(Intro Music Starts)

SH: Hello everyone, I am Sam Hansen

SW: And I’m Sadie Witkowski.

SH: And you are listening to Carry the Two, a podcast from the Institute for Mathematical and Statistical Innovation aka IMSI.

SW: This is the podcast where Sam and I talk about the real world applications of mathematical and statistical research.

(Intro music ends)

SH: Great to see you again Sadie

SW: Great to see you too, and great to be back for another episode of our emerging technologies series here at Carry the Two. Which technology are we going to be talking about today?

SH: Today we are going to be talking about a technology that has been around since before the earth and yet is still emerging!

SW: Are you a troll asking me a riddle as a toll to cross a bridge?

SH: Hahaha,, sure, maybe, sure, maybe, sure

SW: Sam, just tell me what the technology is

SH: How about I let our first guest tell you instead

AC: So I always like to start with our number one fusion engine in the universe, which is the sun and the stars, right? For 13.5 billion years, the universe has been doing fusion without us having to do anything with it.

SH: That is Andrew Christlieb, he is

AC: Professor of mathematics and a professor of computational mathematics science and engineering at Michigan State University.

SH: Where he works on improving modeling and simulations of plasmas for controlling fusion as a safe and clean source of energy using numerical methods. And he is

AC: The director for the Center of Hierarchical and Robust Modeling for Non-Equilibrium Transport. It's a mouthful. It is a Department of Energy center that is really focused on mathematical innovation that will let us basically do a much better job at modeling and simulating fusion energy.

SW: Fusion as a source of energy, that is so exciting! I know we have been trying to achieve it for a long time

SH: Well we have achieved it actually, in both uncontrolled and controlled scenarios. For the former, Nuclear weapons have been based on fusion since the early 1950s. Fortunately, the H-bomb has never been used in a wartime scenario, but the science behind it promises to be an amazing source of energy one day and that's what we're here to talk about. And we will get to the controlled scenario soon enough. But before we get into that, we should actually talk a bit about what fusion actually means. Overall it starts with two particles that you smush together under extreme heat and pressure and what results is an

AC: Energetic particle called an alpha particle, that's a heavier atom, a neutron, and what happens in those two atoms fuses, there's a little bit of mass that's converted into energy under Einstein's formulation of E equals mc squared, so our understanding of how mass gets converted into energy, and out comes that energy as well. What we're after is the energy that comes out.

SW: Well that sounds quite simple really, so what is it that has kept us from achieving it for so long

SH: Well, fusion energy would be simple if it was easy to actually smush those particles together in a controllable way but it isn't. In fact most of the techniques we have tried so have used much more energy than the fusion has created

SW: If it is so hard, then how do stars and the sun do it?

SH: Well, it's simple if you are the sun. But we are not the sun. In particular we don't have one thing that the sun has

AC: The thing that's special there is it uses gravity, right?

SW: That is true, and the sun uses gravity to fuse particles together?

SH: Exactly, with gravity and the high pressures it can help achieve fusion is a lot easier. As Andrew says

AC: We can't control gravity, right? If we could control gravity, we'd be set, right? I could make you a fusion engine like that if we could control gravity. We could do a lot of cool things if we could control gravity.

SW: Oh yeah we could. Honestly I don’t think fusion would be top of my list, I would much rather fly around. Woooooo look at everyone down there, you all look like little ants!

SH: Sadie, Sadie, back to reality please?

SW: Sorry, I am back

SH: Good. Since we can’t control gravity we have to figure out a different way to confine the plasma at the heart of fusion

SW: Whoa, slow down. You mean plasma, an incandescent miasma?

SH: Huh?

SW: From the science album by They Might Be Giants…?

SH: Surrrreeee, sure, sure, sure, but actually . Plasma is a state of matter like gas except

AC: It's the place where you've gone beyond the gas and you've stripped the electrons off of the ions. And now you've got these charged particles running around.

