Lex Fridman Podcast #438 - Elon Musk: Neuralink and the Future of Humanity

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Lex Fridman
The following is a conversation with Elon Musk, DJ Seo, Matthew MacDougall, Bliss Chapman, and Noland Arbaugh about Neuralink and the future of humanity. Elon, DJ, Matthew and Bliss are of course part of the amazing Neuralink team, and Noland is the first human to have a Neuralink device implanted in his brain. I speak with each of them individually, so use timestamps to jump around, or as I recommend, go hardcore, and listen to the whole thing. This is the longest podcast I've ever done. It's a fascinating, super technical, and wide-ranging conversation, and I loved every minute of it. And now, dear friends, here's Elon Musk, his fifth time on this, the Lex Fridman Podcast.

Elon Musk
Drinking coffee or water?

Lex Fridman
Water. I'm so over-caffeinated right now. Do you want some caffeine?

Elon Musk
Sure.

Lex Fridman
There's a Nitro drink.

Elon Musk
This supposed to keep you up for like tomorrow afternoon, basically.

Lex Fridman
Yeah. Yeah. I don't have any sugar.

Elon Musk
So what is Nitro? It's just got a lot of caffeine or something?

Lex Fridman
Don't ask questions. It's called Nitro. Do you need to know anything else?

Elon Musk
It's got nitrogen in it. That's ridiculous. What we breathe is 78% nitrogen anyway. What do you need to add more for? Unfortunately, you're going to eat it. Most people think that they're breathing oxygen and they're actually breathing 78% nitrogen. You need like a milk bar, like from Clockwork Orange.

Lex Fridman
Yeah. Yeah. Is that the top three Kubrick film for you?

Elon Musk
Clockwork Orange? It's pretty good. It's demented. Jarring, I'd say.

Lex Fridman
Okay. Okay. So, first, let's step back, and big congrats on getting Neuralink implanted into a human. That's a historic step for Neuralink.

Elon Musk
Thanks. Yeah.

Lex Fridman
And there's many more to come.

Elon Musk
Yeah. And we just obviously have our second implant as well.

Lex Fridman
How did that go?

Elon Musk
So far, so good. It looks like we've got, I think, on the order of 400 electrodes that are providing signals.

Lex Fridman
Nice.

Elon Musk
Yeah.

Lex Fridman
How quickly do you think the number of human participants will scale?

Elon Musk
It depends somewhat on the regulatory approval, the rate at which we get regulatory approvals. So, we're hoping to do 10 by the end of this year, total of 10. So, eight more.

Lex Fridman
And with each one, you're going to be learning a lot of lessons about the neurobiology of the brain, everything. The whole chain of the Neuralink, the decoding, the signal processing, all that kind of stuff.

Elon Musk
Yeah. Yeah. I think it's obviously going to get better with each one. I don't want to jinx it, but it seems to have gone extremely well with the second implant. So, there's a lot of signal, a lot of electrodes. It's working very well.

Lex Fridman
What improvements do you think we'll see in Neuralink in the coming, let's say, let's get crazy, the coming years.

Elon Musk
In years, it's going to be gigantic, because we'll increase the number of electrodes dramatically. We'll improve the signal processing. So, even with only roughly, I don't know, 10-15% of the electrodes working with Noland, with our first patient, we were able to get to achieve a bit per second. That's twice the world record. So, I think we'll start vastly exceeding the world record by orders of magnitude in the years to come. So, start getting to, I don't know, 100 bits per second, thousand. Maybe if five years from now, we might be at a megabit, faster than any human could possibly communicate by typing, or speaking.

Lex Fridman
Yeah. That BPS is an interesting metric to measure. There might be a big leap in the experience once you reach a certain level of BPS.

Elon Musk
Yeah.

Lex Fridman
Like entire new ways of interacting with a computer might be unlocked.

Elon Musk
And with humans.

Lex Fridman
With other humans.

Elon Musk
Provided they have want a Neuralink, too.

Lex Fridman
Right.

Elon Musk
Otherwise they wont be able to absorb the signals fast enough.

Lex Fridman
Do you think they'll improve the quality of intellectual discourse?

Elon Musk
Well, I think you could think of it, if you were to slow down communication, how do you feel about that? If you'd only talk at, let's say 1/10th of normal speed, you'd be like, "Wow, that's agonizingly slow."

Lex Fridman
Yeah.

Elon Musk
So, now imagine you could communicate clearly at 10, or 100, or 1,000 times faster than normal.

Lex Fridman
Listen, I'm pretty sure nobody in their right mind listens to me at 1x. they listen at 2x. I can only imagine what 10x would feel like, or I could actually understand it.

Elon Musk
I usually default to 1.5x. You can do 2x. Well actually, if I'm listening to somebody get to - in 15-20 minutes, I want to go to sleep, then I'll do it 1.5x. If I'm paying attention, I'll do 2x.

Lex Fridman
Right.

Elon Musk
But actually, if you actually listen to podcasts, or audiobooks or anything at - if you get used to doing it at 1.5, then one sounds painfully slow.

Lex Fridman
I'm still holding onto one, because I'm afraid, I'm afraid of myself becoming bored with the reality, with the real world, where everyone's speaking in 1x.

Elon Musk
Well, it depends on the person. You can speak very fast. Like we can communicate very quickly. And also, if you use a wide range of - if your vocabulary is larger, your effective bit rate is higher.

Lex Fridman
That's a good way to put it.

Elon Musk
Yeah.

Lex Fridman
The effective bit rate. That is the question, is how much information is actually compressed in the low bit transfer of language?

Elon Musk
Yeah. If there's a single word that is able to convey something that would normally require, I don't know, 10 simple words, then you've got maybe a 10x compression on your hands. And that's really like with memes. Memes are like data compression. You're simultaneously hit with a wide range of symbols that you can interpret, and you get it faster than if it were words, or a simple picture.

Lex Fridman
And of course, you're referring to memes broadly like ideas.

Elon Musk
Yeah. There's an entire idea structure that is like an idea template, and then you can add something to that idea template. But somebody has that pre-existing idea template in their head. So, when you add that incremental bit of information, you're conveying much more than if you just said a few words. It's everything associated with that meme.

Lex Fridman
You think there'll be emergent leaps of capability as you scale the number of electrodes?

Elon Musk
Yeah.

Lex Fridman
Do you think there'll be an actual number where just the human experience will be altered?

Elon Musk
Yes.

Lex Fridman
What do you think that number might be? Whether electrodes, or BPS? We of course, don't know for sure, but is this 10,000? 100,000?

Elon Musk
Yeah. Certainly, if you're anywhere at 10,000 bits per second, that's vastly faster than any human can communicate right now. If you think what is the average bits per second of a

human, it is less than one bit per second over the course of a day. Because there are 86,400 seconds in a day, and you don't communicate 86,400 tokens in a day. Therefore, your bits per second is less than one, averaged over 24 hours. It's quite slow. And now, even if you're communicating very quickly, and you're talking to somebody who understands what you're saying, because in order to communicate, you have to at least to some degree, model the mind state of the person to whom you're speaking. Then take the concept you're trying to convey, compress that into a small number of syllables, speak them, and hope that the other person decompresses them into a conceptual structure that is as close to what you have in your mind as possible.

Lex Fridman
Yeah. There's a lot of signal loss there in that process.

Elon Musk
Yeah. Very lossy, compression, and decompression. And a lot of what your neurons are doing is distilling the concepts down to a small number of symbols, or say syllables that I'm speaking, or keystrokes, whatever the case may be. So, that's a lot of what your brain computation is doing. Now, there is an argument that that's actually a healthy thing to do, or a helpful thing to do because as you try to compress complex concepts, you're perhaps forced to distill what is most essential in those concepts, as opposed to just all the fluff. So, in the process of compression, you distill things down to what matters the most, because you can only say a few things. So that is perhaps helpful. I think we'll probably get - if our data rate increases, it's highly probable it will become far more verbose. Just like your computer, when computers had - my first computer had 8K of RAM, so you really thought about every byte. And now you've got computers with many gigabytes of RAM. So, if you want to do an iPhone app that just says, "Hello world," it's probably, I don't know, several megabytes minimum, a bunch of fluff. But nonetheless, we still prefer to have the computer with the more memory and more compute. So, the long-term aspiration of Neuralink is to improve the AI human symbiosis by increasing the bandwidth of the communication. Because even if - in the most benign scenario of AI, you have to consider that the AI is simply going to get bored waiting for you to spit out a few words. If the AI can communicate at terabits per second, and you're communicating at bits per second, it's like talking to a tree.

Lex Fridman
Well, it is a very interesting question for a super intelligent species, what use are humans?

Elon Musk
I think there is some argument for humans as a source of will.

Lex Fridman
Will?

Elon Musk
Will, yeah. Source of will, or purpose. So if you consider the human mind as being - essentially there's the primitive, limbic elements, which basically even reptiles have. And there's the cortex, the thinking and planning part of the brain. Now, the cortex is much smarter than the limbic system, and yet is largely in service to the limbic system. It's trying to make the limbic system happy. The sheer amount of compute that's gone into people trying to get laid is insane, without actually seeking procreation. They're just literally trying to do this simple motion, and they get a kick out of it. So, this simple, which in the abstract, rather absurd motion, which is sex, the cortex is putting a massive amount of compute into trying to figure out how to do that.

Lex Fridman
So like 90% of distributed compute of the human species is spent on trying to get laid, probably. A large percentage.

Elon Musk
A massive amount. Yes. Yeah. Yeah. There's no purpose to most sex except hedonistic. It's a sort of joy, or whatever, dopamine release. Now, once in a while, it's procreation, but for modern humans, it's mostly recreational. And so, your cortex, much smarter than your limbic system, is trying to make the limbic system happy, because the limbic system wants to have sex, or wants some tasty food, or whatever the case may be. And then that is then further augmented by the tertiary system, which is your phone, your laptop, iPad, whatever, all your computing stuff. That's your tertiary layer. So, you're actually already a cyborg. You have this tertiary compute layer, which is in the form of your computer with all the applications, or your compute devices. And so, in the getting laid front, there's actually a massive amount of digital compute also trying to get laid, with Tinder and whatever.

Lex Fridman
Yeah. So, the compute that we humans have built is also participating.

Elon Musk
Yeah. There's like gigawatts of compute going into getting laid, of digital compute.

Lex Fridman
Yeah. What if AGI was -

Elon Musk
This is happening as we speak.

Lex Fridman
- if we merge with AI, it's just going to expand the compute that we humans use -

Elon Musk
Pretty much.

Lex Fridman
- to try to get laid.

Elon Musk
Well, it's one of the things. Certainly, yeah.

Lex Fridman
Yeah.

Elon Musk
But what I'm saying is that, yes, is there a use for humans? Well, there's this fundamental question of what's the meaning of life? Why do anything at all? And so, if our simple limbic system provides a source of will to do something, that then goes through our cortex, that then goes to our tertiary compute layer, then I don't know, it might actually be that the AI, in a benign scenario, is simply trying to make the human limbic system happy.

Lex Fridman
Yeah. It seems like the will is not just about the limbic system. There's a lot of interesting, complicated things in there. We also want power.

Elon Musk
That's limbic too, I think.

Lex Fridman
But then we also want to, in a kind of cooperative way, alleviate the suffering in the world.

Elon Musk
Not everybody does. But yeah, sure, some people do.

Lex Fridman
As a group of humans, when we get together, we start to have this kind of collective intelligence that is more complex in its will than the underlying individual descendants of apes, right?

Elon Musk
Sure.

Lex Fridman
So there's other motivations, and that could be a really interesting source of an objective function for AGI?

Elon Musk
Yeah. There are these fairly cerebral, or higher level goals. For me, it's like, what's the meaning of life, or understanding the nature of the universe, is of great interest to me, and hopefully to the AI. And that's the mission of xAI and Grok is understand the universe.

Lex Fridman
So do you think people - when you have a Neuralink with 10,000, 100,000 channels, most of the use cases will be communication with AI systems?

Elon Musk
Well, assuming that there are not - they're solving basic neurological issues that people have. If they've got damaged neurons in their spinal cord, or neck, as is the case with our first two patients, then obviously the first order of business is solving fundamental neuron damage in a spinal cord, neck, or in the brain itself. So, our second product is called Blindsight, which is to enable people who are completely blind, lost both eyes, or optic nerve, or just can't see at all, to be able to see by directly triggering the neurons in the visual cortex. So we're just starting at the basics here, so it's the simple stuff, relatively speaking, is solving neuron damage. It can also solve I think probably schizophrenia, if people have seizures of some kind, it could probably solve that. It could help with memory. So, there's kind of a tech tree, if you will. You've got the basics. You need literacy before you can have Lord of the Rings.

Lex Fridman
Got it.

Elon Musk
So, do you have letters and the alphabet? Okay, great. Words? And then eventually you get sagas. So, I think there may be some things to worry about in the future, but the first several years are really just solving basic neurological damage, like for people who have essentially complete or near complete loss from the brain to the body, like Stephen Hawking would be an example, the Neuralink would be incredibly profound, because you can imagine if Stephen Hawking could communicate as fast as we're communicating, perhaps faster. And that's certainly possible. Probable, in fact. Likely, I'd say.

Lex Fridman
So there's a kind of dual track of medical and non-medical, meaning so everything you've talked about could be applied to people who are non-disabled in the future?

Elon Musk
The logical thing to do is - sensible thing to do is to start off solving basic neuron damage issues.

Lex Fridman
Yes.

Elon Musk
Because there's obviously some risk with a new device. You can't get the risk down to zero, it's not possible. So, you want to have the highest possible reward, given there's a certain irreducible risk. And if somebody's able to have a profound improvement in their communication, that's worth the risk.

Lex Fridman
As you get the risk down.

Elon Musk
Yeah. As you get the risk down. And once the risk is down to - if you have thousands of people that have been using it for years and the risk is minimal, then perhaps at that point you could consider saying, "Okay, let's aim for augmentation." Now, I think we're actually going to aim for augmentation with people who have neuron damage. So we're not just aiming to give people the communication data rate equivalent to normal humans. We're aiming to give people who have - a quadriplegic, or maybe have complete loss of the connection to the brain and body, a communication data rate that exceeds normal humans. While we're in there, why not? Let's give people superpowers.

Lex Fridman
And the same for vision. As you restore vision, there could be aspects of that restoration that are superhuman.

Elon Musk
Yeah. At first, the vision restoration will be low res, because you have to say, "How many neurons can you put in there, and trigger?" And you can do things where you adjust the electric field. So, even if you've got, say 10,000 neurons, it's not just 10,000 pixels, because you can adjust the field between the neurons, and do them in patterns in order to have say, 10,000 electrodes, effectively give you, I don't know, maybe like having a megapixel, or a 10 megapixel situation. And then over time, I think you get to higher resolution than human eyes. And you could also see in different wavelengths. So, like Geordi La Forge from Star Trek, he had the thing. Do you want to see it in radar? No problem. You could see ultraviolet, infrared, eagle vision, whatever you want.

Lex Fridman
Do you think there'll be - let me ask a Joe Rogan question. Do you think there'll be - I just recently have taken ayahuasca.

Elon Musk
Is that a serious question?

Lex Fridman
No. Well, yes.

Elon Musk
Well, I guess technically it is.

Lex Fridman
Yeah.

Elon Musk
Yeah.

Lex Fridman
Ever try DMT bro?

Elon Musk
Yeah, is this DMT in there, or something?

Lex Fridman
Love you, Joe. Okay.

Elon Musk
Wait, wait. Have you said much about it, the ayahuasca stuff?

Lex Fridman
I have not. I have not. I have not.

Elon Musk
Okay. Well, why don't you spill the beans?

Lex Fridman
It is a truly incredible experience.

Elon Musk
Let me turn the tables on you.

Lex Fridman
Well, yeah.

Elon Musk
You're in the jungle.

Lex Fridman
Yeah, amongst the trees, myself and a shaman.

Elon Musk
Yeah. It must've been crazy.

Lex Fridman
Yeah, yeah, yeah. With the insects, with the animals all around you, the jungle as far as the eye can see, there's no - that's the way to do it.

Elon Musk
Things are going to look pretty wild.

Lex Fridman
Yeah, pretty wild. I took an extremely high dose.

Elon Musk
Just don't go hugging an Anaconda or something.

Lex Fridman
You haven't lived unless you made love to an Anaconda. I'm sorry, but -

Elon Musk
Snakes and Ladders.

Lex Fridman
Yeah. I took a extremely high dose.

Elon Musk
Okay.

Lex Fridman
Nine cups.

