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**Tom Daniel:** Therein lies the massive fundamental difference between sort of synthetic systems and living systems. It's that ability to be plastic, and in part, we built systems that aren't going to change, on purpose. We don't want them to change. Heaven forbid should my car decide, you know, “Nah, I'm not going to do what you say, you know? I'm sorry, Hal, I can't do that.”

[MUSIC]

**KEVIN SCOTT:** Hi, everyone. Welcome to Behind the Tech. I'm your host, Kevin Scott, Chief Technology Officer for Microsoft.

In this podcast, we're going to get behind the tech. We'll talk with some of the people who have made our modern tech world possible and understand what motivated them to create what they did. So, join me to maybe learn a little bit about the history of computing and get a few behind-the-scenes insights into what's happening today. Stick around.

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Hello, and welcome to Behind the Tech. I'm Christina Warren, Senior Cloud Advocate at Microsoft.

**KEVIN SCOTT:** And I'm Kevin Scott.

**CHRISTINA WARREN:** And today our guest is neuroscientist, Tom Daniel.

**KEVIN SCOTT:** I had the chance to meet Tom a couple of months ago in one of these conversations that I've been having with a bunch of biologists and bio-scientists about their work, and Tom was showing me some of the really mind-blowing stuff that he's been doing in his laboratory on bioengineering and biomechanics at the University of Washington, and I thought he would just be an amazing guest to have on the podcast.

**CHRISTINA WARREN:** All right, well, I know that you two have a ton to talk about. So, let's just get into it.

[MUSIC]

**KEVIN SCOTT:** Our guest on the show today is Tom Daniel. Tom has worked at the intersection of biology and engineering for more than 35 years. His research and teaching meld neuroscience, engineering, computing and biomechanics to understand the control and dynamics of movement in biology. At the University of Washington, he's a member of the neuroscience faculty and a professor. Tom is a recipient of a MacArthur Genius Fellowship, and he received his PhD in Biology from Duke and did postdoctoral work at Cal Tech. Welcome to the show, Tom.

**TOM DANIEL:** Great to be here Kevin.

**KEVIN SCOTT:** I love to start these conversations by learning a little bit about how you first got interested in science, in general, and maybe in particular, like how you decided that this interesting melding of disciplines was the thing that you were passionate about.

**TOM DANIEL:** Sure, I think it's to some extent genetic. So, I come from a family of refugees and Holocaust survivors. I'm first-generation US. So, my parents directly had no college education, but my grandparents did. And my grandmother was a physician. She got her MD in 1913 in Germany, and her relatives included a lot of physicists. So, we had this weird mix of medicine and physics, growing up, in the family, and so as a kid, that was sort of in the air, as we were growing up.

I never quite knew whether I wanted to do physics, biology, math, engineering, and to this day, I still don't know. That’s where it all came from, and really, really good biology teachers in high school, and then in college I sort of never made up my mind. I did a bit of engineering, did biology, just kind of spread myself over the place–

**KEVIN SCOTT:** Well, and so talk a little bit more about that because sometimes that can be a hard thing. Like we have – in society sometimes, and in – in like especially I think in some of our institutions like we want to push people into like very specific directions. Was there anything that helped you with this wonderful dilemma that you had of broad curiosity?

**TOM DANIEL:** Yeah, so, so I sort of have two responses. One is what helped me, but also, I think the world has shifted since I was in – an undergraduate. As an undergraduate, I was – I remember distinctly taking an engineering class, and there was a professor also sitting in on the class. This is very rare, at the time, and he happened to sit next to me. And he was a biologist wanting to learn more engineering. And we got to talking, and I just found it fascinating that you could mix these two. There was no such thing, as a bioengineering department. It did not exist back in the time Noah. (Laughter). But his name was Warren Porter, and he melded physics and biology in a very interesting mixture of heat transfer and animals in different climates, and I just found that fascinating.

After a while, he said, “Hey, do you want to join my lab and be a grad student?” And I didn't actually know what graduate school was. I said “Sure!” And so that got me going in this interface. I think today we are really doing more and more to break those barriers. So there are bioengineering departments. And candidly, the word "bio" comes in front of lots of words, you know, bioengineering, you know, biomathematics, biophysics, biochemistry, you know, so.

**KEVIN SCOTT:** So, tell us a little bit about your research that you did as a graduate student.

**TOM DANIEL:** Yeah, I did two different things. So, I started a master's degree at Wisconsin, and I got my PhD at Duke. At Wisconsin, because I was really interested in fluid mechanics, that faculty member said, “You know, fish swim really fast, why is that?” And there was this theory building in the literature that there's something novel about the polymer coating of fish, mucus, right? And nobody had really looked at it in any detailed way. And so, he got me into his lab, and we started doing fluid dynamics experiments on what was called polymer drag reduction. And I ended up publishing as a second-year graduate student, a paper on polymer drag reduction, the novel sort of chemistry and physics of the slimy covering of fish. That's where I began.

**KEVIN SCOTT:** And so– like, you know, whenever I hear fluid dynamics, like I can sort of visualize Novier-Stokes equations and my exposures to fluid dynamics has always been less about the analytical modeling and more about computer simulation of these systems, so were you doing computer simulation stuff in your graduate work?

**TOM DANIEL:** Not then. So, Kevin, I have to remind you of era. (Laughter). This is the 1970s, and yes, I did computer simulations of flow in my undergraduate classes. It was FORTRAN, and we had to write our own numerical solutions to very, very simple things, okay? The project I worked on in my master's was much more a mixture of experimental fluid mechanics and imaging flows, okay?