SH: And once you have all the charged particles it becomes harder to handle because the charged particles repel each other and

AC: it's complicated because now you've got moving charge creates fields, fields push on the particles, and now it's a complicated system to confine and compress.

SW: That has to make smushing those particles together super hard

SH: Which is why fusion scientists have developed techniques to help confine plasma. The two main techniques are achieved through the use of magnetic and inertial forces. The magnetic confinement usually involves a torus, or donut, shaped plasma chamber that has powerful magnets along the outer edge to help control the plasma. The magnetic confinement method was first proposed 1950s and the first working prototype, called a tokamak, was built soon after in the USSR, which achieved fusion, at a power loss, in 1964. Modern magnetic confinement tokamaks are considered one of the best options for fusion reactors though they are not there yet. Inertial confinement on the other hand uses a huge jolt of energy, like say a laser burst, to implode a pellet of fusion fuel. And it was using one of these laser induced inertial methods where scientists managed to get more energy out than the laser put in

AC: December 5th, 2022, we actually did get our first fusion event that was at the National Ignition facility doing this indirect drive of a capsule and causing it to implode. So we are understanding how to reliably make that process happen over and over again at the National Ignition Facility.

SW: And mathematics is helping this happen?

SH: In so, so, so, so many ways, but with Andrew we are going to directly discuss the super important role of mathematical models. And let's start off with a quote

AC: George Box said, "All models are wrong, some models are useful."

SW: But why would people want to use things that are by definition all wrong?

SH: Hahaha, because a correct model would be even less useful

SW: Wait, what?

SH: Let me try to explain. I think a good place to start is with a map. We can both agree that maps are useful things right?

SW: Oh definitely, paper or digital maps help us get where we need to go

SH: Now would you say that a map of Chicago faithfully represents everything about the city? Every business, every pothole, every bus, every person

SW: N, of course not

SH: Now try to think of a map that could do that

SW: Ok, but wouldn't that just have to be the same amount of complexity as the city itself

SH: Exactly! And the reason that a map is useful is that it is less complex. That it provides us with just the information that we need in order to find our way

SW: I get it. A map is technically wrong, but it is useful!

SH: And models of fusion are the same

AC: We can't actually simulate the full high fidelity physics models that we need to simulate in order to capture all of the different instabilities that happen within the plasma, all the different phenomena in the plasma. And so we've been using a patchwork of models that build up resolution, but don't sort of self-consistently all at once simulate the whole device.

SH: And this patch work of models all build on top of each other, with different scales of fidelity ranging from coarse scale averages for the whole system to fine scale modeling of particle movement. There has already been a lot of work done to enable the solving of the coarser models, so now it is those finer scales where the challenges are coming from, particularly to try to understand why the plasmas become unstable and lose confinement before we can get energy out

AC: Many of the plasma instabilities come from other effects in finer scale models, and those finer scale models are the things that we really can't solve at scale.

SW: And that is where the mathematics comes in?

SH: And that ‘s where the mathematics comes in!

AC: That's really what we're trying to do is develop the mathematics that enables us to solve these finer scale models on the length and time scales we need to solve them to make real contributions to the study of fusion.

SH: In order to see what this looks like Andrew told me about work being done with a specific magnetic confinement device in France

AC: ITER is the tokamak that is being built in France by the international community trying to create a large-scale tokamak device for modeling a fusion system

SH: In order to model a system like this, mathematicians develop what is called a discretization. This mainly means splitting up a continuous space, like the torus of the tokamak, into individual sections. In this case, even though it is 100 times bigger than the resolution they would really need, we are going to make our sections square centimeters. And for each square centimeter

AC: The model you need here is a 6D model. It's not a 3D model, so this model has additional information in it that ends up in other dimensions. So the model is what's called a particle distribution model. It describes the probability of finding a particle at a given location with a given velocity at a given time.

SH: And to figure out the probability

AC: That six-dimensional model is a differential integral equation that is one of the more challenging models to solve in physics.