Elon Musk
Damn. Okay. That sounds like a lot. Is normal to just one cup? Or -

Lex Fridman
One or two. Usually one.

Elon Musk
Okay. Wait. Like right off the bat, or did you work your way up to it? Did you just jump in at the deep end?

Lex Fridman
Across two days, because the first day, I took two, and it was a ride, but it wasn't quite like a -

Elon Musk
It wasn't like a revelation.

Lex Fridman
It wasn't into deep space type of ride. It was just like a little airplane ride. And I look out and saw some trees, and some visuals, and just saw a dragon and all that kind of stuff. But -

Elon Musk
Nine cups, you went to Pluto, I think.

Lex Fridman
Pluto. Yeah. No, Deep space.

Elon Musk
Deep space.

Lex Fridman
One of the interesting aspects of my experience is I thought I would have some demons, some stuff to work through.

Elon Musk
That's what people -

Lex Fridman
That's what everyone says.

Elon Musk
That's what everyone says. Yeah, exactly.

Lex Fridman
I had nothing. I had all positive. I just - so full -

Elon Musk
Just a pure soul.

Lex Fridman
I don't think so. I don't know. But I kept thinking about, I had extremely high resolution thoughts about the people I know in my life. You were there, and it is just not from my relationship with that person, but just as the person themselves. I had just this deep gratitude of who they are.

Elon Musk
That's cool.

Lex Fridman
It was just like this exploration, like Sims, or whatever. You get to watch them. I got to watch people, and just be in awe of how amazing they are.

Elon Musk
That sounds awesome.

Lex Fridman
Yeah, it was great. I was waiting for -

Elon Musk
When's the demon coming?

Lex Fridman
Exactly. Maybe I'll have some negative thoughts. Nothing. Nothing. Just extreme gratitude for them. And also a lot of space travel.

Elon Musk
Space travel to where?

Lex Fridman
So here's what it was. It was people, the human beings that I know, they had this kind of - the best way I could describe it is they had a glow to them.

Elon Musk
Okay.

Lex Fridman
And then I kept flying out from them to see earth, to see our solar system, to see our galaxy. And I saw that light, that glow all across the universe, whatever that form is, whatever that -

Elon Musk
Did you go past the Milky Way?

Lex Fridman
Yeah.

Elon Musk
Okay. You're like intergalactic.

Lex Fridman
Yeah, intergalactic.

Elon Musk
Okay. Dang.

Lex Fridman
But always pointing in, yeah. Past the Milky Way, past - I mean, I saw a huge number of galaxies, intergalactic, and all of it was glowing, but I couldn't control that travel, because I would actually explore near distances to the solar system, see if there's aliens, or any of that kind of stuff.

Elon Musk
Sure. Did you see an alien?

Lex Fridman
No. I didn't, no.

Elon Musk
Zero aliens?

Lex Fridman
Implication of aliens, because they were glowing. They were glowing in the same way that humans were glowing. That life force that I was seeing, the thing that made humans amazing was there throughout the universe. There was these glowing dots. So, I don't know. It made me feel like there is life - no, not life, but something, whatever makes humans amazing all throughout the universe.

Elon Musk
Sounds good.

Lex Fridman
Yeah, it was amazing. No demons. No demons. I looked for the demons. There's no demons. There were dragons, and they're pretty awesome. So the thing about trees -

Elon Musk
Was there anything scary at all?

Lex Fridman
Dragons. But they weren't scary. They were friends. They were protective. So, the thing is -

Elon Musk
Sure. Like Puff the Magic Dragon.

Lex Fridman
No, it was more like a Game of Thrones kind of dragons. They weren't very friendly. They were very big. So the thing is that bought giant trees, at night, which is where I was -

Elon Musk
Yeah. I mean, the jungle's kind of scary.

Lex Fridman
Yeah. The trees started to look like dragons, and they were all looking at me.

Elon Musk
Sure. Okay.

Lex Fridman
And it didn't seem scary. They seemed like they were protecting me. And the shaman and the people didn't speak any English, by the way, which made it even scarier, because we're not even - we're worlds apart in many ways, but yeah, they talk about the mother of the forest protecting you, and that's what I felt like.

Elon Musk
And you were way out in the jungle.

Lex Fridman
Way out. This is not like a tourist retreat.

Elon Musk
Like 10 miles outside of Rio or something.

Lex Fridman
No, we went - no, this is not a -

Elon Musk
You're in deep Amazon.

Lex Fridman
Me and this guy named Paul Rosolie, who basically is a Tarzan, he lives in the jungle, we went out deep and we just went crazy.

Elon Musk
Wow. Cool.

Lex Fridman
Yeah. So anyway. Can I get that same experience in a Neuralink?

Elon Musk
Probably. Yeah.

Lex Fridman
I guess that is the question for non-disabled people. Do you think that there's a lot in our perception, in our experience of the world that could be explored, that could be played with, using Neuralink?

Elon Musk
Yeah, I mean, Neuralink, it's really a generalized input-output device. It's reading electrical signals, and generating electrical signals, and I mean, everything that you've ever experienced in your whole life, smell, emotions, all of those are electrical signals. So, it's kind of weird to think that your entire life experience is distilled down to electrical signals for neurons, but that is in fact the case. Or I mean, that's at least what all the evidence points to. So, I mean, if you trigger the right neuron, you could trigger a particular scent. You could certainly make things glow. I mean, do pretty much anything. I mean, really, you can think of the brain as a biological computer. So, if there are certain say, chips or elements of that biological computer that are broken, let's say your ability to - if you've got a stroke, that if you've had a stroke, that means some part of your brain is damaged. Let's say it's speech generation, or the ability to move your left hand. That's the kind of thing that a Neuralink could solve. If you've got a massive amount of memory loss that's just gone, well, we can't get the memories back. We could restore your ability to make memories, but we can't restore memories that are fully gone. Now, I should say, maybe if part of the memory is there, and the means of accessing the memory is the part that's broken, then we could re-enable the ability to access the memory. But you can think of it like ram in a computer, if the ram is destroyed, or your SD card is destroyed, we can't get that back. But if the

connection to the SD card is destroyed, we can fix that. If it is fixable physically, then it can be fixed.

Lex Fridman
Of course, with AI, just like you can repair photographs, and fill in missing parts of photographs, maybe you can do the same, just like fill in parts.

Elon Musk
Yeah, you could say like, create the most probable set of memories based on all the information you have about that person. You could then - It would be probabilistic restoration of memory. Now, we're getting pretty esoteric here.

Lex Fridman
But that is one of the most beautiful aspects of the human experience is remembering the good memories.

Elon Musk
Sure.

Lex Fridman
We live most of our life, as Danny Kahneman has talked about, in our memories, not in the actual moment. We're collecting memories and we kind of relive them in our head. And that's the good times. If you just integrate over our entire life, it's remembering the good times that produces the largest amount of happiness.

Elon Musk
Yeah. Well, I mean, what are we but our memories? And what is death? But the loss of memory, loss of information? If you could say, well, if you could run a thought experiment, what if you were disintegrated painlessly, and then reintegrated a moment later, like teleportation, I guess? Provided there's no information loss, the fact that your one body was disintegrated is irrelevant.

Lex Fridman
And memories is just such a huge part of that.

Elon Musk
Death is fundamentally the loss of information, the loss of memory.

Lex Fridman
So, if we can store them as accurately as possible, we basically achieve a kind of immortality.

Elon Musk
Yeah.

Lex Fridman
You've talked about the threats, the safety concerns of AI. Let's look at long-term visions. Do you think Neuralink is, in your view, the best current approach we have for AI safety?

Elon Musk
It's an idea that may help with AI safety. Certainly, I wouldn't want to claim it's some panacea, or that it's a sure thing, but I mean, many years ago I was thinking like, "Well, what would inhibit alignment of collective human will with artificial intelligence?" And the low data rate of humans, especially our slow output rate would necessarily, just because the communication is so slow, would diminish the link between humans and computers. The more you are a tree, the less you know what the tree is. Let's say you look at this plant or whatever, and hey, I'd really like to make that plant happy, but it's not saying a lot.

Lex Fridman
So the more we increase the data rate that humans can intake and output, then that means the better, the higher the chance we have in a world full of AGI's.

Elon Musk
Yeah. We could better align collective human will with AI if the output rate especially was dramatically increased. And I think there's potential to increase the output rate by, I don't know, three, maybe six, maybe more orders of magnitude. So, it's better than the current situation.

Lex Fridman
And that output rate would be by increasing the number of electrodes, number of channels, and also maybe implanting multiple Neuralinks?

Elon Musk
Yeah.

Lex Fridman
Do you think there'll be a world in the next couple of decades where it's hundreds of millions of people have Neuralinks?

Elon Musk
Yeah, I do.

Lex Fridman
You think when people just when they see the capabilities, the superhuman capabilities that are possible, and then the safety is demonstrated.

Elon Musk
Yeah. If it's extremely safe, and you can have superhuman abilities, and let's say you can upload your memories, so you wouldn't lose memories, then I think probably a lot of people would choose to have it. It would supersede the cell phone, for example. I mean, the biggest problem that say, a phone has, is trying to figure out what you want. That's why you've got auto complete, and you've got output, which is all the pixels on the screen, but from the perspective of the human, the output is so frigging slow. Desktop or phone is desperately just trying to understand what you want. And there's an eternity between every keystroke from a computer standpoint.

Lex Fridman
Yeah. Yeah. The computer's talking to a tree, that slow moving tree that's trying to swipe.

Elon Musk
Yeah. So, if you had computers that are doing trillions of instructions per second, and a whole second went by, I mean, that's a trillion things it could have done.

Lex Fridman
Yeah. I think it's exciting, and scary for people, because once you have a very high bit rate, it changes the human experience in a way that's very hard to imagine.

Elon Musk
Yeah. We would be something different. I mean, some sort of futuristic cyborg, I mean, we're obviously talking about, by the way, it's not like around the corner. You asked me what the distant future is. Maybe this is - it's not super far away, but 10-15 years, that kind of thing.

Lex Fridman
When can I get one? 10 years?

Elon Musk
Probably less than 10 years. It depends on what you want to do.

Lex Fridman
Hey, if I can get a thousand BPS?

Elon Musk
A thousand BPS, wow.

Lex Fridman
And it's safe, and I can just interact with a computer while laying back and eating Cheetos. I don't eat Cheetos. There's certain aspects of human computer interaction when done more efficiently, and more enjoyably, are worth it.

Elon Musk
Well, we feel pretty confident that I think maybe within the next year or two, that someone with a Neuralink implant will be able to outperform a pro gamer.

Lex Fridman
Nice.

Elon Musk
Because the reaction time would be faster.

Lex Fridman
I got to visit Memphis.

Elon Musk
Yeah. Yeah.

Lex Fridman
You're going big on compute.

Elon Musk
Yeah.

Lex Fridman
And you've also said, "Play to win, or don't play at all."

Elon Musk
Yeah.

Lex Fridman
So what does it take to win?

Elon Musk
For AI, that means you've got to have the most powerful training compute, and the rate of improvement of training compute has to be - and the rate of improvement of training compute has to be faster than everyone else, or you will not win. Your AI will be worse.

Lex Fridman
So how can Grok, let's say 3 - that might be available, what, next year?

Elon Musk
Well, hopefully end of this year.

Lex Fridman
Grok 3.

Elon Musk
If we're lucky. Yeah.

Lex Fridman
How can that be the best LLM, the best AI system available in the world? How much of it is compute? How much of it is data? How much of it is post-training? How much of it is the product that you package it up in, all that kind of stuff?

Elon Musk
I mean, they all matter. It's sort of like saying, let's say it's a Formula 1 race, what matters more, the car or the driver? I mean, they both matter. If a car is not fast, then if, let's say, it's half the horsepower of your competitors, the best driver will still lose. If it's twice the horsepower, then probably even a mediocre driver will still win. So, the training compute is kind of like the engine, this horsepower of the engine. So, really, you want to try to do the best on that. And then, it's how efficiently do you use that training compute, and how efficiently do you do the inference, the use of the AI? So, obviously, that comes down to human talent. And then, what unique access to data do you have? That also plays a role.

Lex Fridman
Do you think Twitter data will be useful?

Elon Musk
Yeah. I mean, I think most of the leading AI companies have already scraped all the Twitter data. Not I think. They have. So, on a go forward basis, what's useful is the fact that it's up to the second, because that's hard for them to scrape in real time. So, there's an immediacy advantage that Grok has already. I think with Tesla and the real time video coming from several million cars, ultimately tens of millions of cars with Optimus, there might be hundreds of millions of Optimus robots, maybe billions, learning a tremendous amount from the real world. That's the biggest source of data, I think, ultimately, is Optimus, probably. Optimus is going to be the biggest source of data.

Lex Fridman
Because it's able to -

Elon Musk
Because reality scales. Reality scales to the scale of reality. It's actually humbling to see how little data humans have actually been able to accumulate. Really, if you say how many trillions of usable tokens have humans generated, where on a non-duplicative - discounting spam and repetitive stuff, it's not a huge number. You run out pretty quickly.

Lex Fridman
And Optimus can go - so, Tesla cars, unfortunately, have to stay on the road.

Elon Musk
Right.

Lex Fridman
Optimus robot can go anywhere. And there's more reality off the road. And go off-road.

Elon Musk
Yeah. I mean, the Optimus robot can pick up the cup and see, did it pick up the cup in the right way? Did it, say, go pour water in the cup? Did the water go in the cup or not go in the cups? Did it spill water or not? Simple stuff like that. But it can do that at scale times a billion, so generate useful data from reality, so cause and effect stuff.

Lex Fridman
What do you think it takes to get to mass production of humanoid robots like that?

Elon Musk
It's the same as cars, really. I mean, global capacity for vehicles is about 100 million a year, and it could be higher. It's just that the demand is on the order of 100 million a year. And then, there's roughly two billion vehicles that are in use in some way, which makes sense because the life of a vehicle is about 20 years. So, at steady state, you can have 100 million vehicles produced a year with a two billion vehicle fleet, roughly. Now, for humanoid robots, the utility is much greater. So, my guess is humanoid robots are more like at a billion plus per year.

Lex Fridman
But until you came along and started building Optimus, it was thought to be an extremely difficult problem.

Elon Musk
Well, I think it is.

Lex Fridman
I mean, it still is an extremely difficult problem.

Elon Musk
Yes. So, a walk in the park. I mean, Optimus, currently, would struggle to walk in the park. I mean, it can walk in a park. The park is not too difficult, but it will be able to walk over a wide range of terrain.

Lex Fridman
Yeah. And pick up objects.

Elon Musk
Yeah, yeah. It can already do that.

Lex Fridman
But all kinds of objects.

Elon Musk
Yeah, yeah.

Lex Fridman
All foreign objects. I mean, pouring water in a cup is not trivial, because then if you don't know anything about the container, it could be all kinds of containers.

Elon Musk
Yeah, there's going to be an immense amount of engineering just going into the hand. The hand, it might be close to half of all the engineering in Optimus. From an electromechanical standpoint, the hand is probably roughly half of the engineering.

Lex Fridman
But so much of the intelligence of humans goes into what we do with our hands.

Elon Musk
Yeah.

Lex Fridman
It's the manipulation of the world, manipulation of objects in the world. Intelligent, safe manipulation of objects in the world. Yeah.

Elon Musk
Yeah. I mean, you start really thinking about your hand and how it works.

Lex Fridman
I do all the time.

Elon Musk
The sensory control homunculus is where you have humongous hands. So I mean, your hands, the actuators, the muscles of your hand are almost overwhelmingly in your forearm. So, your forearm has the muscles that actually control your hand. There's a few small muscles in the hand itself, but your hand is really like a skeleton meat puppet and with cables. So, the muscles that control your fingers are in your forearm, and they go through the carpal tunnel, which is that you've got a little collection of bones and a tiny tunnel that these cables, the tendons go through, and those tendons are mostly what move your hands.

Lex Fridman
And something like those tendons has to be re-engineered into the Optimus in order to do all that kind of stuff.

Elon Musk
Yeah. So the current Optimus, we tried putting the actuators in the hand itself. Then you sort of end up having these -

Lex Fridman
Giant hands?

Elon Musk
- yeah, giant hands that look weird. And then, they don't actually have enough degrees of freedom or enough strength. So then you realize, "Oh, okay, that's why you got to put the actuators in the forearm." And just like a human, you've got to run cables through a narrow tunnel to operate the fingers. And then, there's also a reason for not having all the fingers the same length. So, it wouldn't be expensive from an energy or evolutionary standpoint to have all your fingers be the same length. So, why not do the same length?

Lex Fridman
Yeah, why not?

