This is unbelievable.

So I just learned that YFN means your friendly neighborhood hackers.

And look, we brought it with us.

Unbelievable.

This is making my day.

This is making my week.

This is incredible.

And really, I don't know what to say.

This is amazing.

So whoever you are, thank you.

This is awesome.

So where's Laura?

So Laura, next year I think we should give every student one of these.

This will be in our-- so we've got some candy.

We've got T-shirts.

We'll get to those.

We've got welcome to the last lecture.

Oh, there's some T-shirts.

We're going to let TAs throw them out.

We're going to let TAs throw them out.

But you guys got a-- so we got a little bit more to cover on diffusion.

I got a why this matters, and then I got a couple of things I want to say, and then we'll conclude.

And like I said, the plan today is to conclude a little early to give you time to fill out the course evaluations.

We really take this seriously.

We really value any and all input that you have.

And so please do.

If you haven't done it already, please use the last 15 minutes that we'll give you in the class to fill those out.

It means a lot to us.

This is still-- it's hitting me right here.

It's slowing me down.

I can do it.

I'm going to get through it.

So we were talking about Fick's laws, and you're only going to be tested on the first one, but I do want to tell you about the second one.

You are not going to be tested on the second one.

That is correct, unlike last year.

Because we didn't have time to get the lecture in on the second law before the recitation, which was yesterday.

And so look, there will probably will be a diffusion problem, but not on the second law.

But still, I do want to finish the example, and I won't go through it in detail, but I want to set it up and just show it to so you have a sense of what Fick's second law lets you do.

And we ended with the first law, and I wrote the second line down.

Now, the first law, that is something I want you to know about.

And so remember, with the first law, so let me go over here so you have a whole board to use.

So in Fick's first law, what that meant was it's a law that describes the steady state.

So Fick's first law was steady state.

And this is now bringing back memories from two days ago, so steady state, which means no time dependents, no time dependents.

And so we had some examples of that.

In the law itself-- I'll write it down here-- was that the flux is equal to minus this diffusion constant times the change in concentration over some distance.

And so we had this example of a membrane right, and so you could imagine we had the glove.

It was the remember, the butyl glove.

And so we had some distance.

Maybe this is like a delta x, and there was some concentration up here, C1, and some concentration down here, C2.

Now the key in Fick's law is you're going to hold these concentrations constant at the source, at each of these points.

And so you can imagine that it's going to change as you go down the hill, and we frame this in terms of Brownian motion.

We're able to understand why concentration, why diffusion happens down a concentration gradient.

Now that flux, that flux.

Remember.

So J is an amount divided by an area times time.

That's J. That's the flux through the membrane, and that is also going to be constant.

Now, the d, what we assumed in the d is that it's a constant.

So in the Fick's first law problems, we often assume d doesn't depend on concentration.

So that means that if I'm over here at a high concentration, I'm over here at a low concentration, well then-- by the way, this would be like-- oh.

Would you like some candy?

I would like some candy.

Thank you very much.

Do you mind if we walk up and down the aisles?

No, not at all.

No.

Please do.

Yeah.

That's awesome.

This is just getting better.

I'm feeling less and less like talking about Fick's law, but here we are.

I'll go fast.

Now the thing is, look, this is x.

By the way, I really want to know where they got the costumes from, but this is x, and this would be like the concentration.

Now d could depend on concentration.

By the way, it's actually quite interesting.

It does have a small dependence on concentration.

We often don't include it.

So this would be like a straight line.

But if it did, if it did depend on concentration, then you might have a deviation.

You could have something like this, or you could have something like that, and you don't need to have a straight line to use Fick's law.

But in a lot of the problems that we do, we assume d is just independent of concentration.

It's a constant.

So I'm adding more and more carbon into iron.

Does the diffusion of the carbon now depend on how much I added?

Well, yeah, it might a little bit.

By the way, that doesn't mean that it depends on time.

That's the distinction I want to make.

So again, the problems we do with Fick's law, we'll assume d doesn't depend on concentration.

We'll just assume it's a constant, but the main determining factor to see if it's a Fick's second law or Fick's first law problem isn't whether d changes with concentration.

No.

It's whether there's a time dependence.

It's whether there's a time dependence, and that was the problem that we left off on on Monday.

We say, well, you've got to do this thing called case-hardening to a lot of materials.

You make the outside harder.

The inside assets a ductile, otherwise, either it's not strong enough, or it's too ductile.

It just breaks down either way, or it's too brittle.

So you want a case-harden, and that was our Fick's second law problem.

And again, I'm just going to kind of set it up.

I'm not going to go through it all.