SH: Then in order to solve these integrals for each of our square centimeters

AC: you would take all of the RAM that sits on the world's leading supercomputer, Frontier Oak Ridge National Lab, for one instance of this device at a resolution that's 100 times too small in each direction. And then you've got to multiply that by six, right? Or raise that to the sixth power. Not multiply by six, but raise it to the sixth power. So you're way under-resolved. I mean, there's just no hope of solving this model on our best computer. And so we've got to come up with better ways to do this.

SW: (Whistles) Needing to come up with a better way to do this seems like an understatement. Especially as I am guessing there are requirements that these models need to meet?

SH: Just a few

AC: So if I'm just using my kinetic equation to solve a problem that I care about, and there's many cases where I'd want to do this, of course I want mass, momentum, energy, and I want my entropy to do the right thing, to decay at the right rate. We need to develop a numerical method that preserves these properties.

SH: Though remember that during fusion some mass gets converted into energy, so the model should lose some mass and gain some energy but it is important that it happens for the right reasons

AC: What I want to happen is I want that to happen from the physical process, not because I made a numerical error.

SW: And Andrew and his collaborators are working on making sure that this is what happens in the models?

SH: Yes, one of the techniques they are using is one that we all regularly use without knowing it

AC: When you watch a video on Netflix, it's using something called CP decomposition, which is a way of taking high dimensional image for a video, which is of course the 2D spatial information you see on the screen, but then there's a red, green, blue component to it, which makes it a 5D array. And then they use this compression technique that takes that information in time and figures out how to do for many, many frames, how to represent as a very small thing through compression. It's this tensor compression idea called CP. And that's what makes video streaming possible.

SH: Though of course streaming videos and nuclear fusion have rather different risk calculations

AC: Instead of just compressing, like if I lose a few pixels on my screen, I don't care. I do care in my numerical algorithm if I'm not conserving mass, momentum, and energy the way I want, right? So we have to really redesign these algorithms in a way that preserves the mathematical structure that we care about.

SW: So, it’s going to take me a while before I stop seeing a tokamak every time I stream a show isn’t it?

SH: Well I did this interview a while ago and it still hasn’t stopped for me, so probably

SW: Thanks, Sam (sarcastic)

SH: You're welcome (sincere)

SW: (Sighs) So how are they are working to redesign the algorithm

SH: They're using machine learning techniques that allow them to embed the physical structures into the design

AC: By building structure into the neural networks, we're able to get much better solutions to the problems that we care about. And so that's where structure preservation comes in. You're building a mathematical structure into the neural network to accomplish the task

SH: Once they have those networks they then train them on the compressed six dimensional data, and the network helps create an efficient model. That model can help design better fusion systems

AC: It's sort of a zoo of methods and those zoo of methods intertwine with each other in ways that help you do new things.

SW: Sounds like a very egalitarian mathematical system he's helped set up. From each model according to its outputs, to each model according to its inputs

SH: (Laughs) Ohhh, we aren't done yet

SW: Of course we aren't

AC: Our models come in a form that are not good for a computer. A computer is great at subtracting, multiplying, adding, and dividing. It's not really good at solving the equations we write down in physics.

SH: Which is where our old friend discretization comes in. This time transforming the continuous functions you find in physics to the discrete algebra that computers are good at. And it is not a trivial process

AC: How do you write down discretizations in the first place that preserve the physics properties, the mathematical properties that you know to be true that should be conserved at a discrete level? And that's not necessarily easy to do. There's a lot of work that goes into that.

SW: But in what way are they hard?

SH: For example in physics there are many cases where changing a single parameter can shift an equation from being one that describes how something is being transported in a liquid to how it is diffused into a liquid. Except this type of behavior can be really hard to describe discretely so special techniques have to be used

AC: An asymptotic preserving method is one that the discretization naturally does that transformation, giving you a good approximation when this happens.

SW: So, once they have used all these discretization and structure preserving techniques and built their models then what happens?

SH: What do you mean?

SW: Well, modeling fusion is great but how does this actually interact with the people building things?