**KEVIN SCOTT:** Oh, interesting.

**TOM DANIEL:** Then, at Duke, I moved onto looking at a couple of different flow problems in biology. We got very interested in the fluid mechanics of insect feeding, like mosquitos, blood feeding, and things like that-- what is going on that allows the mosquito to feed on blood, how is this related to disease transfer, like malaria, what are the relationships there? And also locomotion and fluids, movement and fluids. And so, it was a variety of things like that, and again, a mix of computational work, and then experimental work.

**KEVIN SCOTT:** I've seen a bunch of your work, which is just absolutely fascinating. So, is your PhD work where you really started thinking about sort of the biodynamics of movement and how you could sort of combine these two disciplines, like how you sort of engineer things to navigate in the real world, inspired by biology?

**TOM DANIEL:** Absolutely. That work was done at Duke, and there was this sort of emerging area at the time. It was called comparative biomechanics. That is looking to the engineering of living systems to figure out how they work, what are the rules governing how they work, and also as inspiration for novel engineering ideas. I worked on a couple different aspects, some at the more cellular level of muscle force generation and what's going on at the level of molecules creating forces in muscle cells. And the other is muscles running movement in whole organisms.

**KEVIN SCOTT:** The thing that I was just blown away with is some of the work that you've done, and this is like skipping way forward on like how insects navigate the world where you're creating these links between their neurobiology and sort of electromechanical systems. But like give us a practical example of like how you – like a real system that you have engineered, inspired by biology.

**TOM DANIEL:** So, maybe I have to take a little bit of a step back. So, just to remind you that movement is sort of this virtuous cycle of sensing the world, right, the information coming into a creature. That sensing is processed centrally by a brain. That brain, information that is encoded has to be decoded into muscle actions, that is controls of muscles. Those muscles have to produce forces and torques around joints and structures, which propel the creature in space, and therefore change the sensory information they're receiving. So, there's this lovely cycle of what we call the sensory motor loop, right? Part of what we do is try and step in, in various steps along that pathway. How is the sensory information encoded? How do neural systems take information like forces or smells, or light, and convert that into signals that the brain understands, which are what we call action potentials.

So, that's part of what we're doing. So, an example would be as insects fly around, they – just like when we try and manipulate something or walk, or do any motor task, we have to acquire information about forces in order for us to regulate our motor tasks. One of the projects we've been working on is how insects measure forces through novel structures. Now, this is going to go down a little bit of a gnarly path here, so bear with me. But when we experience rotations, right, we have a beautiful system in our inner ear called the semicircular canals. And those measure your body rotations through this really weird fluid flow problem of endolymph in the semicircular canals spinning, when we spin, and when we stop spinning, it keeps going, okay?

That's and everybody can experience that. Insects don't have that. They do not have semicircular canals. Now, one could say that while they don't need to measure their spin, or they do it in a different way. And as it turns out, both the wings of insects, and very strange derivatives of wings, which are found in flies, they're called halteres, are packed with mechanosensory cells, neurons, that measure the deformations of these structures, the deformation of a wing, the deformation of a halteres. A haltere is a hindwing of a fly turned into tiny non-aerodynamic knobs that flap just like wings, but they're super tiny.

**KEVIN SCOTT:** And, and so what's their function? Sorry, sorry to interrupt, like are they just – are they just sensing devices, do they--

**TOM DANIEL:** Sure, they – the halteres are purely sensory, right? They're derived from hindwings, they're like tiny dumbbells that the fly oscillates a counter phase to the wings. They're so small, there's no aerodynamic forces, but they're packed, they're festooned with sensory structures. As it turns out, they're like this little knob on a stick, and as that vibrates-- experiences bending forces-- but if the fly rotates in a direction orthogonal to the flap, it generates a Coriolis force, a gyroscopic sensor.

And lo' and behold, these systems are exquisitely sensitive to rotational forces. So, they're basically measuring–I apologize for the math–the cross product of their flap (Laughter) with their body rotation, okay? And so we – we had this idea that they're able – or they're physically able to respond to Coriolis forces, but we really wanted to nail whether the neural system actually has the equipment to measure that. And so we were able to stick electrodes into the neurons that go into these tiny modified hindwings, and measure their encoding properties, and you can show that they encode information at astronomically high rates, and do so for Coriolis forces.

But that sort of led to an interesting question is – these are what you would call a vibrating structural gyroscope, which is basically the same idea that you have in all these gyroscopic sensors in your cellphone, or anything else. They operate at a tiny, tiny fraction of the energy costs. I'm not going to stick a fly inside my cellphone. (Laughter) But bear with me, we do some odd things like that.

**KEVIN SCOTT:** So what you just described, makes me want to ask a thousand questions, but you know maybe an interesting one is in recent years we have gotten better and better at being able to synthesize, to design and synthesize some of these biological structures. And so, I know in a bunch of your earlier work, when you were trying to sort of bridge this biological electromechanical gap you were, you know, in a variety of ways, like trying to graft existing biological structures, taken off of an organism, into an electromechanical system. But like do you think that there's a possibility now that we will be able to sort of engineer these structures, a priori, where you're not having to sort of borrow them in whole from an existing organism?

**TOM DANIEL:** That’s a super question. I think it's possible. I have to be a little careful. Kevin, the hybrid system you're referring to is this hybrid system where we took the chemical sensory structures from an insect, right, andremoved it, what's called their antennae, put electrodes into the harvested structure, right, and then recorded its chemical responses, its responses to chemical signals, okay? And the reason we did that is getting close to the point you're making, which is that we, today, cannot synthesize chemical sensors with the efficiency of sensing that we see in biological systems, okay--

**KEVIN SCOTT:** Right.

**TOM DANIEL:** --today. And the reason is there's this beautiful and elegant protein amplification pathway in chemical sensing, in biology in humans, in dogs, and in insects, in everything, that senses chemicals, which is nearly every living creature.

