, um, is we can think that the amount of or the temperature will be changing quite drastically right for the fluid flowing through these pipes. So from the cooler fluid flowing in at the left at D two or port H across those tubes to the right hand side, Well, because it's going to be warming right as it takes on that energy from the condensing steam. In fact, I have a difference in the temperature of the steel or the metal used to construct this vessel. So on the right hand side, when that fluid gets quite warm, my metal can expand, so thermal expansion will be different to what happens on the left side. And if we don't account for this when we deal with a multi phase exchanger, then in fact will rip some of those tubes away from the wall because they're going to contract or expand differently. And so, for this reason, we end up using what we call a floating head. So one of the signs of the heat exchanger we can see if we look at this left condenser here. So where it's pointing to be one right that side would be allowed to float up and down in the liquid pool. And the whole point with that is that Then, if I have some degree of thermal expansion, I can allow those pipes to move a little bit outward or

float up and down without rupturing the middle and then contaminating the system. But what if we invert the problem? So what if we're trying to use a shell and tube exchanger to boil a liquid right? We'll hear, and we'll touch back into what we started talking about last week. But we need to think about the different types of boiling that can occur, And so if we look at this left hand plot where we're showing on the Y axis is the amount of energy flowing in the flux of energy into the system as a function on the X axis, the temperature difference between the point that the flu is being heated and the contact of the fluid on that heating point. So this could be the contact of water on the kettle wall, for instance, or the kettle base. So as that temperature driving force for boiling, where the temperature difference starts to increase from point A to B to C, I get a relatively mon atomic increase in the amount of energy flux that can be distributed into the fluid. So the hotter my circuits, the more effective my heat transferred the fluid, the more effective my boiled. Now, in each of these cases, and I go through the reader and talk about different kind of at home. Lab exercise is usually based on the kitchen, where we can see heat transfer happening right before our eyes. And in fact, if you observe something like, take the lid off your electric kettle and started up, or look at a pot of water that you put on the stove and start heating it, you can see the different types of boiling occur at that interface of the liquid or the water and the metal container. So if it's a pot on the stove, I can look right at the base of that pot when the flame or the heating is on high and observe as it gets warmer and warmer and warmer, this different type of boiling that will occur at that point. The key insight here is that at some point I'm going to be boiling fluids on the interface so effectively right that in fact, I have an air gap that will emerge. So every piece if I imagine these little pockets of fluid, every pocket of fluid that's in contact with heating surface is now in vapour things. And as soon as it turns into vapour, it rises up to the top of the liquid, only to be replaced by more of a vapour. So once I start to get this emergence of kind of a vapour buffer layer, if you will, uh, that starts to decrease the efficiency or the flux of energy that I can put into my heating system, right? And the insight there is that I'm effectively transferring heat from the metal wall through a almost through a conducting layer. So quite a poor efficiency, but a conducting layer of gas before then, convicting it back into liquid atop that gas. And when I think about boiling in a shell and tube exchanger, then this comes in because I can think, well, how effective is this boiling process going to be as a function of how hot the stuff trying to boil my liquid is so the surface of my tubes or the outside jacket of my exchanger, that temperature, that same temperature driving force plays out in the heat exchanger, as it does in the pot of water sitting on my stove. And so this this inset plot here shows me for a shell and tube modified shell and tube heat exchanger, which in this context recall a kettle type of boiler. This means that I have my heating tube support or tubes on the bottom here. Uh, perhaps steam is running through that side, and this maintains a small boiling volume of liquid where the vapours are trapped in this vapour space and then passed out of the top of the unit. Any kind of liquid that might boil over is then caught in this weird and recycled background. So it kind of, if you can imagine these kettle type of boilers, act as a kind of A If anyone cooks like dumplings on the stove and you have a steaming units, I have my pot of water beneath, and I have a little Vacher trap where I can steam something and then a lid on top. That's a similar basis to how these kettle type boilers were operating. And the key insight here is when I combine both of these slides together, well, I can see that actual measurements in a multi to bundle this kettle type re boiler. I do get an increase in the heat flux as my driving force. My

temperature difference increases, but I still observe that maximum efficiency or effectiveness emerging from what we would call film boiling right. And that's the same limitation at Point C between Point C and Point D Here on this, this individual graph So the take home from this is that I can use my shelter, my basic concept of the shell and tube heat exchanger. I can use that for a single face. Working fluid. Uh, with a single phase heat exchange fluid. As my big case in our laboratory, I can use it for a condensing system as long as I think about well, I'm going to have different temperatures across the system. And so I need to think about having floating heads so that my my tubes don't start snapping off. Or if I put a larger volume head on top of this thing, I can use the same basic approach for boiling. So I want to wrap this up then by thinking about three kind of offshoots of basic heat exchange types that you might come across throughout your career, the first and if anyone, um, in their home washing clothes washing, Uh, circuit has a inside dryer. Well, then, you know, in Perth in the winter, these clothes dryers can generate a lot of humidity. Uh, but in particular because we have such a low dew point here in the winter, I can often see condensation of this water on the walls of, say, a larger room. And so one of the ways around this type of a problem is to insert a dehumidifier into the room. And so what is the dehumidifier do well effectively. If I consider my air to be a 79 multiple set nitrogen, 21% oxygen for most calculations, Um, then we can imagine that as a function of temperature and pressure, there is some equilibrium, amount of water that I can stabilise in that vapour phase. So for all intents and purposes, engineers would call this relative humidity right. This is the same type of relative humidity we can look out the window and see is causing condensation on during the winter's day. Now, if I go in this plot here on the bottom is just a high level. They can map something like this, that with multi flash or how isis. But if I think about the equilibrium, water content in that vapour as a function of the temperature in the system, because it's not very easy to change pressure in household applications. But I can change temperature pretty easily. Well, I can see here that as the temperature increases, the amount of water content in the vapour also increases, right, So the equilibrium water content. So this is not meaning that I'm boiling my water. The temperatures on this graph could well go from 15 to 60 or 70 Celsius. I'm not boiling yet, but the amount of water that's stable dissolved in the vapour phase of my air increases. And I can see these different relative humidity curves fall out for a different equilibrium. Water content. So one of the goals of a dehumidifier is to say, Okay, well, what if we take this relatively warm in the air and we cool it down right in a small unit operation, maybe two or three times the size of my cup of Cobb? Well, as I cool that air down the equilibrium, the thermodynamic equilibrium for how much water is stable in that air decreases. So if I do that and then I can take that water out in liquid phase and eject the cooler air back into the the environment from which it came, I've effectively reduced the number of moles of water that's distributed in that vapour phase. So this is what a common dehumidifier will do, and I can see her. I'm drawing in vapour from the very top and then passing that through the tube side connection to a port here on the bottom, where I'm going to do it effectively. A two phase flash. So I have liquid coming out, the very bottom and vapour coming out the bottom left Access. Now this liquid that's coming in the outlet, most household dehumidifiers. And you go to Harvey Norman or the good guys or someone actually, by one of these things, For a couple $100 in most household applications, this condensate outlet will actually dump the liquid into a volume, maybe the size of the pot of water. And that's the water that will continue to reuse, uh, in this water inlet

and water outlet. Um, so, so running through the shell side of the exchanges. So it's using its own condensed water as a vehicle, uh, to reduce the amount of water dissolved in the gas phase. Now I can achieve a similar approach, but that is by thinking about the purpose. If I look at this dehumidifier, well, I have a multi pass exchange system set up in here, right, So I can trace, I think, where is the water coming in at this point here, while the water is going to flow around these different weirs. And so I'm getting a really high turbulent contact area between the shell side of the exchange and this this cooler water flowing through and the warmer vapour or gas containing water flowing through the tubes side. Quite a bit of turbulence here. Well, to the engineer, you can think to yourself Well, how can I increase the contact area between these two phases that are exchanging energy? And how can I increase the turbulence to promote compensation and a contact condenser is one way of doing that. Now I can think here that the primary purpose if I imagine my contact condenser is going to draw vapour in from the very top right? And this might be the vapour that's containing quite a bit of water. And if I have my water spray or my water inlets and that similar reservoir instead of running it through a shell and tube type or a vertical shell and tube type exchanger, what if I have this water spray that's atomised into my vapour England. So I'm going to take a volume of water and atomised it into these tiny particles, maybe 15 20 microns. H right, not altogether different from our deep water rise and workshop examples. Well, now I have this cool water that's been atomised and it might even be quite cooler than ambient because of the Jewel Thompson expansion effect and this cool water in these all of this surface area. Right? So I'm creating 20 micron droplets Well, that I'm going to have hundreds of square metres of surface area and household size application. And this hundreds of square metres of area is now contacting my vapour containing dissolved water content so naturally very, very efficient process by which then the water in that vapour phase will condense because it will rapidly cool down. And then what we do here on the bottom is have a second portion of water that's injected as a jet, so it almost as a plunger to force the condensed water out of the system, using its momentum to a discharge. And so this is a really nice approach. It relies a bit more on the creation of pressure to just to inform that water inlet spray and the atomization, but otherwise functions quite efficiently when we compare it to a classical shell and tube type dehumidifier and the final example here. We wanted to go through an agitated filming evaporator. So an evaporator, you know. Similarly, the core design would be based on this kettle type heat exchanger. Right. So I'm going to boil. Something re evaporates something off. But oftentimes, you know, the fluids that we work with might not be the most efficient or the most valuable in an engineering environment. An example of this would be something like honey, right where I have a viscosity, upwards of 1 to 5000 centre boys. Very, very difficult to move hunting around the unit operation for the purpose of purification. Well, what I can do in this agitated film exam, evaporator is hate the outside of this this vertical too. But in the inside, we can see we're feeding through this feed inlet, and I have blades that are distributed kind of like spokes on a car wheel or a bike wheel. These blades that are distributed an extruded outward that rotate in time. So as these blades are rotating, they're pushing fluid through a centripetal force to the wall. Now the wall is then heated by a steam jacket. So what it means is my most viscous fluids are then pushed towards the wall for heating, where they then become less viscous. Um and I Then I have the Centre Channel of flowing of the investment fluids that I can pull out as event here on the right hand side. So we don't tend to see very many

examples of agitated film evaporator, although the one in the reader and in the text book, as well as based on evaporating milk. So if you're in a milk industry and you're trying to purify this, you have to be really careful not to over keep the milk whilst at the same for its pasteurisation process. Well, at the same time, um, using a system that can handle the relatively high viscosity of a colloidal suspension like milk. So the reader and the text book go through. This worked example of how you might design an agitated filming evaporator around that. So that brings me to the end of my started a bit long today, but 20 minutes feel on a kind of key concepts from the reader up through Section seven. Again, these are the different types of heat exchangers that we can work with, so we're not going to do a lot of work on these, but instead bias toward the basic shell and tube design that we see in our lab. One report. So let me now pull up the prompt real quick. I'm gonna stop the recording and we'll go through the prompt, um, and take a look at it together, and hopefully we'll see, um, the rest of our class joint and are those that can next Wednesday. And we should be certainly in person in hybrid mode on Wednesday at the zone.

SPEAKER 0

Okay, so recording has now started. Marvellous. Uh, so, yeah, I'm really sorry. After last week, I've still had this cold. And so I thought it's probably better to stay remote this week, but then we'll be in person next Wednesday. So before we begin a few notes for today, Uh, so we're now beginning the absorption or ab absorption model. And I'm gonna make this mistake probably a few times when I talk, because I I work in absorption, so I tend to go forth. Um, so this corresponds to reader section eight and nine. Uh, now, in particular, Section eight is more around reinforcing those foundations of mass transfer that are gonna be required for us to do absorption, distillation and absorption. So, uh, particularly if you might have found the heat and mass transfer unit a bit difficult that hopefully Section eight should be a nice kind of backfill to make sure we're all comfortable with the methods that we're gonna be using. Uh, Section nine is around absorption columns in general and how they operate. So what I have today and what I've done is to take the order of the continent, actually reverse it for our two workshops on this area. So today's workshop is going to focus on what is an absorption. Colin, How does it operate? And what are the key operating equations that we need to know to be able to weaponise it? Uh, next week, we're going to take a few minutes and just make sure we're all comfortable with where things like mass transfer coefficients come from. How do we get them in practise and what are their foundations in things like molecular or volumetric to the city. So I'm gonna mostly focus on reader section nine today, and that's just because we're beginning lab to on absorption, and then we'll circle back to rear section eight next week. The quick note that Quiz Three is due by close of business this Friday. Um, and loud and port number two. So we're now beginning the absorption module. So its do at next week, Friday. Now we have begun the marketing process for the lab one. So my hope is that this should be back to you with, and it will be feedback across every criteria in that rubric, probably by the middle of next week at the latest. So this will at a minimum give you say 48 hours to make sure that any kind of keep structural, grammatical or presentation mistakes can be corrected. All right. Okay, so today, what we're gonna do is actually begin. I can get my drawing tools. There we go. So we're going to begin in talking about absorb ab absorption. There we go. By accepting that in the context of absorption it or mass transfer In general, I can draw a lot of analogue, as you would have done in heat and mass transfer to heat transfer processes. So I have a driving force for heat

transfer and a temperature difference. Similarly, in mass transfer, I have some concentration difference. Um, I have a resistance to that driving force. So in thermal diffusion, it would be the thermal diffuse city, so that the ability for the material itself to transmit energy, um, and in mass transfer, I tend to think about volumetric diffuse city. And I don't have the same kind of analogue of turbulent and laminar or rather flowing non flowing on that we use in heat transfer. So I can't draw the analogue perfectly. But what I can do is think about the ability for, um and I always go back to the metaphor when I teach this of having an assault cube. So if I take a sugar cube or assault Cuban, I drop it into a glass of water. If I just sit there and observe it for a while, what I'm going to see is a diffusion away from that really high concentration assault. And I can visualise that process of mass transfer. If I then start mixing the water with something like a spoon, right? I can start to see, uh, the evolution of that material and the fact that is as I stir it faster. So I increase the turbulence in the system. I do get an improvement of diffuse city and mass transfer. So in this reference frame, we're gonna circle back next, just gone from a windows to an IPAD. So hopefully we'll let me draw. Okay, So we're going to circle back next week and and come back to this idea of a mass transfer coefficient and in particular its relation to volumetric dick lucidity. So we're going to come back into the fundamentals and that relates to section eight. But what we can look at for now, Is this understanding that my molar flux Jason So the ability or the flow rate of moles from a region of high concentration to a region of low concentration is governed? It's proportioned by this mass transfer coalition, which we're going to give the letter little kay. Now, again, we're going to unpack the fundamentals around this next week. But for the purposes of the practical Engineer, then the end of our symmetry between heat and mass transfer allows us to now invoke definitions of the Schmidt number and the Sherwood number. And what we're going to see is that these are put together in the same formalism as my Nestle number correlations where I need to know the Reynolds number in the Crandall number. Right? So Reynolds and Crandall tell me something about how, um, turbulent Eddies in the system are relative to its overall volumetric flow. Whereas the Crandall number tells me about how the thermal properties of the system are evolving relative to their hydrodynamic properties. So I can take that same approach. And what I noticed is that my Sherwood number here on the bottom right, that is fundamentally defined by a mass transfer coefficient. Little kay. So in the same way that I would use a suite of muscle style correlations to ultimately get out the convective heat transfer coefficient age, I can now use Sherwood correlations to get at the effective mass transfer coefficient. Okay, so in the next week set where we're going to look at, um, race that So what, we're going to look at it in next week's workshop is Then what are all those correlations I can draw on now, if you're starting to work with those for the purpose of your laboratory number two, I would advise. Of course, the reader is there. So all of the content that I would talk about in the workshops is already in section nine, and you can see how those same Sherwood style correlations are out laid as a function of the geometry of the flow, the degree of turbulence in some cases, the materials phases that are going to be present. So for our intents and purposes, then what we're going to focus on today is understanding the basis of an absorption column. And this shouldn't take more than about 20 minutes or so to go through the slides, and then, in fact, the workshop prompt that I have for you today is specifically to design. What we're going to look at is a direct air capture unit. So anyone that's been paying attention to the news and the some of the IAEA reporting on climate change and recommendations

for technologies for emissions reduction there are a few pilot plants in the world that are extracting air right large, large volumes of air and trying to directly capture the CO two out of that error into in traffic in the liquid phase. And so absorption is one of the technologies that they can use to do that and in fact, is the leading technology. So we're going to do in the workshop is try to design and scale to to a practical either state or federal level scale. What a D a. C C rig would need to look like to make a meaningful impact on our emissions reduction in bridge. So these these D A. C. Riggs of the direct air capture rates are exemplars of absorption columns. So the idea behind an absorption column is that I have gas coming in that contains some contaminant. Now I call it a contaminant. Doesn't necessarily need to be negative, right? It could also contain some product of value. Maybe it's only reacted and trace quantities, and so I need to extract one mole percent out of this to form my finished product. And the idea is that I bring this gas in so it flows in and it will flow up through a number of distribution camps just so it gets even distribution through a bed and then here, inside of what we call this bed section right, we have a bed filled with packing materials. So when I characterise these beds, I think about the total volume of the bed itself. So I'm going to have some air gaps, and that's depending on the material that I pick. So I characterised by the volume and geometry of that bed and the material that I've chosen, and that's what we're going to go into next. So the purpose of this bet, fundamentally, is to generate a large amount of surface area between my gas and liquid phases, and ideally, it should do so with minimal impact to the momentum balance. So the ideal bed that we would go after, uh, would be one in which I have virtually no pressure laws, an infinite contact area between gas and liquid, and then everything down from that starts to get me into the real world scenario. So in early days, I might have filled these packed beds with something like silica sand, right to go out to a beach and pick some rough sand, and that will give me a relatively well distributed service area. In the past 30 40 years, we started making a lot of progress in the design of what we might fill these beds with, Right? So these are on the bottom, everything from rashford rings that would be more traditional in the 19 eighties, uh, through some of the interlocks and the saddles that are used today and you can see here these types of materials tend to get very high surface area for a relatively minimal impact to pressure drop. And so the idea is that I'm going to flow this gas across this bed filled with these packing materials and then in the top, I'm going to inject some liquid, so this is also sprayed. So it has an even distribution, and this liquid is going to be deficient in whatever that contaminants going to be. Um, And if we go back to our fundamental thermodynamics, we can see Well, I need to choose my liquid pretty carefully, then, based on the knowledge of the contaminant that I'm trying to extract. So if, for instance, I'm dealing with CO two as we're going to do in this this example so we have co two and air. Well, I can't really dissolve a lot of CO two into a liquid hydrocarbon phase. So if my liquid inlet is chosen to be something like a decade, well, then I'm not actually going to get a very good mass transfer, because thermodynamics tells me I can't put a lot of CO two into that decade. Whereas if I take an Aquarius species either water or some combination of alcohols and black holes, I can dissolve a lot more. Co two into that, probably in order factor of 100 more co two. So it critically relies on an understanding that what's ever coming in this inland for the liquid is out of step with the thermodynamic equilibrium of the gas that I'm trying to cleanse or purify. And this this packing material in the bed simply then gives me a sufficient surface area across which I can work. So for each of these types of hacking materials, we would characterise them.

One of the most important factors is the process. We right, So this is going to tell me if I have a total volume of the Pact section. How much of that packed section is going to be vapour, right? How much relative to liquid? So if I have a process of 0.99, that means I only have 1% by volume in the packed section. That's actually solid, and that tends to do quite well for me. When I think about something like pressure drop, it's not a perfect correlation, but it tends to be a direct correlation, and the other factor that they care quite a bit about is the packing factory. And as we're going to see in a few slides, this comes back in when I have to think about the pressure drop. So in the same way that I have to inject this gas well, this is going to have to be at SAPI one whereas the gas coming out of the two or the top is going to be a P to which we can assume will be somewhere around atmosphere. It might be a little bit higher, but traditionally would probably discharged atmosphere. And so we know that P one must be some amount greater than P to buy this relationship for the gas to flow. And so what I really need to think about then is the pressure loss, the momentum pressure loss across this Venn. That itself is a function of that packing factor and then I can see on the left hand columns. I can choose the nominal diameter with the type of packing material and this well. It has a minor effect on the Prasit E and the moderate effects the packing factors. It also lets me relate the bulk density to the total area that it will create so quite critically when I look at something like the surface area because that's my whole purpose of using these materials, right. When I look at the surface area created, we define that surface area relative to the volume of packed material, and that takes into account the fact that it is a porous media. So through a company that might be selling these, they go into their pilot lab, measure all of this and then report back that for every foot of height in that packing material or metre of height, I'm going to create so many metres of service area or foetus, where the service area as we report here. So when I start flowing, then I appreciate that I have some gas and some liquid that are flowing together now because my packing material is mobile, right? So I'm not anchoring it to anything or welding it in place. These are just solid little bits that are floating in like a container. So if the velocities between the gas and the liquid phases are at an opt or the momentum is balanced perfectly, then I can imagine a scenario where I can start to get localised buildups or localised movement of those packing materials. So imagine that the water coming in is not very turbulent, so it's falling down quite quite slowly. But the gas coming in is quite fast, at a very high velocity, and so in turn, that gas can start to balance the momentum of the more dense water and consequentially effectively start to levitate, right some of those packing materials or give the appearance of limitation. So when I think about this situation, and in that when I start turning up that gas velocity, what is going to do is allow the liquid so these solids are starting to levitate up into the column a little bit. Then that liquid can start collecting around each of these solids in the packed bed, and we refer to this phenomenon of local liquid collection as a localised flooding. So in early, right, if I started very low gas velocity and begin turning up gas and liquid velocity as I add more and more liquid to the system, I see an increase in the number and distribution of these localised flooding events. When I start turning up the gas phase, I can start effectively levitating those solids in the bed, which makes it yet easier for the liquid to flood in certain regions because it helps suspend that liquid phase. So when we think about then operating these columns, we tend to want to pick. So these two plots here on the leftist mass velocity for air or gas and on the right is for a liquid phase. We can think about predicting the pressure drop, so we'll focus here on the left for a

minute. If I'm predicting the pressure, drop that Delta P as a function of the mass velocity of air or gas coming across this, I can see I start at some dry condition, right? So I have no liquid in the system. And through each of these successive curves, I'm turning up the amount of liquid higher liquid injection turning up the amount of liquid that's coming across that bone. So, quite naturally, the more liquid I have, the more contact area. And we appreciate from fluid dynamics and thermodynamics that whenever I have an interface between two phases, I lose energy. There's a price I pay for my dynamically for having that interface and putting that interface in motion. And that price is pressure drop. So the more liquid I have, the higher the pressure drop is going to be, and in this case, this particular plot and the reader goes into a few analytical models that complement this. But we tend to predict it in something like the the amount of pressure loss, so this would be inches of water as a measurement of pressure, like millimetres of mercury are similar to. But we could just as easily report atmospheres or bar per height of packing material. Now, if I let's say we nominate our liquid velocity, so then I can see that for a packing size there. Sorry, we set our gas velocity. We're looking at these relationships for how much liquid we're going to put across the column so I can start at something like, uh, as I see, I started my lowest liquid injection flow rate. If I turn that up by a factor of 10. Sorry if I turn this up by a factor just shy. So 10 that I can see now if I'm going to maintain the same pressure draw. So let's say I started 1000 gas velocity and these are in imperial units. But if I begin at this point here and I have except 10000.0.7 inches of water per foot of packing, but I accept a nominated pressure drawn well, if I start turning up the liquid velocity by a factor of 10 to maintain that same pressure drop across the column, which my system is momentum balanced for. In fact, I can only have 1/5 of the air mass velocity coming across. And so these types of relationships, we would typically want to court to measure these in a pilot lab. If we were building something like this for industry, uh, we can start to use tools like Aspen Isis, but they're not going to give me these really realistic pressure. Drop curves the same way as actually measuring left. But this allows the engineer then say Okay, if the most expensive part of my system is like a gas compression, which it would be for these right absorption Columns are notoriously cheap, and and they were one of the first mass transfer operations because of that. So the big expense I have to pay is in that compressor. Well, I'm going to nominate now a limit to that pressure drop that's enforced by the expense of the compressor, and I can see how the rest of my system parameters are going to flow around them now. If I let's say we set the gas velocity and we're going to look on the right side now what happens if we start varying the liquid velocity. And in particular, what I can see is that the, uh I'm plotting these here is a function against the flooding velocity. So the flooding velocity is going to be what happens, or what's the velocity of the liquid? Sorry, the gas phase required to begin this localised flooding build up here on the right. So that's when I start to see a fall off in the efficiency of my column. So if I nominated um, or for looking at different liquid velocities here, so let's focus on will pick one packing size and follow it down. So I'm a liquid velocity of £2000 per cubic foot per hour that I can see here. I I need a gas velocity in excess of what would this be? Probably 11, 1200 of the same units pound per cubic foot per hour. That's going to be the minimum gas velocity required to begin levitating right. Some of the solid particles in the gas phase and allow localised liquid to build up. So we call this the flooding, the flooding velocity, or rather what I would call it the onset of flooding velocity. So together these two parameters help the engineer bound how the column is going to

operate. Right. On one hand, we have a a framework around my most expensive component in that compressor and the pressure drop that it's going to be able to deliver and on the other, making sure that I'm able to operate the column, driving it as hard as possible without tipping into a region of inefficiency with localised flooding. Okay, so if I wanted to predict the pressure drop across these columns, I can use, um, and the reader goes into a few different correlations. Some of them are actually visual court or, uh, correlations from the fifties and sixties. But I can look at a number of correlations to predict, based on the type of packing material that I have and the relative balance of gas liquid velocities. And I can see here when I calculate these are the FP. So the packing factor is going to come into it as well as the thermo physical properties of the liquid in the gas phase. And these allow me to start estimating right So each of these is Isis isil, Barrick drop curves. But curves of constant pressure drawn what I can expect across the column and in the same approach. These types of correlations can be used to estimate right, and so I definitely highlight that this is only an estimating technique, but allow me to estimate the pressure drop across that, not the point of flooding. And so if I appreciate that flooding of the column, meaning I have a really high gas velocity, that's that's pushing those particles up and allowing the liquid to collect around it. The flooding would represent a functional upper limit to the amount of gas that I can flow across the column, whereas the pressure drop at the flooding point is a second bounding limit to the expense and the ultimate scale of the system. So when I have my column. So let's say we've purchased a compressor that's more than suitable for our needs. We know our liquid phases well matched to extract our contaminants from the gas base. Uh, so in this case, we might think about water stripping CO two out of air and for for all intents and purposes, we'll assume the air is 79% nitrogen, 21 more percent oxygen with a residual balance of, say, 350 ppm c 02. So if I know that my system is well designed and I have enough room to run with my compressor, then to design and look at the basis for the absorption column, so we'll draw this here on the right hand side. So here I can see in the main section of the column, this is where my packed material would likely be. So what I can first do is think about drawing a control surface or a drawing a system boundary right across the entirety of the column and then, uh, progressively different sections of the column, and we'll get into to what that looks like. So if I draw in the first instance a total material balance as I extend the thermodynamic service across the entire unit operation that I would only care about what's flowing in and what's flowing out right? So my total material balances shown here for the column. Um, if I know the compositions of what's coming in, then if the column gets me to an equilibrium point between those two phases and all of their species that I can use thermodynamics to tell me what the likely conditions are at the point of exit or the thermodynamic equilibrium conditions. And so I can then apply this to a material balance both within the column, Um, as a whole. And on a component level. Right now, when I look at this total material within the column for a minute, I can see that I can see that I've lost these sub scripts Visa being Elsa, all that we're doing there is looking at. Well, if this control surface is separated to different heights, I'm going to have a different composition in my local liquid and gas space. Right, Because these phases enter out of equilibrium with each other, and as they transmit across each other, they're going to come into equilibrium. So the distance that I am through the column is going to get a different composition in the gas and liquid side. So I can, um what I can do is take the total material balance for, say, component A across the entire column, and I could