SH: Andrew does have a specific goal

AC: Beyond Forward Simulation is really the holy grail.

SW: Which means?

AC: So beyond forward simulation is partly about building next generation surrogates that allow us to do that optimization process in a reliable fast way where those surrogate models preserve the structures we need them to, are trained on high fidelity data coming out of all these things we're doing throughout the center, and are trying to then enable us to be able to do that next step of designing optimal things.

SH: And all of that does relate directly into how these fusion systems are built

AC: Some of the coolest work that happened at the National Ignition Facility, in my view as a computational person, happened about 2014, 2015. Brian Spears, who's now the director of their AI initiatives at Lawrence Livermore National Lab, and his team. took low fidelity simulations of that imploding capsule. They then went ahead and ran thousands of low fidelity simulations to train a neural network. They ran a few higher fidelity simulations to refine that neural network. And then they did something incredibly clever. They did something called transference learning, where you only train the output layer based on new data of your neural network. And they trained it on the experiments. And what they did, because the experiments are like a million dollars a pop, so you don't have a lot of data. So when they did this, they trained it on neutron yield. And then they took that surrogate model they got out of the neural network and they put it in an optimizer. This is what I'm talking about, fast surrogates. And they ran an optimization process and lo and behold, they found something super cool. There are shapes of the capsule they had never thought of that by making the capsule that shape didn't improve the yield, but made the yield reliable. Every time you flip the capsule, it gave you the same number of neutrons out every time you popped it. Right. So by getting something that improved the yield, it allowed them to start thinking about how you step towards improving yield.

Right. So this became a part of the design process, how you improve this. That was, in my view, kind of a genius moment. It was a paradigm shift. How we use neural networks as fast surrogates, it was really sort of a flip in what we do with these things.

SW: That is so cool that models came up with a shape that no one else had thought of. And Andrew and his team are hoping that their work will lead to similar breakthroughs?

SH: That is their hope, and with the tools and techniques they have created and helped progress that hope is high

AC: We're doing it with things called dynamic mode decomposition and something called weak sparse identification of nonlinear dynamics and how we hybridize these things. These are all jargon, but those jargons are we're doing it in different ways than just standard neural networks. But it's the same idea. We're building fast surrogates that preserve structure that then we can use to look at these kinds of problems for optimizing them.

SH: Of course for any of this to work out, there is something that Andrew, his team, and everyone else working on fusion badly needs.

SW: What’s that?

SH: I’ll tell you after I let our audience know about another of the great podcasts from the University of Chicago podcast network

(Ad music)

(Music Ends)

SW: Ok, so what is it that everyone working in fusion so badly needs?

SH: Patience Sadie, patience. We will get there. First let me introduce Cristina Rea

CR: I'm a principal research scientist here at the Plasma Science and Fusion Center. We are an interdepartmental center at MIT, at the Massachusetts Institute of Technology. And I'm also the group leader of the Disruption Studies Group.

SW: Disruption studies? I really don’t like the sound of disruptions when talking about fusion

SH: I don’t know if hearing what they are is going to help then…

CR: Disruptions can be defined as the uncontrolled confinement loss that we experience in this magnetically confined plasma.

SW: Nope, nope, nope definitely doesn’t help. Sounds like a superhero getting created in a lab accident

SH: Maybe this will help

CR: It's typically benign in current experiments. There is no kind of side effects except for potential structural damages or thermal damages that the first wall of our plasma device, of our confinement device, can incur into.

SW: Phew, benign disruptions sound so much nicer

SH: They certainly do. Really these are mostly disruptive for their experiments because when they happen their experiments stop and have to be restarted

SW: Oh man, like when you’re doing a sleep study and your undergrad participant just won’t fall asleep and keep jolting awake and so you can’t mess with their brain and find interesting results (joking)

SH: Ummm, suuuure. Something like that. And while they would love to be able to figure out what the issues are

CR: The issue is that we don't necessarily have first principle models that are able to capture the physics underneath the growing of instabilities that can lead to the final loss of control of our plasmas.