**KEVIN SCOTT:** It just seems like just sort of an extraordinary potential thing, like this gyroscopic system that you were describing, that's biological, that probably outperforms like any of the – you know, so all our cellphones right now have a gyroscopic MEMS, you know, probably a MEMS device which, you know, through some combination of micromachining and lithography and like a bunch of complicated mechanical processes, does something miraculous, right? Like they are, there are far, far better gyroscopes than the big ones that we had 30 years ago, but they still are not even remotely approaching the performance, probably energy efficiency, you know, like – and there may be other things that you could do with your biological gyroscopic devices. And so like imagining how you might be able to use more biology to sort of synthesize some of these structures is a very interesting thought.

**TOM DANIEL:** Yeah, so, let me, let me pull on two threads. I think you bring up a really good point. Thread one is the difference between these manufactured vibrating structural gyroscopes (VSGs) that are micromachines, they're MEMS devices, is they typically deploy, in any one device, relatively few sensors, meaning they're measuring six degrees of freedom, right, but typically with not many more sensors in them, right?

In contrast, living systems have incredible redundancy. So, in the fly, there's may just on one haltere, one little knob sticking off, about a thousand sensors. Okay, maybe I'm exaggerating. Maybe it's 800, but it's a heck of a lot more than a handful, right? And the clues are two-fold. One is the efficiency of information transduction is very, very high, higher than in, say, transistor systems. And because of that, you can afford to deploy a lot of sensors.

So, redundancy is not expensive. And redundancy becomes an advantage. Okay, so that's sort of thread one, the conversion of a mechanical energy into electrical potential or chemoelectrical energy is very efficient in living systems, and efficiency we are still trying to understand, okay? That leads to your deeper question, which is there something we can fabricate that will get this level of efficiency? And the answer is probably. (Laughter) Okay?

The answer is that, with protein engineering, can we build efficient protein systems that do the sorts of energy conversion out of thermodynamic equilibrium? That is, utilizing energy, but in ways that are as efficient as we see in natural use of proteins? I think it's a fool's errand to try and recreate a cell, right, with all of the machinery and all of the machinery– all of the other chemistry that you need to – to replicate what we see. I think the smarter path will be in engineering proteins that can operate under sort of room temperature conditions, right?

**KEVIN SCOTT:** Right, and that's sort of one of the problems with your – your moth antennae example is they're perishable, so you can get the antennae off of the moths and graft them into this electromechanical system, but like they have a very finite lifetime, and they're fragile too, right?

**TOM DANIEL:** No, they're actually pretty robust, no, no, there's no problem on fragility. And you're right, they have a finite lifetime, and as it turns out, so will any sort of biosensor that you have. So, I like to draw the analogy on things that use antibodies for doing testing, or anything that uses natural materials, it's usually a disposable cartridge, or things like a pregnancy test, or an ELISA test, all of those things are sort of cartridges that you use.

Whether we can get these to operate under longer terms, that's an open question. We are able to keep these going well longer than any robot lives, so – you know, we – just like the little teeny robots that we fly them on, they have maybe a 20-minute lifetime. These sensors have hours, and if you put them in the refrigerator, you can keep them for weeks.

**KEVIN SCOTT:** I'm sort of curious about another thing which is the value of perspective, of coming at things from different directions. So, when you talk about these biological control loops, I flash back to the first control loop that I learned about when I was a high school student, which is a temperature control loop that was based on this notion of a proportional integral derivative control, which, to my high school mind, you know, just having taken my calculus class like seemed like a really complicated thing, and I remember this sort of funny thing that I was doing is, I was working for this company that was trying to bootstrap itself as a circuit board manufacturing company.

And this was in the very early days of surface mount manufacturing technology. And so you squeegeed a bunch of lead solder past onto circuit boards, you placed these very tiny, little components into this soft solder, and then you sent them through an oven to melt the solder and electrically and mechanically seat them to the circuit boards. And we didn't have enough money to buy an infrared reflow oven, so my boss gave me a GE toaster oven, and said I need you to turn this into a reflow oven. And so that was where I first learned about PID control.

And it's super simple, like it had a couple of inputs from temperature sensors. It had one output, whether or not to turn a heating element on, it had a second output, it had a connection fan, but like it was more or less on all the time. And the algorithm is relatively simple. So, nothing in your world is even remotely this simple, I would hazard to guess. So, for my electrical engineer's, you know, point of view, like I hear you talk about all of these things, and I don't know where I would start, and like I wonder if that's because I'm coming from this electrical engineer's perspective where I just sort of accept that his is the way things are in my – from my worldview, and like this is what's hard and this is what's easy. Do you think you benefited because you came from a biologist's perspective on this, on this stuff? What, what you're doing just seems very complicated.

**TOM DANIEL:** It's complicated until you get into the weeds yourself. One of the things you can do is you ask do animals do PID control on any sensor? I mean, does it – is it that simple that they're measuring things like a gain, and an integrator and a differentiator? Do they have all of these pieces? And the answer is how would you know, okay? So, I love this question because we actually try and find that out.

The difference between the oven controller and an animal controlling its temperature setting, right, is that in the oven controller, again, you typically have one sensor, one sensor modality, and then on and off. You basically get hot, get not, and how you deal with that sensory information, whether you use some gain on it, or some differentiator, or some integrator, you know, that's kind of up to you and your design specs for that controller.