But in the second law, what you have is an ability now to look at the time dependent.

So you can imagine if I have position x and concentration C and I start somewhere here, so I have some source.

That's why we call it Cs.

So what did we do?

We took this piece of steel, and we asked the question.

I'm case-hardening the steel, so this is iron with carbon.

And I want to put carbon into it but only up to a certain point in a certain amount.

How do I know how long to put it in the oven?

That's a Fick's second law problem because it's a time-dependent process, and I want to know about concentrations into the piece of iron, into the piece of steel as a function of time.

So you can answer questions like this with Fick's second law.

So I had it at 0.25% weight percent carbon, and I carborize the surface.

I carborize only a certain amount of it.

I case-harden it, how long should you keep it in the oven.

And by the way, also what should your carbon, your concentration of source be on the outside.

And all these things kind of go in.

And so you could imagine if the source is there and I'm holding-- maybe I've got some constant, C0, that's the 0.2.

That's the piece of material I started with.

Well.

You can imagine at t0, you've got this.

So this would be time equals t0.

And then as soon as I expose this to this higher concentration of carbon, you might have something like this.

So now you've got t1, and now I wait a little bit longer and it's going to be able to penetrate more in.

So the concentration inside the material changes as a function of time and so forth.

That's what Fick's second law tells us, and the second law is basically a heat equation, which somebody noticed after a lecture yesterday.

And you [? can ?] let's see, dx squared.

So this is a partial differential equation.

But solving it is just talking to our mathematician friends, and they come back and say that's an error function.

And an error function is just a function, And It gives us a solution, C, the concentration at any position and at any time minus the initial concentration divided by this difference in concentrations between the source and the initial is going to equal-- oh, boy.

You'd think I'd have learned.

36 lectures, and I still worked my way into a corner.

I'm going to do the equals this way 1 minus error function of x over 2 root dt.

That is what you get when you solve Fick's second law.

That is what you get when you solve Fick's second law.

And now the error function is just a function.

You don't need to worry about the details of this.

You can think about it as like any other function.

But one thing that I want to share with you about the error function is-- and this is something that, yeah, you're not going to need it on the exam, but you might need this in life.

You might get an error function in life, in IRF.

And if you get into IRF, I don't want you to panic because IRF is just a function, and it just looks like this.

It just looks like it's a linear plot roughly up to about 0.6.

This trick-- and then it kind of goes up to 1-- it's just a function.

Is that 1?

Yeah.

And so if z is less than 0.6 then the error a function of z is roughly z.

Talk about a valuable thing to learn, and that saves you a lot of time, by the way.

But it's just a function and it's a solution to fix second long.

So again, this is how we solve time dependent diffusion problems.

And this is how you could solve this one right here.

And what I'm going to do is I'm not going to actually solve it.

I'm going to give you the answer to that question.

So the time is seven hours.

That's the answer, and I'm also going to leave you with-- oh, there's error function tables.

Look at that, error function tables, and there's this setup of the problem.

So I'm going to leave you actually with a sketch of the setup.

And again, this isn't something we'll have on the exam, but I want you to have this kind of problem at your service.

So these are all embedded in the question.

There is your CS.

There's your c naught.

At this distance, this is what the question asked.

This is the concentration we want.

We know when we look up the diffusion of carbon, we assume it's not dependent on concentration, that D.

And so we just use a constant, and then we plug it in, and we get a time.

You better believe that this is really important.

This is really, really important.

This is how we make stuff.

This is how we make stuff that we make our world out of.

So that's the picture I showed you.

And this gets me now to our last why this matters, and I'm doing it on the backdrop of this beautiful periodic table.

So that's a lot of energy, by the way.

First you had to make these iron pipes, and now you've got to case-harden them or maybe you've got to put even more iron in.

Look at the other 900 C is really hot.

How much energy do we take to make stuff as simple as concrete?

It's just liquid stone.

Didn't you just grind some stones down or something and then pour it out?

Actually, if you think about concrete and other materials like steel, the use of them is skyrocketing.

This is how much we're making.

So look at this, the millions of tons.

Let's see.

There's steel, and there's cement.

Look at that.

There's the world population right there, and this runs out in 2009, 2010, '11, but it's continuing.

It's continuing because it's not just that the population is growing, it's that the places that the population is growing the most are also industrializing.

And that means building.

You go to some of these places and there's a new building.

Literally every block, there's a new building being built.

That takes this stuff.

That takes a lot of ovens at a lot of really high temperatures.

Just the cement alone is accounting for 7% of all CO2 emissions, all CO2 emissions on the planet, 7% of that goes into simply making this magic liquid stone, this powder.

