Everything is Better with Maths: Optimisation, with Prof. Miguel Anjos and Dr. Lars Schewe (S01E07)
Not Another Science Podcast
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Introduction

Intro music plays.

[Tom Edwick] Welcome to Not Another Science Podcast. I'm Tom.

[Helena Cornu] And I'm Helena!

[Tom] This week, we're talking to two mathematicians who work in the field of optimisation. But what is optimisation?

[Helena] As you may have gathered, Tom and I are biologists, so we were quite nervous going into this interview, but we're here for you, to ask the basic questions so that you don't have to.

[Tom] This is also the first four-person interview we've ever done, and we were very much at the mercy of technology. Thankfully, despite some minor hiccups, it was a roaring success.

[Helena] So without further ado, here we go!

Intro music ends.

[Tom] Before we start, this podcast is sponsored by Greiner BioOne, supplying laboratory, diagnostic and medical products to research institutions, higher education, the NHS and others across the UK. For details of the full product range, visit www.gbo.com.

Transition music plays.

Main

[Lars Schewe] Yeah, okay! So my name is Lars Schewe, I'm a lecturer in Operational Research here at the University of Edinburgh in the School of Mathematics. My specialisation is mixed integer nonlinear programming, as we call it. And I mainly have done applications in energy.

[Miguel Anjos] And I'm Miguel Anjos, I'm chair of Operational Research in the School of Mathematics at the University of Edinburgh, and I work in mathematical optimisation in the sub-area of what's called nonlinear optimisation, the simplest version of which is what a lot of people have seen at university when you take a function, and differentiate it to set it equal to 0 to find the highest point or the lowest point. So you start from there and then you can develop much more complicated versions of that idea. And like Lars, I mostly use this knowledge to solve problems in the area of electric energy.

[Tom] So just to kind of get us going, we thought we'd ask you both what is it that attracted you to maths in the first place. So Miguel, if we could start with you?

[Miguel] Sure! The short answer is that I've always liked mathematics. I simply cannot think of a specific reason why, I've just always liked it. And over the years, I've realised that it's a combination of the intellectual exercise and manipulating things in various ways, and coming up with patterns, and coming up with understanding the structure behind the different mathematical constructs. So really enjoying the structure that comes out of it, but also the fact that it's challenging. You've got a starting point, you know where you want to get to, and you've gotta figure out the right steps to get there, so it becomes a challenge to figure: "Can I get from one place to the other?" A bit like when you think of doing a maze exercise. The cheese is in the middle, and you're playing the mouse and you've got to find your way, so you've got a very well clear set of rules, and you've got to figure out how to get there. So in some sense, when you do some mathematics, it's like you're in a big maze and it's not that easy to find your way through, but you've got… First of all, you've got different techniques that help you to get there, and then the other thing is also you've got other people to work with, because mathematics… People often think that mathematics is a solitary sport, but it's actually much more of a team sport than people think.

[Tom] It seems like something that's a bit more challenging to communicate to other people perhaps than the other sciences. I don't know how you feel about that.

[Miguel] It is sometimes harder. I think we've gotten much better at using visualisation, at using… Visualisation and applications as well, to be able to show mathematics in a way that's not just formulas and numbers and abstract entities, but really to show what mathematics can do, and the reality is that there's already a tremendous amount of mathematics in everyday life, for everyone, we just don't realise that it's there. I mean you have, everyone these days has in a pocket, a computer. Essentially a mobile phone is a computer, and within that computer, everything is run using mathematics.

[Lars] In the beginning, when I had to decide what to study and so on, I wasn't really sure, I was drawn to many different things. In the end, mainly the problem-solving aspect made me stick with math. That was really something where you had challenging problems that you wanted to solve, and you could really sort of sink your teeth in. That was really something that I liked and that pushed me forward. So in the beginning I started really thinking about pure math problems, and that was what I worked on, and later I saw the opportunity in applications.