And the animals have the same game to play, evolutionarily, right? They have some gains in the system, some integrators that happen. They have neurons are integrators, and they have differentiators. They have all of that, but they have it in aces. I think that's the difference, and so we like to think of them as – I think the lingo is MIMO systems, multi-input/multi-output, but all of them have gains, they could have differentiators and they can have integrators, right? They can have it all. And evolution doesn't care how complicated it is for us to unravel. It just cares that it works, that – and I'm going to come back to a slightly orthogonal view of this in a second.

Here are the challenges – is you can take a human into a gaming system and you can have them learn the game. And they could move a joystick to control a cursor, and you can adjust the gain. And they got pretty good at it. And you can change the game, and they'd get good at it. And by the way, you can reverse the gain and they can do that. It takes them a little while, but they can get there, right?

You can have memory. You can have a differentiator, you basically put a human in PID loop, and you can play the game, and lo' and behold, you'll find out that they're able to do it, but their performance may vary with gain, with the differentiator, with the parameters of your loop control, and the same is true with the animals. We can put, and have put, a moth in a visual world where it thinks it's flying. And as it flies it can control, in close loop, the horizon, right, it's visual horizon. And how we do that is in the weeds, but it can control the visual horizon with a PID loop. And you can change the gain, and it can do that. It can learn to handle different gains, and you can even reverse the gain, and it has a hard time, but eventually it gets there.

So, the difference between the controller that you had historically made and the controllers of the future lies in learning, right, lies in the capacity of these closed loop systems to be adaptive, to be plastic in their responses, so that's a very neural-inspired feature.

**KEVIN SCOTT:** You know, one of the other things that occurs to me, and I hate to say it this way, like I don't want us to confuse that evolution has human intentionality, but it sort of strikes me, even in this example that evolution in even a temperature-controlled circuit for an animal is trying to solve a slightly different set of problems than I'm trying to solve in the temperature control loop for an oven. And like one of those things may be robustness and like the way that I achieve robustness in the design of this oven temperature controller is like I use parts, I understand, you know, that this op amp is characterized for proper function inside of these temperature bands.

I do a set of things to keep this thing inside of these, and so like I sort of balance a bunch of things, honestly, in a very delicate way sometimes to get this circuit to work in a way that my analytical brain can understand. Like I'm almost engineering towards the simplicity of the control algorithm that I like arrange all of these other constraints in the system around that, so like I can understand like how the circuit is functioning, And that is not what biology is doing.

**TOM DANIEL:** Absolutely, so that's the next thread. So, I said there were two threads. One is, are we really PID control systems, and the answer is not really. We're these, I think the phrase for flight control is called fly by feel. Basically, we have data that comes in, massive sensory data. We listen to it, “we” – living systems, right? And we learn to move in ways that get us to the goals we're seeking. This massive redundancy of information and our capacity to process on the fly, pun intended, such rapid information, massive flows of information, in – you know, tens of milliseconds, on many, many channels, to control dynamic movement, just doesn't exist in synthetic systems, and that's the sweet spot of neural systems.

That is this highly redundant, low-noise, massively parallel sets of channels, right, for sensory information. We haven't been building systems like that because of sort of the technical challenges of lots of sensors. I mean, if you can get by with five, why not get by with five, right, and just do that. Because there are some fabrication challenges that are of less concern naturally in natural systems.

**KEVIN SCOTT:** Well, and a lot of times it's sort of the cost thing that you mentioned before, so like having designed a bunch of things where you're going to build 50,000 of something, like a penny here and a penny there matters. Whereas in biology, like if you can get these things for relatively low cost, like why not have a lot of them, right?

**TOM DANIEL:** That's right. I mean, it's not that cost isn't a – a criterion in evolution, the cost of fabrication, or the cost of running things. It's not like it isn't an objective function of which evolution selection may be acting. But it's only part of the problem. So, at the end of the day, it's “Is this thing going to survive and reproduce better than the other thing?” (Laughter) That's all that mattered, right. So, cost matters to some extent. Fabrication and running costs matter, but also robustness, stability, adaptability, the ability to fly under different circumstances, vastly different circumstances, to navigate, to tolerate, you know, falling, running into things, that's sort of the more natural system approach, right? Living systems are – cost is a concern, but at the end of the day, fitness is the concern.

**KEVIN SCOTT:** Right.

**TOM DANIEL:** Right.

**KEVIN SCOTT:** And the cost is just one of the inputs into the fitness function.

**TOM DANIEL:** Part of it. Part of it, part of it, absolutely.

**KEVIN SCOTT:** Yep.

**TOM DANIEL:** And so, you can play a revolutionary algorithm on a design problem, but you'd have to make sure your objective function includes as many things as you want.

**KEVIN SCOTT:** Yeah, super interesting. You have this beautiful point of view because you've been doing this for a while, so what are some of the interesting things that have changed in the field, other than like it being easier to do some of this interdisciplinary stuff?

**TOM DANIEL:** Yeah, I would say there are probably three big transformations today that are going to propel the field much further forward than I will see in my career, okay? Candidly, ML methods, machine learning is coming to bear on a vast number of problems in neuroscience, everything from imaging to you know, how do we handle the massive data flowing in from neural systems, how does a brain handle massive data, can ML give us some insight?

So, as we said, not too long ago, there's lots and lots of channels coming in. That's a hard problem to do in traditional control theoretic approaches, right? It’s just hard, and by the way, they’re nonlinear, so – you know, ML methods, I think the advent of AI and ML, and our ability to grapple with massive data is transforming the field of neuroscience, period.

It's transforming the field of movement control. We have the same problem in understanding how multiple actuators operate a dynamical system and how billions of motor molecules conspire to create movement in muscle, right? These are all problems that demand extreme advances in computation, not just the hardware of computation, but the ML methods that are coming about. So, even at my late stage of career, I'm finding myself having to learn more and more ML methods. This is great, this is exciting. So, DMNs, even simple just standard classification problems are becoming increasingly important. That's, that's revolution one that's been going on.

