**Sue Nelson**
Hello, I'm Sue Nelson and welcome to the Create the Future podcast brought to you by the Queen Elizabeth Prize for Engineering, celebrating engineering visionaries, and inspiring creative minds.
[Music]
Mark Girolami studied mechanical engineering at the University of Glasgow. Today, he's a Professor of Civil Engineering at the University of Cambridge and Chief Scientist of the Alan Turing Institute in London, the UK's National Institute for Data Science and Artificial Intelligence. During his career, he's also been the chair of statistics at Imperial College London, and a chartered engineer at IBM. So, you can see how this background makes data engineering a natural fit. In a moment, we'll hear about his work on the world's first underground farm below London's Clapham High Street, but we'll begin with how big data was incorporated into engineering practice in the form of a ground-breaking smart bridge.

**Mark Girolami**
It is our pedestrian bridge located in Amsterdam, and it spans one of the canals, it was made in such a way that the material stainless steel was printed additively. And the printing was carried out by robots, that were able to articulate themselves right around 360 degrees, to lay up the material in the additive form. It's the first time that a publicly available pedestrian bridge has been constructed using this type of technology. And so there were a huge number of technical challenges and scientific challenges. That's really when the Alan Turing Institute got involved with this project.

**Sue Nelson**
Now, this bridge is being called a living laboratory, what else was in this bridge that made it be called that?

**Mark Girolami**
One of the big innovations here was that we were able to think about actually putting sensors on the structure that would allow us to, on a continual basis, monitor the performance of the bridge, you know, people sometimes ask the question, 'What do you mean by the performance of the bridge?' a bridge conveys people from one side of, you know, a river or a canal to the other. And that's about it. But of course, one has to think about the integrity of the structure to the various loads that it experiences and then therefore, continually think about monitoring its performance in terms of its safe load bearing capability. Rather than estimating, you know, what would be the greatest load that this bridge could ever experience and then multiplying it by some big factor of safety, and designing and constructing the structure to withstand that, what the designers were able to do was to say, well, we will be able to monitor the performance, we will to monitor the structural integrity on a continual basis, and use that to assess how well the structure is performing. And so the whole question of what are the material properties of 3d printed steel? And what are the structural properties of something like a bridge that has basically been printed from stainless steel? Now, when the outset of this project that wasn't known, and our team we had a multidisciplinary team of material scientists, applied mathematicians, computer scientists, structural engineers, all working together to try and understand what are the properties of the material? What are the structural properties and the levels of integrity that one can expect and guarantee of such a structure using this novel type of construction process, and ultimately material itself. Although we have been able to assure the structural integrity of this structure, this isn't going to be the first one, there are going to be others, which are going to have longer spans. So, the reason that we are calling it a living laboratory is because we are able to, to basically monitor its heartbeat, if you will, on a continual basis, and use that data to study how it performs both historically and into the future. And coupling with the data that comes from this structure, this physical asset, if you will, there is also a digital component which has been developed, one calls them 'digital twins'. So, this is the digital asset, the digital representation, the computer representation of the actual bridge. And what that allows us to do is take the data, take the measurements from the bridge, and fold them into our digital twin and then play out scenarios on the bridge. What happens if

your ambient temperatures reach a particular level that has an impact on the overall structure, including retaining walls and so on? What happens if a whole lot of people potentially close to exceeding the safe operating load are acting in a way that starts to create dynamics that we haven't really been able to think about. This coupling of the physical asset, the physical bridge with the digital representation of the bridge, its twin, the digital twin, allows us again, further access to gain insights into the performance of what is essentially a novel structure, constructed in a novel way using novel materials.

**Sue Nelson**
Now, this 3D printed bridge, it was built to be smart, you knew you were going to be using sensors and getting all that data that you wanted, is it possible to sort of retrofit existing structures to make them smart, as well, so that you can build digital twins of current bridges?

**Mark Girolami**
Yes, absolutely. And in fact, my current role at the University of Cambridge where I hold the Sir Kirby Lang Professorship of Civil Engineering, my predecessor, Professor Lord Robert Mair, was one of the pioneers in producing what is commonly referred to as smart infrastructure. And that's the development of sensors and sensor networks and retrofitting them to structures. So that the structure becomes smart, so that we can obtain data and we can obtain insights into the integrity of the structure. And one example of this is a viaduct in Leeds, in fact, so in England. This viaduct is about 150 years old, if you look at it, it's covered in cracks, it's covered in, it's very clear, that has been a lot of maintenance work over the last century and a half. And some of these cracks were actually growing and looking to be quite dangerous. And so Network Rail, who were the operator, they were looking at, basically, you know, taking this this structure down and rebuilding it. The cost of that, which of course included the cost of shutting down a main central area in a big urban environment like a city such as Leeds, was going to be quite a colossal given the inconvenience that it would cause the city and what Robert and his team did is they retrofitted the structure, this viaduct, with a whole network of fibre optic sensors, and over a period of time they monitored the performance. And the evidence that they accumulated from the data was such that that the structure was probably good and safe for another 150 years. And so there was no real need, there was no real immediate need to demolish the viaduct and build a new one. I think that's a really good example of how smart infrastructure and data driven, if you will, data centric methods of engineering allow you to make better and better informed decisions at this sort of scale.