On the communications side, I would say, if you try to be specialised in your specific problem, you assume so much about what other people already know that it becomes difficult for you to communicate with others and explain to them what it's really about and make it simple. As you said Miguel, we have our phones and they are already in there, but that it's a clever thing that we are able to get, say, a quick route from A to B on our mobile phones, on a map, is something where we don't see necessarily that there's a lot of math involved to get this that quick and that simple. It's just: "Yeah, yeah, computers do it, somebody will do it for us," and people think: "yeah, this just happens", instead of "Yes, this is a challenging problem, challenging optimisation problem, people have thought long and hard about how to make it faster, faster and even faster, before you can actually use it on the scale that we're using it right now."

[Helena] I was just going to say, as I understand it, optimisation is finding the best solution for a problem. Is that right?

[Lars] The short answer: yes! The idea is you have… You define yourself a problem and you have different solutions that are acceptable, and you compare them, and then you try to find the best solution among all the solutions that you have. So if you think about the map problem, the shortest path problem as we call it, so essentially any path between two points would be a feasible solution. You can drive from the city centre in Edinburgh to the city centre of London taking a detour through Glasgow for instance, that's a totally feasible solution, you can do that. You can also make a detour to Aberdeen, or everything is allowed. But if you want the shortest then you want the shortest path between those two points, and that is the best. So the metric with which you decide is distance, or travel time, or instance it could also be something different, but typically it will be travel time, and not distance, because distance might mean you take a route with very many small roads which are not suitable for high speeds. But if you want to do travel time, then well you have to consider that and do travel time.

[Miguel] And then the next step is to take congestion into account. The fastest route may be longer because if you take the shortest one, you get stuck in traffic. So then it's an extra additional complexity in your algorithm, to find the shortest path.

[Tom] And do these systems, do they work in real time. 'Cause I know when you're driving in the car and you're on Google Maps, it knows the traffic that is ahead and it can change your route halfway through.

[Miguel] Yep. And the way it works now is that it uses the information from other phones, that their users are not moving, to deduce that there is congestion. And therefore it turns that little bit of road yellow, or orange, or red, and it recalculates, very quickly as Lars was saying, people have spent years and years figuring out ways of calculating these shortest, these fastest trips, to tell you: "Okay, actually you should… I've changed my mind, you should take a different path because something has obviously happened, and the traffic is not moving somewhere along the way."

[Helena] So then, could you tell us a little bit about the research that you do, in the field of optimisation?

[Miguel] The work that I do on optimisation is really about using optimisation to solve engineering problems, and it basically has to do with finding the best design, the best solution for a particular application. If we think about what an application such as in scheduling, you want to find the cheapest way of assigning, for example, bus drivers to bus routes, so that you achieve the service that you want but you keep the cost as low as possible. And when you want to do something like that, it would be easy to say, “Well I’m just assigning bus drivers to buses in whatever way I think makes sense”, but then there’s all sorts of rules about how long a driver can be on the job, about how many days in a row a driver can work, how many breaks they have to take, et cetera, et cetera, et cetera. So you have thick rulebooks that have to be followed. And so the challenge is to handle the complexity of the problem, and come up with a solution that is still cost-effective for the operating company.

You have the same thing happening in airlines, where they have to figure out not just the staff that’s on the planes, but also the planes themselves. You have to make sure the right plane is in the right place at the right time, and that’s why sometimes planes go around nearly empty or flying overnight, because you actually need that plane to be somewhere else the next morning, because that’s the cheapest solution overall to run your system. So you can take these very complex engineering systems, you have the same thing in healthcare, where you’re looking at flows of patients for example as well, and you want to optimise the decisions taken in terms of how you schedule treatments and you flow patients through hospitals.

The area where I work a lot on is in energy. And so you can ask the same kinds of questions about electricity: how do you generate electricity, how do you operate the electric system? We hear a lot about national grid in the news these days in the UK, well behind the way that things happen, there are a lot of questions that can be answered using optimisation, in terms of finding the best solution for providing the service which is really critical for every country.