Revolution two is of course devices, the advances in device technologies. So, an example of that will be the microfabrication of electrodes that you can implant in neural systems that record from hundreds of simultaneous sites. I almost said thousand because it's at about 900-and-something. I think on the latest sharp electrode developed for mouse brain recordings, okay?

So, those are now device technology, and of course, the ubiquity of microfabrication is influencing even how we make electrodes interfacing with natural systems. Okay, so now you have these two things. You have ML methods, device technologies, hand-in-hand, transforming our ability to understand the encoding and decoding processes of natural systems.

So, what's the third revolution? The third revolution of course is gene editing. Where is gene editing coming into all of this? Well, our ability to look at neural circuits depends on our ability to look at variants in these neural circuits to turn them on, to turn them off, to use optogenetic methods, to use CRISPR, to change the chemosensory pathway on the antenna of an insect with really awesome electrodes inserted into it, and ML methods listening in, right?

So, those are the three technologies I think are transforming not just neuroscience. I think it's transforming – they're all mutually transforming each other. That is, as we need to grapple with ever more complex datasets, I think that's driving development of ML. I think it's driving how we manage and control and handle rapid information flow. Just like real brains, computers are fixed with this real-time challenge, even the brain the size of a sesame seed does astronomical amounts of computing, right, at tiny levels of efficiency, so there's lessons to be learned both ways. You can tell I'm really excited because I see these synergies and the sort of triumvirate of sort of advances in gene editing, advances in device technology, and advances in ML.

**KEVIN SCOTT:** I have to say, I'm as excited as you are and like one of the things that I wonder about is, you know, again, from an engineer's mindset, you sort of think about all of these things, and you know, part of what engineers do is like you build things that accomplish tasks, that solve problems, that hopefully, you know, do something useful, even if the utility is like just marveling at the – you know, the sort of ingenuity of the thing that you've made. One of the things that I'm starting to see is that the engineering process itself, sort of applying some of these techniques to very complicated systems, whether they are the biological ones that we've been talking about today, or they could be applied to some fundamental aspects of physics, for instance.

Like you know understanding fluid dynamics and fluid flow. I think that, as you take these tools, which can be used to build things, like you also at the same time can better understand the naturally occurring phenomenon that you're interacting with. And so you know, this thing that you were talking about with gene editing and like understanding these neural systems. Like the thing that I've never understood, like as a non-biologist, is how much of the stuff that got built up in our biological systems is with intention and purpose, and how much of it is, you know, sort of unnecessary, by some weird notion like human anthropomorphic understanding of utility?

You know, the question with the human brain is like you've got a hundred billion neurons in a human brain, you know, give or take. Are all of those necessary for cognition? I don't know.

**TOM DANIEL:** Well, when you say cognition, what (crosstalk) – you need to be human to have cognitive capabilities. And yes, absolutely not. You can you know, again, we talk about cognitive capabilities and, you know, our vast – our taxonomic range of creatures. And we can down this path of cognition in honeybees. It's a very classic open area of research.

No, do we need all the connections to be functioning wonderfully and normally in society? Absolutely not. There are children and now adults who have had half their brain removed, and you would not be able to tell, except for some minor motor deficits. I mean, hemispherectomy, okay? That, that alone is pretty stunning, okay, and it's a statement about the ability to take whatever circuits you have and to repurpose them.

Therein lies the massive fundamental difference between sort of synthetic systems and living systems, is that ability to be plastic. And in part, we built systems that aren't going to change, on purpose. We don't want them to change. Heaven forbid, you know, should my car decide, you know, nah, I'm not going to do what you say, you know? I'm sorry, Hal, I can't do that, but – so, but there are some parables here.

So, you asked, do we need everything? No. Can we map directly genotype to the phenotype of connections in the brain? Absolutely not. We cannot do that, and that's because the connections are formed and lost and changed by use, by age, by growth. It's a different system. So, getting back to your point is, we need to understand these, we need to understand complex living neural systems towards inspiring new technologies, but also even more importantly towards dealing with neural disorders.

What happens when we lose connections? How robust is our sort of cognitive capability to this sort of loss of connections, notably, things like Alzheimer's and others. Or motor diseases that are still have a central neural pathway like MS, you know, how can we understand and towards that understanding treat or compensate?

**KEVIN SCOTT:** I don't know whether or not any of your work is directed at things that are relevant to COVID-19 and viruses and upper respiratory things, or just as a smart person I'd love to get your take on not what we're doing right now, which you know, in various ways is both very inspiring and like very worrisome. Like I see some of the best of science that I've ever seen happening, and I've seen some just very problematic stuff happening. But I think if you go one step beyond, it's like, okay, we will deal with the horrendous impacts of this thing, at some point, hopefully in the not too distant future, probably not as soon as any of us would like, but at some point we will either conquer the virus or adapt ourselves to it.

But is there anything that you think that we should be thinking about to prepare ourselves for the next time this happens because it seems like there will be a next time?

**TOM DANIEL:** Yeah, so this is getting a little out of my wheelhouse, but let me start by saying I am both an optimist and a pessimist about this, okay? My optimism is I think there will be a vaccine, maybe not as fast as we'd like. I think society has an obligation to pay more attention to policies. This is not a scientific issue. This is a human behavior issue – that are for societal benefit, as opposed to individual benefit.

I know that's a bit controversial, but even simple ideas, simple behavioral changes can make massive disease outcomes differences. Again, it's not my wheelhouse, but I'm enough of an analytics person to get it, right? In terms of scientific advances, there are – again, not my wheelhouse, but there are new emerging antibody techniques, new emerging immunization methods that I think are worth investment.