SW: Oof, so what do they do if they don’t have these first principles from which to build their physics models

SH: They go toward what they do have, the data from their experiments

CR: We need to learn from data paradigm and employ machine learning algorithms to try and predict the occurrence of these instabilities that if growing beyond some controllability threshold can lead to disruptions.

SH: Particularly they are powering their statistical study of their experiments, a lot of which is regression and correlation, using these data driven algorithms

CR: What we are doing is just upgrading that approach using, instead of classical statistics, we are using a bit more advanced statistics. And so neural networks is just a fancier way of saying that we are just trying to define regression laws that are a bit more accurate, that are able to capture the intrinsic correlations in the data space.

SH: Which is already cool, but it gets even cooler because these data driven statistical techniques could also help with those theoretical first principles

CR: And then you can think about informing in a feedback loop the theory or just validating the theory.

SW: And all of that just from data?

SH: Well, plenty of work goes in to that data

CR: A lot of our work is really heavily focused on digging into these big databases, assembling databases that are well curated, and we also tend to use the term validated. Meaning that we run several checks from the domain experts, from subject domain experts, and we address the matters of the questions of, okay, is the diagnostics actually working? Is the data that I'm seeing actually in front of the ranges that are physically reasonable or is this like an outlier or is this, why do we have missing values for this particular processing routine

SH: Because after all

CR: You know, garbage in, garbage out for ML. And so we tend to devote lots of time to quality checks.

SW: Just a second, I figured it out. It’s data that everyone working in fusion energy needs. Isn’t it?

SH: Ding, ding, ding! You got it! It is data that everyone needs, in fact Cristina finds data so useful she sees its availability as a hugely important shift in the field

CR: The change of paradigm here is being able to access an enormous amount of information from experimental data carriers from many different machines that are operating around the world and uncover the correlations across years worth of operations.

SW: That is incredible, it must be great to have all that data!

SH: Not only that, Cristina is leading a project to make sure that everyone has access to this data. It is called

CR: The Open and FAIR Fusion for Machine Learning Applications

SH: And it’s

CR: Part of the broader endeavor sponsored by the Department of Energy where we are trying

SH: Where the FAIR in the name is an acronym which describes four traits that open data should have

CR: Findability, accessibility, interoperability, and reusability.

SW: Oh man, having data that’s actually accessible is such a huge piece in research! What good is it to have a massive data set if you can’t actually use it? We had a data computer that we weren’t allowed to access the internet through because it ran windows vista. All to maintain the data that was recorded on it.

SH: And I am guessing that sharing that data was out of the question?

SW: As long as you were ok with pulling all this super dense data onto an external drive and then uploading it again to your personal computer to actually do anything.

SH: Stories like that are exactly why Cristina is trying to get the FAIR data embedded in fusion science

CR: What we are trying to do is to port some of this really guiding principle for scientific data management into our fusion community.

SH: Because, unsurprisingly

CR: Fusion historically has witnessed siloed sub-communities. It is very intrinsically related to geopolitical environments, and we've been conducting sciences mostly beyond firewalls.

SW: In other words the data has been recorded in different formats with different labels and not shared.

SH: Not shared and definitely not FAIR

CR: We have years and years worth of experimental data. Now making all of that more adherent to fair principle is a huge endeavor.

SW: I can only imagine. So how are Cristina and her project team planning to take this endeavor on?

CR: The way that we are trying to tackle this is through the development of workflows first that do embed those principles in it, where the data that is being basically processed for these workflows, then we'll adhere to fairness principles.