And at the core of it, what is at the core of it?

It's chemistry.

It's clinker.

It's called the clinker.

What is a clinker?

It's this thing.

It's simply a calcium silicate group.

Making that is what takes all this energy.

It takes half of it at least, making that right.

And as always, the chemistry gives us the chance to get out of our constrained optimization.

And so you've got to make this mixture of different types of synthetic rock.

You've got to make mixtures of alite and belite.

They have different names.

And you might be able to make more belite, which takes less energy.

You can cool your oven down by 300 C to make belite compared to alite.

But then even though it's structurally OK, it takes 90 days to dry.

So you can't do that.

So you've got to spend the 300 extra Celsius to make more alite.

Why It's in the chemistry.

It's in the chemistry.

And understanding, what seems like not a very interesting-- cement, is it really that interesting?

You bet it is.

7% of all CO2 emissions is just making this one material, and we're making a lot of it.

We're making a lot of it.

There's a 164 tower in Dubai that opened in 2010 that took a billion kilograms of this stuff.

Now, this makes a lot of CO2, and I've talked about CO2 throughout the semester.

And so one thing I wanted to leave you with was also some things that we're doing about it.

What do we do about CO2?

So how is carbon capture and sequestration going?

Can we take it all out?

We put it in, can we take it out?

And so I'll share a couple of things.

So one of the problems with CO2 capture is that if you don't do it right where you make it, then you have to transport it, and it turns out that's actually really hard to transport CO2.

And there's a lot of problems that have happened over the years.

In the '80s, there was a leak that killed thousands of people.

There have been massive leaks in Canada in transporting this material.

So transporting is actually really hard to do.

There's metal pipe corrosion.

This is a great chemistry problem unsolved.

And then the next part of CO2 sequestration is one is transporting it that's challenging, and the other is storing it.

What do you do with it?

Let's suppose we could capture it.

Well, then what?

And there's ideas around this.

So you could pump it maybe underground, geosequestration.

That's not a sure thing.

We don't know, we don't understand at those scales exactly how well we can in case this material and how long it lasts, so a lot of questions with that.

There's a whole line of thinking on putting it in the ocean.

Right?

Really?

So you want to fix the CO2 problem by acidifying the oceans even faster?

OK.

Interesting.

So transport and sequestration is a big problem, but what about technologies where you simply sequester it right there where you make it, like clean coal.

You may have heard of clean coal, so clean coal.

So I'm going to look at a case study of a clean coal project in the US.

In 2005, I got really excited because eight companies joined, and it was called Future Gen, and the US government was going to put a lot of money into it.

They were going to capture 90% of the CO2.

You get a little bit less efficiency.

Depending on how you think about it, it could be 30% less efficiency, I mean, less power out of the plant, but you sequester the CO2.

And in 2009, construction was planned in Illinois.

In 2010, it was canceled.

In 2010, it was restarted.

In 2012, there was all sorts of discussions with the DOE that agreed to pay $1.1 billion.

It was all located, and then the companies dropped out and the DOE canceled projects.

So that was 10 years.

10 years and $200 million of taxpayer dollars and absolutely nothing has come out of it.

So one of the things I want to point out about this direction, I'm not saying that it's not a good direction to keep pursuing.

But the timescales are long.

So we need to be able to make decisions that can cover longer timescales.

That's a huge part of the challenge with this.

It's a policy challenge as much as it is a technical one.

And tying this back to the cement, there is some really interesting research that's going on in actually instead of-- OK, so you've got the CO2.

It comes out when you make it because the ovens and you're burning stuff, but what if you could take that CO2 and just put it into the thing you're making.

And by the way, if what you're making is a huge scale like cement, then maybe you can put a lot of it in, and maybe that could have a real global impact.

So there's a lot of interest in substantial global carbon uptake by cement carbonation.

So maybe you could get some of it in the cement.

I like this paper.

I'm pointing it out because they say that they used Fick's diffusion law.

They modeled the carbon uptake by applying Fick's diffusion law.

Yeah.

It actually matters.

Right?

You can do this too now.

And just a few weeks ago on CNN, this concrete, yes, concrete is going high tech.

Why?

Because this company has managed to figure out how to put a bunch of CO2 into the concrete while they make it, and it doesn't change the mechanical integrity of the concrete.

And it's in there.

It's actually in there.

This is all chemistry.

This is all chemistry.

So this is, I think, another very interesting direction where technology can play a vital role in this particular global challenge.

And now I'm putting the chalk down, and I come to the conclusion I can't look there.

I'm going to get sad.

You're making me-- the first thing about this that I got to do is I got to thank people.