And if I were the great designer of all, I would say let's invest in education. Let's make sure that our citizens have the basics of science, math and social sciences that they need. It's not just a science thing. It's about the structure of societies, about demographics. I think getting a more quantitative training is better, but then I'm preaching to the converted here. I think if I were investing, I would invest in education and communication of scientific concepts, as critical as distancing and things like that.

**KEVIN SCOTT:** Yeah, and I could not more strongly agree with you. I think that's a nice segue into –I really would love to understand your point of view on like what those experiences could look like for kids in middle or high school. You know, one of the great things about you is you're such an extraordinary teacher, and you're really very interested in trying to convey these very complicated ideas about complex systems to as broad an audience as possible, which is really awesome.

What do you think makes for great educational experience, like how do we – how do we get enough teachers and mentors and advisors to like do this stuff because it's hard. It is hard to be a teacher.

**TOM DANIEL:** So, you cut right to the nub of what I think my justification on the planet is. I love the science I do. I'm enthusiastic about the ability of science generally to help society. But I'm even more passionate about what can we do to engage the next generation, and engage as diverse a group of practitioners of – and now, of course, beyond science. I actually don't care, just scholarly pursuit of knowledge.

I-- there is such an important role for the respect of scholarly pursuit of knowledge that, you know, it's on all of us to help on that, okay? So, what, what can make a difference? I've always been really fond of what I call the transitions in life. What happens between high school and college, what can we do in that space, sort of the upper end of high school and the start of college? What experiences can kids have that can kind of help them through all the other machinery of college?

And I love internships. I love sort of learning by practice, learning through volunteer work, learning through paid internships. I'm particularly fond of paid internships for the reason that some kids actually can't afford to do volunteer work, and we need to be super sensitive to that. So, I'm very focused on that, so I have high school kids in my lab. I can't do whole high school classes, but there are a lot of labs in the world. And there are a lot of high school kids, and as long as they're – and there's businesses and industry, and all of these can have a bigger role in welcoming the next generation, just as experiences, just to give them a sense of what's going on.

If you take all of society together and let a little bit of outreach everywhere, it makes a huge difference, okay? The next transition is between undergraduate and either graduate professionals or some other thing. In the life sciences, we see the vast majority of people receiving Bachelor degrees doing what we call a post-baccalaureate year, a year to further prepare them for medical school, dental school, physical therapy, graduate school, business, industry, you name it, right?

That's a space where we lose a lot of people from science because you know they graduate, they need a job, they need to earn money. But if we can keep them in science, and pay them, right, nobody loses, nobody loses. The scientists win, the student wins, right, research advances and their career benefits, and our progress benefits?

I can give you story after story about students who had no clue that you could do research, had no idea you could do it, and then get into it and make a massive difference? And again, each of those transitions, those are the two dominant ones, that sort of high school to college, college to whatever? Those are the ones where I think there's a large impact to be had. As you proceed onward, it gets easier. But there's still critical transitions where we lose under-represented minorities and women into leadership roles in science, and engineering, and industry, and again, those are the places where we can do some investments, smartly.

**KEVIN SCOTT:** Yeah –

**TOM DANIEL:** It's financial noise, by the way.

**KEVIN SCOTT:** Very much financial noise. I’d make the stronger statement that it is for society financially impoverishing not to make these investments, like we lose more than the savings that we think we're getting by not investing.

**TOM DANIEL:** I'm going to tip my hat to colleagues of mine in the biology department who spend whole careers thinking about exactly the question you're asking. They're really focused, in their case, on biology education, but more generally the writ on how students learn, how students learn science, what are best practices? I think the world has seen a change in how we're teaching science. It's a little less “sage on the stage” okay, just sort of core dumping, although there – you know, there are elements to that. And then there's a fair amount of very, very interactive work.

I think there is ample room for technology to come in, in a smart way, okay, to help democratize access to science and learning, things like –I'm thinking about a particular project we did, actually with Paul Allen, before he passed away, on developing technologies that will help you learn how neurons work. And it wasn't, oh, let's make a cool movie a neuron doing whatever it does. Students had to actually do the neuron game, you know, putting the right proteins in that do the right sort of biochemistry, and it could break, and you could break them, and you could get disease, right?

It was, it was a real neuron game. I really love it, and it was done with beautiful animation as well. And we used it live in the classroom. So, the only challenge is that the professor, that was me, suffered incredible cognitive overload trying to teach using this, but the students actually did really well. And we actually measured the difference in their learning, using the method versus more – the way I normally teach. They did better. We brought up the under-performers. But the top end could go further than they would because they have a tool now to play some interesting things.

I see a space for technology in that way. I see a space for the sort of education we've been doing over the last however many weeks. I taught neuroscience to non-majors for 10 weeks. It was really interesting, and these technologies would be incredibly useful.

**KEVIN SCOTT:** So how did, like I'm really interested in that. You recently taught a 10-week class, so it was all distance learning, right? How was that?

**TOM DANIEL:** Better than I thought. What I missed, and I only got at the very end, was to see the 70 students in the class, live. And I didn't see them live because you can't get 70 faces on your monitor, and even if you could, they'd be teeny. So, what I miss is the visual interaction that you have when you're teaching, and what the students missed is the visual and personal interactions with each other. There's no question about it, and they all said that.

At the end of the course, the students all had to do PowerPoint presentations, six slides, six minutes, sort of – what is that, PechaKucha, or whatever it's called, six slides, six minutes, on the topic of the neuroscience of their interest, okay? And they did it in little teams, and we had sections meetings, so the class had a normal lecture, but they also had discussion sections where the TA would meet with, virtually, 20 students at a time, or 15, or something like that, out of this class, broken up into lots of sections.