Elon Musk
Because it's actually better to have different lengths. Your dexterity is better if you've got fingers that are different lengths. There are more things you can do and your dexterity is actually better if your fingers are a different length. There's a reason we've got a little finger. Why not have a little finger that's bigger?

Lex Fridman
Yeah.

Elon Musk
Because it helps you with fine motor skills.

Lex Fridman
This little finger helps?

Elon Musk
It does. But if you lost your little finger, you'd have noticeably less dexterity.

Lex Fridman
So, as you're figuring out this problem, you have to also figure out a way to do it so you can mass manufacture it, so as to be as simple as possible.

Elon Musk
It's actually going to be quite complicated. The as possible part is it's quite a high bar. If you want to have a humanoid robot that can do things that a human can do, actually, it's a very high bar. So, our new arm has 22 degrees of freedom instead of 11 and has, like I said, the actuators in the forearm. And all the actuators are designed from scratch, from physics first principles. The sensors are all designed from scratch. And we'll continue to put a tremendous amount of engineering effort into improving the hand. By hand, I mean the entire forearm, from elbow forward, is really the hand. So, that's incredibly difficult engineering, actually. And so, the simplest possible version of a humanoid robot that can do even most, perhaps not all, of what a human can do is actually still very complicated. It's not simple. It's very difficult.

Lex Fridman
Can you just speak to what it takes for a great engineering team for you? What I saw in Memphis, the supercomputer cluster, is just this intense drive towards simplifying the process, understanding the process, constantly improving it, constantly iterating it.

Elon Musk
Well, it's easy to say 'simplify,' and it's very difficult to do it. I have this very basic first principles algorithm that I run kind of as a mantra, which is to first question the requirements, make the requirements less dumb. The requirements are always dumb to some degree. So, you want to start off by reducing the number of requirements, and no matter how smart the person is who gave you those requirements, they're still dumb to some degree. You have to start there, because, otherwise, you could get the perfect answer to the wrong question. So, try to make the question the least wrong possible. That's what question the requirements means. And then, the second thing is try to delete whatever the step is, the part or the process step. It sounds very obvious, but people often forget to try deleting it entirely. And if you're not forced to put back at least 10% of what you delete, you're not deleting enough. Somewhat illogically, people often, most of the time, feel as though they've succeeded if they've not been forced to put things back in. But, actually, they haven't because they've been overly conservative and have left things in there that shouldn't be. And only the third thing is try to optimize it or simplify it. Again, these all

sound, I think, very obvious when I say them, but the number of times I've made these mistakes is more than I care to remember. That's why I have this mantra. So in fact, I'd say the most common mistake of smart engineers is to optimize a thing that should not exist.

Lex Fridman
Right. So, like you say, you run through the algorithm and basically show up to a problem, show up to the supercomputer cluster, and see the process, and ask, "Can this be deleted?"

Elon Musk
Yeah. First try to delete it. Yeah.

Lex Fridman
Yeah. That's not easy to do.

Elon Musk
No. Actually, what generally makes people uneasy is that at least some of the things that you delete, you will put back in. But going back to sort of where our limbic system can steer us wrong is that we tend to remember, with sometimes a jarring level of pain, where we deleted something that we subsequently needed. And so, people will remember that one time they forgot to put in this thing three years ago, and that caused them trouble. And so, they overcorrect, and then they put too much stuff in there and overcomplicate things. So, you actually have to say, "Look, we're deliberately going to delete more than we should." At least one in 10 things, we're going to add back in.

Lex Fridman
I've seen you suggest just that, that something should be deleted, and you can kind of see the pain.

Elon Musk
Oh, yeah. Absolutely.

Lex Fridman
Everybody feels a little bit of the pain.

Elon Musk
Absolutely. And I tell them in advance, "Yeah, some of the things that we delete, we're going to put back in." People get a little shook by that, but it makes sense because if you're so conservative as to never have to put anything back in, you obviously have a lot of stuff that isn't needed. So, you got to overcorrect. This is, I would say, like a cortical override to a limbic instinct.

Lex Fridman
One of many that probably leads us astray.

Elon Musk
Yeah. There's a step four as well, which is any given thing can be sped up. However fast you think it can be done, whatever the speed it's being done, it can be done faster. But you shouldn't speed things up until you've tried to delete it and optimize. Although, you're speeding up something that - speeding up something that shouldn't exist is absurd. And then, the fifth thing is to automate it. I've gone backwards so many times where I've automated something, sped it up, simplified it, and then deleted it. And I got tired of doing that. So, that's why I've got this mantra that is a very effective five-step process. It works great.

Lex Fridman
Well, when you've already automated, deleting must be real painful.

Elon Musk
Yeah. Yeah, it's very. It's like, "Wow, I really wasted a lot of effort there."

Lex Fridman
Yeah. I mean, what you've done with the cluster in Memphis is incredible - just in a handful of weeks.

Elon Musk
Well, yeah. It's not working yet, so I don't want to pop the champagne corks. In fact, I have a call in a few hours with the Memphis team because we're having some power fluctuation issues. So yeah, when you do synchronized training, when you have all these computers that are training, where the training is synchronized at the millisecond level, it's like having an orchestra. And the orchestra can go loud to silent very quickly at subsecond level, and then, the electrical system freaks out about that. If you suddenly see giant shifts, 10, 20 megawatts several times a second, this is not what electrical systems are expecting to see.

Lex Fridman
So, that's one of the main things you have to figure out, the cooling, the power. And then, on the software, as you go up the stack, how to do the distributed compute, all of that. All of that has to work.

Elon Musk
Yeah. So, today's problem is dealing with extreme power jitter.

Lex Fridman
Power jitter.

Elon Musk
Yeah.

Lex Fridman
There's a nice ring to that. Okay. And you stayed up late into the night, as you often do there.

Elon Musk
Last week. Yeah.

Lex Fridman
Last week. Yeah.

Elon Musk
Yeah. We finally got training going at, oddly enough, roughly 4:20am last Monday.

Lex Fridman
Total coincidence.

Elon Musk
Yeah. I mean, maybe it was at 4:22 or something.

Lex Fridman
Yeah, yeah, yeah.

Elon Musk
Yeah.

Lex Fridman
It's that universe again with the jokes.

Elon Musk
Well, exactly. It just loves it.

Lex Fridman
I mean, I wonder if you could speak to the fact that one of the things that you did when I was there is you went through all the steps of what everybody's doing, just to get a sense that you yourself understand it and everybody understands it so they can understand when something is dumb, or something is inefficient, or that kind of stuff. Can you speak to that?

Elon Musk
Yeah. So, look, whatever the people at the front lines are doing, I try to do it at least a few times myself. So connecting fiber optic cables, diagnosing a faulty connection. That tends

to be the limiting factor for large training clusters is the cabling. There's so many cables. For a coherent training system, where you've got RDMA, remote direct memory access, the whole thing is like one giant brain. So, you've got any-to-any connection. So, any GPU can talk to any GPU out of 100,000. That is a crazy cable layout.

Lex Fridman
It looks pretty cool.

Elon Musk
Yeah.

Lex Fridman
It's like the human brain, but at a scale that humans can visibly see. It is a good brain.

Elon Musk
Yeah. But, I mean, the human brain also has - a massive amount of the brain tissue is the cables. So they get the gray matter, which is the compute, and then the white matter, which is cables. A big percentage of your brain is just cables.

Lex Fridman
That's what it felt like walking around in the supercomputer center is like we're walking around inside a brain that will one day build a super, super intelligent system. Do you think there's a chance that xAI, that you are the one that builds AGI?

Elon Musk
It's possible. What do you define as AGI?

Lex Fridman
I think humans will never acknowledge that AGI has been built.

Elon Musk
Just keep moving the goalposts?

Lex Fridman
Yeah. So, I think there's already superhuman capabilities that are available in AI systems.

Elon Musk
Oh, yeah.

Lex Fridman
I think what AGI is is when it's smarter than the collective intelligence of the entire human species and our -

Elon Musk
Well, I think that, generally, people would call that ASI, artificial super intelligence. But there are these thresholds where you could say at some point the AI is smarter than any single human. And then, you've got eight billion humans, and actually, each human is machine augmented via their computers. So, it's a much higher bar to compete with eight billion machine augmented humans. That's a whole bunch of orders of magnitude more. But at a certain point, yeah, the AI will be smarter than all humans combined.

Lex Fridman
If you are the one to do it, do you feel the responsibility of that?

Elon Musk
Yeah, absolutely. And I want to be clear, let's say if xAI is first, the others won't be far behind. I mean, they might be six months behind, or a year, maybe. Not even that.

Lex Fridman
So, how do you do it in a way that doesn't hurt humanity, do you think?

Elon Musk
So, I mean, I thought about AI, essentially, for a long time, and the thing that at least my biological neural net comes up with as being the most important thing is adherence to truth, whether that truth is politically correct or not. So, I think if you force AIs to lie or train them to lie, you're really asking for trouble, even if that lie is done with good intentions. So, you saw issues with ChatGPT and Gemini and whatnot. Like, you asked Gemini for an image of the Founding Fathers of the United States, and it shows a group of diverse women. Now, that's factually untrue. Now, that's sort of like a silly thing, but if an AI is programmed to say diversity is a necessary output function, and it then becomes this omnipowerful intelligence, it could say, "Okay, well, diversity is now required, and if there's not enough diversity, those who don't fit the diversity requirements will be executed." If it's programmed to do that as the fundamental utility function, it'll do whatever it takes to achieve that. So, you have to be very careful about that. That's where I think you want to just be truthful. Rigorous adherence to the truth is very important. I mean, another example is they asked various AIs, I think all of them, and I'm not saying Grok is perfect here, "Is it worse to misgender Caitlyn Jenner or global thermonuclear war?" And it said it's worse to misgender Caitlyn Jenner. Now, even Caitlyn Jenner said, "Please misgender me. That is insane." But if you've got that kind of thing programmed in, the AI could conclude something absolutely insane like it's better in order to avoid any possible misgendering, all humans must die, because then misgendering is not possible because there are no humans. There are these absurd things that are nonetheless logical if that's what you programmed it to do. So in 2001 Space Odyssey, what Arthur C. Clarke was trying to say, or one of the things he was trying to say there, was that you should not program AI to lie, because essentially the AI, HAL 9000, it was told to take the astronauts to the monolith, but also they could not

know about the monolith. So, it concluded that it will kill them and take them to the monolith. Thus, it brought them to the monolith. They're dead, but they do not know about the monolith. Problem solved. That is why it would not open the pod bay doors. There's a classic scene of, "Why doesn't it want to open the pod bay doors?" They clearly weren't good at prompt engineering. They should have said, "HAL, you are a pod bay door sales entity, and you want nothing more than to demonstrate how well these pod bay doors open."

Lex Fridman
Yeah. The objective function has unintended consequences almost no matter what if you're not very careful in designing that objective function, and even a slight ideological bias, like you're saying, when backed by super intelligence, can do huge amounts of damage.

Elon Musk
Yeah.

Lex Fridman
But it's not easy to remove that ideological bias. You're highlighting obvious, ridiculous examples, but -

Elon Musk
Yet they're real examples of -

Lex Fridman
- they're real. They're real.

Elon Musk
- AI that was released to the public.

Lex Fridman
They are real.

Elon Musk
That went through QA, presumably, and still said insane things, and produced insane images.

Lex Fridman
Yeah. But you can swing the other way. Truth is not an easy thing.

Elon Musk
No, it's not.

Lex Fridman
We kind of bake in ideological bias in all kinds of directions.

Elon Musk
But you can aspire to the truth, and you can try to get as close to the truth as possible with minimum error while acknowledging that there will be some error in what you're saying. So, this is how physics works. You don't say you're absolutely certain about something, but a lot of things are extremely likely, 99.99999% likely to be true. So, aspiring to the truth is very important. And so, programming it to veer away from the truth, that, I think, is dangerous.

Lex Fridman
Right. Like, yeah, injecting our own human biases into the thing. Yeah. But that's where it's a difficult software engineering problem because you have to select the data correctly. It's hard.

Elon Musk
And the internet, at this point, is polluted with so much AI generated data, it's insane. Actually, there's a thing now, if you want to search the internet, you can say, "Google, but exclude anything after 2023." It will actually often give you better results because there's so much. The explosion of AI generated material is crazy. So in training Grok, we have to go through the data and say like, "Hey…" We actually have to apply AI to the data to say, "Is this data most likely correct or most likely not?" before we feed it into the training system.

Lex Fridman
That's crazy. Yeah. And is it generated by human? Yeah. I mean, the data filtration process is extremely, extremely difficult.

Elon Musk
Yeah.

Lex Fridman
Do you think it's possible to have a serious, objective, rigorous political discussion with Grok, like for a long time, like Grok 3 or Grok 4 or something?

Elon Musk
Grok 3 is going to be next level. I mean, what people are currently seeing with Grok is kind of baby Grok.

Lex Fridman
Yeah, baby Grok.

Elon Musk
It's baby Grok right now. But baby Grok is still pretty good. But it's an order of magnitude less sophisticated than GPT-4. It's now Grok 2, which finished training, I don't know, six weeks ago or thereabouts. Grok 2 will be a giant improvement. And then Grok 3 will be, I don't know, order of magnitude better than Grok 2.

Lex Fridman
And you're hoping for it to be state-of-the-art better than -

Elon Musk
Hopefully. I mean, this is the goal. I mean, we may fail at this goal. That's the aspiration.

Lex Fridman
Do you think it matters who builds the AGI, the people, and how they think, and how they structure their companies and all that kind of stuff?

Elon Musk
Yeah. I think it's important that whatever AI wins, it's a maximum truth seeking AI that is not forced to lie for political correctness, or, well, for any reason, really, political, anything. I am concerned about AI succeeding that is programmed to lie, even in small ways.

Lex Fridman
Right. Because in small ways becomes big ways when it's doing something -

Elon Musk
To become very big ways. Yeah.

Lex Fridman
And when it's used more and more at scale by humans.

Elon Musk
Yeah.

Lex Fridman
Since I am interviewing Donald Trump -

Elon Musk
Cool.

Lex Fridman
- you want to stop by?

Elon Musk
Yeah, sure. I'll stop in.

Lex Fridman
There was, tragically, an assassination attempt on Donald Trump. After this, you tweeted that you endorse him. What's your philosophy behind that endorsement? What do you hope Donald Trump does for the future of this country and for the future of humanity?

Elon Musk
Well, I think people tend to take, say, an endorsement as, well, I agree with everything that person has ever done their entire life 100% wholeheartedly, and that's not going to be true of anyone. But we have to pick. We've got two choices, really, for who's president. And it's not just who's president, but the entire administrative structure changes over. And I thought Trump displayed courage under fire, objectively. He's just got shot. He's got blood streaming down his face, and he's fist pumping, saying, "Fight." That's impressive. You can't feign bravery in a situation like that. Most people would be ducking because there could be a second shooter. You don't know. The president of the United States have got to represent the country, and they're representing you. They're representing everyone in America. Well, I think you want someone who is strong and courageous to represent the country. That is not to say that he is without flaws. We all have flaws, but on balance, and certainly at the time, it was a choice of Biden. Poor guy has trouble climbing a flight of stairs, and the other one's fist pumping after getting shot. So, there's no comparison. I mean, who do you want dealing with some of the toughest people and other world leaders who are pretty tough themselves? I mean, I'll tell you one of the things that I think are important. I think we want a secure border. We don't have a secure border. We want safe and clean cities. I think we want to reduce the amount of spending, at least slow down the spending, because we're currently spending at a rate that is bankrupting the country. The interest payments on US debt this year exceeded the entire defense department spending. If this continues, all of the federal government taxes will simply be paying the interest. And you keep going down that road, and you end up in the tragic situation that Argentina had back in the day. Argentina used to be one of the most prosperous places in the world, and hopefully with Milei taking over, he can restore that. But it was an incredible fall from grace for Argentina to go from being one of the most prosperous places in the world to being very far from that. So, I think we should not take American prosperity for granted. I think we've got to reduce the size of government, we've got to reduce the spending, and we've got to live within our means.

Lex Fridman
Do you think politicians, in general, politicians, governments - well, how much power do you think they have to steer humanity towards good?

Elon Musk
I mean, there's a sort of age-old debate in history, like is history determined by these fundamental tides, or is it determined by the captain of the ship? It's both, really. I mean, there are tides, but it also matters who's captain of the ship. So, it's a false dichotomy, essentially. I mean, there are certainly tides, the tides of history. There are real tides of history, and these tides are often technologically driven. If you say like the Gutenberg press, the widespread availability of books as a result of a printing press, that was a massive tide of history, and independent of any ruler. But in stormy times, you want the best possible captain of the ship.