[Lars] What I’m interested in is specific optimisation problems that combine what we call discrete decisions, that’s what Miguel talked about when it’s something like: “Do we schedule something right now, or do we schedule it an hour later?” So we have decisions which are Yes or No decisions, essentially. Do we do something or do we do something else, and there’s no in between, and combining this with nonlinear models, so often models that come from some physical process, some engineering process, and combining these. Because from a methods point of view we have different methods for these two types of problems, that were suited to these, and combining them is what I’m interested in. And that’s why you get often engineering problems as the application, because they have typically these two sides to their problem: they have a big physical model combined with some decisions which you have to do or don’t have to do, and energy is also one of the main applications that I’m interested in.

I worked a lot on different types of gas networks, for instance, where you have all kinds of questions for instance about the operation -- you can switch on certain things or switch off certain things in the network, so-called compressors, simply to compress the gas, you have to switch it on or off, which is a classical discrete decision -- but if you really want to model the flow of the gas, you get this nonlinear network behaviour. And often what integrates with that, and what is upcoming question is often: how does this interact with how people behave on the markets that are attached to that? So we have an energy market, and now people will behave differently if you do different things, and having this behaviour inside your models is something I’m getting more and more interested in over time.

[Tom] I was interested in wondering, Miguel you mentioned, about the kind of rulebook that you had, and Lars you talk about the behaviours that you have to incorporate in these models as well, how do you bring in these kind of unknown variables? How do you deal with that when you’re working on optimisation?

[Lars] I would say, first you try to do it as simple as possible, and often you can get by with relatively simple models simply because at the big energy markets, big players, sort of big companies operate on these markets, and they are in that sense predictable as they have a pretty clear profit drive. If you’re talking in the aggregate then often you can use much simpler models because on average, people behave much more predictable than each single person on its own.

[Miguel] What we need to do is integrate this, what we call uncertainty, into the optimisation. We’re optimising with uncertainty. And indeed the simpler you can do it, the better, and when working on engineering problems, what is often a good approach is that you’re really trying to help somebody else solve a problem, because they are experts in the area of whatever engineering area you’re working in. And so you come up with a simple model, you show them the results, and then they say: “This is not good," and you say: "Fine, tell me why it's not good." And then you go back to the drawing board and you improve your model, you run it again, you go back and you say: "What about this one?" And you do this iterative process where you start with something simple and you stop making it more complex as soon as you have something that does the job. Sometimes you need to go into very complex models to capture very complex situations, but that's because you have no simpler solution, it's not because… I suppose that I could say as a mathematician I like to look at complex things and have very sophisticated systems and analyse their intricate behaviours, but if you want to actually solve a real problem, you want the opposite: you want to make it as simple as you can to also make it more robust, and more reliable in practice.

[Lars] An example I like to bring up is a former colleague of mine experienced the following: he worked with a railway company and had a model for a problem in freight railway optimisation, and he had a very intricate optimisation model, how to route freight trains around. And finally he had incorporated all their rules that they had, all the speciality rules and so on, and he'd gotten real data from the company, and was finally able to optimise on the scale that they wanted, and produced the optimal solution in his model, and presented it to the people, and they compared against the real world solution by the real world engineers who had planned that day, and the real engineers were much better. The obvious question was: how was that? And then they went into both plans, compared them and saw that the real solution violated a lot of the rules that they had given him. And the question was: why could you violate this? "Yeah well of course we could violate this because we phoned ahead the colleagues at the stations, who can manually override the rules if you phone them in advance and make sure that there's enough personnel at the station, to sort of make a security check that you don't have to obey those rules." And that made it obviously very frustrating for my colleague, at that point, to say: "Okay that's interesting, but how do we get from here?" And that is sometimes where we have to really take into account what is sort of… Where's the border of what we can model and what we want to model, and what we can actually do with these systems. And the answer is to think about what we want to use it for because it was not meant for automating the system, it was more meant for planners to have an idea of how congested the system might be, well then it's fine to have rules and obey the rules even though in practice you might be able to bend them a little bit.

[Helena] I suppose an added difficulty is trying to make sure that the system can resist anything that you don't expect? So I know that Tom and I were thinking about how difficult it must have been to adapt to the pandemic with how suddenly people's patterns of energy usage had shifted.