So, the TA got to see them, and only at the end of the class did I get to see all these faces that were typing in questions on the chat, or you know, emailing, or whatever. I remember distinctly saying I miss seeing the students. And if you look at a picture of the class, which is a thumbnail of every student, you could be in any country in the world. It's really a beautiful diverse group of students,

**KEVIN SCOTT:** Yeah, I mean, I think that there's a real accessibility benefit for this, you know, and like you and I are probably – you know, for instance, doing this, whereas if we had to be in-person, even under non-COVID conditions, it would have been harder to schedule, and I mean, so like I really do appreciate the flexibility these technologies are giving us. But I will just tell you from my point of view one of the things that I worry about with distance learning is I was the type of student where whenever I encountered anything that was hard, and I was struggling, I immediately assumed that I was stupid and that everybody else was smarter than me.

And part of the thing that always helped me was being physically proximate with other students who I could see that they were struggling too, like it was like, “Okay, well this, what I'm going through his normal. Like I don't need to beat up myself because this is hard.” And then we helped each other in a very sort of organic way. One of the things that I missed when – like I grew up in rural central Virginia, and I was – very sparsely populated part of the country, and I spent a huge amount of my childhood alone. And so like I just didn't have anything to benchmark myself to And so I was just constantly, you know, just wondering like whether I was on the right path, and like creating that sense of community with, you know, when we're distanced from one another, like I just sort of wonder how to do that. I'm not saying that it's impossible. I just wonder how we do it.

**TOM DANIEL:** And I so agree. Here are the two tensions. One side of this distance learning is it is incredibly available to everyone, regardless of your income, given that you have access to technology, right, that's something that we need to put – put a nail in –

**KEVIN SCOTT:** Very, very important.

**TOM DANIEL:** We need to – but the class I teach could be taken anywhere in the world, right, theoretically. On mobile devices, with small mobile devices, it's a little harder, right, but still feasible. That's the good news. There's democratization of science. The bad news is there's a loss of the interpersonal that comes with this, and as you point out, the other bad news is sort of this isolation that is – I'm struggling but I don't know, is it me? Right?

Now, there are ways to help. They don't completely fix it. When we teach the class, there are no exams, okay? An exam in this world is just nuts, if you ask me, I – it just doesn't make a lot of sense. Rather, every day, there are questions that you have to answer, and you can do these breakout sessions. People can talk with each other. You can do all that now. That helps, right, but you can also see when I just do a simple poll of the class, “Hey, here's a question, what do you guys think is the correct answer?”

And lo' and behold, you know, 30% get it, you know, and 70% don't. Is it them, or is it me? Chances are, if they didn't get it, it's not them, okay, it's me. Again there are aspects of distance learning that I think are good and aspects that I think are terrible, and today we just live with what it is. We have to, we have to, and so we need to make the best of it, and there are ways to improve it.

**KEVIN SCOTT:** Yep. Well so, we're almost out of time here. One last question for you before we go. I'm really interested to hear what you do outside of your professional passions. What do you do for fun?

**TOM DANIEL:** Yeah, it's a mix. I really love – right now, my wife and I just got an inflatable kayak, so that's what's top of my mind is to go kayaking. It's, by the way, that's fluid dynamics for real. Also jazz keyboard. I love playing piano, when I can get to it.

**KEVIN SCOTT:** Awesome.

**TOM DANIEL:** Yeah, not good enough to give up my day job, but –

**KEVIN SCOTT:** But you, so, it's really interesting. So, I'm not a very good piano player, but I am a – like an almost obsessive fan of the – the keyboard, in particularly classical music, and that's another one of these things where, when you see someone who is virtuosic at the keyboard, you can somehow or another, I think, deceive yourself into thinking that there was no struggle there, that “Oh, my word, this person's a virtuoso, they're so – they're so talented, like – you know, they must have this incredible genius.” And yes, they have to be talented, yes the very highest level performers I think probably are geniuses.

But, my word, you have to work hard to get to that point, where all of it seems easy, which is like – it's almost like a metaphor for teaching. I mean, my – like, we – we look at great teachers, and we're like, “Oh, how easy and wonderful this is.” But, man, it takes a lot of work to get as good at teaching as someone like you.

**TOM DANIEL:** Well, yeah, I wish I was better at teaching, but I – I have to say that when you watch a virtuoso perform, you know, the first word that goes through your head is, “My, how lucky they are, right, they are lucky that they get to do that.” Now, they worked really hard. They worked really, really hard, and that is true for everyone who I think is successful, is they worked really hard, and that hard work is borne out of a mixture of passion, but also reward.

If I step back to the neuroscientist in me, if I get rewarded for doing stuff, the dopamine pathways in my brain just all light up, and say, hey, let's do more of that, right? So, that is our job as educators is to light up dopamine pathways, okay?

**KEVIN SCOTT:** Yeah, that's awesome. Well, thank you, so much, for being with us today. This was just a great conversation, and it makes me happy to know that there are researchers and teachers like you, out there in the world, like making both great science and great students.

**TOM DANIEL:** Well, I have to say, Kevin, doing podcasts and making them available is also part of the fabric of science and discovery, right? So, I have to say thanks to you because we want to get word out, probably to everyone, about as many things as possible, right?

**KEVIN SCOTT:** Yeah, awesome. Thanks, so much. Bye.

**TOM DANIEL:** All righty, take care.

[MUSIC]

**CHRISTINA WARREN**: Okay. So, that was Kevin's chat with neuroscientist Tom Daniel, and what a fantastic conversation. What a really interesting guy. You guys talked about so many interesting things.