First I got to thank the concepts, got to thank the material.

This is what we have talked about all semester.

This is what we have learned.

This is underneath the hood of so much, and I hope that I've conveyed that to you.

This is a starting point for so much.

What have we learned?

Well, we've learned how to go back and forth.

This is what I showed you on day one.

And now what have we done?

We have filled this out.

We filled it out with balancing reactions.

We filled it out with the periodic table, that one.

We filled it out with electrons, Bohr model, Schrodinger, atomic orbitals, molecular orbitals, ionic solids, Lewis dots, VSEPR, Van der Waals, London, H-bonds, all sorts of inner intermolecular forces, metallic bonds, semiconductors, bands, crystals, symmetry, lattices, planes, x-rays, x-ray diffraction, defects, amorphous glassy materials, reaction rates, rate laws, diffusion, solubility, Arrhenius, acids and bases, polymers, and their properties.

That's you guys.

That's you guys that have learned that material.

It blows me away.

That's a lot of stuff, and we've learned it all, and we've integrated it into our lives.

But you couldn't have learned any of this, we couldn't have done any of this without some people.

So now we thank the subjects.

We thank the people.

Laura, would you stand up please?

Yeah.

Many of you have interacted with Laura, and you know and now sometimes you might get a short answer.

You might get a not a short answer.

But why is that?

It's because Laura cares deeply, deeply about you all and about your learning and your experience in this class and at MIT.

She cares deeply.

And that's the kind of thing that makes this class what it is.

We wouldn't have any shot at it without Laura.

So Laura, thank you very much.

It's sort of like when you drop your kids off, if they go to sleep-away camp, there's like the camp parent who makes sure that your kids-- it's like they make sure that your kids will brush their teeth, get to bed, have a blanket.

And they check in on your kids all the time.

And I feel like we have that for this class.

It's Laura.

So thank you, Laura.

But now the thing is now the other, now, I introduce these people to you.

Isaac, I still don't have your picture.

But can the TAs please stand up?

Can the TAs stand up?

Come on.

Thank you.

Thank you.

Thank you.

I am so incredibly lucky to have this quality people, this quality of staff, these kind, caring, passionate, amazing people as our TAs for this class.

And I am so lucky I get to meet with them every week to talk about you guys-- it's always good; don't worry.

it's always good-- and interact even much more than that about education, about teaching, about how to make this a fantastic experience for all of you.

So thanks to the TAs.

And that's why I want the TAs to throw the T-shirts out, and we'll do that in a minute, well, a couple minutes.

No.

One?

But see, it's the TAs that have been here for you, but it's also you all.

There is you.

It's you all that have been here for each other.

And so I see it because I talked to some of you.

I don't talk to all of you, but I see the community that forms, and I am very appreciative of that, and I'd like you to be appreciative of that.

So let's thank each other here for just a minute.

It's really pretty-- this is actually getting me revved up a little bit.

Now, I skipped over.

The goodie bags are amazing, and so I'm thankful to the goodie bags and to the department, if anyone is here from the department, for helping us support these goodie bags, thank you.

Thank you.

Yeah, thank you.

That's good.

So I'm very grateful to that.

I'm grateful to all of you.

And last but not least, I guess just last, I am thankful to Harvard.

I was going to say something else.

But anyway, I'm thankful to all of these resources that we have used.

And so I'm going to give you some closing comments.

I started this semester off in the first lecture, and I asked you all a question.

And the question was, why are you here?

And I said really, really, really, why are you here.

Why did you come to MIT?

And I asked you, did you come here so you can just phone it in, get a stamp in four years, and go out?

Did you come here so you can walk around some place in privilege and look down on other people?

That is not why you're here.

That is not why you came to MIT.

You came to MIT because you know that this is where we will make the transition from being able to answer any question to knowing which question to ask.

That's the transition from student to scholar.

And you know that you came here because you have a passion, and you want to come to a place where you can take that passion and you can try to solve really hard problems together to make the world a better place.

Those are reasons why you came here.

You came here because you know that progress does not happen because of success.

It doesn't.

It happens entirely because of what you choose to do with failure.

That's MIT, that's the MIT way, and that's why you're here, and I asked you to think about that on the first lecture.

And then I gave you a whole lot of examples throughout the class.

I tried to connect our learning and solid state chemistry to global challenges, to global challenges that we face.

And I tried to do that.

So I had 36 opportunities.

There's many more, so I had to pick and choose carefully to try to give you a sense of some of these things.

And the thing is about these challenges, one I just talked about in many others, it's not that these are things that we need to do soon.

There is an urgency of now about these things.