[Miguel] There was something very interesting that happened in that regard. One of the areas where we use optimization to solve the problem, and we can't play with the rules in the way that Lars was describing, is in clearing energy markets, electricity markets, and coming up with the flows of electricity and the prices of electricity. And the system is designed for a particular way of consumption, and especially a particular quantity of consumption. What happened in the spring, when the pandemic hit, is that a lot of economic activity stopped, and as a consequence, the electricity consumption went down, even though people were still consuming, you know instead of consuming at work, you're consuming at home, but if the factory has stopped, well guess what? All the electricity that that factory consumes is not being used. And so suddenly there was this significant amount of energy being generated from, in particular in the UK from wind generation, that didn't really have anywhere to go, because we had no consumption. And so we had extended periods with what are called negative prices. People would actually be paid to consume electricity. There's too much electricity in the system, and when you follow the rules, you get an optimal solution that says you actually want to pay somebody else for consuming electricity, which is completely unusual. So there was a period of a few weeks in the spring when this was happening, and then when economic activity started again, it stopped. Now it happens only rarely, but there was a period where this was happening a lot because the optimal solution was: I pay customers to use electricity, and there is no cheating with the rules, because the market is set the way it is by the regulator, and you can't tell the regulator: "Actually, we'd like to change the rules please so that we…" "No, no, no, no, this is in law. This is completely fixed." So sometimes the optimisation gives you results that are completely unexpected, but then you think about it and you realise: "Oh yes, actually now I see why this is happening," but *a priori* you would not come up with that solution.

[Helena] Yeah, it seems absurd.

[Miguel] But it makes sense! Once you understand enough about the situation and the problem, it makes sense. So that's definitely one aspect where the pandemic hit a lot. Obviously, in other areas of application there would have been significant impacts as well.

[Lars] Certain power plants, for instance, they take a long time to shut down, so often you want to run them… Even if you lose some money if you let them run, you just want to let them run because you don't want to ramp them down and then ramp them up again. You want to generate that electricity, but it has to go somewhere from a technical standpoint. You can't not not consume it, somebody has to do it. So it might be a good idea even to pay someone to consume it, just so you don't have to power down your power plant and then power it up again. On the other hand, you have regulatory aspects that certain people have the right to put in energy into the system, at any time, to incentivise building these plants. People built these big systems of rules, and simply physical reality that interact in a way that nobody has expected, and suddenly you need to make sense of that, and there mathematical models can really help you to untangle all these unexpected interactions.

[Tom] And it seems like potentially with smart grids, they're kind of throwing something else into the mix. They allow some amount of dialogue between the producers and consumers of energy to help deal with these situations?

[Miguel] My way of defining what a smart grid is: it's an electric grid where you have electricity going, not only from the generator to the consumer, but also from the consumer to the generator. What does that mean? Well what it means is that people can now generate electricity in their own homes, or anywhere where they are with solar panels for example that are becoming more and more common, and then as Lars was saying, this electricity has to go somewhere, and so you may sign an agreement with the power company that it will accept the power that you generate but if everybody is generating more than they consume, power has to go somewhere and so you end up with strange situations that the original system was not designed for.

Because the original system was built on this concept of, like Lars was saying, you have big generators that take a while to start and a while to stop, and they produce lots of electricity in a few points in the country, and then that electricity is sent all over by the transmission system to where it's needed. If you now have electricity coming the other way, uh hang on, we have to think about what this means, and how are we going to manage this? And what are the consequences that are not necessarily obvious about these changes in rules and changes of technical reality that can bring about all sorts of surprises, which means that together with this two flow of energy, you need to have a two-way flow of communication, between all the entities and the systems, so that there is some better understanding of what is going on.