rearrange this, uh, in the form of y equals MX plus B as to what this means, all I've done is some trickery with material balance. But if I accept that in particular, um, at some intermediate point in the column, So before we get to the terminal positions, But I don't know X and I don't know why, because they're changing as I go through. So if I say well, the two I can set, why? Equal to some function of X? Well, I know I can't rest my hands on the iPad. Sorry. I know that I have a set inlet gas composition, a set inlet liquid. And I know that I've specified my inlet liquid and vapour. Mueller flow rates. Right. That's what my compressor gives me, and that's what my liquid face pump or water supply will be. So, in fact, the only thing that I don't know is my intermediate gas and liquid compositions and the Mueller flow rates of those, um, intermediate positions. So viene el. So when I write this to solve, why four X? What I can say is okay, I don't know V or I in the middle of the column, but in this form they show up as a ratio of each other. So, in fact, it's one thing I don't know it's wonder. And the second term Well, I can see the numerator of this is fully specified, but also because I have the in the denominator, it too can be taken. This no longer a variable in the equation, right? Because if I know the ratio of L. A and B, then I can set the outcome of the so. What I can do is use this basis and the way that will construct the operating will call an operating line, uh, for absorption. Columns is in y equals X space. Right? So this is the same kind of compositional space at a constant temperature and pressure as the assumption. Uh, but the same kind of compositional space that we would get that we will use for distillation and absorption, right? And the two things I care about Why? So if I'm if I've set my pressure and temperature or assume their constant over the process with nearly constant, then this equilibrium curve here this I can get from three of them, right? And that might emerge from a complex solution two rounds law, where I'm using a cubic equation the State Department down space and appropriate, um, activity coefficient models to handle the liquid phase. I can also use a tool like multi flash right that's available in all the lab computers I put in my compositions. I flash it at a constant reset pressure and temperature, and the compositions that come out the balance of Why versus X for each of my components are what create this operating curve. So as exchanges, what is the corresponding, um, change of why? And I should mention this is for my target component, right? So this would be the curve for CO two, varying in a liquid and gas phase that are otherwise inert. So what I'm doing here is changing. Uh, if I were to do multi flash, I could run up the system and just flash 10 points across the equilibrium curve at the same temperature and pressure, but at different mull fractions of CO two in the liquid, right? And then I would look at what is rather for different amounts of CO two. Overall, what is multi flash predict is the split of CO two and the liquid and gas face and that will form this kind of curve. So the equilibrium curve for absorption and for both of the future mass transfer operations is what's informed by thermodynamics. The operating line is what the engineer brings to it for the unit operation itself and the operating line I can get. So we're going to come back next slide, and I appreciate I'm running a little bit long on this, but I know everyone's getting in the lab to, so I want to make sure we do it. Justice. The operating line. I can, um, do some really cool trickery out of this to estimate things like Ellen V, but fundamentally to create it in first place. I only need to know two things. So these two positions that I've highlighted, I need to know firstly at position A. So what is exiting? That would be the concentration of my target component in the liquid as it enters. And I also need to know, why are they so that's going to be what is the concentration of my target in the gas? So the thing that I'm trying to extract from the gas, what is it

coming in at now, in most cases for doing something like CO two and water, then we would say, Okay, We're going to assume a constant composition of co two. Say, if it's a direct air capture will be 350 ppm co two. And we're going to assume that we have water that is free of CO two. So we're using clean water coming in, and and that would mean extra day or sorry. Why? So they would effectively be zero were very, very, very close to zero. And at the other side B, I need to look at what's leaving the column. I'm sorry expect. Sorry, I made a mistake, Miss Miss. Read that. This is why I said so. What's leading the column in the gas face? Why Said be is down here. Um so why City is going to give me the inlet composition of my contaminant in the gas phase and exhibition is how much of that is leaving in the liquid phase. So, traditionally, I would know, right? Why should be I should know. Except they And what I'll need to use thermodynamics to informed is what is the total amount of mass that I'm gonna move. So I think about gas containing co two and pure water. I'm going to move some number of moles of CO two from the gas phase to the liquid phase per time, right per minute per hour per day. And I'm gonna traditionally assume that that's the only thing that transfers. And so, in fact, why sub A and X A B are related to each other, right? So the amount of stuff I've taken out of my gas phase to go from what screwed up again to go from y So be it the inlet to wasabi at the outlet. That same amount of stuff has gone into my liquid things. So x a B is larger than X sub on that exact numerical basis. So if I'm then trying to predict well, what's the rate of the absorption that's taking place, right? I can like anything in chemical engineering, I can look at a number of different forms of the rate equations of the rate of man is transferred, Uh, for this unit operation. Now, I won't go into a heap of detail today because in fact we're going to need to explore some of the theory on this next workshop before we can unpack this in full. But I can effectively look at two types of mass transfer coefficients in the same way When I have a heat transfer system, I can say, Well, look, I know that thermal diffusion. Right? Um, so conduction of heat in materials is usually right, in most cases going to be 99% of the resistance of the heat transfer that I'm going to deal with. So maybe I'm not going to calculate the additional resistance of having a highly turbulent liquid phase on one side of the equation. Right? So that same thinking that we took from heat transferred, we can apply here. And what we can say is that if I have a liquid and a gas case or liquid and a solid or a gas and a solid, I'm going to have a number of mass transfer resistances that all stacked together, right? And so I can characterise. What I ultimately do is I can characterise the entire mass transfer resistance, or I can go, uh, point by point. Thinking about the individual layered resistance is and I can add those together. But in this case, well, what will focus on here is if I come back to my equilibrium or my X Y plot. So the equilibrium line This is again, what I get from Thermo, my operating line. I would draw two points, right Because I am. I can define those points based on their thermodynamics itself. What I should transfer across, and I can notice here that we call this an operating line. But in fact it has a bit of curvature, and I go into some detail on the reader. But the reason why is that? You can imagine, as we go from the beginning of the column to the end of the column, right, the because I'm transferring little blocks of mass along the way. We'll, in fact these proportions and these ratios are going to change. So put another way, this ratio of L envy is not always constant, right, because l is getting smaller as I go. Sorry, it's getting larger as I go through the column, and V is getting smaller it for something like go to air captured. So I'm moving little molecules of CO two from the vapour to liquid. As a consequence that l over bigger the slope of the line changes

fundamentally giving me occur. So if I look at some intermediate point along the curb, right? The point that we want to take home from this will reinforce it next week is that I've nominated here to say Okay, we want to look at what happens. We're designing this absorption column. Let's look at what happens if I have some intermediate co two concentration. So if I'm going from 3 52 0 is my range for direct air capture? Well, let's look at what might happen when I have 100 MOL ppm of CO. Two in that liquid phase. It was starting to vapour phase. Now when I read these exit out, there we go. So when I read this plot right, it's an important concept that the distance and where this is going to come up again in distillation as well the distance between my operating and my equilibrium line, which I can define in two ways. I can either define that distance separating two horizontally or vertically. Or in fact, I could even define it tangentially as we'll see, uh, come into play distillation. But the distance between these is the driving force for mass transfer, so the further that my operating and equilibrium lines are from each other, the more the faster the rate of mass transfer is going to be. Now, when we look at the equilibrium and operating lines this way right, we come up with a way to characterise this by thinking about So X star is going to be the liquid that is in equilibrium with a composition of why and similarly why star will be that which is in equilibrium with the composition of X. So very simply for the different ways that we can frame this mass transfer rate, I can usually will tend to use these bottom two. Here I relate the overall mass transfer coefficients, So case large case of law. And this is what I'm going to use my Sherwood correlations to get. Now the driving force behind that mass transfer coefficient is why minus y substructure. So the horizontal distance across. Alternatively, I can characterise the liquid phase mass transfer coefficient case of X by thinking about its liquid and vapour sides. And I can similarly right the rate equation for the liquid phase so extra minus X. How quickly does that seem to want to jump into the liquid phase? In that scenario, so I'll try to wrap up here in just the next couple of minutes. I'm sorry, running a bit long. So when I'm designing the absorber absorption column, then and I don't want to spend too much time on this slide, but I can't because we're not going to really do a lot with mass transfer units. You have to do a few calculations in the lab. But in fact, we're going to see the concept of transfer units come up much, much more aggressively in distillation. So I don't want to spend too much time out of here, but effectively, I can look at for each If I'm focusing on this packed bed on the right hand side for a minute, I can think about Well, if I'm going to say, put 10 blocks or eight blocks of mass right between, uh, we're gonna have eight individual transfers of mass between, um, the vapour in the liquid phase in this instance, then I can start to characterise that based on both the overall driving force. So how many units or how many individual instances? I have the overall driving force for mass transfer and the height of the overall column so I can take the same basis for this design and write out well, how high is an individual transfer you're going to be? And how many transfer units do I need to go from my bounding conditions to address on the bottom the thermodynamic equilibrium required. So why not just why some star? So we'll come back to this again next week. I don't think there should be a lot of work in Lab two on the number or height of transfer units. But the point is, I can basically multiply these together as we show in the reader h seven times, and Sambo is going to give me an overall consistent mass transfer rate. So here I can see here the tide of the height of the column z 70 which I can get from analysing the liquid film, the overall liquid, overall gas or the gas film so I can analyse any of the resistance is in the system and they should all output

the same overall column height. That itself is defined as the height of transfer units times the number of transplants. So just wrapping up for for this workshop session for the slides today So to the engineer. Then once the the absorption column is in play, I don't have a lot of levers at my disposal to significantly modify its basis of operation. Right, I can change out the liquid. So let's imagine, how do we do with the process upset? So we get air coming in that might have coming from an industry plant with 10 times the amount of CO two is what I would pull out of the air. So if I have such a process upset into my unit operation, well, I can always think about changing the liquid, right, that that's one option. But if I'm dealing with really large volume systems that may not be reliable or if I have oversized my compressor and I'm operating well below that flooding points, I have enough room to run with the compressor. I can always think about increasing the amount of pressure drops across the column, and the point that I raise here is that if p two so, pressure, um, to would be greater pressure one. So if I draw up this this absorption system for a low pressure P one that I can see here is my equilibrium line. And here's my operating line, so I can then think about how many transfer units are going to be in that system. Uh, and how can I? How much flexibility do I have in the L over the ratio? So the Mueller flow rates of liquid and vapour as the engineer. But if I go to a pressure to that's much higher all of a sudden, if this was the original distance between, these were driving force for mass transferred. All of a sudden, that distance is blown out by almost factor, too, right, so the dash lines here corresponds. Conference condition. So that's one rationale that an engineer might use to say, Look, I'm not going to buy compressor that's sized to 99 while rather 101% of the maximum flooding requirement, maybe we want to make a slightly higher investment up front to build a compressor that gives us room to run so that this particular absorption system can service a number of needs and different feedstocks. And again, I won't go into this in too much detail today, but effectively as well come back to next week. Um, I can take the same approach for an absorption column. And if I run the entire thing in perfect reverse meaning I have a contaminant in my liquid and a gas in which it prefers to be based on the volumes, Then I can exchange that same component from the liquid back to the gas phase needs to be a different pressure and temperature, obviously pressure and or temperature. Um, but we we tend to see we call this a stripping column, and we tend to see industrially the pairing of absorption and stripping Collins because they can be built identically and just piped in, uh, rivers. Okay, so I will, um I'll cover structure and dumped packing next week. It's not material to this problem today. All right, so I will wrap up the workshop, slides there, and we'll get started with the workshop prompt, and we'll end the recording now.

SPEAKER 0

Okay. Marvellous. The recording and transcription had now started. All right, so thank you. I'm so sorry for the last minute notice. I wasn't able to get into campus today. Um, so thank you for joining me online. Today's workshop again, just with the four of us. So we'll try to make this relatively straightforward. I wanted to take a bit of a deeper dive into absorption and actually talk about and and work on a workshop exercise with a really key unit operation that chemical engineers do every day. And that's to look at absorption in sour gases. Specifically, we'll be looking at H two s. So before we go too far, just a few reminders for this week. Well, this will be our second of two weeks on the absorption modules. So if everyone's been treating the reader ahead of time, then by last week, hopefully reader sections 89, respectively, on mass transfer and absorption would be complete, allowing you to then complete the lab

report number two by close of business this Friday, the second of September. All of the marks where the lab one reports have been completed. Uh, those are currently with me to reconcile this afternoon and make sure everything looks good. And then I will be publishing all of those, Uh, objective is later today. So this will give you the opportunity to click in and look at every criteria in reference in the lab. One report how your reports stacked up to that criterion reference. And if it wasn't perfect or it wasn't zero, so we entered something, then there should be feedback for every reference for you. So that in particular what I'd encourage people to look at things like the report, presentation, writing and analysis. Some of these feedback points will be consistent across the four different laboratories. Um, so in the last lecture, we had really kind of rushed forward into talking about absorption before we spent some time revising mass transfer and making sure that we're really comfortable with those fundamental concepts. Um, so I wanted to present it in that order because I appreciate everyone started looking at an absorption lab exercise last week, so I thought it was worth our time to make sure we were all comfortable with how things flow through the unit operation. How we take measurements, the basis of operation and so forth. But the absorption unit critically relies on this understanding that when we bring a gas and liquid into contact with each other, if there is more than one component in the system, then that gives us the opportunity to move molecules between these two phases. Uh, so if we take the exemplar of a binary meaning, it's a two components of a binary two phase system, two components to phases. Then I can see that if I start modifying the composition of one of the phases or the pressure and temperature at which the liquid and gas contact, I will be able to reach an equilibrium condition that's different than the feed. So what that would critically allow me to do if I let's say, have a lot of CO two or H two s or another contaminant, uh, in my feet gas phase. It would allow me to transfer those to to a liquid phase. Now this relies then, on, uh, what we had talked about in the last workshop. The use of Sherwood number correlations, which themselves are estimates or empirically regressed estimates for how molecules are going to migrate between these phases. So the rate of mass transfer. Now, these diffuse cities that we would talk about then fundamentally came from the volumetric diffuse city. So we can think about that in a fundamental context as a property of the system. But unlike a, uh, heat transfer property, something like thermal conductivity, the volumetric diffuse city depends a bit on the composition of the system. So now we bring in. This is why our mass transfer analogue is a in order of magnitude more complex than he transferred. Because we now have to think quite critically about what components are in the system and how those affect the volumetric diffuse city of the molecule I'm trying to target. So one of the I don't expect folks to be very, very, uh, comfortable with using all of these volumetric, diffuse city calculations. What I want to do here is walk through a few examples of where this could come from. Um, if, for instance, we took molecular thermodynamics. So the end of 3006, we took molecular thermodynamics and tried to calculate something like the ability for molecule a or the diffuse city of molecule A in molecule B. And we would write that is large capital d sub baby. So the diversity of molecule A and B and we can see for a very simple estimate of something like binary gas. So two component gas phase. Predicting the diffuse city of Component A in component B is shown. Here is the Chapman and Scott equation. And so let's look for a minute. You know, again, I don't expect folks to be very, very comfortable deploying this, but it's also not too hard. So I wanted to talk a bit about where this equation comes from, and it's actually has its origins in thermodynamics

and how we can use it for relatively simple systems. So first, let's look at the dependencies of the chaplain's got equation so we can see a temperature to the one half. Power is included in here, and we're going to come back as we're going to see that in different forms for the next couple of slides. But we can see that diffuse give diffuse acidity increases with the temperature of the system and critically, right. We can see that if we were to flip out molecules A and B, it wouldn't matter, right? The temperature term is not dependent on the composition. Neither is the pressure. So, in fact, the nature of the Chapmans cog equation gives us to really key insights upfront. First, the diffuse city is more sensitive to temperature than it is to pressure. We can see temperature to the one half and pressure to the first power on the denominator, but also that it increases with temperature and decreases with pressure. So if I look at the form of this equation, if temperature goes up the diffuse, if it goes down, it goes up. If pressure goes up, the diffuse city goes down. So what else does Chapman and ensconced depend on? Well, I can see I hear in looking at kind of a numerical average of sorts of my, um or a weighted average of my molecular weights of my species. So this would be an estimate of the size of the molecules, their security and the ease with which they can flow through different media. And the connection point thermodynamics is in this Sigma A B and Omega D turn these two terms. So the first Sigma, Maybe this is the collision diameter or the effect collision diameter. What this means is that if I assume all of my molecules and my gas are perfect spheres, which they aren't. But if I assume that they are, then I can hear calculate the collision and, uh, effective collision diameter by thinking if I have a molecule of a in a molecule will be collide with one another. What is the overall diameter of that combined collision? So it's a way that if I'm going from a system of CO two and water to something like C 30 or C 36 hex A try content, right? A very, very long large molecule and CEO, too. I can see here that having a large to small molecules versus a small and a large molecule colliding will give me a different type of interaction. And so that's where this effective collision diameter comes in. Now I would look this up in tables for each of the molecules in question. So the example here is in the became seventh edition textbook Appendix 19 shows these, um, sigma values the effect of collision damages for each of my molecules or each each of the common molecules that we're going to consider. And these are reported in extremes now more important and the real connection to chemical physics and thermodynamics. Is this collision integral Omega Dean Now the collision integral. This comes from considering the interaction. So let's go back to that discussion from thermal around. If I have the collision between different molecules, right then I go back to the metaphor of billiard balls on a billiard table, right. For the sake of most thermodynamic calculations and in most cubic equations of state, we assume that these spheres are hard billiard balls, meaning they don't really feel an attraction or repulsion until they collide. And at the point at which they touch each other, they have an infinitely strong repulsion, right? So if I try to take two billiard balls and crush them together with both my hands, I'm not going to get very far. Whereas if I take two crumpled up pieces of paper that are the same size and crush them together, I can do that much more effectively. So this this collision and enrolled then we rely on on an estimate from chemical physics to tell us well at what distance through that molecule. So if I go all the way out to the very edge of the electron cloud. Well, I'm going to have a little bit of play if I try to push the molecule and compact it from the edge of the electron cloud inside. But if I start to compact that more and more and more to the point that I've reached the nuclear centre of the molecule, well, then it's

going to be nearly impossible to compress the molecule any further. And the form of this, this attraction repulsion we would find from chemical physics. So the one that will use here just as an example. Our case is the Leonard Jones 6 12 potential, And this is a very famous chemical potential or molecular potential from the chemical physics physical chemistry. And we talked a bit about into Well, now I don't really expect folks to get too deep into performing calculations with this Japanese dog equation or the Leonard Jones 6 12 potential. But the point that I want to make is the potential itself is characterised by that radius. You might remember the van der Waals radius when you drive the van der Waals equation of state, um, and the depth of the potential wealth. So in the limit that to molecules might be semi attracted to one another. What is the maximum degree of attraction when they're sitting in that kind of sweet spot of each other's potential wells? The maximum attraction that they can yield? And that's my east of 12 term or the collision and a girl that we can get. So, um, when I think about more practical unit operations and so we can see our history volumetric diversity is coming from the chemical physics treatment of how we think about our molecules, right? They're not actually billiard balls. They have some attractive and repulsive potentials, depending on where they are relative to each other. And if I have either a stock standard or an innovative description for those potentials in a simple system like a binary, I can actually get back to the point of calculating or estimating volumetric inclusivity. Now, when I come into a unit operation where I consider poorest media and we're gonna be looking at a few of these things start to change a bit. And the idea here is that if I have molecules in the poorest media, well, if the poorest are around, not perfectly but around the same size as the molecules. Then all of a sudden, the poor throat where the minimum diameter of the poor becomes relevant, right? If the molecules running around and bumping into each other is happening on about the same length scale as they can run around and bump into the wall of the poor. Then all of a sudden I have a geometric constraint from the poorest media that also affects my diffuse city. And this is given by its called nuts and diffusion and what we can see here. We see a similar right that temperature dependence has preserved in kind, meaning I now have a temperature dependence of the one half power. But we see it's it's less in magnitude than for volumetric pure diffusion. Because we have this constraining factor. Now, of course, our support. This is the radius support. So as the poor gets larger, the diffuse city or the nuts and diffuse it, he goes up now, at some point, right I can increase. The parasite is such that the contribution of the nuts and diffuse city is very very, um, it was much higher, right? The nuts and inclusivity being much much, much higher than a volumetric, diffuse city for a large poor system. So in that limit, I can say, Well, actually the knots and diffuse city by putting an infinitely large poor, then the nuts and inclusivity is going to approach infinity. And so if I'm thinking about, uh, an intermediate poor sites where both the geometry of the poorest media and the molecules themselves are going to play a significant role that I can add these together in series meaning one over the actual defeat for the expected diffuse acidity of the poorer system is defined as one on the nuts and effusive itty plus one on the volumetric inclusivity. And so if nuts and diffuse it is going to go to infinity, then I have one over infinity or zero, and my poor, diffuse city collapses to the volumetric capacity. Now, when we get into the liquid phase that it's a bit more difficult. Um, Stokes, Einstein predict or provides, I should say, a very rough estimate for volumetric defensively and liquid. Uh, but it goes with scales with the bolts Man constant directly with the temperatures, are no longer preserved to the 1.5 power

and we can see here. Then we also need to start thinking about the viscosity or mu of the liquid phase. And that is, you might recall from thermodynamics gets very difficult because we cannot use Thermo at this stage, hopefully in the next 2030 years. But thermo, as such, cannot yet directly informed what those viscosity should look like. So we can see here that it's very much an estimate where I have a weld or for Stokes Einstein, a well defined viscosity, a ideally, a spherical molecule, um, and and some understanding of that potential well between them. Now, if I go to relatively low molecular weights and liquid, the will chang correlation so molecular weights below 400 this can be a little bit more accurate than Stokes Einstein, because it does not necessarily require the assumption of the billiard. So the perfect hard spherical molecules. But I do need to think about the association parameter of the solvent, so capital size A B, and you might recall the difference between, say, c. P. A equation of state and a standard cubic is thinking about well, if I have associating molecules in the liquid and vapour phase. Those are going to affect my thermo physical properties, including, of course, volumetric capacity. Um, in a simplification for the will Chang correlation that when I don't have a lot of electrolytes present meaning I don't have salt ions or things like alcoholism or black holes. Then I can start to use, um, this simplification here on bottom, where quite critically, we get rid of the viscosity of the liquid phase mu and replace it with the viscosity of water. So this now scales only with the molar volume of the solitude. Um, that it's normal boiling point. All right, So how does this, then? The slightly deeper explanation. I wanted to make sure that we as a class coming from thermal than in unit hopes, kind of completed the circle and connected, uh, these diffuse cities that we're now actively calculating and trying to get the mass transfer coefficients for our unit operations that we appreciate that those actually come to us fundamentally from thermodynamics and that we appreciate after last semester the limitations of thermodynamics serving 2020 right, that we are a good century away from being able to weaponise the more advanced aspects of thermo um, but fundamentally, Thermo at its core does inform these properties. So the discipline of mass transfer and we get into using things like Sherwood number correlations. This is very much the 20 and likely 21st century engineers ability to approximate these values on the fly without having to rely on first principles Calculations. So what we're going to use, um, in our Sherwood correlations are the the mass transfer coefficients. So we'll give these the letters little k sub seed. And the point that I want to make on this slide is just twofold. First, that my mass transfer coefficient Fundamentally, I look at this top equation here. KFC is in a global approximation of the molar flux of my species. So JSF is the molar flux on the concentration driving force. So if my this relates to the difference of the inter facial concentration in the bulk concentration. So if I have an interface where I let's imagine coming from the liquid phase, let's say coming from the vapour face, right. We have CO two in our paper. We're trying to transfer it into liquid or the same approximation for H two s well, a liquid water phase is going to be much more amenable to accepting CO two or H two s. Uh, then another gas phase. So if I bring that gas in contact with the water, the water is going to start. Um, we were called denuding or preferentially, taking a portion of the vapour face meeting the CO two or the H two s and transferring it into liquid, meaning the inter facial concentration CC bike is significantly lower for the CO two and gas than it is on the bulk. So this difference, right? That C sub ai that tells us effectively how happy the liquid is to take on more co two. If the liquid is already at capacity of CO two and can't handle anything else, then we would expect cease of AI to be equal to see survey. But

insofar as they are not, that is my driving force to be able to shove mass from the gas phase into the liquid. So my mass transfer coefficient K then this fundamentally is a balance of how much stuff in my transferring in time for the flux relative to the driving force that wants to transfer stuff in time or Delta Psi. And I can take that the definition for the flux J. And I can expand that outward, as I've done here to actually show a simplification. So the mass transfer coefficient Little K is fundamentally the volumetric diffuse city on the distance being transferred. So if I have to go through the the 100 I can thermal boundary layers of my gas phase through the interface and through the boundary layers of the liquid phase all in a local region, well, that delta or the distance that my molecules have to travel from one environment to the other Um, that is that this little delta that we balance against the volumetric diversity. So it's basically how diffuse it is. My stuff per length that it needs to defuse is my mass transfer coefficient. So, um, now I would recommend the reader goes into a few examples of different types of gas liquid interventional context. So what I just described in terms of looking at the difference of the interface and bulk concentrations that's captured here on the bottom left hand plots for two different scenarios. One is where, um, I have a much higher content of my target molecule in the gas and one where I have it much higher in the liquid. So the gases of the higher content and the gas is on the left, obviously, and on the liquids in the right. And so I definitely recommend folks spend a few minutes with Section eight and the reader to make sure this concept is comfortable. It works identically. It just tells me what direction my mass transfer is going to take and, of course, understanding these inter facial concentration. So for folks who might be a little bit, um, confused as to how we've talked about equilibrium and operating lines with absorption, I would really, really, really recommend spending time with Section eight and the reader to make sure you're very comfortable with how we arrive at both the equilibrium and operating points, because this is going to come back very strongly in distillation. And in fact, we're going to see some echoes of this even an absorption toward the end of semester. Okay, so practically so we can appreciate if I jump back for a minute that my mass transfer coalition this is what the engineer is going to use. The most practical scenarios because a our thermo is imperfect and incomplete and be even if I can deploy Thermo for a simple system, Um, I can't do a sufficient number of calculations sufficiently fast is to think about heterogeneity in that system. So, for instance, my driving forces and local behaviour will be very different at the head of an AB absorption column. Uh, then it will be at the table, right? So to the practical engineer, then we would try to correlate this and use a correlative approach for the entire mass transfer operation from the beginning to the middle to the end, accounting for all of these variations. And that's where these mass transfer coefficients come into play now, identically, as we did with, um, heat transferred. What I'm gonna do is correlate each of these with the Reynolds number and now the Schmidt number. So, in my analogue between heat and mass transfer, the Schmidt number is the corollary to the Crandall number, and the Sherwood number is the correlated to the muscle number. So what do I do here? Well, I can calculate the Reynolds number pretty easily. I can calculate the Schmidt number if I know the viscosity again. That's something I'd usually measure instead of estimate the density, which is pretty easy to get at the volumetric diversity. Now, critically. I also have the the Sherwood number here on the left hand side that is defined by the mass transfer coefficient, the length scale d across the transfer operation and the volumetric tippy civic. So when I bring these together now, I can say, Okay, I can get the Schmidt