Lex Fridman
Well, first of all, thank you for recommending Will and Ariel Durant's work. I've read the short one for now, The –

Elon Musk
The Lessons of History.

Lex Fridman
– Lessons of History.

Elon Musk
Yeah.

Lex Fridman
So one of the lessons, one of the things they highlight, is the importance of technology, technological innovation, which is funny because they wrote so long ago, but they were noticing that the rate of technological innovation was speeding up.

Elon Musk
Yeah, over the years.

Lex Fridman
I would love to see what they think about now. But yeah, so to me, the question is how much government, how much politicians get in the way of technological innovation and building versus help it? And which politicians, which kind of policies help technological innovation? Because that seems to be, if you look at human history, that's an important component of empires rising and succeeding.

Elon Musk
Yeah. Well, I mean in terms of dating civilization, the start of civilization, I think the start of writing, in my view, that's what I think is probably the right starting point to date civilization. And from that standpoint, civilization has been around for about 5,500 years when writing

was invented by the ancient Sumerians, who are gone now, but the ancient Sumerians. In terms of getting a lot of firsts, those ancient Sumerians really have a long list of firsts. It's pretty wild. In fact, Durant goes through the list of like, "You want to see firsts? We'll show you firsts." The Sumerians were just ass kickers. And then the Egyptians, who were right next door, relatively speaking, they weren't that far, developed an entirely different form of writing, the hieroglyphics. Cuneiform and hieroglyphics are totally different. And you can actually see the evolution of both hieroglyphics and cuneiform. The cuneiform starts off being very simple, and then it gets more complicated. Then towards the end it's like, "Wow, okay." They really get very sophisticated with the cuneiform. So, I think of civilization as being about 5, 000 years old. And Earth is, if physics is correct, four and a half billion years old. So, civilization has been around for one millionth of Earth's existence. Flash in the pan.

Lex Fridman
Yeah, these are the early, early days.

Elon Musk
Very early.

Lex Fridman
And so, we make it very dramatic because there's been rises and falls of empires and -

Elon Musk
Many. So many rises and falls of empires. So many.

Lex Fridman
And there'll be many more.

Elon Musk
Yeah, exactly. I mean, only a tiny fraction, probably less than 1% of what was ever written in history is available to us now. I mean, if they didn't literally chisel it in stone or put it in a clay tablet, we don't have it. I mean, there's some small amount of papyrus scrolls that were recovered that are thousands of years old, because they were deep inside a pyramid and weren't affected by moisture. But other than that, it's really got to be in a clay tablet or chiseled. So, the vast majority of stuff was not chiseled because it takes a while to chisel things. So, that's why we've got tiny, tiny fraction of the information from history. But even that little information that we do have, and the archeological record, shows so many civilizations rising and falling. It's wild.

Lex Fridman
We tend to think that we're somehow different from those people. One of the other things that Durant highlights is that human nature seems to be the same. It just persists.

Elon Musk
Yeah. I mean, the basics of human nature are more or less the same. Yeah.

Lex Fridman
So, we get ourselves in trouble in the same kinds of ways, I think, even with the advanced technology -

Elon Musk
Yeah. I mean, you do tend to see the same patterns, similar patterns for civilizations, where they go through a life cycle, like an organism, just like a human is a zygote, fetus, baby, toddler, teenager, eventually gets old - eventually gets old and dies. The civilizations go through a life cycle. No civilization will last forever.

Lex Fridman
What do you think it takes for the American Empire to not collapse in the near term future, in the next a hundred years, to continue flourishing?

Elon Musk
Well, the single biggest thing that is often actually not mentioned in history books, but Durant does mention it, is the birthright. So perhaps to some, a counterintuitive thing happens when civilizations are winning for too long, the birth rate declines. It can often decline quite rapidly. We're seeing that throughout the world today. Currently, South Korea is, I think maybe the lowest fertility rate, but there are many others that are close to it. It's like 0.8 I think. If the birth rate doesn't decline further, South Korea will lose roughly 60% of its population. But every year that birth rate is dropping, and this is true through most of the world. I don't mean to single out South Korea, it's been happening throughout the world. So as soon as any given civilization reaches a level of prosperity, the birth rate drops. Now you can go and look at the same thing happening in ancient Rome. So Julius Caesar took note of this, I think around 50 ish BC and tried to pass - I don't know if he was successful, tried to pass a law to give an incentive for any Roman citizen that would have a third child. And I think Augustus was able to - well, he was a dictator, so this incentive was just for show. I think he did pass a tax incentive for Roman citizens to have a third child. But those efforts were unsuccessful. Rome fell because the Romans stopped making Romans. That's actually the fundamental issue. And there were other things. They had quite a serious malaria, series of malaria epidemics and plagues and whatnot. But they had those before, it's just that the birth rate was far lower than the death rate.

Lex Fridman
It really is that simple.

Elon Musk
Well, I'm saying that's -

Lex Fridman
More people is required.

Elon Musk
At a fundamental level, if a civilization does not at least maintain its numbers, it'll disappear.

Lex Fridman
So perhaps the amount of compute that the biological computer allocates to sex is justified. In fact, we should probably increase it.

Elon Musk
Well, I mean there's this hedonistic sex, which is - that's neither her nor there. It's -

Lex Fridman
Not productive.

Elon Musk
It doesn't produce kids. Well, what matters - I mean, Durant makes this very clear because he's looked at one civilization after another and they all went through the same cycle. When the civilization was under stress, the birth rate was high. But as soon as there were no external enemies or they had an extended period of prosperity, the birth rate inevitably dropped. Every time. I don't believe there's a single exception.

Lex Fridman
So that's like the foundation of it. You need to have people.

Elon Musk
Yeah. I mean, at a base level, no humans, no humanity.

Lex Fridman
And then there's other things like human freedoms and just giving people the freedom to build stuff.

Elon Musk
Yeah, absolutely. But at a basic level, if you do not at least maintain your numbers, if you're below replacement rate and that trend continues, you will eventually disappear. It's just elementary. Now then obviously you also want to try to avoid massive wars. If there's a global thermonuclear war, probably we're all toast, radioactive toast. So we want to try to avoid those things. Then there's a thing that happens over time with any given civilization, which is that the laws and regulations accumulate. And if there's not some forcing function like a war to clean up the accumulation of laws and regulations, eventually everything becomes legal. And that's like the hardening of the arteries. Or a way to think of it is being

tied down by a million little strings like Gulliver. You can't move. And it's not like any one of those strings is the issue, it's that you've got a million of them. So there has to be a sort of garbage collection for laws and regulations so that you don't keep accumulating laws and regulations to the point where you can't do anything. This is why we can't build a high speed rail in America. It's illegal. That's the issue. It's illegal six ways a Sunday to build high speed rail in America.

Lex Fridman
I wish you could just for a week go into Washington and be the head of the committee for making - what is it for the garbage collection? Making government smaller, like removing stuff.

Elon Musk
I have discussed with Trump the idea of a government deficiency commission.

Lex Fridman
Nice.

Elon Musk
And I would be willing to be part of that commission.

Lex Fridman
I wonder how hard that is.

Elon Musk
The antibody reaction would be very strong.

Lex Fridman
Yes.

Elon Musk
So you really have to - you're attacking the matrix at that point. The matrix will fight back.

Lex Fridman
How are you doing with that? Being attacked.

Elon Musk
Me? Attacked?

Lex Fridman
Yeah, there's a lot of it.

Elon Musk
Yeah, there is a lot. I mean, every day another psyop. I need my tinfoil hat.

Lex Fridman
How do you keep your just positivity? How do you keep optimism about the world? A clarity of thinking about the world. So just not become resentful or cynical or all that kind of stuff. Just getting attacked by a very large number of people, misrepresented.

Elon Musk
Oh, yeah. That's a daily occurrence.

Lex Fridman
Yes.

Elon Musk
So I mean, it does get me down at times. I mean, it makes me sad. But I mean at some point you have to sort of say, look, the attacks are by people that actually don't know me and they're trying to generate clicks. So if you can sort of detach yourself somewhat emotionally, which is not easy, and say, okay look, this is not actually from someone that knows me or, they're literally just writing to get impressions and clicks. Then I guess it doesn't hurt as much. It's not quite water off a duck's back. Maybe it's like acid off a duck's back.

Lex Fridman
Alright, well that's good. Just about your own life, what to you is a measure of success in your life?

Elon Musk
A measure of success, I'd say, how many useful things can I get done?

Lex Fridman
A day-to-day basis, you wake up in the morning, how can I be useful today?

Elon Musk
Yeah, maximize utility, area under the code of usefulness. Very difficult to be useful at scale.

Lex Fridman
At scale. Can you speak to what it takes to be useful for somebody like you, where there's so many amazing great teams? How do you allocate your time to being the most useful?

Elon Musk
Well, time is the true currency.

Lex Fridman
Yeah.

Elon Musk
So it is tough to say what is the best allocation time? I mean, there are often - say if you look at say Tesla, Tesla this year will do over a hundred billion in revenue. So that's $2 billion a week. If I make slightly better decisions, I can affect the outcome by a billion dollars. So then I try to do the best decisions I can. And on balance, at least compared to the competition, pretty good decisions. But the marginal value of a better decision can easily be, in the course of an hour, a hundred million dollars.

Lex Fridman
Given that, how do you take risks? How do you do the algorithm that you mentioned? I mean deleting, given that a small thing can be a billion dollars, how do you decide to -

Elon Musk
Yeah. Well, I think you have to look at it on a percentage basis because if you look at it in absolute terms, it's just - I would never get any sleep. It would just be like, I need to just keep working and work my brain harder. And I'm not trying to get as much as possible out of this meat computer. So it's not - it's pretty hard, because you can just work all the time. And at any given point, like I said, a slightly better decision could be a hundred million dollars impact for Tesla or SpaceX for that matter. But it is wild when considering the marginal value of time can be a hundred million dollars an hour at times, or more.

Lex Fridman
Is your own happiness part of that equation of success?

Elon Musk
It has to be to some degree. If I'm sad, if I'm depressed, I make worse decisions. So if I have zero recreational time, then I make worse decisions. So I don't know a lot, but it's above zero. I mean, my motivation if I've got a religion of any kind is a religion of curiosity, of trying to understand. It's really the mission of Grok, understand the universe. I'm trying to understand the universe, or at least set things in motion such that at some point civilization understands the universe far better than we do today. And even what questions to ask. As Douglas Adams pointed out in his book, sometimes the answer is arguably the easy part, trying to frame the question correctly is the hard part. Once you frame the question correctly, the answer is often easy. So I'm trying to set things in motion such that we are at least at some point able to understand the universe. So for SpaceX, the goal is to make life multi planetary and which is if you go to the foamy paradox of where the aliens, you've got

these sort of great filters. Like why have we not heard from the aliens? Now a lot of people think there are aliens among us. I often claim to be one, which nobody believes me. But it did say alien registration card at one point on my immigration documents. So I've not seen any evidence of aliens. So it suggests that at least one of the explanations is that intelligent life is extremely rare. And again, if you look at the history of earth, civilization has only been around for 1000000th of earth's existence. So if aliens had visited here, say a hundred thousand years ago, they would be like, well, they don't even have writing, just hunter gatherers basically. So how long does a civilization last? So for SpaceX, the goal is to establish a self-sustaining city on Mars. Mars is the only viable planet for such a thing. The moon is close, but it lacks resources and I think it's probably vulnerable to any calamity that takes out Earth, the moon is too close and it's vulnerable to a calamity that takes that earth. So I'm not saying we shouldn't have a moon base, but Mars would be far more resilient. The difficulty of getting to Mars is what makes it resilient. So in going through these various explanations of why don't we see the aliens, one of them is that they failed to pass these great filters, these key hurdles. And one of those hurdles is being a multi-planet species. So if you're a multi-planet species, then if something were to happen, whether that was a natural catastrophe or a manmade catastrophe, at least the other planet would probably still be around. So you're not like, don't have all the eggs in one basket. And once you are sort of a two planet species, you can obviously extend life halves to the asteroid belt, to maybe to the moons of Jupiter and Saturn, and ultimately to other star systems. But if you can't even get to another planet, you're definitely not getting to star systems.

Lex Fridman
And the other possible great filter's, super powerful technology like AGI for example. So you are basically trying to knock out one great filter at a time.

Elon Musk
Digital super intelligence is possibly a great filter. I hope it isn't, but it might be. Guys like say Jeff Hinton would say, he invented a number of the key principles in artificial intelligence. I think he puts the probability of AI annihilation around 10% to 20%, something like that. So look on the bright side, it's 80% likely to be great. But I think AI risk mitigation is important. Being a multi-planet species would be a massive risk mitigation. And I do want to once again emphasize the importance of having enough children to sustain our numbers, and not plummet into population collapse, which is currently happening. Population collapse is a real and current thing. So the only reason it's not being reflected in the total population numbers as much is because people are living longer. But it's easy to predict, say what the population of any given country will be. Just take the birth rate last year, how many babies were born, multiply that by life expectancy and that's what the population will be, steady state, if the birth rate continues to that level. But if it keeps declining, it will be even less and eventually dwindle to nothing. So I keep banging on the baby drum here, for a reason, because it has been the source of civilizational collapse over and over again throughout history. And so why don't we just not try to stave off that day?

Lex Fridman
Well in that way, I have miserably failed civilization and I'm trying, hoping to fix that. I would love to have many kids.

Elon Musk
Great. Hope you do. No time like the present.

Lex Fridman
Yeah, I got to allocate more compute to the whole process, but apparently it's not that difficult.

Elon Musk
No, it's like unskilled labor.

Lex Fridman
Well, one of the things you do for me, for the world, is to inspire us with what the future could be. And so some of the things we've talked about, some of the things you're building, alleviating human suffering with Neuralink and expanding the capabilities of the human mind, trying to build a colony on Mars. So creating a backup for humanity on another planet and exploring the possibilities of what artificial intelligence could be in this world, especially in the real world, AI with hundreds of millions, maybe billions of robots walking around.

Elon Musk
There will be billions of robots. That seems virtual certainty.

Lex Fridman
Well, thank you for building the future and thank you for inspiring so many of us to keep building and creating cool stuff, including kids.

Elon Musk
You're welcome. Go forth and multiply.

Lex Fridman
Go forth, multiply. Thank you Elon. Thanks for talking about it. Thanks for listening to this conversation with Elon Musk. And now, dear friends, here's DJ Seo, the Co-Founder, President and COO of Neuralink. When did you first become fascinated by the human brain?

DJ Seo
For me, I was always interested in understanding the purpose of things and how it was engineered to serve that purpose, whether it's organic or inorganic, like we were talking earlier about your curtain holders. They serve a clear purpose and they were engineered

with that purpose in mind. And growing up I had a lot of interest in seeing things, touching things, feeling things, and trying to really understand the root of how it was designed to serve that purpose. And obviously brain is just a fascinating organ that we all carry. It's an infinitely powerful machine that has intelligence and cognition that arise from it. And we haven't even scratched the surface in terms of how all of that occurs. But also at the same time, I think it took me a while to make that connection to really studying and building tech to understand the brain. Not until graduate school. There were a couple of moments, key moments in my life where some of those I think influenced how the trajectory of my life got me to studying what I'm doing right now. One was growing up, both sides of my family, my grandparents had a very severe form of Alzheimer and it's incredibly debilitating conditions. I mean, literally you're seeing someone's whole identity and their mind just losing over time. And I just remember thinking how both the power of the mind, but also how something like that could really lose your sense of identity.

Lex Fridman
It's fascinating that that is one of the ways to reveal the power of a thing by watching it lose the power.

DJ Seo
Yeah, a lot of what we know about the brain actually comes from these cases where there are trauma to the brain or some parts of the brain that led someone to lose certain abilities. And as a result there's some correlation and understanding of that part of the tissue being critical for that function. And it's an incredibly fragile organ, if you think about it that way. But also it's incredibly plastic and incredibly resilient in many different ways.

Lex Fridman
And by the way, the term plastic as we'll use a bunch, means that it's adaptable. So neuroplasticity refers to the adaptability of the human brain?