[Lars] The information flow is often hoped to, as Miguel said, to have some decentralised, better decentralised control of the system, instead of having a just centralised system that says: "Now we know what is going to happen, everything is pretty clear, we know we have a sort of… The old concept, we have a baseload, and then we layer on top different types of load depending on the time of day." Everything should be much more reactive and quicker, and that means some amount of decentralisation, and much more communication is needed. So at some point people hope to even manage parts of the demand, and telling people: "Now it's a good time to do something, because electricity will be cheap." And this type of control that you, that the system tells a consumer: "Hey, by the way, it might be interesting to consume much electricity now," is something that is not something that we can do very well right now. Say if you have some big consumer of electricity, like say a supermarket that is running big refrigeration units or stuff like this, a big cooling system, maybe it might be interesting to cool a little less for some time, even though you still… As long as you keep all the health rules intact, or cool a little more at some point, and use a little more energy, and sort of save this. Probably you'll see this first only in sort of very big units because there you get most use out of this communication, and people will be willing to do changes because they really look at the bottom line. There are small scale experiments which I don't think -- but Miguel might disagree with me on that -- which I don't think will be coming soon, which is where people always say well, maybe you will leave clothes in your washing machine and then the system will tell you: "Now is a good time to run the washing machine," as a sort of big user of electricity, I'm not sure that that will catch on that soon, because people will not be happy to just leave their clothes in the washing machine on the off chance that now is the time to do the washing.

[Helena] I mean it's, it's funny that you say that 'cause I grew up in Kenya where, actually electricity was really spotty, so sometimes you had to just put your clothes in the wash and hope that at some point during the night it would turn on. Or for example, you knew that you would get electricity from say, midnight to 6am, so that's when you had to run anything electrical that you had. And people just functioned that way because, I guess there was no other option.

[Lars] That's still more plannable that when people expect it. So for this demand management, when they say "Well you just put it on the off-chance that sometime it might", and you don't really know "Of, it's from midnight to 6AM," they just know it might be anytime, right now.

[Miguel] I think we actually agree on that, in the sense that people have to have convenience at the same time, and it has to be reasonable. And there is a major challenge going on with smart grids, which is the question of storage of electricity, storage of energy. We've been talking about all this business of, you know, we're generating and if it's not needed what do you do with it. Implicit in this is the assumption that electricity cannot be stored, that if you generate it you have to consume it. And so the big challenge now is: can we have storage of large enough quantity that we can manage this problem without having all this fuss of washing machines? We just say: "Today there is more electricity than we need, we store it. Tomorrow we have less generation that we need, we use it." And we've made a lot of progress with energy on batteries, specifically in particular for electric vehicles that are becoming more and more autonomous, as the technology progresses, but those quantities of energy that you store in a car, in an electric car, are very small compared to what you need to run a grid. And so there's a question of: can we get big enough storage to really make this balancing of the system without having so many issues with small amounts of energy, or without it getting to the point where we have to say "You only get energy from 12 to 6 and make the most of it because that's what you get for the day"? Things like this could happen if there's no other way to manage it.

[Tom] As we are looking to move… To decarbonise energy production and move towards renewables, does that seem possible within the next 30 years, the timeframe that has been set?

[Lars] So decarbonising electricity, I think for many countries will be very possible. But then you come into other questions like decarbonising heat, which is a whole different thing, where you have the question: how do we replace, say, natural gas, in a short enough timeframe, and how do we integrate this? Because, generating electricity, we have lots of technologies that are proven, we have still the storage problem, but that's something where you have ideas on how to work. On the heat side I think there are quite a lot of challenges that are still open because we're not really sure… We really have very different technological paths which we might want to choose.

[Helena] And I guess it depends as well on what's available from country to country, the different energy mixes and that kind of thing. I watched one of the talks you gave, Miguel, where you were talking about how it was so different in Canada compared to other places where you'd worked, just because the energy mix was so different. 'Cause I think Canada depends heavily on hydroelectricity?

[Miguel] Yeah, it depends which area of Canada, but in several parts of Canada, the electricity system is essentially 100% hydro, or almost, and so, if you have… And we're talking hydro in the sense of having a huge water reservoir, and a huge dam that allows you to put the water through the turbines to generate electricity. If you have that, it's decarbonised, right? You can generate electricity without carbon. So you're done! And a lot of these issues of generating to balance the system and too much and too little go away because you can control the flow of water going through so we're fine. The big challenge is: are you going to run out of water? Because if you run out of water, goodbye. No electricity. So a lot of the issues that other countries struggle with become very simple, but now you have this long term forecasting and planning problem of: how do I make sure I don't run out of water in 5 years, in 10 years, in 20 years? Because if I suddenly have a drought, I don't know how long it's going to last, I don't know when it's going to come, you know? So that becomes the stress point, is how do I make sure I have enough water.