number, right? I can look this up for most gases, we would typically expect Schmidt numbers below two liquids above 100. Um, and I can use the same types of correlative approaches and the ones that I've shown here, for instance, the top. We would recall that that 0.664 was a correction factor for our hydrodynamic laminar boundary layer. So, in fact, the exact same form or very, very similar form of my Nestle correlations can be deployed. What I'm thinking about mass transfer through these Sherwood correlations. Similarly, I can use flow inside a pipe, right. If I have laminar flow in pipes that would obey the same limiting Sherwood number of 3.66 again. That was the same limiting Nussle number for laminar flow and heat transfer operations. But then, more importantly, um, as I start getting into turbulent flow and of course, engineers tend to like turbulent flow. Here, I can see adaptations of each of my approaches of the cedar. Take correlation if I have turbulence and pipes. Uh, there is a mild refinement to that. So if you're using one of these, you can use either one. But if you're in a really turbulent scenario, uh, then you can use the third correlation below if you're an external flow. So that would be normal to the cylinders that we talked about for heat transfer or normal to to bundle. I can see these same or very, very similar correlations can be drawn across. Um, And then finally, when I get into these external systems, so why might I think about mass transfer for an external flowing system? Well, a really good example might be something like mine tailings. Right. Well, we take mine tailings, and we're going to strip them for whatever component might be an interest. So it could be copper take a pic. But then I have this rock exposed in these little bits, and I'm probably going to put them in a tailing spot right or something similar to prevent them from kicking up dust. So here I am going to happen. If I have a tailings pond that's isolated, I would have, uh, natural convection around, uh, these little rocks containing poor material with itself, other components of interest. So if I had some contaminants or what sometimes can happen radioactive components in that forest matrix, then these are the external mass transfer coefficients either passed a single set of spheres or tubes that would be that would be embedded that I can use to figure out how quickly those contaminants are going to be transferred into something like the separation pond. And critically, what I would highlight is on the bottom. I just teased out this rising bubbles are falling droplets. This is interesting because in fact, in that the first couple of weeks, when you're talking about the deepwater horizon and I was sharing with you some of the projects and lessons and battles and insights that we had around that one of the kind of ah ha moments to me is after a few years in none of the other engineering folks working on this problem ever talked about mass transfer operations, right? Or Sherwood numbers or equilibrium because there wasn't a significant chemical engineering presence at the table. And so, in fact, we highlight that, you know, for the types of very simplistic problem solving that was going on with our colleagues in the environmental engineering community. In fact, the chemical engineers for 50 years have understood not only the foundational aspects of how I transfer mass between these phases, but in a specific scenario of having rising, buoyant materials where I have both heat and mass transfer from one phase to another that are, in this case, admissible Well. In fact, we even have practical correlations for that to scale with degrees of turbulence and thermal physical properties. So in the end, we'll get around to then so for absorption, distillation and, to a lesser extent, absorption. More thinking conceptually, These are the sweets of Sherwood. These three so slides 10, 11 and 12. These are the Sherwood correlations that will be most relevant. So in section eight of the reader, I go into

quite a bit of detail around the use of these. But as we approached many to the labs will also focus in on them in the lab held exercises. Okay, so with that, I will end the recording. Now, just a quick teaser for anyone who might not have been able to join class today. You're still welcome to open the class of one note and take a look. Not only at the prompt, but perhaps how we did as a class together. Uh, this is a really important workshop to understand, because we're going to be looking at how h two s not only is distributed systems, but how we as engineers can extract h to us. And we care about this because H two s itself is the most or arguably the most deadly and toxic component that we will work with in our careers. Okay, so I believe in, and I'll post a note on the upcoming timeline, but this should bring us to the semester break. So this is the sixth workshop. Meaning we'll take a week off and we will look forward to hopefully seeing everyone in person. What do you resume after the break? But of course, the tutors and I will probably still be working through the period, so please feel free to use the one note or teams chat if you have any questions. Okay. Oh, thank you. So I'm going to end the recording and we'll get into the workshop.

SPEAKER 0

Okay, so that recording is now started. Marvellous. Okay, so today is a quick reminder then. And by the way, my laptop is about to die, so I will definitely make it through the 30 minutes. But we may have to get creative. And there's only four people in the room, so we can always just start the teams fall here to do the online presentation for the group. Um, so this brings us to the distillation module this week? Um, it is reader. Section 10 only covers distillation, and in fact, we only have two reader sections to go. So hopefully I've had some positive feedback, some negative feedback. Hopefully there are some What? I'd ask this construct improvements. In particular, one student had asked if I could go through and maybe for future years, put in, like, 3 to 5, maybe 10 minutes at most. Just verbal summaries of me talking about the context kind of sandwich throughout the content. So it wasn't strictly a read or have read, um, exercise, but a little bit more multimedia and interactive, which I'm more than happy to do. Um, LMS quiz force. This will largely be around the fundamentals of installation is due this Friday in the lab report three is due by close of business next week. Friday. Um, And again, we have open consultation hours next Monday. Um, so we do have a distillation channel. Please make sure you use that for everything around lab three. So the context of distillation then, um, emerges when we start thinking about our single stage flash will go all the way back to Thermo, right? And the question that comes out of that is to say, Okay, we as engineers, let's say we have some amalgamated multi component mixture and we're going to bring it into a flash special at some different temperature and pressure, and we flash it. So we, as the engineer, by controlling the pressure and temperature of the vessel, can split components on molecular level is whether it wants to go to the vapour side or the liquid side. And this is incredibly powerful because we can do it within a number of components over em. Volumes per minute. We can do an infinitely complex dilution if we want to. Now, when we think about this process that well to the engineer, they say, Okay, I get to choose the pressure and temperature conditions in this right hand vessel. And in that process, that's my choice is the engineered that determines how things split and as a consequence of how rapidly I push stuff into the column, how quickly stuff comes out at that composition, so wouldn't it be and before, before I go on to that? Just taken aside. So the ability to determine how things split into the vapour or into the liquid we can. We call this the relative volatility every component. It's very simple. Exercise. Anyone's ever used

nail polish remover, right? Take a. They look just like water. So take a bit of nail polish remover and pour it out on the desk and pour a little bit of water on the desk next to you and just watch. You'll see the nail polish remover vanish in about 15 seconds. It's enough to be of a pool, and the water will be there for an hour or two, depending on time of year and that sort of thing. That is an example of this relative volatility that itself is telling you at equilibrium. So it's an equilibrium quantity for components A and B. So this is a binary available volatility. How much more does a want to be in the vapour can be? And subsequently, how much more does be want to be in the liquid than a So in that case, for example, of acetone and water if we then mix them together and pour a little bit of that mixture on the desk. What we would find is that in this binary mixture component, a being the acetone is going to preferentially vandalised. So the mole fraction of acetone in that mixture is going to decrease over time, meaning it's going to become more water like now. If I go back to thermodynamics, I can say, Well, wait a minute. If I rearrange this clever, I can see well, I can actually represent relative volatility in terms of round saw. I know how to get lie on ex side of places. And in fact, I've written This is rounding off the kids because I'm assuming ideology. But I don't have to. I could just as easily say why I fee I p equals X, I gamma I P. I said. Now I have all of my non ideology, so the take home message from this is that when the engineer wants to exploit this way of thinking, I have a bunch of stuff and bring it into a new P T environment, and it goes like that preferentially. Well, thermodynamics tells me how it's going to behave. I can go just a pure thermal. And if I know what the species are and the pressure so I can get absolutely pressure, I need temperatures so I can get saturation pressure I can calculate for these different species on the table. How easily is one going to want to jump this direction into the vapour versus the liquid? So then the engineer sits back and says, Okay, well, this is a cool operation and were arguably one of the few disciplines that understands how to really manipulate it at its foundational level. What would be better than one? I can separate end components over Emma volumes per second. Wouldn't it be great if we had J separation units? Right. So the engineer trying to seek this infinitive growth, right? Well, now we have an unlimited number of stages we can put in. So each one on that former slide each, um fine. I control the temperature and preheating or great conditioning. The temperature. I set pressure controlled by, uh, off valve instead of having one tank. Let's have 50,000 tanks. Right? And in that process, Well, if I'm gonna get really fancy, I don't need one off. I could take one here and one here and one here and one here. And gradually take this 10 20 30,000 component mixture and split it into just those things that I want in terms of their vapour pressure. So what can the engineer decide then? When they're designing a so called distillation column, I still get so re boiler duty and temperature. That's my one temperature at that point, the same as I hadn't flashed, I set the pressure not dissimilar early. So I controlled by the ultimate pressure region here, and the condenser duty fluctuates up. I wouldn't call that a variable. It's actually it falls out because I have to be able to condense this stuff and condense the vapour. So how much stuff I pushed through? I need that much NFL be pulling out of the compressor. So realistically, I have three or arguably four variables. Two of which are new when I bring it into a column. So this is the representation of our continuous display Shin column Now up through. So if you meet alumna, we've gone through this programme up through 20 before 2020. We never actually taught engineers here how to do continuous distillation. So the distillation rig you're working on the day you're working with? We've been teaching this for 10 years and we always talk batch

distillation, right? So batch distillation means I don't really have any feed. I'm going to fill up my re boiler in the bottom of the column with some chunk of stuff that I want to separate into the top end and bottom end with things that are high relative volatility and lower relative volatility. I fire up the feed. Alright, fire up the re boiler. So this chunk of raw goods I've added in now we'll start percolating through the column. But if I only have 1000 litres, I might get 200 litres of condemns product 800 litres of what we call bottoms product meaning its unrefined. And that's it. Turn the column off now. I took over this class in 2020 right? So we were sitting around in 2018 and I was looking at this cricket myself. What on earth? I don't know what you're all smoking either too much or not enough. Why would we never, ever, ever run a column like this in batch mode? Not anywhere in the world, Not from any engineering is, um what do you reckon? Okay, it's a really deceptively simple answer. So the old heuristic a rule of them I got. So the person who taught me this was born in 1930 right? The heuristic. That has been true for almost 100 years. Every one of these horizontal lines is a stage every one of these stages cost to Mercedes Benz. And it's been true for almost 100 years since Mercedes started making cars. It's an engineering benchmarking, but I'm going to have to build a 20 stage column. Well, what's the modern cost of a Merc? Well, that's going to be like a $2 million column, plus pressurisation plus temperature. So these things get really, really expensive really fast. So to the engineer, if we're going to use one of these, we want it running 24 7 so we can get to the minimum cost minimum viable product to be able to run it in the first place. And why does it cost so much? Well, if I zoomed into each one of these little stages, which I was previously represented as a horizontal line, well, what I have. So let's focus on this middle picture here. I have some amount of gas in equilibrium with vapour. Now the vapours coming from below, right, so have a warmer temperature. Lower pressure. The liquid is coming from above. It's falling through these little weirdos and spill trays. So have liquid coming down and vapour going up these trays. Above and below are different pressure temperature conditions because of my heaters all the way down in the floor here in my condenser, which is adding cold energies all the way in the roof. So as these two systems are coming together, the vapour and liquid as they enter the same volume are no longer in equilibrium because they're coming from different trays, so they need to exchange mass with one another, and the mass that they're going to exchange is usually my target component for the distillation column. Um, so what I'll do is what I have. They are starting to build up in this space. You can imagine these little bubble caps here were liquid to flow into this tray. I would need to have enough pressure that the bubble cap pops up. The liquid is going to channel through and fall into this tray. So if this pressure is inclined of the bubble capstone pop and I get no down flow and I get no bubble up flow. And so by that setting, I can control it by each of these bubble caps with a spring right, and I select a spring thickness the spring height so it can match the pressure Where the differential pressure of the stage I'm trying to maintain. Um, then I can effectively grade as I pump the bottom to the top of the column a different pressure condition and different temperature condition each time. One heat entry, one cold energy removal, Um, a differential pressure as we go. So this lets me, then stepped my way. There were this lets me step my way instead of having a singular right. So if we were talking about absorption, I have one unit operation. So I'll be focusing right there, right, tiny little subset of my equilibrium line operating line boom. And they have to buy sections of it for an absorption or signal stage column When I get to distillation now. Well, because I have all of these

different equilibrium units stitched together. Now my operating line starts curving and curving quite significantly, right, and in fact, because I have a cold energy from the top and a warm energy from the bottom, I don't have one operating line have to, and that's what we get into today. So this is a picture. If any of you go down to like Margaret River and you see some of the distilleries down there, this will be more of what they'll show that they use for their stills. We tend not to use copper stills very option anymore, but the reason that you would see all of these windows and a steampunk still, as the engineer could look in and make sure that this activity, the bubbling and the down welling activity on each stage looks visually, as though it should have been doing it for 20 years, you can tell well if I take If I gaze into this third stage up, well, I'm not really getting much boiled. Okay. 100 years ago, Chuck, some more coal on the fire. Now we turn up the re boiler duty 20%. Maybe that'll be enough. So what does it look like then? Now, when we started to characterise these things, um, we're going to do what's called McCabe healing method. Now, this is my favourite method in all of engineering. And it's my favourite because the McCabe dealing method returns as complex of an equilibrium outcome as the best of what Isis can offer. But it is a manual and visual method that was invented and wait for it. 1920 right. So this method was invented before modern computation, but in fact can yield just as good of a distillation column today. So you could be completely remote. No Internet, no computer, no nothing. You can physically design a distillation column if you know how to weld. And you have a source of energy and a source of cold removal now. So the way we characterise the McCabe telling method is we're going to look into X and y space, right same way. What the same way we did on the top, right? We're using X and Y space to characterise our absorption column. We're going to do the same with distillation. But the point I want to make before we do is that we can look at the same distillation operation instead of an XY space in T X y space or equivalently in P X y space. Because I'm changing pressure and temperature in every column name. So I like T X Y because it makes the most sense intuitively, right on the bottom of the column. Go back on the bottom of the column I have here on the top of the column. I have a condenser. I am controlling the energy balance on the column. How much energy do I pull out? How much energy do I put in that controls the temperature distribution through the column. Now, if I put this on T X Y space, then let's say that we have played in. So we've hidden for diagram. Attic purposes are bubble caps and are down dwelling on this. But I have played in so the liquid leaving this plate and the Vape going down and the vapour going up from the plate. These are the phases in equilibrium, right? What the plate feels is that down welling liquid and the upwelling gas. So what the plates presented with are the equilibrium outcomes of its left and right neighbours or top and bottom neighbours. What it's producing are its equilibrium, outcomes that only its neighbours feel as incoming. A little bit convoluted. Uh, too much. Okay, so let's focus on this plate and from it. So this down welling in this upwelling to the left and right errors, these are the equilibrium phases or the phases in equilibrium. Well, if I know that that plate is sitting at temperatures of N I don't know where I'm out of this diagram. So it's just general, I'm going to draw a horizontal line in T X Y space, right? Remember this from thermo T X Y p X y diagram. So if I draw a horizontal line because I put a thermometer at stage end and in fact, if we go to an industrial still today, every one of their stages will have pressure and temperature. It's far too cheap, not instrument. Well, I could draw a horizontal line from where ST John is at now. What do you remember from thermal when I have a t x y that who I am? If I have a single

temperature of its bisecting the entire diagram, what does it tell me? What can I glean from that diagram? When I do this well, you can see the compositions in the vein from the liquid. Bingo. Thank you, Emma. Compositions and the liquid invaders. So the liquid composition. So in a in a t s y background my curve on the underside of my bubble curve. So this is the temperature at which the first bubble of gas will emerge. So the composition of that is the liquid composition. So at which point that first bubble look at Xanax, Librium and I do curves on the top. So now I gotta do this on an exam or something. And I appreciate we don't have exams in this class anymore, But if I were, I will always draw a theoretical T x y and P x y and label myself the bubble induced sides of the curve before I do anything just to intuitively make sure. Okay, I'm tracing up and I go to higher and higher and higher temperatures. What's the first thing that happens on my stove? I get a bubble. What's the last thing that happens in my pot of water? I have a drop of liquid before it all evaporates, so I will intuitively reconstruct these as opposed to trying to remember. So for this single by section of teeth event, I can drop out the wise event and ex event, the liquid and vapour compositions that are in equilibrium. Well, let's say we're going to go to plate. No labelling on this is all screwed up. I'm going to go to a lower plate, right? So instead of t seven in the middle of the column, I'm going to go to the one just beneath that. Now it's going to be warmer because it's closer to my re boiling, which is just a shell and tube heat exchanger. So it's going to be a warmer temperature. I'm going to go up one. If I go to a warmer temperature, I have doesn't matter what it is. I have a different split. However, unless these t x y or P S Y are vertical lines, I'm gonna have a different split. And so this is the nature. Then if I say well, I'm going to have a three stages on top of the N feed stage. Well are three stages below, so it's a little warmer. Warmer, warmer. Well, I'm going to hit a point where I'm not going to be able to really extract that much more out of the operation. Now, the way this has been drawn. In fact, um, I have a pretty solid separation potential for every one of these points and temperature. Right? If I go above this point, I can't separate. I go below this temperature. I can't separate to be in the toothpaste. So this then lets the engineers say, okay, based on where I feed the column, I'm going to have to account for different types of behaviour on above that point. So the tops of the column and on the bottoms of the column. So this is the McCabe killing method? Um, what we do, we start. And I tried to put his best responsible really, really, really thorough explanation. And the reader for this I probably went way overkill, but I wanted to make sure everyone gets it when they're done. So we will start calculating ex wife space. So we're not going to be visualising pressure temperature like we have been just going to be an ex wife space for that. But they are changing into and out of if I draw a perfect So I'm going to draw 45 line, and this is kind of my foundation. So here's my black 45 line in an XY box To do the McCabe Thiele method, I only need four things. I first need my equilibrium data. Right. So I've drawn This has occurred. It would probably be points that I'm going to connect over a group. Where might I get equilibrium? Data? What's my favourite reference on the planet? Yes. I also want to flush. Yes. Bingo. So nice. So if you're being paid by as a consulting engineer, right, someone walks up to your office and says, Look, we have this problem like we're going to do today. If you can figure out how to get this method all out of this, this whiskey, I will give you $50,000. Well, if you're going to turn back that report, not only would you not want to be sued for having bad references, which lawyers will totally go after? Um, you'd also want to have them come back so you can do more of that because 50 grand for a weekend's

worth of engineering is pretty nice. So you don't want to hand back to the engineering toolbox references? Would you pay $50,000 for that? I wouldn't right, But if someone says OK, I've gone out to literature. This someone physically measured this system and it's within 1%. Not perfect, but very, very good. The back up to that would be multi flash where then you have to defend. I'm using the right model set, and I know why. It's the right model set because of these references. Here's how the model set compares to NIST data before I'm ever going to undertake an operation with it. So it's multi flash can be a little bit more involved, but still isn't bad. So multiple ash missed others. Uh, we can use a tool called Thermo fast and similar to multi planners for three to get the points that will structure this green line. Then I have to say, Okay, well, my column fundamentally is not one big column, but it's a two columns put together right. One side of the column is going to be enriching my liquor in the stuff that I don't care about. And one side of the column is going to be stripping the thing I do care about out of the vapour product. So I have these, naturally, based on where you choose to feed the column, I have a rectifying section that's the upper bit and stripping section. These names obviously come from, uh, the discipline of absorption, having been 2030 years prior. Now, once I draw my 45 and I have my equilibrium day so you can see we have this nice envelope showing in between the green and the black. My next draw, my rectifying and stripped warns, How do I know where to draw? One of the things the engineer has to do if I go all the way back to what do we specify? Well, either I can specify what I want that column to produce, or you can specify how the columns going to operate. So when I've drawn it like this, just saying the engineer, I have no idea what the colony can produce. We're going to give it a shot and see what we can produce or what we can get out of it. At a minimum, I need to make these four decisions in blue. However, if so, if I make those decisions, I can pretty quickly flash and calculate. Well, what should the product So the top composition of my component be the digital composition except D and which are the bottoms composition. So if I have 10 mol percent, um, it is a good example here, and we were trying to split octane intel. You wait, right. So tell you, we really nasty for the environment. We don't want it anywhere near our fuel systems octane. The primary complaint. If I want to split into, then I need to be able to say something about how much that Italian wants to be around the octane and how difficult it's going to be to rip it away Now. Either I can go through this process and figure out how good will distillation be for me or I can say, Okay, I have a petrol specification. I cannot produce petrol with more than 3% Tell you if I do, it's illegal and I go to jail. Cool. Okay, so 3%. That's going to have to be our upper limit. In fact, I'm an engineer. I'll probably call it 1.5% and back up from there because I really don't want to go to jail. So if I know what this Vista late composition has to be based on, you know, I want 99.9% obtained, minces or I know this bottoms proposition. I need to remove a certain fraction if I can set those two points. Then, in fact, my stripping and operating lines begin just like we did with the absorption as the by section of that composition on both sides with the 45 degrees. So where on the 45 is the distillate in the bottoms composition. So I can actually mark these points in blue and red, and then I can say, Okay, the way I've drawn and they have a pitch. How do I figure out the pitch? Well, just like everything and exploit space, right, things like slopes, because I can use algebraic manipulations of my mass and energy balances things like slopes in X Y space usually have any thermodynamic meeting as to intercept. So if I can begin my rectifying line up here, I know what the distant composition needs to be is a stack. Well, I know where it's going to bisect this y axis, right? That is that the

value of X sub d on far d plus one. So what is already This is my reflux ratio. I'm going to back up a few slides. We're not going back to it. So the reflux ratio very, very, very simply. But I hold the top product out. It's all a vapour, right? 99.9% octane or ethanol. Take a pic. I'm pulling out this top product, and I'm condensing it. It's in a vapour, huge amount of heat out into a condenser. So now I have a pure liquid stream of my product. Do I take all of the product? Do I recycle all of the product into the top of the column, or do I do some amount of both right? The greedy engineer would say, Well, I've pulled on this product out. I'm going to remove 100% of exam in a rush pins. Not to be a great idea. Columns don't like, and we'll get in next week. We start talking about the nuanced column operation. At the end of the day, we tend to split this and we'll put a fraction of our product back into the column to keep it going. And we'll take a fraction of the product as what we're going to sell or put into the next process. The ratio of how much I put back in is my reflux duration. So 100% reflux means that this overhead product is the valve was closed 100% reflux. It all goes back into the column 0% reflux. Pull it all out, and the reflux ratio is one on that. So at 100% reflux, I have a reflux ratio of zero right and a 0% reflects. I have an infinite reflux ratio because I'm dividing by zero. Okay, So if I know Arsene de and I already know except because I had to draw this point in first place, So r s and D, let's call it replace ratio of three right for everyone. Volume I take out I put three volumes back into the calm. Well, access on three plus one. So xD divided about four will be somewhere down here. Well, I can draw a straight line between where these XPS bicep 49 degree on this Y intercept. Boom. So now I've drawn my blue line. I already know my red point, And what do we know? But in fact, that this stripping operating line is going to have to have a slope a lot of real quick this or something else. Uh huh. Oh, that's what it is. Gone in the wrong order. Draw the stripping line last. Okay, so we draw a rectifying line. There are 60 points are y intercept, and then we drop the feed line. Now the feed line right is going to come in at whatever my feed quality is. So in the problem stating for the workshop, You know your initial composition helps your feed composition. It must be on this 45 degree line like everything else begins on that 45 degree line. But what pitch doesn't have right the way I've drawn it? I have my rectifying line. We've already drawn in blue. I know. I'm I'm starting an extrasolar mixture 50 15, but I've put this thing perpendicular to the 45 degree line. Why? Could be anything? It could be a slope from E up through a and this insect. Well, the the slope of this depends on the type of feed that I have, so the most common will be a saturated liquid, right? Meaning I have a liquid that is, um, perfectly on the left hand side of that to phase region. It's not in coexistence of any of its favour in that limit. The quality of the feed is one, um, and the slope here, this is the slope of the feed line or the Y equals MX, plus the equation for it. So the slope of the feed line Q on Q Plus one will have Q equals one that I have a perfectly perpendicular line to the 45 degrees if I start going into a saturated vapour so this might emerge if I'm taking my foot and taking my feet out of this, re boiling in it. But pass it through the re boiler or as Schelling Tube host free boiler to get some pre heating. If I preheat that feed too much. So I start to get into a section where now I have bubbles emerging in my feed line. I'm going to be changing the quality of that. So what happens in my McCabe Taylor diagram is that instead of having a perfectly perpendicular feeding this purple here, it's going to start tilting down. I've heated the feed too much. Similarly, if I have a cold feet not up to the two faced Michigan and sub pool, I may get a slope upward. So I know where the feed line I know. All three of my lines begin on the 45 degree at the nominated compositions, Slope of the Blue is