There is an urgency of now.

There's no more time to talk about it.

And so these challenges, it's not like something happens over here, happens over there.

These are planetary challenges.

These cover the whole thing.

So it's all on the table.

It's all on the line.

And by the way, if it's a planetary challenge, it means the challenge doesn't care if you're in a blue State or a red State or if you live in Europe or Africa or here.

It doesn't care.

So we better figure out how to get our act together and work together to solve these very hard problems.

And that's why you're here.

That's why you're here.

And so on the first lecture, I asked you to think about why you're here, and on this very last lecture, I'm asking you to think about what you want to do about that.

What do you want to do about that?

And there's a lot of things you can do.

I don't mean that you have to work on one of these things we've talked about in this class.

That's not what I mean.

I mean, think about what it is that you really want to do and how you want to do it, and then go for it.

You might have figured that out before you came here.

You may know-- gesundheit-- already way before you got here.

You may be figuring it out right now.

You may have no clue what you want to do when you graduate.

All of those are fine.

All of those are fine.

But what I want to leave you with is a framework and some thinking that what can I leave you with as a suggestion, as a framework.

And it really comes down to three ingredients, three ingredients that I'm asking you to think about when you go off and do, when you leave here, when you go off and do.

What are you going to do?

How are you going to frame this?

And so the first ingredient is kindness.

Now OK.

Bear with me.

Because you're all thinking, what is he talking about?

This is a chemistry class, and you're talking about kindness.

But you see, the thing is, I'm trying to think about what is a framework that if you follow it you will do good.

You will help change this world for the better, which is what we do at MIT.

It's how we think.

And the thing is I don't care if you define kindness as love or as helping someone or as community or as on one of those dates when the candle was in the room and you did the calculation and you saved the day because you knew oxygen was going to run out.

That's all kindness.

All of that is kindness.

But the thing is that if you have kindness in what you do, it's really hard to do bad.

Is that under the hood?

Is there an element of kindness?

You can't have too much of it.

We need that vector.

We need that vector in this world.

So that's one ingredient, and the second ingredient is knowledge.

Now, what I mean by this is acquisition of knowledge.

And we have done a lot of that here in this class, and you do a lot of that at MIT, and we celebrate these acquisitions.

What I'm asking you to do is think about this as you go forward.

How are you acquiring knowledge?

How are you learning?

That sounds cliche.

Always learn.

You guys have to keep doing that.

You have to keep doing that because, for you, it's nourishment, and it's another one of these vectors.

You can't do any harm by learning.

You can only do good for yourself and for everyone that you care about.

So keep doing it.

The rate might change of learning acquisition as a reaction, the rate constant might be lower.

We know places where that's already the case.

And that's OK.

Maybe the order is lower too down there, but I think they probably are learning something.

Keep that going.

And the last thing is passion.

And this involves your talents.

You all have talents already.

You all have them because that's part of who you are and why you're here.

Those are things that you bring a passion to.

What are those talents?

Maybe some of them are hidden, but work on them and pursue them.

Do things that you literally are so excited about you can't sleep sometimes because of the excitement.

That's what I'm talking about.

Follow that.

Feed it.

And while you do, lose the fear.

Avoid greed, and embrace challenge.

That's what MT is.

That's why we're here.

That's why we're here.

So I feel like these three ingredients, I've thought about this, and I thought about these three ingredients, and I've thought about-- we have these already.

You all have these ingredients because that is also MIT, and you are here, and you are MIT.

And so what I'm asking you to do is to hold onto them and keep thinking about them.

There's a lot of reasons why I love to teach, but one of the big ones is when I think about the challenges that I share with you guys and I have 36 chances to look up in the room and I think about those challenges and I think about these ingredients and I think about all of you, I actually feel like we have a shot.

I actually feel that.

And so with that, good luck on the final, and have a fantastic break.

Thank you so much.

Thank you.

Thank you, guys.

Thank you, guys.

Thank you.

Thank you.

Thank you so much.

Thank you.

You guys are amazing.

Thank you.

Thank you.

Thank you all so much.

I'm going to have to leave here, or I'm going to get really emotional.

I've clearly got a lot of other dance moves the TAs have helped me, so I can practice those.

Thank you so much.

That's just incredible.

You guys are all incredible, and this has been incredible.

So we do have 10 minutes.

I'm going to leave.

So you guys can fill evaluations out without me being in the room.

And so you can say whatever you want.

Again, don't let the free T-shirts being thrown at you influence your opinion or the free candy.

But thanks, everyone, for a fantastic semester.

Thank you.

Thanks.

That was amazing, you guys.