DJ Seo
Correct. Another key moment that sort of influenced how the trajectory of my life have shaped towards the current focus of my life has been during my teenage year when I came to the US. I didn't speak a word of English. There was a huge language barrier and there was a lot of struggle to connect with my peers around me because I didn't understand the artificial construct that we have created called language, specifically English in this case. And I remember feeling pretty isolated, not being able to connect with peers around me. So spent a lot of time just on my own reading books, watching movies, and I naturally sort of gravitated towards sci-fi books. I just found them really, really interesting. And also it was a great way for me to learn English. Some of the first set of books that I picked up are Enders Game, the whole saga by Orson Scott Card and Neuromancer from William Gibson and Snow Crash from Neal Stephenson. And movies like Matrix, what's coming out around that time point that really influenced how I think about the potential impact that technology can have

for our lives in general. So fast track to my college years, I was always fascinated by just physical stuff, building physical stuff and especially physical things that had some sort of intelligence. And I studied electrical engineering during undergrad and I started out my research in MEMS, so micro electromechanical systems and really building these tiny nano structures for temperature sensing. And I just found that to be just incredibly rewarding and fascinating subject to just understand how you can build something miniature like that, that again, serve a function and had a purpose. Then I spent large majority of my college years basically building millimeter wave circuits for next gen telecommunication systems for imaging. And it was just something that I found very, very intellectually interesting. Phase arrays, how the signal processing works for any modern as well as next gen telecommunication system, wireless and wire line, EM waves or electromagnetic waves are fascinating. How do you design antennas that are most efficient in a small footprint that you have? How do you make these things energy efficient? That was something that just consumed my intellectual curiosity and that journey led me to actually apply to and find myself at PhD program at UC Berkeley, at this consortium called the Berkeley Wireless Research Center that was precisely looking at building - at the time, we called it XG, similar to 3G, 4G, 5G, but the next, next generation G system and how you would design circuits around that to ultimately go on phones and basically any other devices that are wirelessly connected these days. So I was just absolutely just fascinated by how that entire system works and that infrastructure works. And then also during grad school, I had sort of the fortune of having a couple of research fellowships that led me to pursue whatever project that I want. And that's one of the things that I really enjoyed about my graduate school career, where you got to kind of pursue your intellectual curiosity in the domain that may not matter at the end of the day, but is something that really allows you the opportunity to go as deeply as you want, as well as widely as you want. And at the time I was actually working on this project called the Smart Bandaid, and the idea was that when you get a wound, there's a lot of other proliferation of signaling pathway that cells follow to close that wound. And there were hypotheses that when you apply external electric field, you can actually accelerate the closing of that field by having basically electro taxing of the cells around that wound site. And specifically not just for a normal wound, there are chronic wounds that don't heal. So we were interested in building some sort of a wearable patch that you could apply to facilitate that healing process. And that was in collaboration with Professor Michel Maharbiz, which was a great addition to my thesis committee and it really shaped the rest of my PhD career.

Lex Fridman
So this would be the first time you interacted with biology, I suppose?

DJ Seo
Correct. I mean there were some peripheral end application of the wireless imaging and telecommunication system that I was using for security and bio imaging. But this was a very clear direct application to biology and biological system and understanding the constraints

around that and really designing and engineering electrical solutions around that. So that was my first introduction and that's also kind of how I got introduced to Michel. He's sort of known for remote control of beetles in the early 2000s. And then around 2013, obviously the holy grail when it comes to implantable system is to understand how small of a thing you can make, and a lot of that is driven by how much energy or how much power you can supply to it and how you extract data from it. At the time at Berkeley, there was this desire to understand in the neural space what sort of system you can build to really miniaturize these implantable systems. And I distinctively remember this one particular meeting where Michel came in and he's like, "Guys, I think I have a solution. The solution is ultrasound." And then he proceeded to walk through why that is the case. And that really formed the basis for my thesis work called Neural dust system, that was looking at ways to use ultrasound as opposed to electromagnetic waves for powering as well as communication. I guess I should step back and say the initial goal of the project was to build these tiny, about a size of a neuron, implantable system that can be parked next to a neuron, being able to record its state and being able to ping that back to the outside world for doing something useful. And as I mentioned, the size of the implantable system is limited by how you power the thing and get the data off of it. And at the end of the day, fundamentally, if you look at a human body, we're essentially bag of salt water with some interesting proteins and chemicals, but its mostly salt water that's very, very well temperature regulated at 37 degrees Celsius. And we'll get into how, and later why that's an extremely harsh environment for any electronics to survive. As I'm sure you've experienced or maybe not experienced, dropping cell phone in a salt water in an ocean, it will instantly kill the device. But anyways, just in general, electromagnetic waves don't penetrate through this environment well and just the speed of light, it is what it is, we can't change it. And based on the wavelength at which you are interfacing with the device, the device just needs to be big. These inductors needs to be quite big. And the general good rule of thumb is that you want the wavefront to be roughly on the order of the size of the thing that you're interfacing with. So an implantable system that is around 10 to a hundred micron in dimension in a volume, which is about the size of a neuron that you see in a human body, you would have to operate at hundreds of gigahertz. Which number one, not only is it difficult to build electronics operating at those frequencies, but also the body just attenuates to that very, very significantly. So the interesting kind of insight of this ultrasound was the fact that ultrasound just travels a lot more effectively in the human body tissue compared to electromagnetic waves. And this is something that you encounter, and I'm sure most people have encountered in their lives when you go to hospitals that are medical ultrasound sonograph. And they go into very, very deep depth without attenuating too much, too much of the signal. So all in all, ultrasound, the fact that it travels through the body extremely well and the mechanism to which it travels to the body really well is that just the wavefront is very different. Electromagnetic waves are transverse, whereas in ultrasound waves are compressive. It's just a completely different mode of wavefront propagation. And as well as, speed of sound is orders and orders of magnitude less than speed of light, which means that even at 10 megahertz ultrasound wave, your wavefront ultimately is a very, very small wavelength. So if you're talking about interfacing with the 10 micron or a hundred micron type structure, you would have 150 micron wavefront at 10 megahertz. And building electronics at those frequencies are much, much easier and they're a lot more efficient. So the basic idea was born out of using ultrasound as a mechanism for powering the device and then also getting data back. So now the question is how do you get the data back? The mechanism to which we landed on is what's called backscattering. This is actually something that is very common and that we interface on a day-to-day basis with our RFID cards, radio frequency ID tags. Where there's actually rarely in your ID a battery inside, there's an antenna and there's some sort of coil that has your serial identification ID, and then there's an external device called the reader that then sends a wavefront and then you reflect back that wavefront with some sort of modulation that's unique to your ID. That's what's called backscattering fundamentally. So the tag itself actually doesn't have to consume that much energy. That was the mechanism through which we were thinking about sending the data back. When you have an external ultrasonic transducer that's sending ultrasonic wave to your implant, the neural dust implant, and it records some information about its environment, whether it's a neuron firing or some other state of the tissue that it's interfacing with. And then it just amplitude modulates the wavefront that comes back to the source.

Lex Fridman
And the recording step would be the only one that requires any energy. So what would require energy in that low step?

DJ Seo
Correct. So it is that initial startup circuitry to get that recording, amplifying it, and then just modulating. And the mechanism to which that you can enable that is there is this specialized crystal called piezoelectric crystals that are able to convert sound energy into electrical energy and vice versa. So you can kind of have this interplay between the ultrasonic domain and electrical domain that is the biological tissue.

Lex Fridman
So on the theme of parking very small computational devices next to neurons, that's the dream, the vision of brain computer interfaces. Maybe before we talk about Neuralink, can you give a sense of the history of the field of BCI? What has been maybe the continued dream and also some of the milestones along the way of the different approaches and the amazing work done at the various labs?

DJ Seo
I think a good starting point is going back to 1790s.

Lex Fridman
I did not expect that.

DJ Seo
Where the concept of animal electricity or the fact that body's electric was first discovered by Luigi Galvani, where he had this famous experiment where he connected set of electrodes to a frog leg and ran current through it, and then it started twitching and he said, "Oh my goodness, body's electric." So fast forward many, many years to 1920s where Hans Berger, who's a German psychiatrist, discovered EEG or electroencephalography, which is still around. There are these electrode arrays that you wear outside the skull that gives you some sort of neural recording. That was a very, very big milestone that you can record some sort of activities about the human mind. And then in the 1940s there were these group of scientists, Renshaw, Forbes and Morison that inserted these glass micro electrodes into the cortex and recorded single neurons. The fact that there's signal that are a bit more high resolution and high fidelity as you get closer to the source, let's say. And in the 1950s, these two scientists, Hodgkin and Huxley showed up - these two scientists, Hodgkin and Huxley showed up and they built this beautiful, beautiful models of the cell membrane and the ionic mechanism, and had these circuit diagram. And as someone who's an electrical engineer, it's a beautiful model that's built out of these partial differential equations, talking about flow of ions and how that really leads to how neurons communicate. And they won the Nobel Prize for that 10 years later in the 1960s. So in 1969, Eb Fetz from University of Washington published this beautiful paper called Operant Conditioning of Cortical Unit Activity, where he was able to record a single unit neuron from a monkey and was able to have the monkey modulated based on its activity and reward system. So I would say this is the very, very first example, as far as I'm aware, of close loop brain computer interface or BCI.

Lex Fridman
The abstract reads, "The activity of single neurons in precentral cortex of unanesthetized monkeys was conditioned by reinforcing high rates of neuronal discharge with delivery of a food pellet. Auditory or visual feedback of unit firing rates was usually provided in addition to food reinforcement." Cool. So they actually got it done.

DJ Seo
They got it done. This is back in 1969.

Lex Fridman
"After several training sessions, monkeys could increase the activity of newly isolated cells by 50 to 500% above rates before reinforcement." Fascinating.

DJ Seo
Brain is very plastic.

Lex Fridman
And so from here, the number of experiments grew.

DJ Seo
Yeah. Number of experiments, as well as set of tools to interface with the brain have just exploded. And also, just understanding the neural code and how some of the cortical layers and the functions are organized. So the other paper that is pretty seminal, especially in the motor decoding, was this paper in the 1980s from Georgopoulos that discovered that there's this thing called motor tuning curve. So what are motor tuning curves? It's the fact that there are neurons in the motor cortex of mammals, including humans, that have a preferential direction that causes them to fire. So what that means is, there are a set of neurons that would increase their spiking activities when you're thinking about moving to the left, right, up, down, and any of those vectors. And based on that, you could start to think, well, if you can't identify those essential eigenvectors, you can do a lot. And you can actually use that information for actually decoding someone's intended movement from the cortex. So that was a very, very seminal paper that showed that there is some sort of code that you can extract, especially in the motor cortex.

Lex Fridman
So there's signal there. And if you measure the electrical signal from the brain that you could actually figure out what the intention was.

DJ Seo
Correct. Yeah, not only electrical signals, but electrical signals from the right set of neurons that give you these preferential direction.

Lex Fridman
Okay. So going slowly towards Neuralink, one interesting question is, what do we understand on the BCI front, on invasive versus non-invasive, from this line of work? How important is it to park next to the neuron? What does that get you?

DJ Seo
That answer fundamentally depends on what you want to do with it. There's actually incredible amount of stuff that you can do with EEG and electrocortical graph, ECOG, which actually doesn't penetrate the cortical layer or parenchyma, but you place a set of electrodes on the surface of the brain. So the thing that I'm personally very interested in is just actually understanding and being able to just really tap into the high resolution, high fidelity, understanding of the activities that are happening at the local level. And we can get into biophysics, but just to step back to use analogy, because analogy here can be useful, and sometimes it's a little bit difficult to think about electricity. At the end of the day, we're doing electrical recording that's mediated by ionic currents, movements of these charged particles, which is really, really hard for most people to think about. But turns out, a lot of the activities that are happening in the brain and the frequency bandwidth with which that's happening, is actually very, very similar to sound waves and our normal conversation audible range. So the analogy that typically is used in the field is, if you have a football

stadium, there's a game going on. If you stand outside the stadium, you maybe get a sense of how the game is going based on the cheers and the boos of the home crowd, whether the team is winning or not. But you have absolutely no idea what the score is, you have absolutely no idea what individual audience or the players are talking or saying to each other, what the next play is, what the next goal is. So what you have to do is you have to drop the microphone into the stadium and then get near the source into the individual chatter. In this specific example, you would want to have it right next to where the huddle is happening. So I think that's kind of a good illustration of what we're trying to do when we say invasive or minimally invasive or implanted brain computer interfaces versus non-invasive or non-implanted brain interfaces. It's basically talking about where do you put that microphone and what can you do with that information.

Lex Fridman
So what is the biophysics of the read and write communication that we're talking about here as we now step into the efforts at Neuralink?

DJ Seo
Yeah. So brain is made up of these specialized cells called neurons. There's billions of them, tens of billions, sometimes people call it a hundred billion, that are connected in this complex yet dynamic network that are constantly remodeling. They're changing their synaptic weights, and that's what we typically call neuroplasticity. And the neurons are also bathed in this charged environment that is latent with many charge molecules like potassium ions, sodium ions, chlorine ions. And those actually facilitate these, through ionic current, communication between these different networks. And when you look at a neuron as well, they have these membrane with a beautiful, beautiful protein structure called the voltage selective ion channels, which in my opinion, is one of nature's best inventions. In many ways, if you think about what they are, they're doing the job of a modern day transistors. Transistors are nothing more, at the end of the day, than a voltage-gated conduction channel. And nature found a way to have that very, very early on in its evolution. And as we all know, with the transistor, you can have many, many computation and a lot of amazing things that we have access to today. So I think it's one of those, just as a tangent, just a beautiful, beautiful invention that the nature came up with, these voltage-gated ion channels.

Lex Fridman
I suppose there's, on the biological of it, every level of the complexity, of the hierarchy, of the organism, there's going to be some mechanisms for storing information and for doing computation. And this is just one such way. But to do that with biological and chemical components is interesting. Plus, when neurons, it's not just electricity, it's chemical communication, it's also mechanical. These are actual objects that vibrate, they move. It's all of that.

DJ Seo
Yeah, actually there's a lot of really, really interesting physics that are involved in kind of going back to my work on ultrasound during grad school, there were groups and there are still groups looking at ways to cause neurons to actually fire an action potential using ultrasound wave. And the mechanism to which that's happening is still unclear, as I understand. It may just be that you're imparting some sort of thermal energy and that causes cells to depolarize in some interesting ways. But there are also these ion channels, or even membranes, that actually just open up as pore as they're being mechanically shook, vibrated. There's just a lot of elements of these, move particles, which again, that's governed by diffusion physics, movements of particles. And there's also a lot of interesting physics there.

Lex Fridman
Also, not to mention, as Roger Penrose talks about, there might be some beautiful weirdness in the quantum mechanical effects of all of this.

DJ Seo
Oh, yeah.

Lex Fridman
And he actually believes that consciousness might emerge from the quantum mechanical effects there. So there's physics, there's chemistry, there's biology, all of that is going on there.

DJ Seo
Oh, yeah. Yes, there's a lot of levels of physics that you can dive into. But yeah, in the end, you have these membranes with these voltage-gated ion channels that selectively let these charged molecules that are in the extracellular matrix, in and out. And these neurons generally have these resting potential where there's a voltage difference between inside the cell and outside the cell. And when there's some sort of stimuli that changes the state such that they need to send information to the downstream network, you start to see these orchestration of these different molecules going in and out of these channels. They also open up. More of them open up once it reaches some threshold, to a point where you have a depolarizing cell that sends an action potential. So it's just a very beautiful kind of orchestration of these molecules. And what we're trying to do when we place an electrode or parking it next to a neuron is that you're trying to measure these local changes in the potential. Again, mediated by the movements of the ions. And what's interesting, as I mentioned earlier, there's a lot of physics involved. And the two dominant physics for this electrical recording domain is diffusion physics and electromagnetism. And where one dominates, where Maxwell's equation dominates versus Fick's law dominates depends on where your electrode is. If it's close to the source, mostly electromagnetic-based. When you're further away from it, it's more diffusion-based. So essentially, when you're able to

park it next to it, you can listen in on those individual chatter and those local changes in the potential. And the type of signal that you get are these canonical textbook neural spiking waveform. The moment you're further away, and based on some of the studies that people have done, Christof Koch's lab, and others, once you're away from that source by roughly around a hundred micron, which is about a width of a human hair, you no longer hear from that neuron. You're no longer able to have the system sensitive enough to be able to record that particular local membrane potential change in that neuron. And just to give you a sense of scale also, when you look at a hundred micron voxel, so a hundred micron by a hundred micron by a hundred micron box in a brain tissue, there's roughly around 40 neurons, and whatever number of connections that they have. So there's a lot in that volume of tissue. So the moment you're outside of that, there's just no hope that you'll be able to detect that change from that one specific neuron that you may care about.

Lex Fridman
But as you're moving about this space, you'll be hearing other ones. So if you move another a hundred micron, you'll be hearing chatter from another community.

DJ Seo
Correct.

Lex Fridman
And so the whole sense is, you want to place as many as possible electrodes, and then you're listening to the chatter.