determined by the reflux ratio. Slope of the feet is determined by its quality. Even in today's workshop, we're going to use a saturated liquid feed quality. So now the only thing I'm not drawn on this is my red now, right, But I have a bisexual between the purple and the blue. So the stripping line by six all three. So I don't need to know this slope where the terminus appointed my red line. I know that has to go through all three now. So at that point, what if we had to know? We've had to know the compositions on the top, the bottom of the feed. We had to know where guests Something reasonable about the quality of the feed coming in. So it's a liquid at room temperature. Pretty reasonable. It's not too hot or too cold. And the equilibrium data that we're always going to come back to and the reflux ratio that's been the one thing I've had to speak to get sense. But now, once I have this basis for McCabe dealing, what do I do? So for the folks online, I'm so my battery's dying. But I'm going to try to put on my camera here. You can see me trace through. Why is this not working? Come on. There we go. Uh, turn off background effects. All right. Um, well, so you're able to everyone online able to see this more or less. Oh, no. Oh, shoot. Well, that was a huge fail. There we go. Okay. So for the folks online, you may not be able to see me trace this through really well, but there's an example in the reader that does exactly what I'm doing. So once we have this construction right now trying to articulate, I have to know a few things and and guess, probably the reflex operation to do it. The purpose of the McCabe Thiele diagram is to figure out how many stages do I need My column. How many absorbs needed, so many flashing it. So I need to stitch together to get this thing that I want. So once I constructed it, I will start on the 45 degree line at these dashed blue intersections of the discipline intersection, and I go horizontal left until I think the equilibrium line and vertically down horizontal left vertically down. Now, once I get into this tripartite region here, I'm going to step across, and now I follow the red line back. So on the upper portion, I'm bouncing. We call the stair stepping. I'm stair stepping between the rectifying blue line and my equilibrium line and the bottom side. I'm stair step between the strip in line and the equilibrium. So if I start to do this, maybe I can draw with my mouse without making a horrible, horrible mess. We'll see. Here it goes. It's gonna be terrible. I'll go horizontal and down. That is my first stage of the distillation column. Then I go again. Where is all down? There's my second stage, third stage, fourth stage and now I'm going to pause for a minute. Fifth stage. And let's just imagine these are perfectly straight. Okay, so my fifth stick now on my fifth stage, this stair step encapsulates my feed stripping and operating lines. This tells me the fifth stage is the optimal stage for where to feed my column. If I try to feed it on Stage one, the whole thing is going to come undone, and I feed it on stage end at the bottom, saying things going to happen. I want to feed it somewhere in the middle. And McCabe Tilly tells me, Stage five. So we go Stage six, age seven eight. Imagine they're straining. So now at the end, I need I have eight stair steps and, in fact, that eighth one where my drawing straight that eighth one is on a little bit too far, right? So the outlet at the very bottom, the XB. When I come back to this, the 45 degree line the bottoms composition with that configuration gives me will be pure than what I've asked for, right? It's good to bad thing. As an engineer, I would never design something on marching. Always have some tolerance. So this kind of buffer, maybe this is coming out 3% of my contaminant, and the design aspect was four or 5%. Cool. I stay out of jail, right? Alternatively, what if this represents the ability to handle a broader set of inputs? So maybe I'm not pulling methanol out of a drink or I'm not rectifying petroleum trunks that were made. Maybe I have a column that's meant to work for one town in five

operations, and each of these operations might have a contaminant crop up from time to time. So one column system with multiple feeds that I can take a batch of stuff and distil it out to get its impurities on. So for that reason, I might actually choose to keep a bit of play in this column, right? So that I can say, Well, I don't actually need a full eight stages. I can take a feed product instead of 50%. You can give me a feed at 40% Still handle it or 60%. And so this is one of the more kind of seasoned engineering decisions of the cheapest possible column is made precisely to spec. But the best engineering operation might have it would cost up front to be able to take a more robust feedstock. Okay, now one of the things. Okay, so one of the reason that we like McCabe telling the reason it's magical, right? I find it magical. Is that these stripping? And so we said that this, uh, timeline intercept is meaningful. But the rectifying and stripping slopes also tell me the molar flow rate in the top and the bottom of the column of age phase. So these the slopes of the blue and the red lines here correspond to an internal mass balance on each half of the column for each section because it's not perfect times. So if I can draw this, I can actually use this to completely solve my mass balances. I don't need Aspen now. What does aspirin do, right? Has been solved all of the material balances and the thermodynamics upfront and then says, Okay, let's play with the design parameters of having 45678 stages and let's do a matrix and will simulate it 1000 times. Where am I going to put the feed? How is it going to change the performance? So Aniston is taking the exact inverse approach to solving this problem, and the outlet that aspect gives you is you need minimum eight stages as well tell you 4.796 stages, but they come and integers so we are gonna have seven or we have eight, and you should feed it on the fifth. I find it magical that instead of doing two hours of aspirin work, I can draw a figure by hand. Right? And I begin by getting the answer, and I can back up into more detail as I need it. I think that's genius. Um, and for anyone who bought the textbook, this is the same McCain. This is why we like McCabe's textbook, because it's like what he was one of 10 people that founded chemical engineering, and we've not really done very well since we're still still using these old tricks. Okay, so the reader will build upon this. It basically walks you through the same thought exercise. I do spend a bit of time. I felt like a bit of time writing it. Probably way too much time, Um, kind of banging on about the different nuances of where an engineer is going to want more tolerance here versus there, versus all of the advantages that having a either an imperfect or overcompensated design can help you with as a practising engineer. Okay, so the prompt for this week. So what? I probably everyone in person we can do one table and online to another that sound good.

SPEAKER 0

presentation slides. Okay, Marvellous. So the recording started. Um, all download and re upload to echo after classes done today. So what we're looking at now, I wanted to spend just a few of us together. So anyone in the room or Marshall Online feel free to just interrupt me. Um, if you want to chat or have questions as I'm going through it, this is the last set of the slides talking about multi component distillation and one of the reasons. Well, sorry. Admin stuff first. Uh, sorry I'm late today. Came from academic board. There's an old joke. Do you know that the social media thing that went around tell me something without telling me or something, Right. One of them was Tell me you're an academic without telling me you're an academic. And so I said, welcome to this committee. The first order of business is to decide who should be on the committee and how many people the committee should represent. Because that's literally all we fight about. Very little business and all about

representation across the disciplines. So that was our fight this morning. Um, so this week, of course, we have the distillation lab due this Friday by midnight. Um, I just talked to David and Jason, and I think they have to. Lab reports left Mark, so those will be reconciled out. Probably 56 p. M. Tonight. Um And then, of course, open consultation. I was next Monday. I also did have someone asked me, and I asked him to put it on the team's chat as well, but about the use of the multi flash, um, Excel added. So if if what you'd like in during the workshop, I can also load my computer and go through the example of how to do that. Um, for those, you clear you're on Monday, so you probably got most of that. Okay, I can rerun it if it would be helpful. Um, so in addition to thinking about the McCain Teeley diagram for figuring out what's the minimum number of stages? So there are two aspects that we wanted to introduce around us, Um, one of these. So we can imagine that the beauty of this and we saw this last week the beauty of McCabe dealers that we can pull real data. So we looked at all of those different curves and then identified Wolf real physical, measured data. We can capture all of the non ideology and the liquid vapour. All of that is captured in the slope or curvature of this equilibrium line. But if we make the assumption that the components are ideal, then we can go back to the definition of how we were doing to stay relative volatility. And it's a very simple application rounds law, which means because it's linearize, I can use something like the Fenske equation to call it an ideal. Mixtures are ideal liquid ideal vapour, and I can actually calculate, because this equilibrium line becomes a line and not a curve. Under ideal circumstances, I can directly calculate the number of minimum stages. So whether we're doing this workshop problem or in your labs, this is an interesting comparison point to McKay Dee Lee and and asking prices because it tells you how non ideal or the impact of non ideology. So, for instance, if you were working with the system where you're trying to get methanol out of an Aquarius system, if you wanted to tear or if your boss said, how much more money do we have to pay? Because it's methanol and not a glycol or an alcohol or something else. One way to approach an answer like that would be compare what is the ideal setup versus the real villain group? Or the real equilibrium curve and the difference between those two and how many stages I need. So if I'm working with an ideal mixture, maybe I need six stages. If I go to a real mixture, I need nine. And so all of a sudden I'm paying what in today's money? Half a million dollars. Three Mercedes Benz? I don't know. It's for 600,000 Perth, right? I have to pay another half a million dollars just because I'm dealing with a highly non ideal, um, system now to the chemical engineer, right. If you were hired as a chemical engineer, they would say, Okay, well, how might you manipulate the ideology or the non ideology of that system? So then you go back to Thermo, right? What makes it non ideal, And what can we draw in, uh, to start modifying them? Um, so when we think about the reflux ratio, as we're talking about a bit before, so the two boundary conditions, um when we go to start the columns, of course, we want to keep all of the reflux directed into the column, and we have no mass flow at the inlet, right? So the entire mass of the column stays constant during its warm up pressurisation and exploration period. And then, as we initially turned down the reflux ratio from infinity to some vintage, remember, we would turn up the feed so that we balance the mass load in and out of the column and then gradually bring this into our desired set point. Now there would, if we start thinking about well, if I'm changing right, we know that reflux ratio is the denominator of the operating line was our plus one, I think, um, and so naturally, if if the McCabe Thiele diagram is an equilibrium, steady state design, well, if we're manipulating the reflux ratio as we go,

then it's going to change the capability set up, meaning it's going to change the product quality and the number of stages that we're going to need to get our desired product. But because the stages are fixed and I've already bought them, they're not changing, which means my product quality is going to fluctuate like this until I get to that equilibrium set up. So one example would be as I start turning, Let me get this right as I start turning up the reflux ratio, the curves. If I'm looking at these different operating lines C, D, E and F right, I'm going to start pushing the operating line up, which is going to push this convergence point between those three operating lines from the stripping, operating and feed. It's going to push that convergence point higher toward the equilibrium line. So one can imagine, then that I can start turning the reflux down further and further and further, and it's going to push this curb higher and higher and higher until at some point it bisects the equilibrium line. Now, if I zoomed in on this and said, Okay, I'm gonna McCabe Keeley, which I used as a verb. I'm gonna Katie Lee this around the operating line a D where I have a bisexual with the equilibrium. So this classically is what we call a pinch point. And we saw, I think come up in a simpler form and absorption. But the challenge with pinch and distillation columns is that if I try to zoom in here, how many stages do you reckon I would need to get through that? And it's a trick question because there's two answers. The real answer is infinite. So at a perfect by section, I need an infinite number of stages, uh, to get across that pinch point. Practically. What I will get is a silly torrey behaviour, right? So it doesn't mean the column stops operating in terms of efficiency when that point is crossed on that stage. But rather, um, I will get a build up of material below, and then it will break through. And so I'm changing the composition, and I won't ever get a steady output from the column. So we call this when we change the drop, the reflux far enough to pinch it against the equilibrium curd. We call this the minimum reflux condition, and so traditionally, what engineers will do is then specify. If you're working in the plant, maybe your reflux ratio is designed to be 3.5. As for that example or 2.5, they will also go through the calculation and say, What's the minimum tolerable reflux meaning we can still afford to pay the power bill to run the column based on what we're making to sell and what is the absolute minimum reflux condition, meaning? If you drop it below this, the column is simply not going to function at all. And you're not going to produce valuable product and why we care about that. And we imagine we were taking off cuts, either from the top of the bottom of the column around a pinch point, and that was an inlet to another series of unit operations. Well, I'm going to require that column to the operating steady state for each of the success of unit operations to work. So if I get a significant process upset, then these pinch points can restrict, um, the rest of the plant in terms of operation. So if we say that the minimum reflux condition is that which is required to get around the pinch point. So I'm bounded by the physical equilibrium curve. Chemical physics of the universe is enforcing that boundary, and we say, Okay, well, on the other side, if I have maximum or infinite reflux, I get no product, so neither of these is a tolerable limit. But how does the engineer know what are should be? And I think this probably gets to your question from earlier egg. So what is the correct reflux operation now? The way that I would tend to think about this is monetary right? And that's because these columns are both very expensive to buy, but also very expensive to operate. Uh, and they tend to work with really volatile and toxic components, so they also have a lot of HFC impacts that gender cost with them. So if we look at, um, this left hand line so maybe this curve would be the price of the column, Um, in terms of the absolute medal on

the ground for each of my trays and my condenser and my editor at that one and then this curved E going up is the cost of actually running in terms of heating power, cooling, power, personnel or or measurement time. And so the merger of these two, which is a simple summation, we tell me my optimal reflex condition. So traditionally we can't answer a question like on a theoretical design. What's our optimal reflux until we have costing so we need to know the scale of, um right back up a minute. We can design a theoretical column independent of flowing right. We can design it on, like a one mole per hour basis. And the whole thing will scale in terms of volume because I'm caring about the number of stages and the number of equilibrium steps required once I know my feed flow rate or, what's more common, my product delivery flow rate. So if this column is powering a downstream plant, or if it's producing a commodity that sold on contract, I must have 1000 kilogrammes of either stuff coming in or stuff going out per day. Once I have that number, then I can go from my say, one mole per hour per second whatever basis and scale the whole system up linearly, and that lets me go to vendors. Find for the five or six different column vendors, the world. What are the fixed cost curve is going to be? And then what would be quite, um, relevant today? Where am I going to get my energy from? And if I'm running this column with a lifetime of 50 years, how are those energy costs going to change over 50 years at something like emissions prices are brought in. So what's my total cost and the reflux, so that the reason that we then use reflux ratios as the kind of lever is it's the one thing the engineer can change on the fly. Once we physically put the metal in place, decisions are done. We have no choice. But the reflux ratio can always be modified. So this gives us a lever both during the construction phase to modify it as well as during operation. Um, so when I was talking earlier about the difference between the sorry brains still in policy and governance, uh, as we were talking earlier about the difference between the ideal mixture and what a distillation column for an ideal system and that for a real system where I have non ideology in the liquid or vapour well, another way to characterise these two things is through the efficiency of the column process itself. So the efficiency of each of my equilibrium and I call it a tray efficiency. But that's just because physically there are trays in the Librium stage. I would call it the stage efficiency. So for each of these flash stages that I've put together, each one will have a different efficiency. And the unit operation as a whole has an efficiency. This stage or tray efficiency, also called the plate efficiency, captures the difference between the ideal and non ideal components. Because, of course, nothing is ideal. So I have to deal with that non ideal in the gap. Um, that is put in here as well as inefficiencies from the actual design. So this is where, like, Jeremy C F D. He's done transport yet? No, we just talked about that, didn't we? Uh, so in transport, Jeremy is going to do a lot of computational fluid dynamics. It's one of his famous things, and I get it. Um, this is where C F D becomes really, really powerful. So oftentimes you can't really use. I mean, Jeremy would say otherwise, but you can't really use C F D on systems that are bigger than say about that table physically, that's the limit of the biggest, baddest computer and code that we can throw at. Anything in the world right now is simulating that volume, and even that would be like IBM level, but these little caps are about the size of my bottle cap here. So actually, I can do fluid dynamics around this really, really well. And I can run C F D across different fluid types, turbulence levels, thermo physical properties, you name it and different designs to figure out what's going to give me the best flow efficiency around this. So the tray efficiency effectively goes back to that same principle of the ideal and non ideal

equilibrium curves. But it's figuring out what is the gap between what I should have in equilibrium. Remember, the Y star is the gas composition in equilibrium with the liquid. So that's the actual or what I should have. Theoretically, um, same demonstrators absorption, Um, so between the two, each two trays or stages and what I actually give. So if I go into the column and start physically measuring the composition of the gas or I can equivalently do the liquid on or I'm sorry, I have to do both gas liquid. So this is what I get from the equilibrium curve measuring the liquid, and this is what I physically measured from the gas. So the difference between those then tells me how efficient each of those stages is now in practise. Um, if you had a column with 20 or 30 stages vertically, you probably not measure composition on each one because these types of measurements, uh, you know, one G C setup is going to be 50 grand if you're doing liquid, and you're dealing with high, toxic or flammable component. Since you're probably looking at a quarter mil. So in the same price of how much money you have to pay for a non ideal extra in the column, I'm going to have to to spend on characterisation. But so we would tend to try to take a few selective compositional measurements throughout, and one of the things that will look for right is whether these efficiencies are changing in time. Now, if I So does this make sense? This Y star a hand waiting that too quickly. Excellent. So if I measure that on any given stage, the gas and the liquid, I can go to that liquid and I can flash it in multi flash right and say, What is the gas that should be in equilibrium with that? And I'm just comparing it in this case to the tray above. But I can equivalently do the trade below, and so it's just a very nice to find these now. If I detect a rapid or an acute change in the trade efficiency, what do you reckon that would be indicative of? There's a couple different answers for possibilities around there. Like if I was measuring these tray efficiencies and they should be 80 ish percent right for our columns in the lab. So if I was measuring 80 80 80 and then it dropped 50 in a day's time, What sort of thing do you think could cause that mm, the fouling? But it would be really, really late stage fouling like almost death of the column fouling. But typically those would indicate process upsets. So if my feet stop, coming into the column is always this perfect ideal composition or a specified composition. Um, and I get a process upset where one of my components fluctuates by 20 or 30 per mole percent. I will see an acute change in that trade efficiency. Another example would be if I had a A cutout in either the heating or cooling potential, so if my re boiler or my condenser stops operating, um, that could be driven by following. Could be driven by power or access to energy. Now, I'm sorry. What was I thinking? The what is fouling? Yes. Okay, So the reason that we care about that acute process upset and you would be surprised how often this shows up in incident reports operators. So the you know, if your job is the engineers to design, you'll probably be in an ivory tower somewhere surrounded by computers and white boards. Right now, the folks that actually run these things are trained through different engineering pathway. So they're looking at your right up and your prescription and saying Okay, is what I'm getting consistent with what the engineer has suspect. And this is why you always get tension between engineers and operators. They think engineers are all, um no, no, you can't do anything. We're not practical. We can't build anything right, because we don't actually know how to change the So this tension between engineering and operating an operator will have a few different measurements to determine whether they're column is running properly. One of them will be a feed composition analysis. So everything coming into this column they'll have every hour, two hours set, uh, measurement of its

composition. They'll also be measuring at a few select trays to make sure the column is staying proper if the feedstock composition analysis goes offline. Or rather, if the sensors of that amount of that measurement start to fail, how does the operator No, right, If I If I go to take someone's temperature with a thermometer, how do I know that that's right or wrong? If it's somewhere between 36 40 well, it's not an emergency, but I have no way of knowing whether that thermometer has started to fail, right, because measuring composition is one of the hardest things the engineer can ever do the number of times that upstream. And we call this upstream compositional measurement right. So upstream of whatever my unit operation is going to be that upstream composition going offline, or rather, one of the centres going offline, they may not know and they have no way of not knowing until they see a process upset. Show up. Now, you know. And I think part of the growth of engineering is trying to get engineers closer to the operators and trying to get operators more experience in doing the engineering design. So there's a better relationship there because an operator would look at that and say, if a trade efficiency goes offline Oh, we might need to shut down the column to clean it. It could be fouling right, Or it could be a re boilers going bad or one of the heating coils is going off because the feedstock analysis is fine. It's been steady the whole time. What's the problem without realising? Well, it could very well be that sensor died. Um, so? So that would be one example of why we care about efficiency is not so much in the design of the column, but very critical for its operation and and watching for those process upsets. Um, because, like we said last time, these columns in an industry can take months to come to steady state. So if an operator says, Oh, I think there's fouling, we're going to shut this down to clean the whole column. That could be a billion dollars in lost revenue For the engineer. That probably means they're looking for a new job. If it is falling. I'm going to see something different. I will see it show up in the efficiency, but it won't be a cute. It will be a chronic type of condition. So if I start with an efficiency of, let's say, 50 or 80 if it's a fouling problem, I will typically see it go down linearly with time. And the exceptions are where I'm flowing in, something like a cylindrical flow channel where I get fouling on the exterior. Because, of course, I have a linear deposition rate. So is the channel close that goes with R squared? Is that the impact on flow velocity? Um, but I would tend to see that deficiency dropping by, like, 1% per day. And that would be quite indicative of Okay, we know this is a continuous and very slow phenomenon. We need to plan for a routine maintenance in three weeks time to avoid a critical outage, and then that gives the engineers and operators time to bring online, say, a backup column where transition to a different set of columns. I think I've covered it. Any going to stop me and this is it boring? Is it helpful, insightful, okay, I don't want to waste too much because I know we got some design steps Do. I did go on a little bit last time about batch distillation and how it's rarely, if ever done, because it's a horrible waste of money in most cases, Um, if you ever do need to look at a batch installation, the concept of a bat still is basically old school, uh, whiskey making right. I have some kind of, uh, component that I need to flash off a fraction of it in a single stage. Now, if I have a 10 stage column. So if this upper portion above where it says bat still of this upper portion could be a 10 stage column or it could be a pipe for the sake of the batch distillation, it doesn't really care. And so I'm taking some volume that I'm going to flash off the proportion of it, depending on the pressure operated that, and how much energy and steam or whatever how much heat I put in will determine the fraction that's flashed off very, very simply so because I have no feed and I have no

stripping line, I run the entire I can design. So here's my equilibrium. Curve my 45. I can look at him a cable, really tight diagram, but solely with an operating line, and it will tell me the further I run it down. So the longer I I operate, I'm going to get a different bottoms composition, right? So if I went and we'll come to this in the workshop example, But if I begin up here, I'm first going to flash off the highest vapour pressure material. So let's say it's steam. 100 degrees c. Methanol, ethanol water. The methanol is the first thing to go off, so I lose all of my methanol upfront. But let's say I wanted to purify the water. We don't want whiskey or vodka. We want drinking water. We're out of drinking water. Pity to have to kill vodka for drinking water. But it's possible, so if I flash the methanol off first because it's the highest vapour pressure. If I continue heating, next goes the ethanol. And if I continue heating, next goes the water or portion of the water. Now, if I was maintaining right so we can imagine from a heat transfer setup even though the steam is at a constant temperature, I'm pushing a constant eat into the system, so that allows me to then move through these different vapour pressures in different component molecular weights. But what else is going to change? This is a fun thermodynamics question. If I am methanol, ethanol and water in this batch still flash the methanol off first. What's changing in the liquid of that still want thermo physical properties? So back to the days of Thermo? What? What's changing in the properties of that? Still, once I lose my light components. Bingo. So the composition is changing, and from Thermo, we know composition dictates what key properties? Everything. That's why I love thermos. So much so. And in fact, I'm a I love to cook. I wouldn't call myself an amateur cook, but I love to cook right and back in Thermo in 2020 did anyone do 2020 with me? So you're in Covid right? Was like, How do you do Thermo examples and Thermo labs when we're all at home, like ah, thermos in cooking Everything you do in cooking Thermo shows up So a really fun example. Um, if you're reducing, taking a reduction of some liquid on a stove. This is exactly what you're doing. So you notice if you take a whisk and trying to thicken a reduction, it gets more viscous. It also heats up better. So the more reduced tickets I have to turn the flame down or all sear it because I'm losing my light components. The heat capacity is going up because everything's packed together more tightly. Brilliant, right? I can tell the people that cook right, because instantly it's like, Oh, my God, Thermo is in everyday life. So, um, yes, I wouldn't ever recommend doing batch distillation, but if you need to um, yeah, the McCabe process can still be used. So what? I wanted to get into a bit today was around and this will lead us into our workshop prompt. After which I'll stop the recording, um, around how we do multi component installation. So in the last time, we looked at methanol, ethanol and water and found a brilliant paper where that equilibrium curve was physically measured. And then compare that I thought quite well to what multi flash would put out. So you can see from the paper will give us the bounding conditions. We could even zero in on our mixture composition or estimate. It could even use a linear balance to estimate from that paper. And it's going to be pretty close within, you know, one tray plus or minus. Um, what the multiply shot but will be How do I deal with this if I start to get 10, 15, 20 components and how complex doesn't get so these K factors right? In the same way we're effectively define that I go through case. I don't think I talked about K factors last time, so these k factor I think we did over there, but it's very hand waving. Brief K factors are we want to talk about the key components. The reason we call them keys is the Watson K Factor K. So this was originally done for crude oil distillation, and the person who developed this approach to figure out how do I take 10,000 components

in an oil and split them perfectly? Was Watson. And so he he looked at Rose law and relative volatility and instead of calling it relative relative volatility, called it a K factor. The wanting specifically the Watson K factor. Very petroleum engineering. Let's name at everything after ourselves. Um, so you can see from the definition of this, right, I can flip in routes law. If it's ideal vapour pressure on absolute pressure. My approach would also be to put in on why I v i p x y gamble i p i s s so activity coefficient and gasoline coefficient so I can deal with non ideology across the entire system. Whether I'm doing relative volatility or not, we're calling a relative volatility or a k factor doesn't doesn't change, and it's on a per component basis. So just like in our ideal systems and thermo, my K factors will multiply effectively the liquid mole fraction so I can write a bubble point relationship if I want to solve a bubble point curve in a 10 component system. Uh, I think in the reader I put in a video example of doing like a four or five component. I want to say, and calculating this out and showing how it's kind of a guess and check approach do point relationship is the same thing now, And I should say you're going to get a lot of this in advance, Thermo. So I'm kind of giving a preview. But hopefully in a way that advanced thermal will be much easier. It's my hope and set you up to fly through the first two weeks of so now in the context of what I'm going to care about. And that's doing a distillation on some huge number of components at once. How do we figure out when if we're trying to solve this flash? If I start changing, I'm gonna go back here. If I bring in the definitions of non ideology into these K factors, well, then it either. So whether I'm calculating a bubble point, a dew point or more practically, doing a P T flash in the two phase region, my K factors are dependent on my compositions. But when I physically calculate, the flash is to determine the resultant flashed compositions, which then informed my K factors right? Or inform my relative volatilities because my activity coefficients into gas city coefficients change with the with the compositions, so this naturally then leads to How on earth does the engineer solve this? Because you have to know one to solve the other so What do you reckon we do? Being the engineers that we know we are? Yes. And check. Absolutely. It's my favourite. So informal nomenclature. It's the rash rashford race equation. Practically, it's guess and check. It's taking a material balance across the stage and doing a guess and check with the definition of the cave factor. And so advanced thermal, we'll go into more detail around Rashford rice. Um, there are a few different ways it can be presented and written. If we go back to to be where this is coming from, right, This is simply a material balance across a single flash stage, and then I can expand that out based on the number of components. So if I have a single component right here and I flipped around on K factor, more than one component dropped some in front of it. Um, so the approach that we would take this is the version, uh, and they're all equivalent, But this is the version I tend to like because it tells me I need to only know my feedstock composition to exit the feed for each component. Um kay. So by are going to be my k factors and F is the only unknown in that equation. F is the fraction vaporised, so it's my my mole fraction balance between V of moles per second vapour flow rate and L multiple second liquid flow rate. So you can also set this equal to zero. I can subtract one from both sides. You can use Excel to solve it, or you can put it into a workbook and just iterate over and over and over until you get convergence. So you're iterating. Then you guess what the K factors are. I typically start with ideology, so I only look at vapour pressures, Um, and then I'll. What I'll typically do in Excel is I'll put in terms for a few capacity and activity coefficients and set them all the one. So I start with an ideal system