SW: What a great idea, not just telling people what they would have to do to make their data FAIR but making sure that the workflows that collect the data have findability, accessibility, interoperability, and reusability baked in

SH: And part of making these workflows output interoperable data relates back to what you mentioned just a minute ago about different formats and different labels

SW: Of course, if the data formats and labels change depending on who is collecting the data other people will have a hard time getting it to work with their systems

SH: A problem Cristina is well aware of

CR: I was kind of onboarded into this job at MIT 10 years ago almost with the task of assembling these big databases for ML applications. And I was working with data from three different devices. So the DIII-D as I was mentioning, and then Alcator C-Mod, which was hosted here at the PSLC up until 2016. And then I was working also with colleagues in China on this experiment. And so basically at the time we had a collection of MATLAB scripts scattered throughout the three different systems that were customized depending on the user who was modifying them. And so you would have to keep in mind that, you know, the plasma current on DIII-D had that name and the plasma current on (unintelligible) had that name.

SH: Which of course made harmonizing these data sets super tough. So, one of the things which Cristina is help pushing forward with this project is to get fusion researchers to all start using the data labels defined in ITER's Integrated Modelling and Analysis Suite, which is from the French fusion organization Andrew mentioned earlier

SW: So next time someone wants to label the plasma current values, they will all use the same thing?

SH: Yes, yes, hopefully, hopefully they will! And even better ITER recently made IMAS open source which means

CR: That is a big deal for the community because we cannot contribute back and say oh okay so you're missing this particular area for mapping the data ontology so we can contribute back

SW: Beyond helping people say train more machine learning models, does Cristina see other potential benefits of moving toward open data in fusion

SH: She does, especially around helping researchers not redo experiments that other people have already done and helping to find more global consensus

CR: So having more openly accessible data sets will enable all this more robust and standardized benchmarks for just, you know, improving and go towards convergence in a sense, quicker onto a solution.

SH: That includes in her own area of disruptions

CR: And I'm pretty much concerned about disruptions because yes, that's an open area where we don't necessarily have first principles that would just validate or disprove, a solution, right? So we need to have community consensus around the way to tackle these problems and the way to design these solutions. If they have to be ML driven, then they need to go through like standardized processes for benchmarks and validation and validation of performance metrics that are associated to developing these algorithms.

SH: There is also a non-research specific issue that Cristina believes these open data sets help with

CR: Having more datasets available and that really broadens engagements towards a more diversified workforce and a diversified community.

SH: Which she herself has witnessed

CR: We've seen that, for example, in some initiatives that I've run in the past, like for example, hackathons or data challenges, and that has been so much fun to see. And you can see how when you open up the field to really diversify the workforce, you come up with creative solutions that you were not thinking about before.

SW: That totally makes sense. When data is open and available to everyone then it can be used for things like coding challenges, collaboration outside their silos, and as a way to avoid some of the gatekeeping that happens in the academic and industry worlds. Not to mention that someone could just go download the data and play with it on their own time. Though there must be people who are pushing back on this

SH: There are. For one there is an increasing number of public/private partnerships and they have concerns

CR: We are seeing our concerns about IP protection, right? Intellectual property protection.

SH: Though Cristina has an approach that should work for that

CR: Those can be addressed by modularizing the access to the information and then making as reusable and as accessible as possible all the layers above what you want to protect. And we are working with collaborators in that action, for sure.

SH: And then, the other major concern is

SW: (Interrupting) Oh, please let me guess: what if I get scooped on my results?

SH: Yep yep yep, the ever present academic priority concern. And while Cristina encourages early career researchers to do things like publishing their results and then publishing their data, she sees it more as

CR: It's a kind of a cultural change.

SH: And culture changes take time

CR: And as soon as it's widely adopted, then I think the fear of being scooped goes away.

SW: Are those the only two big concerns?

SH: And last episode, I said you knew me well. No, there's another. It's a big one

CR: We are still worried about the amount of data that we release with our proper quality control

SH: I mean we don't want a bunch of research on non-validated data floating around

CR: Because we are worried that, you know, being… Once you kind of let go of all the barriers, you could claim you solved the fusion. Well, you know, there needs to be kind of a panel expert and review, like a review process for that type of validation. Um so I think though that we are heading towards the direction of having as much information as possible, publicly accessible, and then establishing some sort of quality controls that will make sure that the information that is out there is also high standard.