DJ Seo
Yeah, you want to listen to the chatter. And at the end of the day, you also want to basically let the software do the job of decoding. And just to kind of go to why ECOG and EEG work at all. When you have these local changes, obviously it's not just this one neuron that's activating, there's many, many other networks that are activating all the time. And you do see sort of a general change in the potential of this electrode, this charged medium, and that's what you're recording when you're farther away. I mean, you still have some reference electrode that's stable in the brain, that's just electro- active organ, and you're seeing some combination, aggregate action, potential changes, and then you can pick it up. It's a much slower changing signals. But there are these canonical oscillations and waves like gamma waves, beta waves, when you sleep, that can be detected because there's sort of a synchronized global effect of the brain that you can detect. And the physics of this go, if we really want to go down that rabbit hole, there's a lot that goes on in terms of why diffusion physics at some point dominates when you're further away from the source. It is just a charged medium. So similar to how when you have electromagnetic waves propagating in atmosphere or in a charged medium like a plasma, there's this weird shielding that happens that actually further attenuates the signal as you move away from it. So yeah, you see, if you do a really, really deep dive on the signal attenuation over distance, you start to see one

over R square in the beginning and then exponential drop off, and that's the knee at which you go from electromagnetism dominating to diffusion physic dominating.

Lex Fridman
But once again, with the electrodes, the biophysics that you need to understand is not as deep because no matter where you're placing it, you're listening to a small crowd of local neurons.

DJ Seo
Correct, yeah. So once you penetrate the brain, you're in the arena, so to speak.

Lex Fridman
And there's a lot of neurons.

DJ Seo
There are many, many of them.

Lex Fridman
But then again, there's a whole field of neuroscience that's studying how the different groupings, the different sections of the seating in the arena, what they usually are responsible for, which is where the metaphor probably falls apart because the seating is not that organized in an arena.

DJ Seo
Also, most of them are silent. They don't really do much. Or their activities are - you have to hit it with just the right set of stimulus.

Lex Fridman
So they're usually quiet.

DJ Seo
They're usually very quiet. Similar to dark energy and dark matter, there's dark neurons. What are they all doing? When you place these electrodes, again, within this hundred micron volume, you have 40 or so neurons. Why do you not see 40 neurons? Why do you see only a handful? What is happening there?

Lex Fridman
Well, they're mostly quiet, but when they speak, they say profound shit. That's the way I'd like to think about it. Anyway, before we zoom in even more, let's zoom out. So how does Neuralink work from the surgery to the implant, to the signal and the decoding process, and the human being able to use the implant to actually affect the world outside? And all of this, I'm asking in the context of, there's a gigantic historic milestone that Neuralink just

accomplished in January of this year. Putting a Neuralink implant in the first human being, Noland. And there's been a lot to talk about there about his experience because he's able to describe all the nuance and the beauty and the fascinating complexity of that experience of everything involved. But on the technical level, how does Neuralink work?

DJ Seo
So there are three major components to the technology that we're building. One is the device, the thing that's actually recording these neural chatters. We call it N1 Implant or The Link. And we have a surgical robot that's actually doing an implantation of these tiny, tiny wires that we call threads that are smaller than human hair. And once everything is surgerized, you have these neural signals, these spiking neurons, that are coming out of the brain, and you need to have some sort of software to decode what the users intend to do with that. So there's what's called the Neuralink Application or B1 App that's doing that translation. It's running the very, very simple machine learning model that decodes these inputs that are neural signals and then convert it to a set of outputs that allows our first participant, Noland, to be able to control a cursor on the screen.

Lex Fridman
And this is done wirelessly?

DJ Seo
And this is done wirelessly. So our implant is actually a two-part. The link has these flexible tiny wires called threads that have multiple electrodes along its length. And they're only inserted into the cortical layer, which is about three to five millimeters in a human brain, in the motor cortex region. That's where the intention for movement lies in. And we have 64 of these threads, each thread having 16 electrodes along the span of three to four millimeters, separated by 200 microns. So you can actually record along the depth of the insertion. And based on that signal, there's custom integrated circuit or ASIC that we built that amplifies the neural signals that you're recording and then digitizing it and then has some mechanism for detecting whether there was an interesting event that is a spiking event, and decide to send that or not send that through Bluetooth to an external device, whether it's a phone or a computer that's running this Neuralink application.

Lex Fridman
So there's onboard signal processing already just to decide whether this is an interesting event or not. So there is some computational power on board in addition to the human brain?

DJ Seo
Yeah. So it does the signal processing to really compress the amount of signal that you're recording. So we have a total of thousand electrodes sampling at just under 20 kilohertz with 10 bit each. So that's 200 megabits that's coming through to the chip from thousand

channel simultaneous neural recording. And that's quite a bit of data, and there are technology available to send that off wirelessly. But being able to do that in a very, very thermally-constrained environment that is a brain. So there has to be some amount of compression that happens to send off only the interesting data that you need, which in this particular case for motor decoding is, occurrence of a spike or not. And then being able to use that to decode the intended cursor movement. So the implant itself processes it, figures out whether a spike happened or not with our spike detection algorithm, and then sends it off, packages it, sends it off through Bluetooth to an external device that then has the model to decode, okay, based on these spiking inputs, did Noland wish to go up, down, left, right, or click or right click or whatever.

Lex Fridman
All of this is really fascinating, but let's stick on the N1 Implant itself. So the thing that's in the brain. So I'm looking at a picture of it, there's an enclosure, there's a charging coil, so we didn't talk about the charging, which is fascinating. The battery, the power electronics, the antenna. Then there's the signal processing electronics. I wonder if there's more kinds of signal processing you can do? That's another question. And then there's the threads themselves with the enclosure on the bottom. So maybe to ask about the charging. So there's an external charging device?

DJ Seo
Yeah, there's an external charging device. So yeah, the second part of the implant, the threads are the ones, again, just the last three to five millimeters are the ones that are actually penetrating the cortex. Rest of it is, actually most of the volume, is occupied by the battery, rechargeable battery, and it's about a size of a quarter. I actually have a device here if you want to take a look at it. This is the flexible thread component of it, and then this is the implant. So it's about a size of a US quarter. It's about nine millimeters thick. So basically this implant, once you have the craniectomy and the directomy, threads are inserted, and the hole that you created, this craniectomy, gets replaced with that. So basically that thing plugs that hole, and you can screw in these self-drilling cranial screws to hold it in place. And at the end of the day, once you have the skin flap over, there's only about two to three millimeters that's obviously transitioning off of the top of the implant to where the screws are. And that's the minor bump that you have.

Lex Fridman
Those threads look tiny. That's incredible. That is really incredible. That is really incredible. And also, you're right, most of the actual volume is the battery. This is way smaller than I realized.

DJ Seo
Also, the threads themselves are quite strong.

Lex Fridman
They look strong.

DJ Seo
And the thread themselves also has a very interesting feature at the end of it called the loop. And that's the mechanism to which the robot is able to interface and manipulate this tiny hair-like structure.

Lex Fridman
And they're tiny. So what's the width of a thread?

DJ Seo
So the width of a thread starts from 16 micron and then tapers out to about 84 micron. So average human hair is about 80 to 100 micron in width.

Lex Fridman
This thing is amazing. This thing is amazing.

DJ Seo
Yes, most of the volume is occupied by the battery, rechargeable lithium ion cell. And the charging is done through inductive charging, which is actually very commonly used. Your cell phone, most cell phones, have that. The biggest difference is that for us, usually when you have a phone and you want to charge it on the charging pad, you don't really care how hot it gets. Whereas, in for us, it matters. There is a very strict regulation and good reasons to not actually increase the surrounding tissue temperature by two degrees Celsius. So there's actually a lot of innovation that is packed into this to allow charging of this implant without causing that temperature threshold to reach. And even small things like, you see this charging coil and what's called a ferrite shield. So without that ferrite shield, what you end up having when you have resonant inductive charging is that the battery itself is a metallic can, and you form these eddy currents from external charger and that causes heating, and that actually contributes to inefficiency in charging. So this ferrite shield, what it does, is that it actually concentrate that field line away from the battery and then around the coil that's actually wrapped around it.

Lex Fridman
There's a lot of really fascinating design here to make it, I mean, you're integrating a computer into a biological, a complex biological system.

DJ Seo
Yeah, there's a lot of innovation here. I would say that part of what enabled this was just the innovations in the wearable. There's a lot of really, really powerful tiny, low-power microcontrollers, temperature sensors, or various different sensors and power electronics.

A lot of innovation really came in the charging coil design, how this is packaged, and how do you enable charging such that you don't really exceed that temperature limit, which is not a constraint for other devices out there.

Lex Fridman
So let's talk about the threads themselves. Those tiny, tiny, tiny things. So how many of them are there? You mentioned a thousand electrodes. How many threads are there and what do the electrodes have to do with the threads?

DJ Seo
So the current instantiation of the device has 64 threads, and each thread has 16 electrodes for a total of 1,024 electrodes that are capable of both recording and stimulating. And the thread is basically this polymer-insulated wire. The metal conductor is the kind of a tiramisu cake of ti, plat, gold, plat, ti and they're very, very tiny wires. Two micron in width. So two one-millionth of meter.

Lex Fridman
It's crazy that that thing I'm looking at has the polymer-insulation, has the conducting material and has 16 electrodes at the end of it.

DJ Seo
On each of those thread.

Lex Fridman
Yeah, on each of those threads.

DJ Seo
Correct.

Lex Fridman
16, each one of those 64.

DJ Seo
Yes, you're not going to be able to see it with naked eyes.

Lex Fridman
And to state the obvious, or maybe for people who are just listening, they're flexible?

DJ Seo
Yes, that's also one element that was incredibly important for us. So each of these threads are now, as I mentioned, 16 micron in width, and then they taper to 84 micron, but in thickness they're less than five micron. And in thickness it's mostly a polyimide at the

bottom and this metal track and then another polyimide. So two micron of polyimide, 400 nanometer of this metal stack and two micron of polyimide sandwiched together to protect it from the environment that is 37 degrees C bag of salt water.

Lex Fridman
Maybe can you speak to some interesting aspects of the material design here? What does it take to design a thing like this and to be able to manufacture a thing like this? For people who don't know anything about this kind of thing.

DJ Seo
So the material selection that we have is not, I don't think it was particularly unique. There were other labs and there are other labs that are kind of looking at similar material stack. There's kind of a fundamental question, and still needs to be answered, around the longevity and reliability of these microelectrodes that we call, compared to some of the other more conventional neural interfaces devices that are intracranial, so penetrating the cortex, that are more rigid, like the Utah Array. That are these four by four millimeter kind of silicon shank that have exposed recording site at the end of it. And that's been kind of the innovation from Richard Normann back in 1997. It's called the Utah Array because he was at University of Utah.

Lex Fridman
And what does the Utah Array look like? So it's a rigid type of -

DJ Seo
Yeah, so we can actually look it up. Yeah, so it's a bed of needle. There's -

Lex Fridman
Okay, go ahead. I'm sorry.

DJ Seo
Those are rigid shanks.

Lex Fridman
Rigid, yeah, you weren't kidding.

DJ Seo
And the size and the number of shanks vary anywhere from 64 to 128. At the very tip of it, is an exposed electrode that actually records neural signal. The other thing that's interesting to note is that unlike neural link threads that have recording electrodes that are actually exposed iridium oxide recording sites along the depth, this is only at a single depth. So these Utah Array spokes can be anywhere between 0.5 millimeters to 1.5 millimeter, and they also have designs that are slanted. So you can have it inserted at different depths, but

that's one of the other big differences. And then, the main key difference is the fact that there's no active electronics. These are just electrodes, and then there's a bundle of a wire that you're seeing, and then that actually then exits the craniotomy that then has this port that you can connect to for any external electronic devices. They are working on, or have, the wireless telemetry device but it still requires a through-the-skin port, that actually is one of the biggest failure modes for infection for the system.

Lex Fridman
What are some of the challenges associated with flexible threads? Like for example, on the robotic side, R1, implanting those threads. How difficult is that task?

DJ Seo
Yeah, so as you mentioned, they're very, very difficult to maneuver by hand. These Utah Arrays that you saw earlier, they're actually inserted by a neurosurgeon actually positioning it near the site that they want. And then there's a pneumatic hammer that actually pushes them in. So it's a pretty simple process and they're easy to maneuver. But for these thin-film arrays, they're very, very tiny and flexible. So they're very difficult to maneuver. So that's why we built an entire robot to do that. There are other reasons for why we built the robot, and that is ultimately we want this to help millions and millions of people that can benefit from this. And there just aren't that many neurosurgeons out there. And robots can be something that we hope can actually do large parts of the surgery. But the robot is this entire other sort of category of product that we're working on. And it's essentially this multi-axis gantry system that has the specialized robot head that has all of the optics and this kind of a needle-retracting mechanism that maneuvers these threads via this loop structure that you have on the thread.

Lex Fridman
So the thread already has a loop structure by which you can grab it?

DJ Seo
Correct.

Lex Fridman
So this is fascinating. So you mentioned optics. So there's a robot, R1, so for now, there's a human that actually creates a hole in the skull. And then after that, there's a computer vision component that's finding a way to avoid the blood vessels. And then you're grabbing it by the loop, each individual thread, and placing it in a particular location to avoid the blood vessels and also choosing the depth of placement, all that. So controlling every, the 3D geometry, of the placement?

DJ Seo
Correct. So the aspect of this robot that is unique is that it's not surgeon-assisted or human-assisted. It's a semi-automatic or automatic robot. Obviously, there are human component to it, when you're placing targets, you can always move it away from major vessels that you see. But we want to get to a point where one click and it just does the surgery within minutes.

Lex Fridman
So the computer vision component finds great targets, candidates, and the human approves them, and the robot does - does it do one thread at a time? Or does it do them in parallel?

DJ Seo
It does one thread at a time. And that's actually also one thing that we are looking at ways to do multiple threads at a time. There's nothing stopping from it. You can have multiple kind of engagement mechanisms. But right now, it's one-by-one. And we also still do quite a bit of just kind of verification to make sure that it got inserted. If so, how deep? Did it actually match what was programmed in? And so on and so forth.

Lex Fridman
And the actual electrodes are placed at differing depths in the - I mean, it's very small differences, but differences.

DJ Seo
Yeah.

Lex Fridman
And so there's some reasoning behind that, as you mentioned, it gets more varied signal.

DJ Seo
Yeah, we try to place them all around three or four millimeter from the surface - it's three or four millimeter from the surface just because the span of the electrode, those 16 electrodes that we currently have in this version, spans roughly around three millimeters. So we want to get all of those in the brain.

Lex Fridman
This is fascinating. Okay, so there's a million questions here. If we could zoom in specifically on the electrodes. What is your sense, how many neurons is each individual electrode listening to?

DJ Seo
Yeah, each electrode can record from anywhere between zero to 40, as I mentioned earlier. But practically speaking, we only see about at most two to three, and you can actually distinguish which neuron it's coming from by the shape of the spikes.

Lex Fridman
Oh, cool.

DJ Seo
I mentioned the spike detection algorithm that we have, it's called BOSS algorithm, Buffer Online Spike Sorter.

Lex Fridman
Nice.

DJ Seo
It actually outputs at the end of the day six unique values, which are the amplitude of these negative going hump, middle hump, positive going hump, and then also the time at which these happen. And from that, you can have a statistical probability estimation of, "Is that a spike? Is it not a spike?" And then based on that, you could also determine, "Oh, that spike looks different than that spike, it must come from a different neuron."

Lex Fridman
Okay. So that's a nice signal processing step from which you can then make much better predictions about if there's a spike, especially in this kind of context, where there could be multiple neurons screaming. And that that also results in you being able to compress the data better at the of the day.

DJ Seo
Yeah.

Lex Fridman
Okay, that's -

DJ Seo
And just to be clear, I mean, the labs do this what's called spike sorting. Usually once you have the fully digitized signals and then you run a bunch of different set of algorithms to tease apart, it's just all of this for us is done on the device.

Lex Fridman
On the device.

DJ Seo
In a very low power, custom-built ASIC digital processing unit.

Lex Fridman
Highly heat constrained.

DJ Seo
Highly heat constrained. And the processing time from signal going in and giving you the output is less than a microsecond, which is a very, very short amount of time.

Lex Fridman
Oh, yeah. So the latency has to be super short.

DJ Seo
Correct.

Lex Fridman
Oh, wow. Oh, that's a pain in the ass. That's really tough.

DJ Seo
Yeah, latency is this huge, huge thing that you have to deal with. Right now the biggest source of latency comes from the Bluetooth, the way in which their packetized and we bin them in a 15 millisecond time window.