where it's not compositionally dependent and figure out what's the fraction vaporized F for that ideal system. And then, as I start layering in the non ideology, I know where to start guessing. So don't iterate for too long. But probably three or four different iterations would be sufficient. So I don't think, um, we've not asked you to do this on this lab. But I know that there I've written some problems for advanced thermo. It's like, 10 years ago, but I think they still use them. Unfortunately, uh, that, uh, that go into actually, how are practising using this? So before I wrap up, I just want to put on the screen here. So the rest of the folks online can Sorry watching the recording and get, uh, see this as well. I'm just gonna Where's the teams? So, Marshall, are you still able to see the screen with the one note? Oh, cool. Okay, so I walked through the prompt so quick, and then I'll wrap up the recording. So, in the example of, say, three or four component distillation you know would be targeting a singular product that we're trying to find or a singular impurity or toxin trying to allowed where desolation is typically deployed is to create chemical feedstocks. Um, so currently, virtually all of our global manufacturing uses crude oil as the chemical feedstock, of course, as the raw feedstock to then put through distillation systems and split into what is practically 10,000 chemical products. Now these go into everything from Ziploc bags to clothing. Um, so I think there are only a few types of clothing that are un impacted. I know hemp is one, and I think there's a type of cotton and I need to read more into it. But pretty much every piece of clothing that everyone wears is in some way carrying crude oil on it, either in its di clothing, protective fabric softeners, you name it. What makes this not the 18th century of clothing is because we have one of these 10,000 chemicals used in its manufacturing process. And this gets really interesting in my mind from an emissions perspective, right? Because things like electrifying the grid electrifying cars, totally low hanging fruit, expensive. But we know how to do it totally fine. And I pointed this out at an academic board conversation last year. We have no idea how to replace this. We simply don't. We don't have a raw source that contains these 10,000 chemicals because the engineers not modifying these right? We're taking this raw feedstock and splitting one volume into 10,000 individual streams. Literally. Um, if it's something you're interested in, there are some really cool articles that articulate each of these 10,000 products. So and this is one of the reasons why chemical engineers are so in demand. So if I don't have a raw feedstock that can do that how honour, like we don't want to stop using Ziploc bags, right? Like imagine the food waste that we're going to generate if we have to throw everything in the rubbish filled, Um, we don't all want to go back to wearing 18th century clothing. I don't think right. These threads are way too comfortable. They're cheap, but they're comfortable. So if we don't know how to solve this, this to me is actually my greatest concern where emissions are right now because it's not something that's getting a lot of attention and funding because no one really wants to talk about funding a better understanding of crude oil. It feels disingenuous in the context of climate change, but this is one of those huge gaps that separates industry, where industrial processes and economy from environment and and chemical engineers are one of the few disciplines that link the two. So we're often in the firing line where these debates come up now, one of the really cool initiatives. And so this is where the problem I wanted to do today, one of the really cool initiatives coming out. And in fact, the first one that launched was BP putting a half a billion dollars into Stanford in 2010 to try to say, Okay, if we need to replicate this feedstock, call it crude oil right now. But let's imagine a generic feedstock. Okay? We're gonna probably get to a point where we can get away from

using jet fuel. Right? So we're gonna probably electrify aeroplanes. Might be a hydrogen combination. We have a few different projects in this space, but probably we'll sort that out. Probably aren't going to need a lot of gasoline. Um, maybe from a military standpoint for, like, a national security reserve thing. But by and large, vehicles will be sort of you taking lighter products. Yeah, I probably don't need those on, like eventually, right. I personally hate cooking on electric. I can't deal with it. I put way too much effort into actually cooking to screw it up with an electric stuff, but that's this bottom bit. This is the trouble. This is real real trouble. Um, and It comes from the complexity of the chemicals when we get to what we call this heavy of a cut. So if we take a typical crude oil well, well, fracking initially or not, frack frack. But Frank into, um, say eight different what we call cuts. Then each of these eight cuts goes into at least two or three additional distillation columns to separate out into primary products that then go into further distillation columns for the secondaries. Once I get down to these fuel oils, right and we're cutting this intent so 1000 Fahrenheit, we can actually go quite a bit hotter when we get hotter than that. What's left is what we make asphalt out of habitual, so we don't have a feedstock that can produce that now. VP looked at this in 2010, and it's been cloned now by other energy companies by governments to say, What do we have? A lot of that we know has chemical diversity, and in fact, I just mentioned it rubbish trash. Not so much. I'm like recycling shirt but trash. We have a lot of trash, and it's growing exponentially. We, for whatever reason, the species will not stop consuming at an ever greater quantum and that consumption continuously produces rubbish. But the rubbish contains all of these diverse chemicals, and right now we're just bearing it back. So in a sense, what that's going to do for us is produced a renewable crude oil in, like, two billion years, the way outside of our timeline for being able to use so v p and then followed by the US government. Now Europe said Okay, what if we took that rubbish? Say a volume the size of this room. And instead of bearing on the ground, what if we built a gigantic reactor brought that up to Earth's core conditions were halfway through the mantle. So put it under 1000 bar pressure 800 Celsius and an OxiClean. So in the absence of oxygen, cook it, cook it back down into the liquid from whence it came. Kind of seems practical, right, because a lot of our products don't. They're not significant chemical manipulations. They're just taking it up to 10,000 opponent mix, pulling one component out that we want and putting it into a Ziploc bag or to make a Ziploc bag. So if I combine the right stuff in the right mix at the right conditions for the right time. I can accelerate that natural oil production process and get back to a point where I can now use rubbish to generate bio fuel. Um, so this there's a lot of work going on. I think my personal bias is that this is the only way we are ever going to solve that last and arguably the nastiest trench of emissions. It is the only thing we can look out to do it unless people want to give up the clothing. Ziploc bags, the chairs. You know, everything in this room, every service. Right now, absolutely Everyone is derived from crude oil, including the concrete. So, um, this is a very, very simplified approximation of what would typically be an anathema cut. So the NAFTA cut, um, tends to be quite light. Right? So here's what we're putting our park. Here's the powers they wouldn't say Qantas plane, but a plane, Um and so the NAFTA cuts what's It's kind of between them, and this is where we get a lot of our plastic upstream feedstocks from, so I would typically expect it to nap the cut that we're going to see something in between hexane and octane. So if we know that Sorry. Um, sorry between octane and decades. So by the time we get to dough decking, this is the primary cut or the primary component in jet fuel. And

octane, of course, is the primary component gasoline. So we're targeting NAFTA. What we want to do is a multi component distillation that is going to preferentially enrich this decade cut. And if we imagine that this was a composition averaged 10 measurements just to give an indication. But if this was a composition of the rubbish in the room after we compressed it pressurised, it cooked it for, well, probably two or three years and then extracted it back out from use. So it's a carbon neutral process because we're taking trash off the system. Then how am I? What is the type of quality of decade rich cut that I can walk out with? And how many stages do I need to get there? Okay, so I'll stop the recording now. And, Marshall, there's only a few of us in person here, so Oh, is Marshall gone? Oh, okay. Let's stop recording now.
SPEAKER 0

Okay. Marvellous. So the recordings now started, Uh, a quick admin reminder for this week. So we're gonna begin now our fourth of four, um, unit operations modules. This one will be on ad absorption. So a D, as opposed to a B absorption. Um, this will be covering Reader section 11. And the Associated Lab report will be due at the end of next week. So the seventh of October. So I know this is a bit of a tighter lab report relative to the previous, because we were able to extend the deadline for lab three until Tuesday. Um, yesterday, as it were, just a quick reminder because I've got a few emails for those listening to the recording. That does not mean that there's an automatic extension if you have a special consideration already. So if it doesn't add days to a special consideration So if you plan to submit after yesterday within the normal time frame with no penalty, then you will still need to update or apply for special consideration. Um, so so, so far, what we've been looking at our different methods right when we're focusing on steady state unit operations. We've been looking at different methods by which we can move material from one phase to another. And that's been quite useful for us because it allows us to conduct separations on a molecular scale, right? So in the same way that we might have a very dilute species of interest, whether it's a toxic species to get rid of or a product species of value, we tend to be working in systems where those are very dilute. And so we can't do a bulk operation where we're going to try to separate off some species not of interest, but rather designing a unit operation that leverages our understanding of thermodynamics so that we can specifically target those components in which we're interested. So ab absorption is probably the simplest among these, and it considers, basically that we're going to take two different systems that we put them together. They come out of equilibrium, so we might have a liquid and the vapour where we want to transfer mass between the two and initially, these two phases are at equilibrium on their own, but the second we join them in a physical space, there are no longer an equilibrium and so re establishing that equilibrium means we're going to move molecules from one phase to another. We can take this same concept, and instead of manipulating something like the availability of phase or that would be manipulating composition, we can manipulate pressure and temperature. And that takes us from absorption to a single stage or flash distillation. And then, as we realise that bringing each of these PT stages into different conditions allows us to move mass more effectively, well, then follows the very logical idea. Let's not have one stage, but 5, 10 or 20 stages, and we can gradually move more and more and more mass until we end up with a very high purity product stream. Now, in each of those cases were thinking about steady state processes. So when I say steady state, what it means is we know where the equilibrium of the system is because we understand the thermodynamics. And so we

know we're out of equilibrium, meaning the system will relax toward equilibrium. And that's a really critical insight to have right, because it means that we are leveraging or thermodynamics to, um, exploit the natural ability of a system to want to achieve its equilibrium. And if we know what that a delivery, um will be ahead of the system. We can take advantage of that for processes like separation. Now, when we come to add absorption, this is the one unit operation we will look at that is not steady state, and so quite, quite quickly, most of us realise Oh, goodness right. Our energy balances are mass balances are momentum balances. None of these can be applied in the same way because we're no longer dealing with the time during that. It goes to zero. Now with absorption. The nature of the process is not that we're moving between inert phases, but rather that we have some capturing phase, which we will call an absorbent or absorbing phase that has these little slights. Almost the way I tend to think of it metaphorically is almost like little hotel rooms, right that this absorbent material can rent out to different species that can fit in the hotel room. And so it might be that a solid crystal of absorbent begins with a million or a billion or trillion sites or a little hotel rooms in which molecules can rest for a while at certain conditions. And then, if I go to regenerate that absorbent, all of those Molly guest molecules will leave, usually in a very high purity phase. So the physical process behind it then is pictured here on the bottom, where I might begin with some inert material, and I tend to think of a metaphor. Is something like a grain of sand, right? I have a solid service. I can do a lot of operations, but I'm probably not going to change the chemical character of a grain of sand. But in each of those service sites, I can deposit stuff onto the grain of sand. And if the stuff that I have available to deposit is stuff that that grain of sand or it's little rooms really like to hold, then there will be a positive movement toward this absorption process for these molecules to sit down and bind to that certain. So going in from the left hand to the right hand picture here would be an example of a process of absorption where I am absorbing five molecules tooth service. Now, once these molecules are at the surface, uh, they are bound in the same way that we would have, say, Vander Wal's or long term long range interactions between molecules in the liquid so they're not chemically fused to the surface, right? They're not. They have not been chemically reacted to bind into the surface, but rather they're using their electrostatic forces. And the surface is a simply a lower energy place to be in terms of those electrostatic forces than out in the bulk fluid running around. And so the absorbing material in this case we're looking at something like co two or water molecules as they're floating around in their long range interactions begin to detect the presence of the surface. They naturally feel a gradient of lower energy as they move toward the surface. Now this then begets the question of, Well, how much can I absorb to a material, right? If I'm going to start observing some molecules of interest, how do I know when it starts? And how do I know when it stops and the way that we characterise? This isn't thinking about the number of sites or little hotel rooms that are given. Circus has, um, and in fact, absorbent materials are designed and characteristic on that basis, so it might be that a good material for every, uh, you know, it's a millimetre of material or cubic centimetre material. I might have a million little hotel rooms that these molecules can absorb, too. An outstanding material for that same volume of one cubic centimetre might have a billion hotel rooms. And so a lot of the material science and engineering is around how we can, uh, invent or or manipulate materials to get more and more absorbent places or observing locations whilst generating an ever better energy profile that drives these materials to the surface. Now, from an engineering

standpoint, we characterise this by thinking of the capacity. So the C in C, not term, which we use for the Y axis here, this is telling me to see not is the potential So the capacity for the material to take stuff on effectively, see not as how many hotel rooms I have available at the beginning and see which is the term that I'm measuring Here are how many of them are filled. So when CNN C not goes to one, all of my hotel rooms in an imperial are filled when it's zero. All of the hotel rooms are vacant and the process of absorption that we characteristic is the process of filling up those rooms one by one. So we tend to plot this in a dimension lys, um context CNC not as opposed to it an absolute value, because we can compare them different materials through an engineering process. We also think about the time so as I introduce some material that can absorb well when I first introduced that nothing has absorbed from the very 1st, 2nd, but over some amount of time as I begin flushing more and more material across the surfaces. Eventually, those little molecules that can ads or we'll check into a hotel room, and gradually those begin getting filled up until I reach a capacity of one. And I filled all potential spaces. And we'll come back to this plot a few times in the coming week to look at how we can analyse this both from our laboratory standpoint and compare different materials from a theory standpoint. So the concept of an absorption column, then is actually remarkably simple. What we would do is fill up, so here we have a diagram of two simple columns or would fill up with some absorbent material of interest. Now that might be silica sand. It could be activated charcoal, who knows? And we will flood a liquid across that or a fluid across that I should say so it can be a liquid or gas containing some component of interest. Once I fill all of these hotel rooms of these absorbent sites, the bed we call is saturated so all of my hotel rooms are used. The bed is saturated. I can no longer absorb new material into this. And so what happens? We go from filling, say, our first column to filling our second, which is going to have raw material whilst regenerating our first. So we'll go through what that looks like in a second now for this very simple process that we've drawn. Let's look at where fluid is going to flow first. So if I'm filling up this checked area with some acerbic material, say it's activated charcoal. Initially, I have a choice of where I'm going to feed this so I can feed to both beds, but traditionally we would feed to one bed, wait till it's full and then continue to feed to the second bed will come back to why in a minute. So let's imagine that we're first going to feed the left hand bed here as I begin flowing from the top to the bottom through this bed, let's say I have one or two MOL percent of my target material. Well, that's going to begin absorbing to the sites or the hotel rooms at the top of the column, simply because they're the first ones that come across well. Those sites become saturated over time, but the sites beneath them are empty. They have not encountered any absorbent material yet, And so over time the second row of sites or a layer of sites become saturated and so on and so forth. So I can see that I begin saturating at the top, and over time I will end or conclude saturating at the bottom of the column. Now, meanwhile, once that happens, I can shut this top valve, which redirects the flow into my second bed. Once I do that, I will start absorbing in the same process in my second bed. But the engineer I must do something to regenerate the first dead, where I have all of my material has been absorbed and traditionally will either use pressure or temperature to control these absorption processes. So in the same way, right that these molecules prefer to be absorbed to the surface because there's a slightly better energy distribution. In doing so, I can disgorge them by adding a bit of energy or decreasing the energy benefit of absorbing to that service. So if I'm using temperature something like, if I make the

surface really, really hot, then all of a sudden the energy benefit of those molecules binding to the surface doesn't really isn't high magnitude anymore, right? If I start heating that surface higher and higher and higher will, eventually the surface will get so hot and that that energy is conducted to my species of interest that, in fact, it's a lower energy configuration for those species to D's orb and go back into some fluid of interest. Now, that process, if I begin, then using steam so steam comes up and begins flowing through this saturated bed here on the left, that steam will warm up the bed material and disease orb the species of interest. The disease or vision process will happen, a bit faster than ads or vision traditionally, but the nature of it is quite the same. I begin disarming here at the bottom. I would end dissolving at the top and if we've balanced our load, coming in from the feed and our regenerative warm steam that in fact, around the same time the deception bet has been regenerated my ad absorption. But on the right hand side is saturated, and I simply flip the system again and around and around we go. So engineers will use these to put two absorption beds next to each other because it allows them to operate a continuous process even though the the mass transfer operation being employed is transient, meaning it depends or changes with time. So a few of the more practical examples of why do we like ads? Orbits well, One of the things hopefully that's come across so far is that although things like multi component distillation are relatively complex in the scheme of all engineering operations that are possible, um, you know when I look at things like flash or multimodal distillation, they're really not that complex, right? I'm not leveraging that much understanding of thermodynamics to be able to design something like a distillation column. And in fact, the amount of Thermo that we know means that is far superior to the amount that we're going to use. And so absorption is one of those domains where I can, uh, invoke or utilise a ever increasing amount of knowledge about the physical chemistry and the thermodynamics of whatever species I care about, um, to conduct this mass transfer operation and specifically within that I can design absorbent materials that can be highly, highly selected to component of interest. So let's imagine, for instance, and I flagged. This is the first practical example here. Toxic or unwanted components. So let's say I have point Oh, one more percent of H two s coming out of a product string. So it's It's well above the amount that could easily kill somebody if they were to inhale toxic stream. But it's not, you know, point when MOL percent is not really high enough, mole fraction that I'm gonna be able to exploit a really good distillation process, right? I'm not. I'm going to have a reflux ratio that is so high that out at the top end of the column I'm going to get a trickle feed of H two s rich fluid. So things like a distillation column while I could use that for the recovery or removal of H two s at low concentrations or dilute concentrations would be a very, very expensive thing to do. That is not really well suited for that dilute environment, where as I could with my knowledge of the H two s molecule design and observant material, I can first design it in a computational physics realm or computational chemistry, bring it into a materials manufacturing realm and then tested at an absorption column specifically to capture H two s in its chemical environment and at the pressure and temperature conditions I want. And so, in that way, the design of absorbent materials leverages a significant lead. Greater amount of understanding about the chemistry itself, as opposed to something like a distillation column. And as we you know, layer in an increasing requirements placed on the engineer to both understand and manage either unwanted or byproduct streams in a process, things like absorption are becoming an increasingly greater focus of that effort. One really good example

comes from dilute natural gas systems So if you have a either something like a landfill, where you have an off gas of methane probably surrounded by some additional gases that you can't use, or perhaps a traditional hydrocarbon asset where you have a very low quality methane gas so currently right in either a waste operation or hydrocarbon asset operation most of the time dilute methane gases are vented to the atmosphere, right, And they're vented because if it's 30 mol percent methane, I can't ignite it. So I don't have an energetic use for it. Um, I don't know what to do other than, you know, vented into the atmosphere, and there's no real mass transfer operation that could somehow take advantage of it. Now, of course, that becomes really problematic from a climate change perspective, because methane is 100 times the potency of of C 02. So if if we're worried about emissions profiles and a warming prospect getting unwanted methane out of vents, strange is a absolute first priority or the highest priority. Um, well, in fact, it was a group from U W A that invented and ultimately patented an absorbing material zero light, uh, that was able to capture the world's greatest selectivity of methane capture in these dilute environments. So what happened there? Right as we take this zero light, you're gonna, um So the solid service would represent the zero light, and these little molecules, in that case, would be dilute methane. So once the absorption process begins, I have more or less pure methane bound to the zero, like in the absorbing dead. And when I go to strip that back off, we might use, like, warm nitrogen or something. Uh, it will vent a relatively high, pure methane stream. Sorry, high purity methane stream. And if I don't use something like temperature to regenerate it but in fact, pressure. So I turn up the pressure of the column during the absorption process, meaning it's easier for the molecules to sit down to the surface and then drop the pressure to regenerate the material. Well, what I'm pulling out of that is now a 90 to 95% pure methane stream so that the group w A then took this to China and the US and started manufacturing and bringing this into industrial processes. Not only does that allow companies to significantly dropped their emissions profile. But they can then take that methane that would have otherwise become a very bad greenhouse gas and turn that into a useful fuel. So it becomes when you compare it to the current option on the market, it becomes a carbon negative enterprise. Because I'm not only saving the environment from an admission, I'm using that because of this cleverly designed absorbent material to power my process moving forward so that that is one good, very useful application. I think we're gonna start seeing a lot more of that as we go. Things like carbon capture. So C. C. U S carbon capture and utilisation and storage Uh, the CC part of that for carbon capture. It's going to rely ever more increasingly on things like cheap and readily accessible Zia lights, which we also call molecular sieves, uh, to be able to capture that material at a relatively low cost. So I I mentioned earlier and will kind of wrap up here in a few minutes. But I've mentioned earlier around comparing these different types of isis terms. This allows us to understand how different segments of the bed are going to perform from the top of the bed to the bottom or to compare different materials. And so, for instance, if I'm looking at something like the amount of that material that's been absorbed to this, this zero lack of interest as now a function of bed length instead of time right this would be called profile plots because I'm looking at the entire profile of the column and how that profile evolves in time. I can see here that well, how much of my material is available or has been absorbed relative to the capacity of the bed to do so well at time. One I see what I'm observing a majority of my material. But as soon as I get into the bed, I've lost all of it, right, because I'm

allowing that material to fully absorb into the the zero lighted, impulsive as I progressed further in time. Well, now that first segment of the bed has been saturated, so it's not until maybe 10 or 15% of the length into the bed that I begin absorbing at time, too, and this will now absorb in the middle of the column as well. Time three, and then time for us. We've drawn it here will now have saturated so much of my bed. That material can't begin absorbing until I reached the ladder or the end section of the bed. And in fact, what we know this in time for here is that by the time I reached the end of the length of the bed, I still haven't captured all of my material. So the engineer will traditionally fill these beds with an absorbent and measured the outlet gas. Right? And I'm looking for where is my target material in the outlet gas. I should see during the absorption process a measurement of zero, right. If I picked the right ads orbit, I've sized the bed correctly and my flow rate is good and I don't have any kind of preferential fluid flow or tortuous city through the bed. Well, at some point, by measuring the effluent concentration, I'm going to start seeing that target materials show up in the effluent as the bed becomes exhausted, were saturated and we would call that breakthrough. So when I noticed the breakthrough of of target material in in my effluent stream, that's what tells me the bed has started to become saturated So this T four indicates a period where I can detect breakthrough because this now at the end of the bed is a non zero number. Now, instead of characterising this as a profile, we can also show the same thing in time. So what this is looking on the right hand side is that same concentration profile but now measured at the end of the bed. So how much of my target material is coming out of the end of the bed as a function of time? So one location and we would call this a trend plot because it's how one location trends over time. Well, I can see, just as I've drawn on the left here from T one to t two t three, my measurement should be zero right? None of my target material is coming at the end of the bed, but suddenly, after t three, that measurement starts to pick up and from t three right up through what we might call t five or t six. Here I see an ever increasing amount of material. So this curve here, which looks a bit like An s shape, we would call the breakthrough curve and it begins at the breakthrough point and goes through the saturation point. Now, this then begets the question of Well, if I'm sitting at the end of the bed, is the engineer measuring the effluent concentration? How do I know? How do I make the call? The bed is saturated when it's 0.1% or 0.1% or 5% coming through and the answer tends to be around 5% right? That we would call this mass transfer zone of where I'm actually absorbing material into the zero light or the bed where my concentrations that the effluent are somewhere between five and 95%. Right? So this is why t three would technically be the point at which I probably see an inflexion up from zero. But it's not until I hit about 5% of that value that we call it the breakthrough point. And after that, the breakthrough curve will continue. Now, you might be looking at this saying, OK, well, what is this t star and why do we draw t star like this? Well, if my s curve is symmetric here, right? Meaning I have a relatively well distributed absorbent material a homogeneous flow, meaning I don't have any preferential flow around sections of the bed. Then I'll have a symmetric breakthrough curve, meaning T star is drawn at a place where the integral under the left hand side of the curve and one minus the integral. So this right hand area that I'm highlighting here, those areas are the same. Now, why do we care? We've drawn this way. Well, this means that I can figure out how What is the capacity of my bed In practise? I have picked my material, picked my operating conditions, but I still need to calibrate my capacity in practise. I can now simply multiply. I'm going from 0 to 1 on the Y

axis. I can multiply one times T star to get the total capacity of the bed. So that's why we draw this like this is a simple way to do an estimated total capacity and how that changes for different operating conditions or different dialects. So early on, I talked about the use of hot materials like warm steam or warm nitrogen as a regenerative method for the bed. I can also use pressure like we did in our example on capturing methane. So either way, I can think that if I'm going to take a target species from a fluid phase, whether liquid or gas right to put a fluid phase species on a material of interest, that's a solid. That fluid material is going to carry more energy than it would in its solid phase. Right? Meaning I'm not at the freezing point of the material, So it's gonna be pretty hard to get that sitting on the solid for some time. Well, quite naturally, then I can think, well, if I cool the system down, things like to become solid, more easily right. Cooling things down leads to solid formation in the same way of increasing pressure helps things become a solid. It's less obtuse for a fluid to solidify under pressure or lip high pressure or low temperature. So in both ways, I can use either a temperature or pressure condition to control the absorption and description of the bed. And traditionally we would call these respectively temperature, swing or pressure swing absorption because I am manipulating or swinging the temperature and the pressure of my two beds to control which one is in the absorbing region and which one is India's orbit now, the way I would fundamentally characterise that. So if if we say invented in New Zealand in the lab and we've done some basic characterisation, then we have to figure out what are the conditions which absorption is most effective. And the simple answer is we probably wouldn't get that answer from computational chemistry. We would have to run hundreds of experiments, right? And we would need a laboratory scale process that can run through each of these. So when we then start characterising So I've invented this this new absorbent material or testing it out for a research clients. And we need to figure out Well, how does this compare? We'll use what's called isis terms to try to map the behaviour of the material Now in this class, we're not gonna get too deep into observes Nice affirms, because they tend to be a much more advanced, uh, sub discipline of chemical engineering. Uh, so the purpose here is I just want to introduce you to the concept of the ice affirms. And more importantly, perhaps the land nearby system is the most common. So we're a little bit familiar with what that means and perhaps how to use it. So if what? I'm fundamentally measuring right in this this integral plot going back here. So this measurement of how much stuff from CNC not can I absorb out of my my f for my feed stream as a function of time? And I simply I can pick a T star that lets me integrate by hand, or I can also just measure this curve and manually or numerically integrated right. Either way, I'm looking for the integral of this non rectilinear bit. That's the whole amount of stuff I can put on this solid now because I can design absorbent columns at any, uh, scale. We characterise that as amount of stuff per volume per volume of material. So whether my absorption column is, you know, one ft or 100 ft high, I'm normalising by the volume of material in the column. And the question to the engineer is, how is that integral? How much stuff can I fit into that volume of material? So this is the measurement that we're taking on the Y axis here. Grammes absorbed per gramme or volume of solid when it's packed. This is physically what I would measure in the laboratory. And here what we're varying is the amount of stuff that I in the feed stream, right? So I might take this measurement at one point, right? I'll do this this measurement in the lab and plot this breakthrough curve for a certain feed concentration. Call it 100 ppm ill. Then do it again for 203 104 100 figure out what is the range of concentration in which this