**Sue Nelson**
That's a really good example and you can see how it would, well for starters, save an organisation money as well as the fact that as you said, in terms of allow longevity of existing structures, are there any other organisations or companies that are using digital twins as well?

**Mark Girolami**
This notion of the digital asset being coupled to the physical asset and using that at all stages, whether it is for redesign, whether it is for control, whether it is for monitoring and assurance purposes, it actually, this concept cuts across just about every sector, you can imagine, from agriculture to structural engineering, geotechnical engineering, aerospace engineering. Rolls Royce, were probably the pioneers of this whole idea of development of digital twins, you know, coupling a computer based representation of a gas turbine to the actual gas turbine, which itself is heavily instrumented, lots of data and lots of information about performance and so on. So, aerospace uses digital twins quite an awful lot. The process industries, food industries, and even in medicine. So, we are working with a team at St. Thomas's in London, who have been working for quite some time on what one could describe as digital twins of cardiac systems in human patients. So, this is a very general concept, its implications and its applications spans you know, not just the engineering sector, but many different types of sectors. Another example is one where we are working with financial regulators and they are building what one

would call ‘digital twins of financial systems’, economic systems, this is a very powerful, very wide ranging concept that has huge implications in terms of safety in terms of efficiency, in terms of economic viability, and so on.

**Sue Nelson**

At the Alan Turing Institute, your data centric engineering programme is also working on a number of quite a range of projects. And I was interested to see that you were working with the world's first underground farm which to be honest, I had never heard of and it's below a station, isn't it? Could you explain where this underground farm is?

**Mark Girolami**

There are a number of disused undergrounds. And when I say underground, I mean, London tube lines, in London, a very enterprising company had the idea of using that space to grow herbs, to grow, you know, green vegetables and supply that particular food market. And using technologies such as hydroponics. What's very interesting about using disused tube lines is that there's a number of interesting challenges. One is you don't have natural light, you don't have natural ventilation, and so the control of the environment. On the one hand, it may well be easier to control than standard farming, agricultural farming. But on the other hand, the physics of removing heat, of removing carbon dioxide, of controlling light underground is actually quite a challenge. And so, our team at the Alan Turing Institute and our partners with the Centre for Smart Infrastructure and Construction at Cambridge, they worked with the company, the farmers, in developing a digital twinned system to control and ultimately to optimise the yield from the farm itself. And that comprised of several things. So first of all, the development of the appropriate types of sensors that measured levels of $CO_2$, that measured environmental conditions such as humidity, rates of heat removal and various other indicators, getting those types of sensors, those types of sensor networks deployed within the farm, and then building the digital representations of the physics and of the environment within the farm, and then coupling those together in such a way that what you could then do is you could start to play out particular schedules to optimise yield of certain crops. That's been really fascinating, because clearly the sort of herbs that are grown in this farm are going to lots of the top class Michelin starred restaurants in London. So, everything has been growing locally, almost under their feet, as it were, rather than having to be shipped from wherever. So, the implications of this locality of agriculture are really quite far reaching and really important.

**Sue Nelson**

Did the pandemic change any of the projects that you've been focusing on during the last sort of 18 months or so, coming up to two years now?

**Mark Girolami**

Yes, we have been partnering with the Mayor's Office, the Greater London Authority on tackling the air quality crisis within London. We were approached by the Greater London Authority to help them in reaching some of the targets that the Mayor's Office had set in terms of levels of improvement of air quality in London. And one of the big issues that you face in doing this, and there are many big issues, I must say, it follows the dictum of the great Victorian engineer and physicist Lord Kelvin, who is famously quoted as saying that if you want to improve something, you have to measure it. So, if you don't measure something, then you can't improve it, it was absolutely clear to us that one of the things that had to be improved was the way in which air quality was being measured and subsequently reported across the capital. And so, we had a team of research scientists that were working on ways of super resolving the air quality measurements within London and making much more refined maps of the hotspots of certain levels of pollutants.

**Sue Nelson**

Would you class your digital twins under the umbrella of artificial intelligence?