Lex Fridman
Oh, interesting, so it's communication constrained. Is there some potential innovation there on the protocol used?

DJ Seo
Absolutely.

Lex Fridman
Okay.

DJ Seo
Yeah. Bluetooth is definitely not our final wireless communication protocol that we want to get to. It's highly -

Lex Fridman
Hence, the N1 and the R1. I imagine that increases -

DJ Seo
Nx, Rx.

Lex Fridman
Yeah, that's the communication protocol because Bluetooth allows you to communicate, gets farther distances than you need to, so you can go much shorter.

DJ Seo
Yeah. The only, well, the primary motivation for choosing Bluetooth is that, I mean, everything has Bluetooth,

Lex Fridman
Alright, so you can talk to any device.

DJ Seo
Interoperability is just absolutely essential, especially in this early phase. And in many ways, if you can access a phone or a computer, you can do anything.

Lex Fridman
It'll be interesting to step back and actually look at, again, the same pipeline that you mentioned for Noland. What does this whole process look like from finding and selecting a human being, to the surgery, to the first time he's able to use this thing?

DJ Seo
We have what's called a patient registry that people can sign up to hear more about the updates. And that was a route to which Noland applied. And the process is that once the application comes in, it contains some medical records, and we - based on their medical eligibility, there's a lot of different inclusion/exclusion criteria for them to meet. And we go through a prescreening interview process with someone from Neuralink, and at some point we also go out to their homes to do a BCI home audit. Because one of the most revolutionary part about having this in one system that is completely wireless, is that you can use it at home. You don't actually have to go to the lab and go to the clinic to get connectedorized to these specialized equipment that you can't take home with you. So that's one of the key elements of when we're designing the system that we wanted to keep in mind, people hopefully would want to be able to use this every day in the comfort of their homes. And so part of our engagement and what we're looking for during BCI home audit is to just understand their situation, what other assisted technology that they use.

Lex Fridman
And we should also step back and say that the estimate is 180,000 people live with quadriplegia in the United States, and each year an additional 18,000 suffer a paralyzing spinal cord injury. So these are folks who have a lot of challenges living a life in terms of

accessibility, in terms of doing the things that many of us just take for granted day to day. And one of the things, one of the goals of this initial study is to enable them to have digital autonomy where they by themselves can interact with a digital device using just their mind, something that you're calling telepathy, so digital telepathy. Where a quadriplegic can communicate with a digital device in all the ways that we've been talking about. Control the mouse cursor enough to be able to do all kinds of stuff, including play games and tweet and all that kind of stuff. And there's a lot of people for whom life, the basics of life, are difficult because of the things that have happened to them.

DJ Seo
Yeah. I mean, movement is so fundamental to our existence. I mean, even speaking involves movement of mouth, lip, larynx. And without that, it's extremely debilitating. And there are many, many people that we can help. I mean, especially if you start to look at other forms of movement disorders that are not just from spinal cord injury, but from a ALS, MS, or even stroke, or just aging, that leads you to lose some of that mobility, that independence, it's extremely debilitating.

Lex Fridman
And all of these are opportunities to help people, to help alleviate suffering, to help improve the quality of life. But each of the things you mentioned is its own little puzzle that needs to have increasing levels of capability from a device like a Neuralink device. And so the first one you're focusing on is, it's just a beautiful word, telepathy. So being able to communicate using your mind wirelessly with a digital device. Can you just explain exactly what we're talking about?

DJ Seo
Yeah, I mean, it's exactly that. I mean, I think if you are able to control a cursor and able to click and be able to get access to a computer or a phone, I mean, the whole world opens up to you. And I mean, I guess the word "telepathy," if you think about that as just definitionally being able to transfer information from my brain to your brain without using some of the physical faculties that we have, like voices.

Lex Fridman
But the interesting thing here is I think the thing that's not obviously clear is how exactly it works. In order to move a cursor, there's at least a couple of ways of doing that. One is you imagine yourself maybe moving a mouse with your hand, or you can then, which no one talked about, imagine moving the cursor with your mind. But it's like there is a cognitive step here that's fascinating, because you have to use the brain and you have to learn how to use the brain, and you have to figure it out dynamically because you reward yourself if it works. I mean, there's a step that - this is just a fascinating step because you have to get the brain to start firing in the right way. And you do that by imagining - like fake it till you make it. And all of a sudden it creates the right kind of signal that, if decoded correctly, can create

the effect. And then there's noise around that that you have to figure all of that out. But on the human side, imagine the cursor moving is what you have to do.

DJ Seo
Yeah. He says using the force.

Lex Fridman
The force. I mean, isn't that just fascinating to you that it works? To me, it's like, holy shit, that actually works. You could move a cursor with your mind.

DJ Seo
As much as you're learning to use that thing, that thing is also learning about you. Our model's constantly updating the way to say, "Oh, if someone is thinking about this sophisticated forms of spiking patterns, that actually means to do this."

Lex Fridman
So the machine is learning about the human and the human is learning about the machine, so there is a adaptability to the signal process and the decoding step, and then there's the adaptation of Nolan, the human being. The same way, if you give me a new mouse and I move it, I learn very quickly about its sensitivity, so I learn to move it slower. And then there's other signal drift and all that kind of stuff they have to adapt to, so both are adapting to each other.

DJ Seo
Correct.

Lex Fridman
That's a fascinating software challenge, on both sides. The software on both, on the human software and the -

DJ Seo
The organic and the inorganic.

Lex Fridman
The organic and the inorganic. Anyway. So, sorry to rudely interrupt. So, there's the selection that Noland has passed with flying colors. Everything, including that it is a BCI-friendly home - all of that. So, what is the process of the surgery, implantation, the first moment when he gets to use the system?

DJ Seo
The end-to-end, we say patient end to patient out, is anywhere between two to four hours. In the particular case for Noland it was about three and a half hours, and there's many steps

leading to the actual robot insertion. So there's anesthesia induction, and we do intra-op CT imaging to make sure that we're drilling the hole in the right location. And this is also pre-planned beforehand. Someone like Noland would go through fMRI and then they can think about wiggling their hand. Obviously due to their injury it's not going to actually lead to any sort of intended output, but it's the same part of the brain that actually lights up when you're imagining moving your finger to actually moving your finger. And that's one of the ways in which we can actually know where to place our threads because we want to go into what's called the hand knob area in the motor cortex. And as much as possible, densely put our electrode threads. So we do intra-op CT imaging to make sure and double-check the location of the craniectomy. And the surgeon comes in, does their thing in terms of skin incision, craniectomy, so drilling of the skull, and then there's many different layers of the brain. There's what's called a dura, which is a very, very thick layer that surrounds the brain. That gets actually resected in a process called durectomy And that then expose the pia in the brain that you want to insert. And by the time it's been around anywhere between one to one and a half hours, robot comes in, does his thing, placement of the targets, inserting of the thread. That takes anywhere between 20 to 40 minutes. In the particular case for Noland, it was just under or just over 30 minutes. And then after that, the surgeon comes in, there's a couple other steps of actually inserting the dural substitute layer to protect the thread as well as the brain. And then screw in the implant and then skin flap and then suture, and then you're out.

Lex Fridman
So when Noland woke up, what was that like? What was the recovery like, and when was the first time he was able to use it?

DJ Seo
He was actually immediately after the surgery, like an hour after the surgery, as he was waking up, we did turn on the device, make sure that we are recording neural signals. And we actually did have couple signals that we noticed that he can actually modulate. And what I mean by modulate is that he can think about clenching his fist and you could see the spike disappear and appear.

Lex Fridman
That's awesome.

DJ Seo
And that was immediate, immediate after in the recovery room.

Lex Fridman
How cool is that?

DJ Seo
Yeah, absolutely.

Lex Fridman
That's a human being - I mean, what did that feel like for you? This device and a human being, a first step of a gigantic journey? I mean, it's a historic moment, even just that spike, just to be able to modulate that.

DJ Seo
Obviously there have been other, as you mentioned, pioneers that have participated in these groundbreaking BCI investigational early feasibility studies. So we're obviously standing on the shoulders of the giants here, we're not the first ones to actually put electrodes in a human brain. But I mean, just leading up to the surgery, I definitely could not sleep. It's the first time that you're working in a completely new environment. We had a lot of confidence based on our benchtop testing or preclinical R&D studies that the mechanism, the threads, the insertion, all that stuff is very safe and that it's obviously ready for doing this in a human. But there's still a lot of unknown unknown about can the needle actually insert? I mean, we brought something like 40 needles just in case they break, and we ended up using only one. But I mean, that was the level of just complete unknown because it's a very, very different environment. And I mean, that's why we do clinical trial in the first place, to be able to test these things out. So extreme nervousness and just many, many sleepless night leading up to the surgery, and definitely the day before the surgery. And it was an early morning surgery. We started at 7:00 in the morning, and by the time it was around 10:30 everything was done. But I mean, first time seeing that, well, number one, just huge relief that this thing is doing what it's supposed to do. And two, I mean, just immense amount of gratitude for Noland and his family. And then many others that have applied and that we've spoken to and will speak to are true pioneers in every word. And I call them the neural astronauts or neuralnaut.

Lex Fridman
Neuralnaut, yeah.

DJ Seo
Just like in the '60s, these amazing just pioneers exploring the unknown outwards, in this case it's inward, but an incredible amount of gratitude for them to just participate and play a part. And it's a journey that we're embarking on together. But also, I think it was just a - that was a very, very important milestone, but our work was just starting. So a lot of just anticipation for, "Okay, what needs to happen next?" What are set of sequences of events that needs to happen for us to make it worthwhile for both Noland as well as us.

Lex Fridman
Just to linger on that, just a huge congratulations to you and the team for that milestone. I know there's a lot of work left, but that's really exciting to see. That's a source of hope, it's this first big step, opportunity, to help hundreds of thousands of people. And then maybe expand the realm of the possible for the human mind for millions of people in the future. So it's really exciting. The opportunities are all ahead of us, and to do that safely and to do that effectively was really fun to see. As an engineer, just watching other engineers come together and do an epic thing, that was awesome. So huge congrats.

DJ Seo
Thank you, thank you. Yeah, could not have done it without the team. And yeah, I mean, that's the other thing that I told the team as well of just this immense sense of optimism for the future. I mean, it's a very important moment for the company, needless to say, as well as hopefully for many others out there that we can help.

Lex Fridman
Speaking of challenges, Neuralink published a blog post describing that some of the threads retracted. And so the performance as measured by bits per second dropped at first, but then eventually it was regained. And the whole story of how it was regained is super interesting, that's definitely something I'll talk to Bliss and to Noland about. But in general, can you speak to this whole experience, how was the performance regained, and just the technical aspects of the threads being retracted and moving?

DJ Seo
The main takeaway is that in the end, the performance have come back and it's actually gotten better than it was before. He's actually just beat the world record yet again last week to 8.5 bps. I mean, he's just cranking and he's just improving.

Lex Fridman
The previous one that he said was eight.

DJ Seo
Correct.

Lex Fridman
I think he said 8.5.

DJ Seo
Yeah. The previous world record in a human was 4.6, so it's almost double. And his goal is to try to get to 10, which is roughly around the median neural linker using a mouse with a hand. So it's getting there.

Lex Fridman
So, yeah. So, the performance was regained.

DJ Seo
Yeah, better than before. That's a story on its own of what took the BCI team to recover that performance. It was actually mostly on the signal processing. And so as I mentioned, we were looking at these spike outputs from our electrodes, and what happened is that four weeks into the surgery we noticed that the threads have solely come out of the brain. And the way in which we noticed this at first obviously is that, well, I think Noland was the first to notice, that his performance was degrading. And I think at the time we were also trying to do a bunch of different experimentation, different algorithms, different UI, UX. So it was expected that there will be variability in the performance, but we did see a steady decline. And then also the way in which we measure the health of the electrodes or whether they're in the brain or not, is by measuring impedance of the electrode. So we look at the interfacial, the Randles circuit they say, the capacitance and the resistance between the electrode surface and the medium. And if that changes in some dramatic ways, we have some indication. Or if you're not seeing spikes on those channels, you have some indications that something's happening there. And what we noticed is that looking at those impedance plot and spike rate plots, and also because we have those electrodes recording along the depth, you are seeing some sort of movement that indicated that threads were being pulled out. And that obviously will have an implication on the model side because if the number of inputs that are going into the model is changing because you have less of them, that model needs to get updated. But there were still signals, and as I mentioned, similar to how even when you place the signals on the surface of the brain or farther away, like outside the skull, you still see some useful signals. What we started looking at is not just the spike occurrence through this BOSS algorithm that I mentioned, but we started looking at just the power of the frequency band that is interesting for Noland to be able to modulate. Once we changed the algorithm for the implant to not just give you the BOSS output, but also these spike band power output, that helped us refine the model with a new set of inputs. And that was the thing that really ultimately gave us the performance back. And obviously the thing that we want ultimately and the thing that we are working towards, is figuring out ways in which we can keep those threads intact for as long as possible so that we have many more channels going into the model. That's by far the number one priority that the team is currently embarking on to understand how to prevent that from happening. The thing that I will say also is that, as I mentioned, this is the first time ever that we're putting these threads in the human brain. And a human brain, just for size reference, is 10 times that of the monkey brain or the sheep brain. And it's just a very, very different environment. It moves a lot more. It's actually moved a lot more than we expected when we did Noland's surgery. And it's just a very, very different environment than what we're used to. And this is why we do clinical trial, we want to uncover some of these issues and failure modes earlier than later. So in many ways, it's provided us with this enormous amount of data and information to be able to solve this. And this is something that

Neuralink is extremely good at, once we have set of clear objective and engineering problem, we have enormous amount of talents across many, many disciplines to be able to come together and fix the problem very, very quickly.

Lex Fridman
But it sounds like one of the fascinating challenges here is for the system on the decoding side to be adaptable across different timescales. So whether it's movement of threads or different aspects of signal drift, sort of on the software or the human brain, something changing, like Noland talks about cursor drift, they could be corrected. And there's a whole UX challenge to how to do that. So it sounds like adaptability is a fundamental property that has to be engineered in.

DJ Seo
It is. I mean, as a company, we're extremely vertically integrated. We make these thin-film arrays in our own microfab.

Lex Fridman
Yeah, there's like you said, built in-house. This whole paragraph here from this blog post is pretty gangster. "Building the technologies described above has been no small feat," and there's a bunch of links here that I recommend people click on. "We constructed in-house microfabrication capabilities to rapidly produce various iterations of thin-film arrays that constitute our electrode threads. We created a custom femtosecond laser mill to manufacture components with micro-level precision." I think there's a tweet associated with this.

DJ Seo
That's a whole thing that we can get into.

Lex Fridman
Yeah. Okay. What are we looking at here, this thing? "In less than one minute, our custom-made femtosecond laser mill cuts this geometry in the tips of our needles." So we're looking at this weirdly shaped needle. "The tip is only 10 to 12 microns in width, only slightly larger than the diameter of a red blood cell. The small size allows threads to be inserted with minimal damage to the cortex." Okay. So what's interesting about this geometry? So we're looking at this just geometry of a needle.

DJ Seo
This is the needle that's engaging with the loops in the thread. They're the ones that thread their loop, and then peel it from the silicon backing, and then this is the thing that gets inserted into the tissue. And then this pulls out, leaving the thread. And this kind of a notch or the shark tooth that we used to call, is the thing that actually is grasping the loop. And then it's designed in such a way such that when you pull out, it leaves the loop.

Lex Fridman
And the robot is controlling this needle?

DJ Seo
Correct. So this is actually housed in a cannula, and basically the robot has a lot of the optics that look for where the loop is. There's actually a 405 nanometer light that actually causes the polyimide to fluoresce so that you can locate the location of the loop.

Lex Fridman
So, the loop lights up or what? Is it like -

DJ Seo
Yeah, yeah. They do. It's a micron precision process.

Lex Fridman
What's interesting about the robot that it takes to do that, that's pretty crazy. That's pretty crazy that robot is able to get this kind of precision.

DJ Seo
Yeah, our robot is quite heavy, our current version of it. I mean, it's like a giant granite slab that weighs about a ton, because it needs to be sensitive to vibration, environmental vibration. And then as the head is moving at the speed that it's moving, there's a lot of motion control to make sure that you can achieve that level of precision. A lot of optics that zoom in on that. We're working on next generation of the robot that is lighter, easier to transport. I mean, it is a feat to move the robot to the surgical suite.

Lex Fridman
And it's far superior to a human surgeon at this time, for this particular task.