material works the best, and then I can proceed to analyse the ice term for it. So here I am, varying the concentration, and I'm measuring the amount of stuff that's gone on to the solid. This plot shows me a few different types of representative ice affirms that I can observe write, so the simplest is going to be a linear isis. All that means is, the more stuff I add, uh, the more stuff goes on in material. But the amount of stuff in the material doesn't really depend or doesn't vary with national does. Very. The nature of the absorption does not vary with how much I have to feed. All right, So the more I have in the feed, I get more absorption. I might compare that then to something like a favourable absorption Ice cream. That means if I go too low concentration. So let's look here. I go to a low concentration, say, 50 ppm. I'm going to get more bang for my buck in this material, more stuff will absorb than if I go to, say, 300 ppm, right where a linear profile would see me go up here from that initial slow? Well, by the time I get to 300 ppm, limit the curve, right? I have a negative curvature, meaning the higher the concentration, the more will interact with or inhibit the ability of this material to absorb to the zero life. Similarly, if I'm in an unfair favourable region, I'm below the linear isil. So if I started a very, very dilute concentration, I'm not going to get very much stuff absorbing to that material. And in fact, I have to go to higher and higher and higher concentrations before I start seeing a positive impact of as absorption. And so I tend to think of them. Here were plotting strongly favourable and favourable as comparison. What I would think of is simply linear, unfavourable and favourable right were relative to that linear, icy therm. Is it easier to work with dilute systems? Or do I have in the favourable case, or do I have to be, um, in a a very high concentration system for that unfavourable case to work? Now, one of the most common types that will look at is the Langmuir icing room. Uh, so this tends to work pretty well for simple systems where the absorption process is not highly dependent on is not highly variable with with the amount of material or the type of absorbent and the way that will plot this is looking at the maximum capacity or w sub Max. And I'll characterise this ice therm on two parameters, one of which is the concentration. So you can see here I'm going to have to take four or five different measurements in concentration to start plotting out that I say K k is simply a proportionality constant. Um, So what I would do is, you know, I'm measuring W Max with the total stuff I can add to this this material per volume. And I'm choosing what concentrations I test this over. So, K is simply the one fitting factor that I will use, um, to the absorbent behaviour. Okay, so we'll look at one set of example observance here, and then we'll come back next week and do more around how we analyse some of the state and make sense of it. But traditionally, here, what I would look at would be the absorption of water and error at, say, 20 between 20 and 50 degrees C. Now, where we would care about this is something like natural gas export, right, if we're running gas from the north west, shelf down to Perth or were preparing gas for export prior to liquefaction, we have to be very, very careful about the amount of water, uh, in that gas book from a corrosion standpoint, as well as additional organic type solids that can crop up. And so we we often use these molecular sieves as representative absorbent to capture that very dilute water out of air it now between 20 and 50 c. We know that that's pretty common living conditions. So, in fact, what we're plotting here is the percent relative humidity going between 20 and 50 degrees c. Um, simply because this is our our experience. And as we look at three different absorbent material so silica, gel, aluminium and impulsive, we can see that that, in fact, we have a different ability to absorb under different humidity conditions. Now it should come as no surprise, then, that the molecular sieve, which tends to follow that

more, more idealistic case of irreversible absorption so it has a relatively low poor profile. It's not going to interact with the absorbing species very much, and it doesn't really vary that much with temperature, Right? Uh, we would tend to select this material because I can see where a silica gel or an aluminium might be great at high relative humidity. But what happens if we have a not very humid day? We'll all of a sudden my absorption process is going to tank, And so, in fact, I can't really perform effective absorption below 20% humidity. So this is one example of where we might have to characterise the isil in the absorption profile to make an engineering choice as to what will function over the range of conditions I'm gonna expect most commonly from my operation. As I was explaining before them these breakthrough curves, right? This is the example that we would draw on top where we would ideally have a perfectly symmetric s curve, meaning we can very easily draw this dash line. But what happens if we don't write no materials? Perfect. No processes ideal. All I'm going to do is simply integrate wherever this curve sits, right, whether it's a wide mass transfer zone, so that would be indicative of a difficult absorption process, meaning a number of my molecules are going to pass through most of the bed before they are able to absorb. Or a very narrow mass transfer zone, meaning a majority of my absorption takes place in a truncated environment. Either way, all I'm doing is is plotting this out. So how much I'm measuring my influence relative to how much I have coming in in the feet and plotting that over time at the end of the bed. So at the point, the affluence measuring and I manually or numerically integrating this group that is telling me the total amount and in each case, my breakthrough time is going to be indicative of what I'm 5% right. I have a value of 5% equal to C and C nod. Now, I can use this this equation here if I'm looking for a numerical balance of t star, so this equation might come in useful when you're doing some of your lab for analysis again appreciating that's meant for a symmetric profile. So would probably be a good idea to plot that breaks for profile first and make your own assessment as to whether, uh, an equation like this is going to appropriately represent what we're trying to get at in this numerical interval. So with that, that's kind of a basic introduction. This should be most of the skill set that we're going to require to tackle lab for when we come back next week. We'll look at a few more esoteric examples of where absorption crops up for engineers as well as some more advanced analysis. Uh, the one point that I would make is that we are not going to be getting into mathematics of absorption in the same way that we have distillation and our other unit operations, and that's simply because when we start dealing with the transient or time dependent process. All of our balances become very, very difficult and very fast. Now, we're very, uh, take a long time to use. We can still operate with those, but it means things like Aspen High Isis are no longer valid. We have to go to something like Aspen absorption where I don't really have a guarantee I can close those balances. And in fact, I have to work quite hard. So the prompt for this week I will end the recording here. But the prompt will be getting into how we can use absorbent materials for co two capture out of an industrial flue gas, which will be one of what I would suspect the most common applications over the next 20 or 30 years. Okay, so I'll let me end the recording.

SPEAKER 0

There we go. And the recording is now started. Um, So, uh, this week we are going to conclude our discussions around the absorption modules. So this is the second of the two. Uh, workshop modules are unpacking, in this case, a bit more about the practical aspects of absorption and how we might find that an industry and both in

chemistry and engineering operations before we begin. Then, of course, we're working in Counsellor and in, uh, synchronous with lab for submission. We had originally scheduled that to be submitted the close of business this Friday. So that was the original timeline. In talking through this, we've decided that because the lab three submission was pushed back from the holiday, it wouldn't really be fair to give the absorption module only 10 days of time to work on. So to try to maintain some semblance of time through the semester, we've extended that deadline now to the end of Sunday. So added two additional days where there will be no penalty for submitting late. And so I'll post a note on that two teams and, um, an email out through LMS shortly Now, of course, if you have it done and you'd like to submit on Friday. There's a course. No drama. If you are planning to submit after that extended deadline of Sunday the ninth of October now at 11. 59 then you will also need to follow a traditional special consideration, uh, policy. And, of course, then we'll follow up with more open consultation hours next Monday. So once we conclude this absorption module, uh, and the lab report that goes with it, that will be the end of the four individual lab reports that we've been working on through the semester. Our fifth and final assessment activity will be the group based engineering design report. Um, so when we get into next week, I will publish a, uh, we already have the prompt for it, but I will publish the teams so the teams are assigned based on the L. M S C. It's not a pick your own group sort of thing, but you can log into the LMS and you'll find which team you're in. Um, and I'll hold on Monday some discussion and consultation hours and again. We'll focus on Wednesday, Um, kind of a Q and A as to how an engineering team might go about addressing that group design project. So in the last, uh, workshop we had focused, what I was trying to do is focus pretty heavily on what are the key concepts around absorption that you need to know to really get stuck into this laboratory. Prompt? Um, so I wanted to then take the second week and back up a little bit and fill in some of the gaps not necessarily related to the prompt, but where we might find absorption more generally in the engineering and chemistry industries. So, in essence, are absorption. Process is the concept of taking a select component out of a liquid and binding it to a solid or an absorbent. There are fundamentally two ways, uh, that that we, as junior chemists, might go about doing that. We can either look at physics option, and this is what I was speaking to a lot last week and in physics or vision, right? We don't have a chemical bond or a co Valent bond that's been formed between the target species and the absorbent material, but we rather have a Vander Wal's type interaction, so it might be that we have a positively or slight electrostatic positive charge on our target species and a slight like tonight electrostatic negative charge on our absorbent material. And these can come together and form a weak interaction to hold that target species at the solid for some amount of time until it's been regenerated. As engineers, we tend to really like fizz, absorbing materials or physics. Option is a process because it requires a lot less energy than chemist or Bishan. We'll talk about a minute, but a lot less energy to revert. So if I have a physics or option scenario, perhaps I'm absorbing a target species. It could be a toxin, or it could be a valuable product that I'm trying to purify. Uh, I will tend to want physics option because then, to get that species back off the observant material, I don't have to put all that much energy into it. So what we're looking at in this plot here, this is effectively a free energy metric as a function of distance away from the absorbing material. So if I imagine when I hit zero here, this is the solid surface of the absorbing material, all right, and as I start to get a little bit away from that. I appreciate that. My atoms and molecules do have a

finite volume, so that's what we're accounting for here. Now. If I go all the way, say hundreds or thousands of Angstrom is away from that service, Well, neither of my physics or vision or cannot absorption processes are going to be able to take place, right, because my target species and my solid are just too far apart. Now, if I go from, we're going to read this plot. Counterintuitively, we're going to go from the right to the left. So if I then start bringing that species closer and closer and closer to my observing material in either fizz or Kemah absorption, I see a a slightly negative right in a local minima, or global minima in the free energy at some finite distance between when I was far away. And when we're right next to that observing material. Now, if I'm this finite distance, let's call this a kind of a sweet spot for free energy, right? We know that systems prefer in thermodynamic equilibrium. They will seek a local minima and free energy or stated more absolutely a global maximum and entropy generation. Now, if I have this local minima in free energy, this will be the distance at which my target material so it could be a toxin could be a product wants to interact and engage Vander Waals interactions with that absorbing material. So this kind of plot tells me why if this absorption works because I need only a little bit of energy, right, that this is the difference between that zero line and this local minima here in pink. I need only that little amount of energy to boot this thing back off the surface, right and get it into a target phase. So if it were a valuable product, I don't want to have to put a lot of energy into it, because in doing so, I might equally damage the product that I've spent so much time reacting and creating. Now when I come to Kim Absorption, this is the much stronger version, right? So now I'm going to form a coalition bond or a chemical bond between whatever my target is and not solid. Uh, and we tend not to let Cam absorption because it is a very strong, energetic reaction in the same way all Covalin bonds hold a very strong relationship between two molecules, but also that it will effectively eliminate that observance, material or ability to be regenerated as a useful material. There are some exceptions to this, and I can perform some chemical reactions to regenerate. Some can absorb materials that function of kim absorption. But by and large, um, I would prefer as an engineer to have a material that I can rinse and repeat with minimal effort, minimal energy in a minimal time. And so for that reason and continuous processes, we tend to prefer face absorption, a point to make Coming back to our thermodynamic descriptions here is that if we think about this, this why access is effectively a free energy as a function of distance between my hands open to my target. Well, this is effectively representing Delta G, right? So the change in free energy as I bring some target material closer and closer and closer to that absorbent well, I can think to myself Well, I know that Delta G, from our thermodynamics class is fundamentally defined as the change in the end therapy. So the entropy of having that single molecule free versus absorbed in any way and the change in entropy we don't ask as qualified by the operating temperature. So Delta H plus t Delta s. So if we look at this right hand side for a minute, we can see something really critical. We know we know from thermodynamics that don't as must always be positive, right? We cannot have a process, a localised process in which I am generating a negative entropy. So if Delta s is going to be positive, we can also appreciate that if the absorption process has a negative, free energy has to be drawn here. Both of these local minimum are below zero. So I have a negative Delta G and a positive Delta s and I can seductively say to myself, OK, this means that Delta age, therefore must be negative, right? It doesn't matter what the magnitude is, but the quantum delta H must be negative in this relationship. So when I have a negative changing or a

negative end healthy change, what that tells me is the engineer is the process, but will be spontaneous, and it will be exact clinic so we can think about this that if I have a bed now of observant materials, the reason we we gravitate toward and we see a much an increasing amount of absorption in process engineering is that I don't have to do anything right. The engineer is ultimately trying to minimise their efforts and their energy as well. I don't have to do anything to get this species to absorb, because it is a spontaneous process that will occur naturally at these operating conditions. If I pull the temperature or the pressure out absorbing region, what I will find is the process is no longer spontaneous, right, and this is tell me exactly why in a physics or vision process, temperature swinging work so well to regenerate the bed. If the ads or vision itself is negative, it's an exo, thermic process that I must add energy or treated as an endo thermic uh, in reverse, right? But I'm adding energy to the system to boot these species off the surface. Now, in the last workshop we worked through and it looked at a number of ice affirms, and so I won't rehash this slide too much, but I just wanted to give us a quick reminder of where these ice affirms come into play. Specifically, we want to look for a minute that the irreversible Isis, right? So what this is meaning is that the ability to absorb by target species to my solid does not depend on how much target species is out there. And we typically we like to use things like in this case, they're irreversible ice of terms, but more generally engineering. We like to use these kind of benchmark models because they allow us to to look at dependencies when there is no difference in potential. So we unpack that for a minute. If we look at the linear, I sold them for a minute. The more species I have, let's for a second. So I'm trying to strip a toxic species out of the fluid. The more of that toxic species I have, the greater the potential for that species to absorb to the solid so that the capacity of the solid is going to increase with the amount of, um, target species I have in the fluid. So this is telling me that the driving force for ads origin is changing as a function of concentration. It's relating the two now in all practical terms. And we're going to look at the mathematics of this and a few sides and all practical aspects we need as engineers to be able to account for this and in fact, beyond absorption. We must account for this phenomenon more generally. Uh, and this is, in fact is the birthplace of the discipline of reaction kinetics. This is where the concepts come from, and we're going to end by actually looking at linkages between unit operations and reactions, which will be taking in the MP for chemical engineering. But to understand that properly, it's easiest for our minds to first consider the case where there is no differential potential. Right? So we begin with the case where it doesn't matter if I have one molecule right on the left hand side of this plot or a billion molecules or avocados. Number of molecules on the right hand side. In any case, the molecule has a constant potential to absorb the solid. Now, if I take that base case of irreversible Anzor machine, I can start to write out the mathematics of this transient process, right? And this is really what we're trying to get to is how do we mathematically describe something that's changing in time? So to do that, we're first going to look at the irreversible right where I don't have a differential potential and then expanded to a reversible system. Um, if I then look at the irreversible absorption, uh, jump forward to slide here and then go back. So if I'm looking at a full differential right of how I can pull mass in will unpack this map on the next as we get to this line. But I have a changing concentration in time, and I have a changing amount in time of my stuff. Now, if the process is irreversible, it doesn't care how much of that concentration is going to be there, right? The potential for absorption is not going to vary with it. So I get a proportionality of the mass transfer

rate directly to the fluid concentration as opposed to the amount of stuff, depending on the fluid concentration in that that limiting case, my map simplifies quite substantially. So through the bed length, which will call, uh, partial l or a constant length, I can relate the amount of stuff so partial sea at any length in that column partial L as a function now of this K c A. So the area of absorption and that global concentration See? And we're going to get to Casey and and unpack this in a minute because this is representing the, uh, partition coefficient. But it's a molecular characterisation of how much my absorbent or my target species wants to be on the solid, right? So it has a very high partition coefficient. I can see mathematically that species is going to very much wanted to absorb the solid versus a very low Casey. I can see in this relationship it's going to be pretty hard to do so I can take this then because I only have one differential. I've knocked out the time derivative here. I can integrate that directly to get the concentration profile as a function of these four parameters and much like we did last week, we read the concentration is simply see on scene on, or the amount absorbed relative to how many sites there are on the total material, so that it could be a million billion. Oppegard grows number, but it's a hard upper limit to how many sites can be occupied. So I can then say, Well, I have this relationship as a function of length so I can relate concentration to length. So if I define that at any point in the column, right, So what I've written here is just saying when l equals L. So at the end of the bed, I can relate. I can write a form or relationship for concentration. At that point, as it's changing now we're going to come back in a few slides to this, but this is an exemplar. So when you get into reaction kinetics, you'll start learning about different what we call orders of reactions or orders of kinetics. But most commonly you'll deal with zero with order, First order and second order. This is an exemplar of a zero order kinetic. We call it zeroth order, which is a very strange term. We call it zeroth order because there is no time dependence. So rather, the absorption process or the kinetics of the absorption depend on time to the zero with power, right? Well, anything to the zero of power is going to equal one, meaning the process does not depend on time, but we highlighted that irreversible is kind of a conceptual benchmark so we can get that part of the the process, straighten our head and then start to unpack. What happens when it's transient? So let's look at this. This top equation here, this is now if we're going to start writing the amount of observed material as a function of both space and time now I'm considering the concentration right And what I'm multiplying Epsilon here, one minus epsilon, which we can see in the second term, is effectively the volume fraction of solid of observant materials in this tiny little cross section. Therefore, epsilon is the volume fraction of flowing fluid could be liquid, could be gas. So I can relate these in the same form to effectively the amount of stuff I had before this This differential time, plus the amount of stuff I've absorbed in this differential time and then I can simplify this. So this becomes my final equation where I'm relating now, the concentration of stuff on my solid as a function of both time and distance and we've what we've done in this formalism is to collapse the spatial dimension to one. So we're not considering heterogeneity and, uh, the cross sectional profile, for instance. This is meaning. I'm assuming that the engineer has packed this bed randomly. So there's really not an effective difference as to whether my solid of absorption is at the centre line or the wall. Now I can. When I look at this that I'm saying, Okay, now I have a partial differential equation where I have a dependency in both space and time. And so to be able to solve these and further you go in chemical engineering coursework, the more you will see these types of

mathematical expressions emerge, and they are extremely or they can be extremely difficult to solve because we effectively are looking for a function. See is itself a function of all this stuff containing time and distance or length or volume. And so what I need to do then is typically write an approximation, right? Um, some of our partial differentials will have exact solutions that I can use in a really famous example. If anyone's ever used nicotine patch right, the mathematics of how nicotine patches work are exempt of chemical engineering and in fact, mathematics and chemical engineering because I have some finite reservoir of nicotine that must transfer into the human body, transfer across the membrane at a constant rate or a near constant rate, where the reservoir itself attach is depleting from 100% capacity to near zero over time. And the concentration of nicotine in the blood stream is also changing over time. And so I have to imagine the early days of can manage mathematics. If I have a filling sink problem where I have two faucets coming in and and one drain going out and we're trying to balance and figure out what's the equilibrium volume and then you say, Well, I'm going to actually write that in the function of time. This is now a challenge because I have two things and they're connected. So, um, oftentimes as we start getting into the more complex mathematical relationships, we will say, Look, we either don't have an analytical solution for this differential equation, or it is so infinitely complex, uh, that the 99% of the accuracy can be approximated if I collapse a few terms. So that's what I wanted to walk you through this slide in the next not to the end that I would expect you to have to use this, um, in practise, but rather this You're familiar with how this is going to start connecting into higher level coursework so I can take this this partial differential with two terms and I can approximate the driving force on the right side shown here. So instead of a a singular rather, I can collapse into a singular resistance to this mass transfer K. C. And of course, if I unpacked Casey, that's ultimately going to be a series resistance of the internal and external mass transfer resistances. As that molecule goes from a way out the distance to, uh, the interface of being absorbed now the challenge, then, is to get this Casey. So I know the surface area, or I would measure that in a laboratory. Or perhaps the vendor I'm buying the observant material would already know that hopefully, I would also know the concentrations both equilibrium sea star and the act of concentration I have injected. Um, I would know the density of the particles rose would be, and I would know the volume fraction right? These are characteristics that would be given to me by the vendor. So the thing I really don't know And of course, this is a mass transfer process, so we always come back to the same square one. The thing I don't know is the resistance to mass transfer. But I know that there is a free energy minimum is I bring that molecule and the right in the sweet spot for whether Ken or fist absorption. But I don't know how hard it's going to be to do that. And so this is where I can approximate that Casey by thinking about the inter facial resistance as I bring that molecule into the inter facial region of the absorbent material and the difference between the particle size of the observant and the pathway of the molecule that's taken, um, so D c b the effective diffusion coefficient. This will tell me something about the characteristics of the particle as I have, um, as I'm trying to pass a fluid around at this tortuous path, right, so it depends on porosity diameter and so forth. Now, just as with our previous mass transfer operations, we can approximate this using a Sherwood correlation, and in fact, we can see that we preserve things like having the Schmidt number raised to the one third power, right? So my my external inter facial mass transfer resistance case of C is simply going to be a function now of

Reynolds Number and Schmidt number. And I can use this calculation and it is approximate. But I can use this to get a case obscene. And from that I can get at the overall mass transfer resistance. Now this you know, this is a one approach to solve this type of problem. However, if I wanted to solve this explicit thing, right, in fact, this differential equation, because it's it's first order, its first order differential, and it only depends on two parameters. I do have an exact analytical solution for that and the way that will, right, this is shown here. Now again, I'm not trying to overwhelm anyone by showing this, but rather just to demonstrate a really fundamental method that chemical engineers use when they approach these these gnarly mathematical problems and that is we will tend to invoke dimensional species as a way to compare different solutions in different uh, scenarios or or different absorbing materials in this case. So instead of if I go back, what I can see here, we're looking at things like absolute time, an absolute concentration. Well, when I go to the analytical solution for this P D or partial differential equation, in fact, what I'll invoke as a dimension this time and we'll write this as TNT stars. So meaning, if I remember that X Axis T star was when I had the integral of the breakthrough curve in the area behind it was equivalent to the total amount of material that had been absorbed. So effectively T star is the end of my absorption process in time. And so the only thing we are the only thing we're doing and non financial leasing it is thinking, How much time out of my total time have I taken? Therefore, the taxes go from 0 to 1, and I can do a similar thing looking at the number of mass transfer units and so forth. Now we like that right, because if we're trying to compare, let's say a very large nicotine patch to a very small nicotine patch, well, the absolute time scales of both are going to vary drastically and so when we invoke a dimensional quantity, it allows us to compare them 1 to 1, as it were. And we tend to like these quantities that go between 01. Um so again, for the lab, there's no strict necessity to know this or to apply it. Rather, I just wanted to demonstrate to you a connection as you start coming into the more advanced mathematics of damage. So when we go from our example of zeroth order So we had our irreversible absorption where there was effectively no time dependency. We looked at a case where there was a first order, a linear dependence in time. And I can also go to more complex relationship. So it's second order rate of wage. And, um, I would have a second order dependence in time. And if I took this simplified form and, uh separated it and integrated it, which I could do in this sorry in this relationship and in fact, I would see time showing up as a secondary variable. So when we get into reaction kinetics right, we're thinking about bringing two molecules together, and they're going to have some interaction than some bonding. And I'm going to get a product that's different to the what was input to the system. It's thought about much the same way. And in fact, the same framework is applied for reaction kinetics. So I won't go much farther into this. Um, but Y k and the, uh, the first reactions course will introduce these concepts and apply them. Uh, it's different chemical reactions, and then Mike and eight are in the upper level Reactions course will go much deeper into that. Um, for the last part of the workshop, what I wanted to focus on is actually a really practical aspect of absorption that we might not think of quite the same way. But then, in fact, engineers and in particular chemists use on a near daily basis. So and that is that the use of chromatography? Um, So if you imagine that, you know, we've spent most of our mass transfer time focusing on relatively simple systems, right? So we looked at perhaps having a binary separation where we have to, uh, species mixed together, and we're simply trying to purify one from the other for any very event. But throughout that, I've commented that most of

our engineering work tends to be on really complex, multi component systems. And when I say multi component, I don't really mean three or four or five components to me. You know, it starts to get interesting when we have 20 and a practical, multi component problem is probably going to have between 501,000 components. And so that becomes really difficult for the engineer to get a hold of and figure out. Well, how do I even predict the thermodynamics? How do I predict mass transfer rates? And all of these are dependent on thermal physical or thermodynamic lee derived properties. And, of course, if we go back to thermodynamics, the three things that we must have a stranglehold on are the operating pressure and temperature as well as the composition. So chromatography is where I can utilise absorption processes to get a measurement or an approximation of concept of differential concentration in a large system. So this is what I wanted to show you as an example. So the idea is, if I have a multi component mixtures, let's say, for argument's sake, we're dealing with 1000 components. Well, I can appreciate because my absorption process is transient right, meaning the process itself. The mass transfer is changing as a function of time, then if I have some target amount of species. So let's say we have one gramme of our 1000 component mixture. Well, if I can put that in the carrier fluid something that won't ads or maybe it's pure nitrogen or pure argon, I can put that in a carrier fluid and run that through an absorption or an absorption column exactly like you're working on in your lab. Well, if I'm not dealing with one or two components, but 1000 I can say, Well, I know that the vapour intrinsically vapour pressures of these housing opponents must be different, meaning their desire to be in a gas phase versus absorbed to a solid will be different as well. Right? If I come back to this this early diagram will this local minima right and free energy the target of physics options. So the thing that will bind it well, I can imagine that's going to be different for every one of my 1000 molecules. Right? So perhaps this is the absorption profile for the heaviest molecule, right? And I have a very small window of the absorbing or a small window of free energy difference. But what if I have a molecule that is around the same size, so it's going to start its vertical path at around the same point? But maybe it has a much lower being. Compression right? Meaning it doesn't mind being absorbed to a solid when it would normally be in fluid doesn't mind it as much as my very light molecule that has very high vapour pressure. So this gives me a different free energy of absorption and consequently a different mentality and different entropy of the absorption process. Now, if I go through them, 1000 components, well, this is going to feature as every one of these components starts to try to absorb. It's going to be looking at a differential free energy, right, And in fact, if my column is packed with the same material, then where a components going to drop out and absorb in this vertically orientated column will tell me something about its vapour pressure, and it's binding to that service. So the typically and I'm not going to get too deep into the functional or the chemistry of the chromatography process, but in general we tend to use gas chromatography. Um, and in fact, for complex mixtures will look at high temperature gas chromatography or H T G C on the next life. So when I have a G C system will use nitrogen, we can also use hydrogen or preferentially helium for obvious safety concerns. And the idea is that I will take this. Let's say, helium. I'm going to inject a very small amount right of my multi ethnic mixture into this, but they suspect it is vaporized and then swept through a column containing and absorbing material. So an image of this process has shown a diagram on the right hand side, and a picture is shown on the left right now. What's happening? You can see these little coils here, right? And this is what