**Mark Girolami**
When we talk about artificial intelligence, we should think of what that actually means in reality, and artificial intelligence as we talk about it is very much an umbrella term for a set of technologies that we can use for our benefit. And these technologies, the sort of technologies that we take for granted in our mobile phones, the face recognition with our personal assistants that recognise our voices and activate themselves and so on. These are technologies which are based on three components, three ingredients, and the three ingredients are data, advanced computer systems, and very clever algorithms. And together, they provide technologies which go under the banner of artificial intelligence. Working with that definition of artificial intelligence, then yes, I would claim that digital twins are use cases of artificial intelligence technologies. And in fact, one of the things we are discussing at Turing at the moment is that digital twinning and digital twin capability may well be one of the biggest use cases for artificial intelligence technologies that is going to emerge. If you think that digital twinning is going to have major impact in medicine, it's having major impact on structural engineering, as we discussed, it's having major impact in agriculture, it's having major impact on climate and weather. There isn't really any area that isn't being touched by digital twinning. And digital twinning in this sense, is being enabled by artificial intelligence technologies, which of course, are comprised of the need for data, the need for advanced novel computing systems, and the need for clever, mathematically sound efficient algorithms. And you put all that together. And what you end up with is what we understand today as AI. It's the umbrella term that we use for all of these different types of technologies, whether it is speech recognition, speaker verification, facial recognition, gesture recognition, and on it goes.

**Sue Nelson**
And what was it that made you end up working within data centric engineering, because you'd studied mechanical engineering at Glasgow University, I know you spent a long time at IBM as a chartered engineer as a computational statistician. Was it sort of gradual evolution that you began to realise that data centric engineering was this exciting area, or did you have a moment of inspiration?

**Mark Girolami**
In terms of my career, I was very happy being a professor of statistics at Imperial College and the maths department there and probably would still be there and still be very happy if the call hadn't come from the Alan Turing Institute asking me to lead this programme that they were starting on data centric engineering, and I'd never heard of the term data centric engineering. So I was intrigued and as a term sounded quite exciting, and I was persuaded to lead and define this whole programme on data centric engineering. I should say that the whole phrase is actually quite a strange one, because the idea of data centric engineering is absolutely nothing new in engineering, engineering science, the practice of engineering has always been centred around data, the empirical laws of geotechnical engineering, the empirical laws of fluid mechanics and fluid dynamics, the empirical laws of soil mechanics are all based on experimentation, measurement, and ultimately the gathering of data and then drawing conclusions and then inferring laws from that data. So, engineers have been doing data centric engineering forever. So, there is nothing new. But what is new is the ability to gather data, the development of sensors, of sensor systems, of networks of sensors to measure at large scale, whether it is the use of satellites to gain images of landmass, or whether it is nanotechnology style sensors that are allowing us to measure the activity of proteins in a particular fluid. Under every scale in-between those, our ability to gather data on physical, chemical, natural processes and engineered systems has just exploded within the last 20 years. And so, what we now have are incredible opportunities to learn about new complex processes via data, in the same way that, you know, the founding fathers of various engineering disciplines that they conducted experiments, made measurements, gathered data. And then inferred laws from those, we are now being able to do that at scales, and at speeds that we never were able to do before. It also means that in terms

of the practice of engineering, that we were talking about smart structures and smart infrastructure. Well we have smart devices, whether it's our phones, whether it's our watches, whether it's our Fitbits, they are all gathering data, and using that to, in many cases, make our lives better, but it means then that new opportunities, new markets, new businesses are starting to emerge. And so, all of this together, then also motivates the requirement for the development of new theory, new foundations, new technologies, new products, new services, new processes, new businesses, new markets. Then that makes this area of data centric engineering, on the one hand, nothing new, but on the other hand, such an inspiring, exciting place to be working and to be leading in.

**Sue Nelson**
And for those who are listening and who are inspired and thinking 'this is perhaps an area I'd like to go into', would you say that the sort of engineer you are looking for is an engineer who's heavily into the maths side of things, the stats side of things?

**Mark Girolami**
We need engineers that are heavily into everything and clearly, you know, these renaissance type people are few and far between. What we need are multidisciplinary teams, teams that bring different aspects of disciplines, whether it is mathematicians, or computer scientists, computer programmers, artists, ethicists, bringing these multidisciplinary teams together is probably more important now than it has ever been. And the example that I gave you the 3D printed bridge, we had to bring a multidisciplinary team, as I said, of structural engineers of material scientists, of statisticians of mathematicians, stochastic geometers, computer scientists that worked on a machine learning, computer scientists that worked on detailed simulation systems, and bringing them together to be able to work on a common cause was the way that we were able to succeed with that project. And we're seeing that more and more in the engineering sciences that these silos of mechanical engineers or civil engineers or chemical engineers have been broken down and becoming much more diffuse.

**Sue Nelson**
Professor Mark Girolami, thank you very much for joining me on the Create the Future podcast. Find out more about the Queen Elizabeth Prize for Engineering by following @qeprize on Twitter and Instagram or visit qeprize.org. Thanks for listening and join me again next time.