**KEVIN SCOTT:** So, yeah. Tom really is one of the most amazing scientists and educators that I've ever met, and I think he's really understated. You, you sort of forget, talking to him, that he has won a MacArthur Genius grant and that his research has been so transformative because he has this very natural way about him, and I think it may be one of the reasons that he's such a great educator.

**CHRISTINA WARREN:** Yeah, no, that's what I was thinking. I was like, “Oh, I would love to take his classes, I would love to be a student in his classes.” Because you just get the sense, just from your conversation, that you would learn so much because he's obviously brilliant but has a fantastic ability to express that brilliance in something that is approachable, and isn't going over your head and doesn't make you feel dumb, and that's what you want out of a great educator, and probably frankly I would think what you really want out of a great scientist.

**KEVIN SCOTT:** Yeah, indeed. I mean, I think a big part of science and I'm going to paraphrase something that I think some other famous scientist said, is that you're fundamental task is distilling extremely complicated things down to their simplest essence. And that's what you need teachers to do, as well. And so the fact that he's able to bridge that gap, which not all people are able to do. There are some very brilliant scientists, who do amazing work, who aren't equivalent brilliant at teaching, but you know, it –

One of the reasons why I chose the path that I did, versus – you know, versus remaining an educator is like I couldn't figure out, as a computer science professor, how to do as much of the educating part of my job as I felt compelled to do. And I always told myself that that was the highest impact part of my job, that I'm going to have a much bigger impact, potentially, on the world by inspiring students to go off and have great careers in computer science, than I am through the research that I'm doing.

**CHRISTINA WARREN:** Yeah, no, I think that that's a great point, and being able to inspire people and have that impact is great. What was actually interesting, kind of speaking of education, is I loved the conversation that you two were having towards the end about what remote education is going to look like and some of the trade-offs between that because that's something that I've been thinking a lot about in my own work. And I've kind of had the similar struggles that Tom was describing where, on the one hand, you have the democratization, as he was saying, of science and – you know, people have the ability, assuming that they have access to, you know, learn from wherever they are, but on the other hand, as you were kind of pointing out, you do lose that maybe sense of community and that ability to ask questions and feel like maybe you can ask questions.

From your perspective, especially somebody who – you know has been a teacher and is involved in technology, I look at this, and I think that this is something that technology might be able to solve, but I feel like it might be a design problem. What are your thoughts?

**KEVIN SCOTT:** Oh, I think it's probably more of a design problem than it is a technology problem. Like I'm guessing that the technological building blocks are already in the place to mitigate a whole bunch of this stuff, and we just have to figure out how to use them. We may discover that there is, for a whole bunch of things, no substitute for proximity.

**CHRISTINA WARREN:** Yeah.

**KEVIN SCOTT:** And I'm guessing it's not a – it's not a uniform thing. I would hazard to guess that I'm navigating all of this social isolation that we have right now, a little bit better than most because I've always been introverted. I've always been happy to spend huge amounts of time all by myself, but even for me, like this is a little bit much right now.

**CHRISTINA WARREN:** Right, you know, there was – it's like the meme, where it says, “Oh, I've been preparing for this my whole life.” But then you actually get into it, and you realize, no, there are some instances where it doesn't work. I have to feel like there's some way we could design our systems to make it better.

**KEVIN SCOTT:**

The, the thing that I'm hopeful about, and this has been my experience, and I'd be curious about yours. I think both of us spend a fair amount of our working time is – was remote already, before this.

**CHRISTINA WARREN:** Yeah.

**KEVIN SCOTT:** So, I live in California, like a big chunk of my job is in Washington State. Like I know you have a similar, a similar dynamic. It was harder to do my work remotely before than it is now because I was often the only remote person and it – now, at least, we're all in it together, and like a whole bunch of things have already improved, not because of technology just, but just because we're figuring out a culture of remoteness now –

**CHRISTINA WARREN:** Right.

**KEVIN SCOTT:** …that we weren't forced to figure out before.

**CHRISTINA WARREN:** Yeah, no, I think you have a – I think that's a great point. When everyone is on the same playing field, you're not othered in that way. And I have a feeling that's probably also true for education because although there have been MOOCs and online classes for decades, that hasn't been how a lot of professors have taught their classes, as Tom was explaining. And maybe next semester or in the future that does become a more expected part of the dynamic, and so that changes the approach, and makes – you know, the – I guess maybe the divide between, you know, people who are in person versus remote, even in education, less pronounced than it currently is.

**KEVIN SCOTT:** Yeah, and like one thing that I think we should just remind everyone of, and Tom touched on it when we were talking about remote learning, is that it is not an equal experience right now because there are a very substantial fractions of the population who don't have a device at home that they can use to engage with remote education. They don't have a good Internet connection. They don't have the support structure that they need.

They don't have the time, necessarily, that they need to go, you know, avail themselves of these resources that are now available. And so in addition to sort of fixing the culture of remoteness that we have right now, whether it's for work or learning, like we also have to fix these problems of access as well.

**CHRISTINA WARREN:** Yeah, no, I thought that was a great point that he had that, yeah, you need to have that access, and that's something that we can work on, and that I'm hopeful about will further the democratization of not just of science, but of education, and work, and play, and all kinds of other things.

**KEVIN SCOTT:** Yeah, for sure.

**CHRISTINA WARREN:** All right, well that does it for us. A special thanks again to Tom Daniel from the University of Washington, and as always, you can reach out to us any time at [behindthetech@microsoft.com](mailto:behindthetech@microsoft.com). And please be sure to tell your friends, your colleagues, your students if you're a teacher, your teachers if you're a student, you're – you know, parents, your kids, whoever, about our show, and be well.

**KEVIN SCOTT:** Yeah. See you next time.

[MUSIC]