we're calling the column. So the GC column. So this is different to the large scale column that you were a Meso scale column we've done in a laboratory, but it's actually function in the same way, because the diameter of that wound spiral column is sufficiently small relative to its length that the fluids running through it are not feeling the curvature, if you will, of these spirals. And so it's effectively treating it as a very, very small, very, very long, um, column containing absorbent material that is going to differentially pick up each of my species as they run through. Sorry. So if we, um, pulse the feed, meaning I'm running hydrogen or helium or or, uh, nitrogen, and I'm going to inject a pulse one pulse of my 1000 component feedstock. Well, initially that pulses that first enters the column. I have all 1000 components and all of their original quantities. Nothing is absorbed is that pulse first hits the, you know, say the first differential thickness or the differential layer of absorbent material. The things that don't mind absorbing as much are going to absorb first. And the things that really want to be in the vapour phase that really don't want to absorb are going to add or black. And so I had a continuum in this process, and I'll back up in a bit and we can talk about liquid chromatography. Is this a very similar basis? I just have to worry about the fluid mechanics of working with liquids. Large pressure drops as opposed to gas. So if I am then focusing on this, this differential absorption well, at any point in that column or spiral around the unwinding, I can see a column. I can relate the local mole fraction. So if I start stripping out the heavier components first and lighter and lighter, I can write that equilibrium mole fraction relationship as a function of the partial pressures. How much of my 1000 components and each one is in the vapour phase. But I can also look at this and sound. I'm operating in low temperature, very low pressure and high temperature. Well, that's pretty much like, uh, an ideal gas. So if I'm a writing mobile, fraction is a partial pressure on total pressure. Well, I don't need to treat the gas phase non ideally, because I don't have that many non ideal components that I've pulsed. One gramme of feed into a tank of nitrogen were supported by a tank of nitrogen. I have a very dilute system. However, when that molecule goes to ads or will the interactions of that molecule in the non vapour fades right? Then I have to start thinking about non ideology because I can certainly assume that a molecule of, say, 80 carbons with 50 sulphur and 20 oxygen, right that are large scale molecule that is going to behave non ideally. So we have this convenience of gas chromatography where I can treat things in the gas phase ideally without much loss of accuracy, which allows me then to take my measurement and say something about the non ideology of the liquid or the absorbed liquid solid phase. Now, I can rewrite all this on a concentration basis, which is again because we're dealing with chemists. We know that chemists like to use concentration, whereas engineers tend to like to use more fraction so we can write this either way. But if you're working with the chemistry group, you'll tend to see it written in concentration. And in fact, then I can write a relationship. Um, so what's in this? This bracket here, This is my k case of a term or my partition coefficient term. So, in fact, I can write the massive of solvent, right. It's going to be a person or the mass of my absorbed material, M. C. J. As a function now. So here Epsilon is my void Fraction. And apart from that I have to deal with this this non ideology of that absorption process. And we're going to call this partition coefficient case of a. So the really wicked part here, right, is that as long as I can maintain that assumption, we're reasonably so that my vapour phase can be treated. Ideally, I can now relate through this equation the breakthrough time, so t stars a day. So the time at which that particular component of interest might be the second or third component out of 1000

that the breakthrough time We're sorry we had the retention time. How long that component stays in the column is related to its degree of non ideology, right? So if we were looking at in our simple binary absorption process, we have a T star that characterised the whole bed. But what if I flip my mental model and think for a minute about T star on an individual basis? Right. Every component of my thousands gonna hang out in the column for different times because each has a different degree of non ideology when it begins to interact strongly with other components that are absorbed at a different ability to carry through. And so I can relate. Uh, break that retention time, How long a component stays in the column and this is the absolutely critical that I can relate the time that it takes to move through the column to the partition coefficient or to the non ideal reality. So this means that when I can maintain a constant epsilon constant void, fraction through the column again. Assuming that we've packed the column Homogeneous Lee and it's ice, a tropic potential in all directions. I can then relate the difference of breakthrough over retention times. So for Components A and B say it's a T star, a on T Star B I can relate those directly two k A or the partition coefficient molecule a on the partition coefficient molecule Be Now, if I take one final step, I'm going to say, Well, look, the densities aren't really changing. So we can you know the densities are changing and the absolute pressure is shared by all things in the in the local space. So really what? I'm comparing K A on KB. What I'm comparing is this turn down here or the non ideology of that absorbed molecule. So I can write that as t star a on T starving or the difference in retention times to the activity coefficient of the molecule B on the activity coefficient of molecule a qualified by their vapour pressure. So if we go back to Thermo and I mentioned that something like the NIST Chemical Web book, right, that we can draw Antoine relationships, these are absolutely critical for virtually all chemical engineering processes. This is a perfect example because I go into my G C lab. I'm physically measuring ta on TV. How long does a thing hang out in the column? But if I understand enough of the mathematics, I know what the vapour pressures are. So here in I as long as I know one activity coefficient, I can get at an estimate of every other activity coefficient in 1000 component system within the resolution of my G C to measure. Right. So if I buy a cheap G c and I have a cheap detector and I minimise the cost, maybe I can only pick up a resolution of 100 components, right? But I could spend twice the money and pick up 1000 components. And if you go to, uh, complex chemistry conferences, in fact, there are a few groups around the world. It's one in Florida and one in the UK uh, that have G C systems that are worth millions of dollars that can pick up tens of thousands of components when they're looking at complex mixtures. And so, hopefully everyone that's kinda followed along with this by this point has a pretty, uh, aha moment that getting at things like the experimental measurement, uh, activity coefficients in a complex system meaning multi component is really a holy grail of permanent adults, Right? We spend a lot of effort, and for those that were with me last semester and Thermo, we spent a lot of time trying to predict these from first principles. Well, if we want to know, how do we refine those models or those physical models that predict activity coalition? This is one of the key experimental pathways we can take to do so. So I wanted to end this just by showing a few examples of what does this look like in practise, right? If we go to do a big G C measurements on a huge multi component system. What do I actually walk away with? Um, And so this is one example. Um, for those that might have had Brendan, I don't know if anyone's had Brendan yet for lecture, but probably coming up. If not, uh, Brendan is an expert in chromatography and the comments

department. And so he was nice enough to share this example that we could use for class here of a high temperature gas chromatograph measurement, and this was performed on a complex hydrocarbon mixture. So in this case, right, Because I know that in a complex, complex hydrocarbon. So this was a This was a crude oil from the north west shelf in that fluid mixture, right. I have to think about at least 10,000 components, so I cannot use an inexpensive G. C right. I must use the most complex G c I can find to get that kind of resolution. Well, if I look here on the right hand side, What the GCS giving me out. So the retention time, it's converting to a relative content right through that exact same pathway. We just talked about the retention time itself for each component is related to the partition coefficient, which is fundamentally or related to the amount of stuff in the system. So I can take that measurement of retention time, and I can effectively plot that as a relative content. How much of each of these components distributed was in that system? And if I know how much of my species I injected in the first place, I can translate that to an approximation of the original composition of the material. So this is what it would look like in a crude oil where I have 10,000 components in here. And in fact, as we go to higher and higher and higher retention times, I have larger and larger and larger numbers of components. What does this mean, right? Well, I'm losing resolution here, right? We can very clearly see on the early retention times. These are my light molecules they want to run through. They have no no drama, the absorption process. So they're gonna jet straight through the column. Well, as I begin stripping that material out was a longer retention times. This might be 10, 15, 20 minutes. This starts to get me into my heavier components all of a sudden I don't start to see those very clear spikes indicating compositions of Let's say here and what do I have here? See, 10 to this little spike here we can see would be decades. Well, as I start to get to see 20 or C 30 I have a much higher attention time and critically, my G c is less able to differentiate that because these are now very large molecules. So one of the ways that we can handle this is by temperature ramping. So we might start at a temperature around out of the laboratory. But run the G C all the way up to 450 c, um, as a way of vaporising those heavier components to get them back in to the analysis straight. Now, I mentioned a group in Florida, right, That does very, very high resolution. So here I can see if I go back to Brandon an example. Here. This was C 30 this little spike. Right? So when I get to see 30 I have a really hard time differentiating how much of that C 30 block is in my material. But if I go to a very high resolution GC on slightly cleaner sample. So this is on the right hand side of a condensate, a less complex hydrocarbon mixture. Now I can see incredibly clear spikes for each one of my primary, um, el Canes and in fact, the L King grouping around that. So I might have ice layers that are going to be blocked in with it so I can go all the way through in this case, C 45 or C 50. Um, now, because I have this clean resolution, I can also say pretty clearly at the end of that process, I've exhausted the amount of material or the number of species that were originally in them. And what I wanted to show here is on the left hand side. This is one of those extremely high resolution, expensive G C or H T G C measurements. Uh, and this came from a colleague at Chevron who's unfortunately since passed. But I wanted to share this because it was kind of an eye opening moment for me when he said, Well, look, you know, inside the company when we take these measurements here on the top, we're looking at that same broad profile. But if we have a really nice G C, we can actually get in to each of the ice emerged and so we can start to look out. For instance, if I come down to pen Tane here, well, plantain is only going to have a few ice in person

so I can cleanly pick those up at middle of second variations and retention time. And, as I in fact, with an expensive G C, I can capture those I summers up through C 20 c 30. And it's only the very, very large molecules that I have a hard time characterising in this way simply because the number of ice simmers becomes intractable to solve, at least with period techniques. So all of that to say, um, one of the things I would expect most chemical engineers to come across is how on earth do you go about characterising this feedstock of interest right now, this example with Chevron looking at a crude oil or condensate. But you could say the same thing when you get into recyclable materials, right or biofuels that have been freed, and you're going to end up with a naturally occurring massive distribution of chemistry and you as the engineer in charge, figuring out Okay, what's in this? And how do we manipulate it into something useful for civilisation and effectively, the combination of G c and and mass spectrometry of the tools that we go to tools? Rather. Um, And if we go to a very nice juicy, we can start to unpack it So I can take, for instance, this left hand distribution. Well, I can start to calculate individual, um uh, activity coefficients. Or I can go to a computational tool to do that, like multi flash. Based on this knowledge of what the distribution and chemistry is, I can then run that through the GFC and saying, Well, what would be the estimate of the activity coefficients and by that process, figure out Am I dealing with the species that's behaving as though I say a Wilson model might gain, or am I dealing with a degree of non ideology that I've not seen before? And so it serves both as a a very useful tool for, uh, compositional characterisation, as well as a sanity check on the use of activity coefficient models and whether we're seeing an outcome that's, you know, within 10 2030% of what we might expect. So I appreciate I've probably run the longest in this workshop. But I I didn't want to leave the chromatography material out because I've had a really great example. Um, so I will stop the recording here and we'll jump across to the workshop prompt, which should now be available for everyone in the one note.

SPEAKER 0

So the recording is now started. Marvellous. Um, and Amy and Emma, I can't actually see the screen, So please feel free to just, um, mute and interrupt me if you have questions you want to go through. So this is our final module engineering design. So I appreciate the engineering design shows up in a lot of places throughout the curriculum. And in fact, this is not an engineering design class. Um, what I'm trying to do with this assignment is start taking a step forward into what you're going to get in years four and five if it's the MP or years three and four in the B and that is taking each of these individual unit operations and stitching them together So we can Hopefully you've seen by now. We can do that manually, right? I can take just a book and start writing out things and illustrating how a heat exchanger relates to Distillation column How a process upset of a feedstock to distillation column changes the downstream duty requirement. And how does that change the emissions profile? If I have a feedstock variation as you go further into engineering design, you'll be doing that a lot with Isis, right? So I love the mind that I would tend to start the first few rounds of the design process manually and when I say Emmanuel, I mean in Excel, uh, and then migrate to something like Isis, where you've locked in a solution and you've made those choices. And it's a bit harder to remember how you've gone through the optimisation process when it's all one window with options. The reports are group based. Of course, it's only 10% of your mark. I don't have pure evaluation marks in any of the group stuff. I pulled that out from last year. It just felt, too, to Assumpta. I've on my right like you're all writing

feedback and surveys of each other, and I'm getting marks on that basis. I'd rather not really have a smaller number of marks on the project, but more authentic assessment that in reality, if I'm doing a consulting project and imperative someone who's useless, tough, it's my project now, and we're going to do it together. So it's meant to be more of a reflective sorry, an authentic assessment in that kind. Um, if you are going to put in for a special consideration, right? I don't mind, but I don't know what the rules are around group based activities if that's going to be viable. But if the student support office is happy to support it, I don't care right. I'll be marking from now until when grades are, too, and we will have one final set of open consultation hours. My guess is that next Monday and next Wednesday, we're going to be seeing a lot of the students in the class because it's like how where do we draw the boundaries of this project? Right, And that's one of the things I've done intentionally here. A very, very open ended problem with a billion possible and viable solutions is a very practical assignment. Okay, so really far less so in the context of the design plans, right. What you've been given is to say we have a you know, we as engineers, that the nature of our discipline was one of people had problems repeatedly in civilisation, and there was a group of people that they ended up going to over and over that would help solve it. And then, in the late 18 hundreds that started to be codified into. Well, we keep solving the same thing. So we'll call this a discipline and start training young people preemptively how to do it because these problems keep emerging. I think the classical one was horse manure in London began civil engineering. So you have friends and civil engineering read into the books and tell him a bit about their origin story. So in this remote right, we obviously think about freshwater, uh, procuring fresh water in the context of desalination and specifically reverse osmosis membranes. The reason I've selected this is the problem is because you don't have to use in our own membrane. Uh, it's obviously one of the the most used and certainly the most common in W. A. But there are a variety of unit operations you can deploy for this. If you are going to look at a membrane, then in the context of how we've approached class right effectively, we're looking at a mass transfer operation where I have some semi permeable product or a semi permeable layer where the uh, properties of that layer, and particularly the surface properties, are such that either the pore size or the inter facial or search free energy only allow certain things to go through. And so in that way I have an ability to to sit out on a molecular level, um, one portion of the feedstock from the other. So I'm thinking through this, then if I have multiple components in the fee and this goes back to our thermodynamics discussion, of course, everything is always soluble in everything else. So when people say, Oh, this is insoluble, not really. It's infanticide, only low soluble it. It's so low, it's practically zero. But actually we can dissolve a little bit of anything in a little bit of anything else. So, naturally, if I have a multiple feedstock, I do have to think there will absolutely be a finite amount of stuff. Of all my components that goes from one side to the other, the question will be how much. And so in that same way, the resistance system that we have thinking about our overall mass transfer resistance and our components, I still have a blowing boundary layer resistance on the left and on the right, and then I have this membrane resistance. Now, if I take it back to the analogue heat transfer. It works much the same way as a combined convective conductive problem. Right where I if I'm calculating all my convicted resistance is so step flowing in the feet and flowing in the product. Those are going to add less than 1% of the overall resistance of the problem. It's always the conduction through materials. That's the rate limiting stuff.

And so in this, I can think about the characteristic of the membrane. So this, uh, mass transfer resistance in the membrane itself would be my, uh, linear dependence here is primarily the source of resistance of the overall mass transfer problem. So as I'm looking at different membrane properties, this is the number that matters more than how fast, right? The feed or the product streams are flowing. Now, when I get into the membrane resistance case event Sorry, I ran across hair oblique shape. If I look at the membrane resistance, I think well, this is going to vary with both the properties of the material and the poor size so effectively, this is proportional to the effective diffuse city through the membrane d sub on the thickness of the membrane. So much like I have a conduction problem. The amount of resistance that conducting through a thickness of steel is going to provide Well, the total resistance is that property of thermal conductivity times the thickness that that has to conduct through. And so I can go to membrane vendors, for instance, and find what that effective, diffuse it is going to be and thereby if I multiply that by thickness, get back to, um, divided by the thickness. Get back to case of them now. So you've learned about reverse osmosis from 30 18? Okay, what drives reverse osmosis test owner is the owner of mind to top that part. And, uh, what drives burgers? Hospitals? If I ask you from a thermodynamic standpoint, right, The one the one and only. Truth is, what if, from a thermodynamic standpoint, just finds that reverse osmosis must work the pressure? Exactly. So because I can apply a pressure to a system I'm able to reverse the natural gradient of mass transfer from a thermodynamic standpoint, if I write out the definition for free energy specifically gives for energy, right? So d g is equal to what minus s d t plus the chemical potential. So if I have to have a marker. No, I don't have a market. So in my gifts free energy I have my mechanical potential. So that and I remember the mechanical potential. His DP. Because it's pressures the mechanical. So if I say it's easy way to remember off the top of your head mechanical thermal chemical, those are the potentials and gives brings them all together. So I mechanical potentials driven by depicting. But pressure only has meaning, and volume temperature only has meaning in an entropy field. And because I was negative as it changes, which is why I have a negative sign in front and chemical potential. Bermudian expectedly the gradient of stuff flowing from high concentration to low. So the natural problem if I have an an an osmotic system, if I have salt water and a little bit of fresh water, well, the fresh water is going to say I don't have any salt that's not fair. I want some salt. Naturally, the system will flow in the chemical potential gradient from high salt content to low. It must that's it's That's the nature of this particular universe. So if I'm using pressure, what do I do being against me as not? Yes. So when we say osmotic pressure, that's a I hate that term, right, because it's actually a mask of chemical potential. But it's the osmotic pressure that is a chemical potential driving force. So I'm saying I have a natural chemical potential gradient. Well, if I want to overwhelm that because I wanted to flow from saltwater to freshwater, I want to keep purifying, and I want to concentrate salt in the saline face. So if I want to go, not just to balance out the natural gradients of life I want to go against, I only have two other potentials that the universe or that humankind is found in the universe so far. So either I have to kick it with a heck of a thermal potential or a reasonably high mechanical potential. And because we don't like cooking membrane material at 600 Calvin, we go for mechanical potential. So really, what I'm doing is using the formalism of gives energy to say, If nature wants to do this, I only have two levers I can pull to tell nature. You must go the other direction, and that's what we do so if we then look at. And I think the reader does

have a few examples of calculating this from tables that were originally referenced in, uh, McCabe and Perry's Handbook. But if I'm looking at the amount of water and in particular because I'm thinking about dilute concentrations of salt if I have a dilute salt or saline mixture, the amount of salt is proportional to the activity of the water, so it's very dilute levels. Concentration is proportional to activity, and in that living activity is proportional to chemical potential. So what I'm really trying to do is for say, is that that natural chemical potential shows up as an approximate concentration driving force. So now, once I get to more than, say, five or six weight percent salt, that argument really quickly falls over. But if I'm down in the percent of stuff, I can use this approach so as I just mentioned, because this is a very old discipline, the whole concept of how we manipulate chemical potential wasn't really well established when this began, so we called osmotic pressure how much pressure you need to overwhelm or to effectively bring d G 20 is the osmotic pressure. Everything beyond that makes your process productive. So for the high pressure side, how much do we need? So 22 50 atmospheres, right? If I were to use a thermal potential to do this and I ran the calculation in 2020 just for fun, it was something like six or 700 Calvin, right? So well beyond the range in which the phase I care about would be stable anymore. So if my activity is, um what defined is equal to one at the osmotic pressure, that's the same the same. If the activity is one of the driving forces, zero d g is zero effectively. So to calculate this this difference and osmotic pressure, I can go back to the gifts formalism I can effectively writing need delta end here, assuming you hasn't changed all that much. Or I can write this as a function of the difference between the applied pressure and the osmotic pressure that I need. So does that kind of sort of not going too fast. So, like it, it is transport phenomena, right? But it's actually just thermal that I can write d g anyway, I want with any wealth with any one of my potential sort of combination thereof. But this is the approach we would then typically say so if I want to calculate. Well, what is the osmotic pressure for a system of interest? Well, we're looking. How many in this case Grammes sitting fluoride per kilogramme of water. And we can see here is report density on your sodium chloride. This would be, uh, so for sea salt because this is a sea salt is a really diverse set of ions, so we tend not to look at a characterisation and density rather just than weight percent of salt. Um, of course, this third row would be standard model seawater. You can see that I need somewhere right around 25 atmospheres of pressure to naturally reverse that gradient at more or less room temperature. So as you're thinking about how to approach this within your project, right going, what I would recommend is using a simplistic approach like this first to figure out how much pressure do we need because these systems are defined by two things. The money that I pay for these membranes and the both operating and capital that I have to pay for the compression system to drive it. So the challenge in my mind right is that these types of membranes are not simple materials. So if you start putting a $200 a tonne carbon tariff across the board hollow, five remem brains don't look quite the same. Particularly not if you're talking about a remote community that's really hard to get this stuff in and out of it, not repairable and, you know, really complex feedstocks. And if I want to make them carbon neutral, I find whatever the price from DuPont is and put a zero behind it. These are really, really exotic materials. So one of the remit of the project that I want to emphasise is that it's not building a diesel plant in 1980. It's building it in 2025 which means whatever that plants built from and whatever it uses will be in play. When we will have a $200 a tonne price, however we get and whatever means by which civilisation decides on it,

that's about number that we're gonna need, and it will come down to being an economic lever. It can't not right So now that's my opinion. Obviously, however you want to build that assumption in is fine with me. But it is to be expected that this plant is operating in 2050 and so there needs to be a consideration as to Are we taking the most efficient route to get to this separation? So my inclination would be to say, when you're starting to look at the diversity of methods available to make fresh water right? It's one of the oldest engineering problems on the planet. I would think through them in terms of total energy first and probably a binary Does this or does this not use an exotic material? If it doesn't use an exotic material, you can pretty well guarantee it's not gonna change between now and 2050 and otherwise you can balance the system or balance comparative trade offs based on how productive is this system per pound of energy. I have to put in to drive. You will also need to think about. So if the current generation of membranes right, and we're looking at not just how much, but what are the specs of, um, how many membranes were the redundancies behind them. How many series of potential my brain separations do we have If the current generation is 99% salt rejection right from. And this is from DuPont, where it is about that you're gonna need at least two stages, right to get this water to the point that it's drinkable. That means you need a reference right for W A. What is the government expectation for assault in water to the point it can be consumed, but also to think about in a community like this derby right here in a community like Derby, is drinking water the only valuable use of water? And if the answer is no, do the other uses of water need to have salt free water? Or can I use slightly salty water for some? For instance, agricultural, um, efforts. The question being, if I don't have to run 100% of my water to completion through 234 stage membrane separation. Well, if I start stripping out by products in each of these stages, are there different use cases for them that minimise the total energy whilst maximising the productivity? But then finally, in the very last round of the design projects would be my recommendation. Referencing my slides. Great for a lab projects never gonna fly for industry. Right. So the second you can graduate, get a business card and you're practising engineer. They're never reference. Zach said on slide 13. Right? No boss is going to take that. So if you're looking at this kind of design project, Well, what membrane vendors are available to us? And the details in terms of the performance of the membranes for a simple application like this should be available from them on their websites. So I would absolutely suggest pulling that in. Okay, Um, so 30 18, you've gone through spiral round and hollow fibre membrane systems. Look, relatively, people haven't taken. Some people haven't taken 38. Okay, so what we're primarily going to be looking at? If so, if I have. And let's focus on the spiral wound on top. So if I have some feedstock coming into this, I'm effectively taking layers of this membrane. Right? So I have that diagram where I have a linear mass transfer resistance. The membrane material itself. Well, I have to think about a few considerations, right? So if here is so this pure white layers, my membrane Well, I can see just above and just below I have this cross crashing right. Meaning the purpose of that is to help generate and homogeneous flow before it crosses the membrane boundary. And if I'm laying all of this out in the sheep from, say, here to the other wall and I started winding this round and round and round and I pressure up feed on the front face of this right that I'm going to have feet driving through each of these little cross hash channels. And as the pressure from the feed side goes up, it will drive freshwater into a collection pipe through successive layers of membrane. So what problems now that we've done our four laps, what problems

can you imagine? My emerge to the practising engineer who's bought this membrane system. Maybe in one stage where you have 100 of these things another stage in the building next door with another 100 on an individual membrane. If I'm flowing water from the sea, right, I probably put it through some separator. Hopefully we're a basic collection separator, but I'm flowing seawater through this. What do you reckon is going to happen here over time. Okay. Now, Okay. What types of fouling? Directing in general terms. Okay. Yeah, it is a general term. Um, so yeah, the type of founding and I raised this because you're susceptible to multiple types. So because I'm dealing with ion content, I can get mineral value. Meaning I have a local build up. Maybe I have a huge collection of islands. Um, that actually approaches the point at which some of those ions are at their scalability limits in water, and they're going to collect. And if I have a flow stagnation point, maybe it's a manufacturing defect in these crossed the rating material that if I have a local collection of that water stops just long enough, and it surpasses the point at which, uh, sign will be limited violins. Then I'm going to have minerals dropout like calcium carbonate. If you go to the dentist and they scrape all that crap off your teeth, right. Calcium carbonate build up from the ions in the water that we drink. But I also have because I'm using seawater. I care about bio fountain, but I'm pulling into water with tonnes of microbial critters. Well, critters, because I'm not dealing at a high temperature and we know seawater critters don't mind high pressure. So they're pretty comfortable in most of this environment and they can start replicating. So I can then also get the build up of bio fouling within these The point being one of the greatest and and are actually does quite a bit of research and consulting around this, but with a few other colleagues, One of the greatest problems for Perth Diesel Systems is that you? If you go to a diesel plant, they'll have, like, 1000 of these online simultaneously, all 1000 of them have to have fouling checks constantly. So they have an operations team that goes around one by one by one and quantifies How cooked is this separation unit from 0 to 100%. And then they have a purchase schedule. Okay. Every year we're going to have to pull in 50 new membrane units, plug and play, and round and round we go. And the difficulty they have is because these types of bounding processes are driven by manufacturing defects, local buildups. There are randomised processes. And so I end up not knowing what units need to be pulled out, right? I have a high likelihood that today or this month it's going to be building for But I could not tell you which ones until I go physically interrogate them. So the the mm, the cost in terms of human time to continually monitor and replace and test on these is not a trivial aspect of the problem. Let's see. Okay, so, mm. In a hollow fibre membrane, you can see that it will function very, very similarly. The only difference right is that I have a pack of membrane material, and the centre pipe that runs through it contains my feed, as opposed to the outer layer, where it's pressurised and then coming through each of these successive membrane layers. So if my stock is coming in here, it will push through this outer membrane material and effectively collect from the out on the extra Earth on the outside of this unit in the show. So if um, whether or not you go with a hollow fibre or a spiral wound is not of particular concern to me, um, from an engineering standpoint, no engineering design project would engender changing something like a membrane design, right? If we're hired, if you that would be like a engineering research project. If you're on an engineering design project that here are the eight vendors in the world, here are the two products they each offer. And here are the specs across age. I'm going to knock out all products that are going to have shipping