SW: And what does Cristina envision this quality controlled data looking like so that people are not using it incorrectly?

CR: In order to release information that is not misused, I think it's extremely important to also associate metadata information and therefore being adherent to the FAIR principle in all aspects. So basically, not just releasing a data dump of whatever it is in your archive, but making sure that what you're releasing is also accompanied by the explanation of what everything that is in there. And so metadata information, both about data itself as well as a model developed on those data

SW: Well I wish her the absolute best of luck. But after all this talk about fusion research, I have one last question for you Sam?

SH: Yes?

SW: When the hell is my electricity going to be coming from a fusion reactor?

SH: Well lucky for you, I was wondering the same thing and asked our guests. First let's hear from Andrew

AC: Do I feel like we're getting close? I really do. I think in my lifetime, we're really going to see this happen. This is not a pipe dream anymore. This is something that's really going to happen.

SH: As sure as he is that it is going to happen, his timeline is not certain

AC: I admit it's not, it's more than 10 years away, but we're seeing real progress right now. And if we keep pushing, if we were to dump more money into it, we could actually make it happen faster. But I really see we're getting there and it really feels good to see this.

SW: Ok, ok. That sounds hopeful. What about Cristina?

CR: There is a really good chance at de-risking the whole fusion challenge in the next three to five years, I want to say, where we should be able to see a burning plasma in a magnetically confined device in a tokamak.

SW: Amazing, so functioning magnetic confined fusion in a lab! But that still doesn't get me fusion energy

SH: And Cristina is not entirely sure it will ever be commercially viable. But Commonwealth Fusion System did recently announce that it will be building the first Fusion Reactor in Virginia

CR: Construction is starting as we speak. So, uh, is this later to operate in the 2030s. So yeah, if you think about it, it's like five years from now, and we should be able to see, uh, this happening on time scales that, uh, yeah, we always used to joke about.

SW: That's what I wanted to hear! Let's hope they stick with their timeline!

SH: I will certainly be crossing my fingers that they do, maybe our listeners will do so too!

SW: I know how construction goes, fingers crossed!

(outro music)

SH: Don't forget to check out our show notes in the podcast description for more Andrew and Cristina, including links to their work that we discussed on this episode

SW: And if you like the show, give us a review on apple podcast or spotify or wherever you listen. By rating and reviewing the show, you really help us spread the word about Carry the Two so that other listeners can discover us.

SH: And for more on the math research being shared at IMSI, be sure to check us out online at our homepage: IMSI dot institute. We're also on Bluesky at IMSI dot institute, as well as instagram at IMSI dot institute! That's IMSI, spelled I M S I.

SW: And do you have a burning math question? Maybe you have an idea for a story on how mathematics and statistics connect with the world around us. Send us an email with your idea!

SH: You can send your feedback, ideas, and more to sam AT IMSI dot institute. That's S A M at I M S I dot institute.

SW: We'd also like to thank Blue Dot Sessions for the music we use in Carry the Two.

SH: Lastly, Carry the Two is made possible by the Institute for Mathematical and Statistical Innovation, located on the gorgeous campus of the University of Chicago. We are supported by the National Science Foundation and the University of Chicago.

SH: I took a breath at the wrong time (laughs)

SW: (Laughs)

SH: It doesn't work but just the laser it does

SW: Just the laser it's fine

SH: Just the laser

SH: There's too many ands in the sentence

SW: And this and then that and then the model

SH: brain stops working apparently at 10 am

SW: Yeah keep going

SH: I think I know what I need to do. I just need to make these fonts bigger.

SW: Old man font.Let's just zoom in.

SH: This is now where it is.

SW: There you go.

SH: Yeah.

SH: Like, no, that person died.

SW: Why would I know that

SH: They retired before I was even a PhD student.

SW: That will not be going in the outtakes.

SH: (Laughs)

SH: (Laughs)

SW: (Laughs) Nailed it.

(Outro music ends)

SH: Vocalizing