If you move to the UK, we're now in a system where the wind is going up a lot, and we have some nuclear. The combination of wind and nuclear makes it complicated, because nuclear tends to be very fixed in terms of output, it's very hard to fluctuate nuclear, and wind fluctuates a lot, so how do you manage this combination of things that behave in very different ways, and you want to try to follow the amount of energy that people need? You don't need to think 5 years, or 10 years, or 20 years down the line, it's here and now, how am I going to balance the system? So you get very different issues depending on the nature of the system. And then we start asking questions like we're asking in the UK of, well, should we build another nuclear plant? There's the whole cost issue, which is not trivial, but even if you leave that aside, is it really the best choice, from a purely engineering viewpoint, a purely providing-the-needs-of-the-country viewpoint.

[Lars] And, I mean, I mentioned decarbonising heat which is obviously more the problem of a country like the UK or specifically Scotland, whereas other countries often struggle with decarbonising cooling, or having a good cooling system. That is something very specific to each region and each country, what they need. And often there are good historical reasons why countries have developed like they have developed, and you can look at the history, and that also gives you a hint where the problems lie and who are the stakeholders that you need to discuss things with. So you cannot… We can build these models and say: "Well this might be optimal," but often people came there for a reason and you have different stakeholders who have different interests, and you have different combinations of technologies that people want to use, or have used, and so that's something where our models can help but they are definitely not the end all be all answer for these questions.

[Tom] You mentioned dealing with these long term issues. I read a really interesting Nature paper recently where they actually used optimisation to determine where the best places to restore habitat were. I just wondered if there were other kind of big challenges where you can use optimisation to really make a dent in them I suppose.

[Lars] I think often we have these sort of very specific questions where people know a general direction where they want to go, but they want to now know how to make the detailed planning. Some colleagues of ours in the Netherlands have worked on where's the optimal place to put in, to strengthen dikes and put up dikes to prevent floods. So they have a big project where they said: "Well, we could just raise every dike by a certain amount, and then we would be fine, but that's probably not the best way to do it." But if you then more detailed, how the system might evolve or what floods might come, then you can sort of decide well the most important parts to really reinforce the system. So these kind of questions are often where optimisation models can help you to fine tune your decisions, and sort of make the best decision, once you have a general idea where you want to go, and our role as people from optimisation is simply, not only to do the modelling ourselves and then solve it, but also simply provide tools that other disciplines can use without us having to talk to them, so that they can just use it and know it's okay and it works, and they don't have to worry about complicated things, and how this actually works and what happens, they can rely on the tools, and I think that's a big role of us.

However, for many problems we can't do that yet, and so it's important to have this dialogue between people who want to apply our methods and our methods, to get the point where we can say: "This technique is now… This technology is now reliable for non-specialists to use," so that they can just use it and know they get good results, and they, with their domain knowledge, can focus on modeling the problem and just using mathematical technology without having to worry about, sort of "Oh, if you do it this way then nothing will work, you have to do this trick that only the specialists know and then everything becomes easy or so."

[Miguel] The ultimate is something like the Google Maps system that we were talking earlier of you don't have to know any mathematics. You take up your phone, you say where you want to go, and it will tell you how to do it. And it's completely transparent to the user even though there's a lot of mathematics behind it.

[Helena] I think that brings us to quite a nice, nice little…[1] back to the start. But we like to finish by asking people what are the least favourite and most favourite things about their job.

[Miguel] For me, it's clear that the best thing that I like about being an academic, being a professor, is the freedom. You have a lot of freedom in terms of what you do, the research you do. Even when you teach, you have a lot of freedom in how you teach and how you present things and so on. So we have an important role to play, we have a job to do, but we have a tremendous amount of freedom in the way we carry it out.