more than 5000 kilometres away because the emissions profile will be untenable in 2050. Therefore, I only have these products I can look at. This is the one we're going to pick because it's the best for the conditions. Period would be the approach that I think and then in thinking about the stages. So and this is where so it would be a good idea to have a group and we're doing a high level kind of lay the land survey of where the vendors are, what products are relevant for these conditions or or that are suited for seawater. But in most cases, at least, everyone that I've seen a single stage so that each of these, um imagine one stage might be 100 membrane units that are all aligned along the wall feed comes in, is split in parallel and pushes through all 100 to come out the other side. Unless that's drinkable water. I'm not done, unfortunately have to do something else. So we would typically look at something like a second stage membrane. But they would then take it from 99 to, say 99.9% in terms of fouling, right? Um, it would also be a good idea. So we know that mineral fouling bio value It would be a good idea to have one group member looking on Google Scholar for papers in terms of founding timelines. How long does it take the valve? Pretty sure a Nars written a couple. I didn't give talks, but I don't know if he's published. Um, but my understanding from at least the work I've seen him present on the order of 5 to 10 years. So in this length of a project, you're absolutely looking at fouling replacement in most of these membranes. So a single one off purchase would not be sufficient to meet the project deliverables, and they cost. If we're buying an exotic material, the cost will be different 20 years from now, not just with our 2 to 3% growth per year, but with the cost of emissions to get it manufactured and get it here. Okay, Sorry. Just right. So then the final point, if you are going to take a membrane approach, you have your osmotic pressure, right? So that's the amount of pressure you need to apply to bring DJ to zero. Well, then we want to be productive, so we have to go above that. So if I'm sitting at, say, 25 atmospheres is required to equal liberate the natural chemical potential gradients probably double it, almost double it to get into something productive. But then I'm flowing. I'm blowing across a manufacturing poorest media, right. Either laterally here or on in the axis of the pipe here. So what we would have seen so far? Any time you put flow across any kind of porous media, you're going to have a massive pressure drop associated with it. So if you say I'm going to bring the upstream of the system, if I need 25 atmospheres will take it to 50 of that 50. You're going to lose a significant portion in every one of the membranes, which is why you'd run them in parallel and not in serious. So these bottom if you have a constant flux, you can use this bottom correlation as a ballpark of how much pressure you're going to lose flowing across that membrane as a porous material so that realistically should be added to the front end of the system. So you buy even a bigger compressor that can drive this and then appreciating When you get into your second stage of membrane. This thing is coming in at a substantially lower pressure to the osmotic gradient is not the same in each one of my stages because ideally, I want to buy one compressor. Right? Um, well, I think Okay, so when we get into compression, right, So this would be relevant for most of your systems. Um, obviously, everything is piped, so we need to talk a bit about pipe selection. But if you're buying a compressor for any one of the systems or a liquid punk that will be the single most expensive purchase in the entire project by a country mile. So you want to size it to have enough room that if if you need to change in out of your system. Or if you want to account for fouling, you have enough latitude to turn that compressor up. But most compressors, as you buy them, also have a minimum flow specification in terms of how they're designed. So if you

start fouling, that will introduce an upper limit to how much pressure you can pull out of the compressor. But you also because if it has a lower limit to its operations, you cannot run it under a certain pressure. So from a design standpoint, if you were taking your membranes approach and thinking, okay, I'm going to have two stages like we drew, but notice both of the first stages. We didn't plug in this one. When you go from one block diagram into the second block diagram, right, because if I start getting too much fouling, I'm going to have to pull one of the membrane systems offline because I only have enough pressure right to to drive a highly fouled first stage set of membranes. Similarly, if the compressor or the liquid pump cannot deliver less than a minimum volume specification, what happens if I want to operate my fresh water plant at half of its capacity. I don't want to be creating water that's not used. And I certainly don't want the water I create to be evaporating. That would be a terrible choice. So in this way, I need to think about Well, if I buy this particular liquid pump and I turn it on to its minimum blow, right, is that enough to drive my a finite portion of my first stage and then the rest of my second stage? Does that make sense for me getting to hand waving kind of makes sense. Okay, so hopefully from fluid mechanics, I don't need to go too much in terms of how pumps at head and we can use a virtually equation if we're taking 100% liquid flow through this, Um, what you would need to look at is the pump curve, right, So we can use the Bernoulli expression to get an approximation of what flow rate we can expect out of that pump. But I'm actually gonna jump jump ahead, and then I'll come back to capitation and pump types. So what you're looking for so lots of types of pumps and we'll come back to the But whenever pump you pick just showing your bodily expression and saying, I need 45 kilowatts driving that liquid pump, double this amount of water at that velocity and put it over there. That would be a year to chemical engineering problem. If it's a design problem, what type of pump and what are its operating limits? This is not something that theory can inform necessarily. So we actually need to go to pump vendors. And what you're looking for is called a pump curve. And so each vendor, when they build and design and validate the pump, will then go out and effectively run performance testing comprehensive performance testing over the entire range of pump operation. And this is how they then inform Well, there are minimum and maximum flow rates, depending on in this case, how much horsepower, how many giga jewels or, uh, gigawatts of energy. I'm drawing into that pipe system. So for each of these, how much head am I adding to the system in from the newly float expression? What's the flow rate that I get out of it? And each of these dash lines is telling me how fast the pump system is driving or approximately how much energy is going into it to drive now, within that, each pump is going to then have different potential efficiency based on its operation. So here we're looking at Well, these are the lines of efficiency where the pump can operate. So I say, Okay, I'm going to be looking at 79% efficiency. Well, then I can draw that through and say if I know I must have this flow rate right, because engineers are going to design it based on what they have to deliver first. So this is the flow rate I must meet. And this is the head that I must have for the system to operate. Right? So these are both independent variables. If I can't meet those two things, I don't have a system. This then tells you you can read in How much power do I need? Right? And the hash lines to drive that system and approximately, what is the efficiency that pump within it? So if I say I need 100 and 60 gallons a minute and I'm delivering, say, 60 ft, 60 ft of liquid head, it's obviously way pre s. I, um I'm sitting at about 80% efficiency, and I will require about three horsepower of energy to draw the one example. So when we

start looking at, what pumps can we use then? Okay, come back to gravitation. So, um, something like a reciprocating positive displacement pump, right? All these things are motors. Where I'm I'm creating, uh, I'm oscillating between creating a partial vacuum and creating a pressurised environment. And each pump mechanism for liquid pumping is going to be a variation on that concept. Like from an 18th century standpoint, I have a very, very basic crankshaft. And as this thing goes in and out, all I'm doing is dropping internal pressure and because it's an in compressible fluid, pushing the pressure back up so that it ejects the kicker is that I have one wave Alps. It's a flow can only come from one direction, and it can only exit one direction. And so in that environment, then it creates pumping motion or a pumping effect simply by a mechanical meat. Now, the value of positive displacement pumps is that I can, because of the simplicity of the concept, scaled them up to very, very large systems with reasonably high discharge pressures. Um, if I start going beyond something like basic steel into more exotic materials, I can get much, much higher pressures, Right? My guess is that well, and you'll see this. If you look at their have one team member on pumps, you're going to select the membrane design. There will be gradations in terms of this pump that I'm sorry, the design, the basis of the operation will change. But I can only manufacture this stuff from four or five known materials. Right can do stain walk into carbon steel. I'm really reckless. I can do stainless steel. And as soon as I get to to something like high density alloy that's corrosion resistant all of a sudden that will jump from, say, 100 atmospheres of operating pressure of 2000. It's not a continuum, right? So I only have these certain options. So I have three different materials that these pumps can be made from. Well, I don't really want to pump operating it 10% of its maximum capacity to be a terrible life choice, so I'm going to opera. I'm gonna run them pretty high and 80% efficiency, right, but within, say, 20% of its maximum operating condition. Which means that the nature of having step changes in what the pumps can do that gets step changes in my engineering design, right? So there are three different maximum operating pressures in my head. I'm looking at three variants of a membrane R O system, each operating at a different pressure. So from a deductive standpoint, I would suggest going out and saying Okay for a ideally local vendor because you want something that's quite easily repairable. But, um, starting off with those operating pressure limits will then let you d convoy to say Okay, well, we can knock out this condition because it's not nearly enough pressure to overwhelm or to a quick break gives energy so that one's out. Probably not going to run this at 100 times what it should be, so that the space alloy option also out. And if I'm left with two in the middle, we'll let me run up basic engineering calculations for what both of them can deliver in a narrow sense and figure out. Does it make sense to double the size and maybe build a water export pipe from Derby 30 K's Inland could be a much cheaper option than going with a moderate system that's only doing its job. So comment. So the one challenger, the nature of a pump operating like this is that you can imagine you get pulsation in the discharge, right? So from a fluid mechanics standpoint, I now have a pulsing downstream flow rate. Um, not necessarily a problem for most applications. But if I'm worried about localised stagnation in the membrane material, then having a pulsing momentum behind it is going to lead. It's going to open up opportunities for flow stagnation, so you can start to to even that out. If you can connect and say to write suction and discharge systems to each side of this crankshaft and then you blend them together so as it's pulling in one and it's pushing out the other and you tend to get a more uniform velocity until, that is, you

get to something like a rotary displacement pump. So these tend to operate much, much, much larger volumes and lower pressures. Then, um, positive, displaced or sorry, then that positive displacement. So here we're simply drawing in from the suction slot. We still have a central crankshaft, but now it's running into the board as opposed to, uh from the side. And it's simply pulling in fluid and by the nature of only being able to contact one side at a time. I tend to get a more uniform flow, belong together out of scholar cities. So light oil this would be south of five Senate poise, maybe 10 Senate poise, waters. One Senate poised. So it's very well suited for water and pretty well suited for the pressure range. And I'm probably operating under right probably wouldn't put a membrane under 1000 atmospheres, but 50 maybe an upper limit of 100 is not unreasonable. Um, let's see. Yeah, and then Paris Don't so just completely peristaltic designs you would not find in large scale industrial applications. But these are off takes of of rotary displacement camps that you find in the laboratory applications where you have to have, um, extreme precision right over the any leaks that might occur. Yep, and then centrifugal pumps. Of course, these are even larger flow rates that can come through them, but at lower pressures are operating pressures So I think, Yeah, the point that we wanted to make here. So with pump that you're going to pit If these are the two of them sees that you're optimising from right. You need to think about where is your unit likely to be placed relative to a source of water. Right. So before we go through every pump vendor in every option because I know it's only two weeks and we don't talk about I look at a map of the town of Derby, probably going to be somewhere in town and the waters some distance away. So right there, I have a minimum head as to what's gonna be implied. I add that a minimum of 25 atmospheres. So because I have to overcome the great into seawater that the osmotic pressure seawater So right there, I have a minimum total head just to begin producing fresh water. So then, if we look at, say, double the osmotic gradient, that's going to give me a range from the bare minimum to the double of the osmotic gradient, A range of head I can look at and you've been given a flurry of specification. They say they're going to add 30% on either side of that. That gives you the window to look at. And these are the two variables from which you can then select upon. So you go to the vendor websites just like with the membrane materials. You're looking for a pump that can deliver this many gallons a minute or leaders a second at this head in atmospheres during this range. Uh, that will narrow down the options very, very, very, very fast. The systems like this tend to have one or two designs manufactured over a massive range of of potential head and flow rate options. And then you're looking inside of that to say, Okay, at that point, how much? How much energy am I going to take And really, what I would do before looking at the energy? Because you know that it's the efficiency. That's the argument. Very within that is the system I'm going to pick operating at its highest potential efficiency relative to other options. And that will be pretty quick to circle in on. Okay, there are two or three pumps that could work, uh, bearing in mind. Oh, that's what I was gonna one more thing. One more thing. There we go. Calculation. So, um, as if you are pulling in seawater, this would apply to any system you're going to build and you're using a liquid face pump. To do it, you must must must must think about how do you guarantee that that pump only ever sees water? So maybe that's having a flash vessel inside of it or multiple knockout drums. So there is no way more than one or two volume percent gas that will be distributed in the water phase hitting those pump blades of any kind. And the reason why is that? Um, if you start well, any gas that would be coming into the pumping system. Imagine this blade right

here, Right as this is turning, where is the maximal shear stress that it's applying to the liquid it was a liquid face would be in this outrage. The nature of these is that if the liquid is in compressible, then that pump is applying a significant amount of pressure. Right? So I'm creating an inert I'm compressing. And in compressible system, that means that I don't actually have to the integrity of my material. It doesn't have to be all that hot because it's not all that hard to create pressure in an incredible liquid. Um, many of you end up doing like an onerous project that works with high pressure stuff. We have keeps the high pressure pumps here. It's a fun exercise to take a high pressure pump, evacuate all the era, seal it and then tell the pump to start compressing because I've seen fluid mechanics, Right? Water is always in compressible. Not really. You can compress it and then measuring. How fast does that pressure rise? Based on how much I can press it. So, as an example, if the syringe system I was looking at something like a peristaltic pump had an internal volume of this by the time I compress that much, I'd be at 500 bar. And it is wicked cool to see that pressure go up that fast as you're watching a syringe, um, or something twist. So because of that, if I then have bubbles that are flowing within this right or little bits of gas that have been trapped in their transmitting system effectively at those pressures, uh, that gas is going to rapidly expand as the pump or as the fluid leaves the pump interface. This has the potential to what we call Cavett eight the internal blades of the pump meeting. I'm effectively getting an erosion phenomena, but from a secondary phase that the pump was never designed to handle. Now, 20 years ago, you would have to pick I have a liquid pump or have a gas compressor, but never the two shall meet in the past 20 years. You can now start to get what we would call Multiphase pumps where you can handle up to 10 or 20% of the secondary phase dispersed in, uh, the primary face either liquid or gas. But for a project like this, you would not want to go to the expense of the multi face pump. It will be 10 to 100 times the price of a single face pump. Um, and the application would not warrant it. Unfortunately, not for the not when the engineering design around the risk of gravitation from the outset. Okay, so I know that was a lot really fast. Um, do you have any questions on this that we want to go through? Otherwise, I'm happy to end. Let's say I'll stop the the recording A Me and Emma and I think I should have

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sure it's kind of some motive. End of workshop slides is done. I will then end the team's meeting here. So Renzo and whoever else joins in, if you're able to call into your group members if they're in the room. Otherwise just call me directly and we'll socialise to each group and go around to answer confidential questions. So, um, our final modules, this is the engineering design report is 10% of the final mark. Um, it will be marked as a group, so everyone in the group gets the same mark, something that actually had not come up before. So we needed to check into this. If any member of the group gets a special consideration, it will delay the entire submission of the group submission. So just as a heads up for everyone, anyone make sure it's your responsibility to talk to your group members if that extension is approved, um, and I do apologise. Make sure you probably socialise at first because you don't want to extend it into the exam period. If, say, two or three group members are going to have exams on the day, the extended reports do be pretty unfair to them, so just make sure that's that's balanced if you put it in. I was actually surprised. Nothing in our assessment of special consideration policies talks about group work, which is a terrible concern. So, um, so I wanted to wrap up with a few things about how to unit

operations connect together. This relates to both what you're doing in your projects and also where you're going to start learning things like reactions engineering, uh, more advanced engineering design. And I'll end on that point. Um, and I typically like to frame this around looking at what is the flow of free energy. So the three potentials that we have in the system mechanical potential thermal potential chemical potential, right? Any time we're going to try to bring a process online engineers will always, always always put pressure transducers on it because it's the one thing we can measure. What we're really trying to do is build. You probably heard the name digital twins. We kind of call them digital cousins at the moment because there's no way we can actually build a digital twin. Despite what Grasso and seamen's might promote on their websites. What we're really trying to do is replicate the flow of gives energy in simulation space. But that's really hard to do online. So we need to start measuring. We don't have an energy o metre to measure this, right? You measure mechanical and usually thermal, uh, well temperature and pressure to get mechanical and thermal potentials and what we're doing in simulation spaces solving for the Gibbs Energy at each stage through this process. Now, up until about 2000, it was impossible really to get an online assessment of chemical potential to plug into a simulator that was running alongside it a process in the past 10 to 15 years that there's now measurement technology, some of its spectroscopic and others that are coming into this space. We're starting to see chemical potential as something we can solve for. And the only reason I want to point this out is if you imagine right when we look at each of these terms, we say, Well, these are the three potentials I care about. But if I'm measuring pressure, I have a point, right? So I'm solving a simulation space where there are 15 2025 under constrained variables. If I'm measuring a thing, right? That's one data point I can put in to say, Is the simulator accurate or not? If not, the tool will refine itself, will refine its correlations to get better, but add temperature to that. Cool. Now I have two points I'm solving for, But if I'm in a complex system and hopefully we appreciate all systems are complex by this point composition. How many components do I have? Right? Every one of those components in every phase is a data point. So in the example we did, was it, uh, eight component distillation column a couple weeks ago that we were talking through? Well, if I have two phases present and I'm able to measure the composition of both phases, I have one data point to data points and 16 data points. So for a simulator where the amount of data I can feed it to refine itself matters, composition is something that in your careers will go from. The older engineers would never think to do this to the younger. And we will rely on doing this all the time, more so than even pressure and temperature. And so one of the consequences when we get into actual real unit operations and process operations is that if we have more than one phase present and we've talked about examples of things like distillation columns, it's really uncommon that these phases don't disperse in each other to some extent, and sometimes we want that dispersion to happen. So for transferring mass from a liquid acquis phase two, a liquid hydrocarbon phase and were intentionally creating surface area to transfer mass, great. But oftentimes we don't intend this to happen. And so the degree to which we get one phase mixed up in another phase affects the overall energy burden on our system, and it comes into that mechanical potential at the very end. For those that had thermal with me at the very end, I went through kind of how we can take definition to say it gives energy, and we can collapse it to a two dimensional system. The only thing that changes is I no longer have a volume in two dimensions, right? Cartoons don't have volume, so it must be an area and my

pressure collapses to it, a new term we call an international attention. Otherwise, entropy chemical potential remain the same were slightly modified, but pretty much the same. And the point being this fresher term right that collapses into inter facial tension dictates how my faces are going to mix together. Now, this is going to be a subject that you're going to get into more in some of the advanced level four and really level five units. Uh, some of the gas processing units going to the physics of this. I think y k also touches on it a little bit. Um, but this is something that a lot of engineers don't I don't know about because it's still a really active area of research, right? So we tend not to have this an undergraduate curricula. But as we go forward in our careers, understanding inter facial science is becoming absolutely critical to chemical engineering. One of the consequences. And I'm sure if anyone's taking transport at the moment, this is probably a bit traumatising to watch, But this is a C. F. D. Stimulation of two phases mixing and in fact, we're going for a steady state flow regime of having perfectly stratified flow because of the nature of how energy is transmitted. If I have interfaces that can be created or can be destroyed. All of a sudden, I have the ability to affect in that way the flow regime. So if I'm trying to predict a unit operation or process operation, and I start to get these kind of flow upsets where energy is going to build up in one part of the flow and be depleted in another part of the flow, then eyes and engineer need to be very aware of that, right? None of my flow simulators can predict this and in your lifetimes. It would be highly improbable that tools you'll use from Dassault or Siemens or any of these online digital twins can actually capture this behaviour accurately, despite what the marketing guidelines tell you. So this is something where the engineering intuition is required to say, Okay, the, you know, in a classroom that might be Aspen crisis, right? How, Isis predicts, where it stratified flow. Do I think that's actually going to happen? Probably not, especially now if I'm starting up or shutting down the unit operation. And so now I have to go outside of the simulator gone what we've done into this class and go into the literature, go into the lab and actually assess If I go to turn this system on until it gets to the point of studies that operation, what are the additional safety concerns? Additional process concerns that I have to think of one of these and we have not gone into this at all. Will come up in level five minutes if anyone takes the gas processing stuff is crystallisation and in particular? The reason I wanted to mention it is that crystallisation we've We've danced around the edge of it as fouling right that we care about things like mineral scale so ions dropping out of an aqueous phase and fouling the unit operation we're working on. There are some cases where we want to crystallise the purpose of the process or the unit operation is to create crystals of a very controllable kind. And so, if you end up in this kind of space, there are a couple of considerations to think of. If I'm trying to to make a crystal phase from a liquid, one of the things I have to do is think about the free energy difference of what is that crystalline phase versus the liquid itself. So there's not a difference in free energy between a glass of liquid, right? And if I cool it down, so I put it in the freezer and I cool it down and it crystallises it is at a lower free energy than when it was in liquid. So the difference in that free energy is the driving force for it to crystallise in the first place. Now the rub is something really special happens with Crystallisation, and I bring it up because I don't know that any other class is going to accept gas processing one in a detail. When you go to crystallise a liquid into a solid, there is an induction process that happens that is not replicated in its magnitude and any other phase transition, right? So in thermal, I tell you, pretty much all phase transitions are the same and ish, and that's a lie when it comes to

Crystallisation. So when I take a liquid, if I go to crystallise it, I can't put it on the phase boundary and wait for it to crystallise. It will take hundreds and hundreds and hundreds of hours. I have to take it deep into the phase space right Where that that crystal phases solid by two or three or four times the amount of energy or free energy I would traditionally expect So An example is uhm your freezers. If you turn the freezer up to negative one and you put ice cubes in, it will take 1000 times longer to crystallise. Right. Then, if you have your freezer at the traditional negative 13 to negative 17 and the more exotic the phases are or the more exotically crystal, the deeper that induction goes. The reason we care is if you're hired to create crystals for a living. The driving force, the free energy driving force at which nuclear fission occurs, dictates how perfect the crystal lives. Right. So anyway, I'm seeing the show breaking bad. Okay, so I see some smiles in the back. One of the punch lines of that show was creating a perfect crystal. I don't know what he was talking like, what he was creating out of it, but he was creating a perfect crystal. There is an example of, if you knew, created crystal at a very, very, very low induction force. So, Gibbs Energy driving force, you create a more perfect crystal bearing in mind. No, crystal is perfect. You will always have imperfections in the real world. So we go back to Gibbs Energy right Real quick. What I'm really doing is using pressure and temperature to pull that phase, that liquid phase into where a solid is stable, meaning I'm pulling. That gives energy into a phase where the solid state or the solid is stable. Face the higher that gives energy driving for us, the more imperfect my crystal. But because these things any kind of crystal has to be under a pretty high driving force in the first place to nuclear reasonable time, I have to think about a trip, right? So you see that the inherent contradiction if I put it under a high driving force to get an imperfect crystal, but it happens quickly. So one of the tricks that is used when we come into unit operations is to think about seed crystals. So this is an example of a vacuum crystallisation unit. So I have some kind of liquor feed coming in where I'm going to crystallise a fraction of that, right? So maybe there's two or three components that are going to drop out into a second fit in that right there coming in at a warm temperature above the crystallisation point cooling down. This is a drawing vacuum on the system. And then as I come here, the crystals are forming in this flow, pulls it over to centrifuge, spins the crystals out and pulls them out as a product, Right? One of the ways that we can do this is if we look at what is the chemistry of the crystal we're trying to form. We can look at existing solids, um, that have a similar periodicity of hydrogen bonding sites. Or in a way, if all of my liquid was going to absorb to that solid is the absorption point of the liquid, similarly structured to where the vertex is of the crystal will be. So if I know the material chemistry of my solid and I know the material industry, my crystal and I matched those to use something like a seed solid to accelerate this process at a very low Gibbs energy driving force. Right? So that was, of course, the premise of breaking Bad was not using a vacuum crystallisation unit, but This is a very common technique. If you come in to, say the pharmaceutical industry, and so we we tend to balance both the unit operations against our knowledge of chemistry in particular materials chemistry. Um, one thing that engineers tend to not be well equipped to talk about in these kinds of processes. So as opposed to putting ice cubes in the freezer here I have flow where a reacting crystal inflow, and I like that because it means I can run the unit operation continuously. Something we're not well trained in because we don't know a lot about it is the second I have solid in a liquid flowing or solids and gaps, whatever they may be. The viscosity, the resistance to flow does not go up linearly with how much solid I

have or the type of liquidity so Einstein proposed. And this is, I think, one of the latter things he worked on before he died. A linear correlation for the effective. Some use that as the effective slurry viscosity, how much energy we are going to need to put in to transmit this solid and liquid slurry as a function of the amount of solid which is fee. This is valid up to 5%. So if I have 30 or 40 or 50% solid, we do not have accurate correlations to predict how much energy you're going to need to put into pump that kind of slurry. And this is an area where some process engineering, um, or a lot of research is ongoing and process engineering for that reason. So I won't say too much more on why K does quite a bit on slurry viscosity. So, uh, he should be teaching some of this. Um, but you can look at our literature and in fact, probably a third of the work is specifically on measuring and trying to predict why viscosity is go up in a certain way. The final thing I'll leave you with Does anyone have recruited the Chevron Eagle speak? Okay, so this was developed by Chevron back in the 19 eighties. I want to say, and pretty much most of the large international industry that builds projects for living, whether or not it's oil and gas tends to use this. So the same logical apply to large scale wind farms. For instance. The idea was that you break up a project and this is relevant to your group design report. You break up a project into some number of phases, right? So in this case, they're using the example of five. But you could just as easily do three for a small scale project or eight for a very large projects, for instance. And the idea here is that everyone starts at the bottom left always every engineer on every project and every prompt forever what we do in the first one or two. So the 1st 3rd of the projects and the thinking that we bring to bear. So how if we used inductive reasoning to turn out these engineering design reports meeting? I already have a preconception of what I want that project to conclude. Therefore, I will find the evidence to justify what I want to see happen versus deductive thinking. Drop the ego. What I want is irrelevant to start with every possible opportunity and narrow it down from there. That's the whole gist of what this eagles being is showing and blow your eyes a little bit. It looks like the a side profile of an eagle this coloured in. So the point of that is that once you get into these first how you're going to define the project and this is fundamentally where your group engineering report ends is the definition of what are we going to do? It doesn't get into a huge amount of detail. But are we going to go left or right up or down? Right When you get into this point of defining, here's the project I think we should build that sets the value of the project period, even though you're only investing 100 hours up front here. This work to design it in detail, executed build it, optimise it hundreds of thousands of hours for a large scale project among hundreds of people. This doesn't create value. It optimises, but it is the first definition of the project that ultimately sets the value. So we don't I don't think we do a good enough job in engineering worldwide of teaching this. To make the point, engineers must must must approach these questions without ego, right? What I want and what I think is absolutely irrelevant. I'm here to to bring together as much science as I can understand and to drop it into this project and from that seductively identify what is the best possible project definition for this fund. And the reason we highlight this in terms of value right is it's not that we're all about making money, but it's someone that has hired you. So in this prompt. It's the shire of burden that has hired you. It's not very ethical for us to give them a project that's going to waste their money right, that they have to then take a trade off and not do something else. Because we've brought our ego or used inductive logic and justifying your engineering students. Okay? And on the right, I wanted to show you one. This is a kind of a reductive

example, but an idea around how you could choose to organise different designs. Routine is considered right. I put this. I would always push for the use of quantitative metrics. So things like the NPV of the project you might get into in some engineering economics or 38 30 18 do NPV. Uh, C net Present values are really good. Quantitative, comparative. Also risk. What is the risk the project is going to fail in terms of percent risk of failure in a 30 or comparative operational lifetime. And these help then, as you summarise the different project definitions that have gone into that 1st 3rd of the eagles be. This is one way to organise different project alternatives to justify to the client why your deductive logic has resulted in this outcome. Now it might be that the client has not shared with you all of the relevant information. Maybe you don't know their bank account or you don't know their risk appetite or their ability to clean things up right. If there's a spill, is absolutely so. It's helpful to represent all of that in this kind of table as quantitatively as possible so that they might be able to come behind you and say, Well, okay, we told them that we were broke, but you know, they're working for us. They don't deserve to know everything about our bank accounts. And so actually we have plenty of money, so we're not going to optimise this on the basis finances, but rather risk of delivery because what we don't want is a lack of drinkable water, So that would be one approach. You can take whatever you like, as long as everyone is comfortable with what this is trying to get across in the context of defining an engineering project. All right. I promise. I keep it quick. 20 minutes, so I will stop the formal presentation. Do you have any questions on this before I wrap up? Okay. And I'll go team by team. So, Renzo is anyone in the room? Okay, so do you want to call into your colleagues in the room? And then I'll go to that table and we can chat there. Yeah, we'll do that.