The worst thing about it is the freedom, because you have so much freedom that you have a tendency to want to do too many things, it's easy to overcommit, it's easy to also become a perfectionist, because in some sense you can keep improving your solution as much as you want, so where do you stop? It's a risk that there is no boss that tells you: "Okay, fine, stop. This is good enough, move on to something else," because you have the freedom to explore the problem as long and as deeply as you want. So it's really balancing… this balancing act of having so much freedom to work with that is both the best and the worst of the job for me, but I love it! I think it's a fantastic job.

[Lars] For me it's really… It would really say, being exposed to new problems, and seeing new problems from all areas is what I like. I mean it ties into the freedom thing of course, by having the freedom to pursue this, but nevertheless it's really this is the most specific aspect that I really like, to see new things and say: "Oh! This is interesting, how can we do this?"

Similarly the worst thing is really this big pile of open problems and projects that are not yet finished, and where I'm not really sure whether I will ever finish them. And where I have to decide whether I should finally say that I will never finish them, or where…

Laughs.

That is essentially what I would say is the worst, to know that this more metaphorical than real pile exists, yeah, that's probably the worst.

[1] Loop, loop is the word I was looking for. Or a circle?

[Helena] I mean, if it’s any reassurance, I think that applies to most jobs. Well thank you so much, to both of you, for a really interesting conversation. I was… I think we were both really nervous that we would be really confused and not really think of any questions, but it’s been really interesting.

[Miguel] Good! Wonderful.

[Tom] Yeah, we understand optimisation now. We are masters.

Everyone laughs. Outro music starts.

Yeah, it’s been a pleasure.

[Miguel] Thanks for having us.

[Lars] Exactly, yeah. Thanks!

Outro

[Tom] Massive thank you to Miguel and Lars for coming on the podcast. It was such a fascinating conversation, and they were both very understanding of our serious lack of mathematical knowledge. They are both part of the Edinburgh Research Group in Optimisation, so if you want to go and have a look at the research they’re doing, you can head to their website at maths.ed.ac.uk/ergo. And as usual, we’ll put all the links in the shownotes.

[Helena] This episode brings us to the end of our very first season, and it’s been a wild journey, let me tell you. In each episode, we explored fascinating themes and ideas, talked to awesome researchers about their work, and found out about the science being done by our very own staff and students, here at the University.

[Tom] If you have any feedback for us, or if you’d like to get in touch with a question or suggestion, you can reach us on our Facebook page, Edinburgh University Science Media, or at our Twitter @EUSCI, that’s @-E-U-S-C-I. You can also drop us an email at eusci.podcast@gmail.com and you can find the show notes and the latest issues of the magazine at eusci.org.uk. We’re already planning our second season, so if you’d like to be featured on the podcast, please get in touch, and keep an eye on our social media for more information.

[Helena] This episode was co-created by me, Helena Cornu, along with my partner in crime, Tom Edwick. The podcast logo was designed by EUSci chief editor Apple Chew, and the awesome podcast episode art was designed by Heather Jones, our social media and marketing genius. The intro music is an edited version of Funkorama and the outro music is an edited version of Funk Game Loop both by Kevin McLeod. Thank you for listening, and until next season,

[Tom] Keep it science.

Outro music ends.

Post-outro shenanigans

[Helena] And as a special bonus, here is proof of Tom's inability to say the word laboratory.

> **[Tom]** Supplying labor-, ooh labor-, la-. Why do I struggle with that word?
>
> **[Helena]** *Laughs.* I know, every time.
>
> **[Tom]** Okay, I will start from "Supplying…"
>
> **[Helena]** Okay, go. Oooh okay.
>
> **[Tom]** Labo, lab… What is that word?
>
> *They laugh.*
>
> **[Tom]** Labratory, labratory.
>
> **[Helena]** *Still laughing.* Please send me this audio, I'll put it at the end.
>
> *Tom laughs.*
>
> **[Tom]** Lab, labo, lab… Labratory. Labratory. Labratory.
>
> **[Helena]** You can do it!
>
> **[Tom]** Is that a word? You know when you say a word so much that it doesn't sound real anymore. Alright, I'll try my best.

[Helena] You can do it!