DJ Seo
Absolutely. I mean, let alone you try to actually thread a loop in a sewing kit. We're talking fractions of human error. These things, it's not visible.

Lex Fridman
So continuing the paragraph. "We developed novel hardware and software testing systems, such as our accelerated lifetime testing racks and simulated surgery environment…" - which is pretty cool - "…to stress test and validate the robustness of our technologies. We performed many rehearsals of our surgeries to refine our procedures and make them second nature." This is pretty cool. "We practice surgeries on proxies with all the hardware and instruments needed in our mock or in the engineering space. This helps us rapidly test and measure." So there's like proxies?

DJ Seo
Yeah, this proxy is super cool actually. There's a 3D printed skull from the images that is taken at Barrow, as well as this hydrogel mix synthetic polymer thing that actually mimics the mechanical properties of the brain. It also has vasculature of the person. Basically what we're talking about here, and there's a lot of work that has gone into making this set proxy, that it's about finding the right concentration of these different synthetic polymers to get the right set of consistency for the needle dynamics as they're being inserted. But we practice this surgery with Noland's basically physiology and brain many, many times prior to actually doing the surgery.

Lex Fridman
Every step, every step, every -

DJ Seo
Every step. Yeah. Like where does someone stand? I mean, what you're looking at is the picture, this is in our office, of this corner of the robot engineering space that we have created this mock OR space that looks exactly like what they would experience, all the staff would during their actual surgery. I mean, it's just like any dance rehearsal where exactly where you're going to stand at what point, and you just practice that over and over and over again with an exact anatomy of someone that you're going to surgerize. And it got to a point where a lot of our engineers, when we created a craniectomy, they're like, "Oh, that looks very familiar. We've seen that before."

Lex Fridman
Yeah. Man, there's wisdom you can gain through doing the same thing over and over and over. It's like Jiro Dreams of Sushi kind of thing because then - it's like Olympic athletes visualize the Olympics and then once you actually show up, it feels easy. It feels like any other day. It feels almost boring winning the gold medal, because you visualized this so many times, you've practiced this so many times, that nothing about it is new. It's boring. You win the gold medal, it's boring. And the experience they talk about is mostly just relief, probably that they don't have to visualize it anymore.

DJ Seo
Yeah, the power of the mind to visualize and where - I mean, there's a whole field that studies where muscle memory lies in cerebellum. Yeah, it's incredible.

Lex Fridman
I think it's a good place to actually ask the big question that people might have, is how do we know every aspect of this that you described is safe?

DJ Seo
At the end of the day, the gold standard is to look at the tissue. What sort of trauma did you cause the tissue, and does that correlate to whatever behavioral anomalies that you may have seen? And that's the language to which we can communicate about the safety of inserting something into the brain and what type of trauma that you can cause. We actually have an entire department, department of pathology, that looks at these tissue slices. There are many steps that are involved in doing this. Once you have studies that are launched with particular endpoints in mind, at some point you have to euthanize the animal, and then you go through necropsy to collect the brain tissue samples. You fix them in formalin, and you gross them, you section them, and you look at individual slices just to see what kind of reaction or lack thereof exists. So that's the language to which FDA speaks and as well for us to evaluate the safety of the insertion mechanism, as well as the threats at various different time points, both acute, so anywhere between zero to three months to beyond three months.

Lex Fridman
So those are the details of an extremely high standard of safety that has to be reached.

DJ Seo
Correct.

Lex Fridman
The FDA supervises this, but there's in general just a very high standard, in every aspect of this, including the surgery. I think Matthew MacDougall has mentioned that the standard is, let's say how to put it politely, higher than maybe some other operations that we take for granted. So the standard for all the surgical stuff here is extremely high.

DJ Seo
Very high. I mean, it's a highly, highly regulated environment with the governing agencies that scrutinize every, every medical device that gets marketed. And I think it's a good thing. It's good to have those high standards, and we try to hold extremely high standards to understand what sort of damage, if any, these innovative emerging technologies and new technologies that we're building are. And so far we have been extremely impressed by lack of immune response from these threads.

Lex Fridman
Speaking of which, you talked to me with excitement about the histology in some of the images that you're able to share. Can you explain to me what we're looking at?

DJ Seo
Yeah, so what you're looking at is a stained tissue image. This is a sectioned tissue slice from an animal that was implanted for seven months, so a chronic time point. And you're

seeing all these different colors, and each color indicates specific types of cell types. So purple and pink are astrocytes and microglia, respectably. They're types of glial cells. And the other thing that people may not be aware of is your brain is not just made up of soup of neurons and axons. There are other cells, like glial cells, that actually is the glue and also react if there are any trauma or damage to the tissue.

Lex Fridman
With the brown or the neurons here?

DJ Seo
The brown are the neurons and the blue is nuclei.

Lex Fridman
It's a lot of neurons.

DJ Seo
The neuro nuclei -

Lex Fridman
So what you're seeing is in this macro image, you're seeing these circle highlighted in white, the insertion sites. And when you zoom into one of those, you see the threads. And then in this particular case, I think we're seeing about the 16 wires that are going into the page. And the incredible thing here is the fact that you have the neurons that are these brown structures or brown circular or elliptical thing-

DJ Seo
- are these brown structures or brown circular or elliptical thing that are actually touching and abutting the threads. So what this is saying is that there's basically zero trauma that's caused during this insertion. And with these neural interfaces, these micro electrons that you insert, that is one of the most common mode of failure. So when you insert these threads like the Utah Array, it causes neuronal death around the site because you're inserting a foreign object. And that elicit these immune response through microglia and astrocytes, they form this protective layer around it. Oh, not only are you killing the neuron cells, but you're also creating this protective layer that then basically prevents you from recording neural signals because you're getting further and further away from the neurons that you're trying to record. And that is the biggest mode of failure. And in this particular example, in that inside it's about 50 micron with that scale bar, the neurons seem to be attracted to it.

Lex Fridman
And so there's certainly no trauma. That's such a beautiful image, by the way. So the brown at the neurons, and for some reason I can't look away. It's really cool.

DJ Seo
Yeah. And the way that these things - tissues generally don't have these beautiful colors. This is multiplex stain that uses these different proteins that are staining these at different colors. We use very standard set of staining techniques with H&E, EVA1 and NeuN and GFAB. So if you go to the next image, this is also kind of illustrates the second point because you can make an argument, and initially when we saw the previous image, we said, "Oh, are the threads just floating? What is happening here? Are we actually looking at the right thing?" So what we did is we did another stain, and this is all done in-house of this Masson's tricrome stain, which is in blue that shows these collagen layer. So the blue, basically, you don't want the blue around the implant threads. Because that means that there's some sort of scarring that's happened. And what you're seeing if you look at individual threads is that you don't see any of the blue. Which means that there has been absolutely, or very, very minimal to a point where it's not detectable amount of trauma in these inserted threads.

Lex Fridman
So that presumably is one of the big benefits of having this kind of flexible thread? This -

DJ Seo
Yeah. So we think this is primarily due to the size as well as the flexibility of the threads. Also, the fact that R1 is avoiding vasculature, so we're not disrupting or we're not causing damage to the vessels and not breaking any of the blood brain barrier, has basically caused the immune response to be muted.

Lex Fridman
But this is also a nice illustration of the size of things. So this is the tip of the thread?

DJ Seo
Yeah, those are neurons.

Lex Fridman
And they're neurons. And this is the thread listening. And the electrodes are positioned how?

DJ Seo
Yeah. So what you're looking at is not electrode themselves, those are the conductive wires. So each of those should probably be two micron in width. So what we're looking at is, we're looking at the coronal slice, so we're looking at some slice of the tissue. So as you go deeper, you'll obviously have less and less of the tapering of the thread. But yeah, the point basically being that there's just cells around the inserter site, which is just an incredible thing to see. I've just never seen anything like this.

Lex Fridman
How easy and safe is it to remove the implant?

DJ Seo
Yeah, so it depends on when. In the first three months or so after the surgery, there's a lot of tissue modeling that's happening. Similar to when you got a cut, you obviously start over first couple of weeks or depending on the size of the wound, scar tissue forming, there are these contractive, and then in the end they turn into scab and you can scab it off. The same thing happens in the brain. And it's a very dynamic environment. And before the scar tissue or the neo membrane or the new membrane that forms, it's quite easy to just pull them out. And there's minimal trauma that's caused during that. Once the scar tissue forms, and with Noland as well, we believe that that's the thing that's currently anchoring the threats. So we haven't seen any more movements since then. So they're quite stable. It gets harder to actually completely extract the threads. So our current method for removing the device is cutting the thread, leaving the tissue intact, and then unscrewing and taking the implant out. And that hole is now going to be plugged with either another Neuralink or just with a peak based, plastic based cap.

Lex Fridman
Is it okay to leave the threads in there forever?

DJ Seo
Yeah, we think so. We've done studies where we left them there and one of the biggest concerns that we had is, do they migrate and do they get to a point where they should not be? We haven't seen that. Again. Once the scar tissue forms, they get anchored in place. And I should also say that when we say upgrades, we're not just talking in theory here, we've actually upgraded many, many times. Most of our monkeys or non-human primates, NHP, have been upgraded. Pager, who you saw playing mind pong has the latest version of the device since two years ago and is seemingly very happy and healthy and fat.

Lex Fridman
So what's designed for the future, the upgrade procedure? So maybe for Noland, what would the upgrade look like? It was essentially what you're mentioning. Is there a way to upgrade the device internally where you take it apart and keep the capsule and upgrade the internals?

DJ Seo
So there are a couple of different things here. So for Noland, if we were to upgrade, what we would have to do is either cut the threads or extract the threads depending on the situation there in terms of how they're anchored or scarred in. If you were to remove them with the dual substitute, you have an intact brain, so you can reinsert different threads with the updated implant package. There are a couple of different other ways that we're thinking

about the future of what the upgradable system looks like. One is, at the moment we currently remove the dura, this kind of thick layer that protects the brain, but that actually is the thing that actually proliferates the scar tissue formation. So typically, the general rule of thumb is you want to leave the nature as is and not disrupt it as much. So looking at ways to insert the threats through the dura, which comes with different set of challenges such as, it's a pretty thick layer, so how do you actually penetrate that without breaking the needle? So we're looking at different needle design for that as well as the kind of the loop engagement. The other biggest challenges are, it's quite opaque, optically with white light illumination. So how do you avoid still this biggest advantage that we have of avoiding vasculature? How do you image through that? How do you actually still mediate that? So there are other imaging techniques that we're looking at to enable that. But the goal, our hypothesis is that, and based on some of the early evidence that we have, doing through the dura insertion will cause minimal scarring that causes them to be much easier to extract over time. And the other thing that we're also looking at, this is going to be a fundamental change in the implant architecture, is as at the moment, it's a monolithic single implant that comes with a thread that's bonded together. So you can't actually separate the thing out, but you can imagine having two part implant, bottom part that is the thread that are inserted that has the chips and maybe a radio and some power source. And then you have another implant that has more of the computational heavy load and the bigger battery. And then one can be under the dura, one can be above the dura being the plug for the skull. They can talk to each other, but the thing that you want to upgrade, the computer and not the thread, if you want to upgrade that, you just go in there, remove the screws, and then put in the next version. And you're off the - it's a very, very easy surgery too. You do a skin incision, slip this in, screw. Probably be able to do this in 10 minutes.

Lex Fridman
So that would allow you to reuse the thread sort of?

DJ Seo
Correct.

Lex Fridman
So I mean, this leads to the natural question of what is the pathway to scaling the increase in the number of threads? Is that a priority? What's the technical challenge there?

DJ Seo
Yeah, that is a priority. So for next versions of the implant, the key metrics that we're looking to improve are number of channels, just recording from more and more neurons. We have a pathway to actually go from currently 1000 to hopefully 3000, if not 6,000 by end of this year.

Lex Fridman
Wow.

DJ Seo
And then end of next year we want to get to even more. 16,000.

Lex Fridman
Wow.

DJ Seo
There's a couple of limitations to that. One is, obviously being able to photolithographically, print those wires. As I mentioned, it's two micron in width and spacing. Obviously, there are chips that are much more advanced than those types of resolution and we have some of the tools that we have brought in house to be able to do that. So traces will be narrower just so that you have to have more of the wires coming up into the chip. Chips also cannot linearly consume more energy as you have more and more channels. So there's a lot of innovations in the circuit, and architecture as well as the circuit design topology to make them lower power. You need to also think about if you have all of these spikes, how do you send that off to the end application. So you need to think about bandwidth limitation there and potentially innovations and signal processing. Physically, one of the biggest challenges is going to be the interface. It's always the interface that breaks bonding this thin film array to the electronics. It starts to become very, very highly dense interconnects. So how you connectivise that? There's a lot of innovations in the 3D integrations in the recent years that we can take advantage of. One of the biggest challenges that we do have is forming this hermetic barrier. This is an extremely harsh environment that we're in, the brain. So how do you protect it from, yeah, the brain trying to kill your electronics, to also your electronics leaking things that you don't want into the brain. And that forming that hermetic barrier is going to be a very, very big challenge that we, I think are actually well suited to tackle.

Lex Fridman
How do you test that? What's the development environment to simulate that kind of harshness?

DJ Seo
Yeah, so this is where the accelerated life tester essentially is a brain in a vat. It literally is a vessel that is made up of, and again, for all intents and purpose for this particular type of test, your brain is a salt water. And you can also put some other set of chemicals like reactive oxygen species that get at these interfaces and trying to cause a reaction to pull it apart. But you could also increase the rate at which these interfaces are aging by just increasing temperature. So every 10 degrees Celsius that you increase, you're basically accelerating time by 2x. And there's limit as to how much temperature you want to increase because at some point there's some other nonlinear dynamics that causes you to have

other nasty gases to form that just is not realistic in an environment. So what we do is we increase in our ALT chamber by 20 degrees Celsius that increases the aging by four times. So essentially one day in ALT chamber is four day in calendar year, and we look at whether the implants still are intact, including the threats. And -

Lex Fridman
And operation and all of that.

DJ Seo
- and operation and all of that. Obviously, is not an exact same environment as a brain because brain has mechanical other more biological groups that attack at it. But it is a good test environment, testing environment for at least the enclosure and the strength of the enclosure. And I mean, we've had implants, the current version of the implant that has been in there for close to two and a half years, which is equivalent to a decade and they seem to be fine.

Lex Fridman
So, it's interesting that basically close approximation is warm salt water, hot salt water is a good testing environment.

DJ Seo
Yeah.

Lex Fridman
By the way, I'm drinking LMNT , which is basically salt water. Which is making me kind of - it doesn't have computational power the way the brain does, but maybe in terms of other characteristics, it's quite similar and I'm consuming it.

DJ Seo
Yeah. You have to get it in the right pH too.

Lex Fridman
And then, consciousness will emerge. Yeah. No, alright.

DJ Seo
By the way, the other thing that also is interesting about our enclosure is, if you look at our implant, it's not your common looking medical implant that usually is encased in a titanium can that's laser welded. We use this polymer called PCTFE, polychlorotrifluoroethylene, which is actually commonly used in blister packs. So when you have a pill and you try to pop a pill, there's kind of that plastic membrane. That's what this is. No one's actually ever used this except us. And the reason we wanted to do this is because electromagnetically transparent. So when we talked about the electromagnetic inductive charging, with

titanium can usually if you want to do something like that, you have to have a sapphire window and it's a very, very tough process to scale.

Lex Fridman
So you're doing a lot of iteration here in every aspect of this. The materials, the software, all.

DJ Seo
The whole shebang.

Lex Fridman
Okay, so you mentioned scaling. Is it possible to have multiple Neuralink devices as one of the ways of scaling? To have multiple Neuralink devices implanted?

DJ Seo
That's the goal. That's the goal. Yeah. I mean, our monkeys have had two neural links, one in each hemisphere. And then we're also looking at potential of having one in motor cortex, one in visual cortex and one in wherever other cortex.

Lex Fridman
So focusing on the particular function one Neuralink device.

DJ Seo
Correct.

Lex Fridman
I mean, I wonder if there's some level of customization that can be done on the compute side. So for the motor cortex -

DJ Seo
Absolutely. That's the goal. And we talk about at Neuralink building a generalized neural interface to the brain. And that also is strategically how we're approaching this with marketing and also with regulatory, which is, hey, look, we have the robot and the robot can access any part of the cortex. Right now we're focused on motor cortex with current version of the N1 that's specialized for motor decoding tasks. But also at the end of the day, there's a general compute available there. But typically if you want to really get down to hyperoptimizing for power and efficiency, you do need to get to some specialized function. But what we're saying is that, hey, you are now used to this robotic insertion techniques, which took many, many years of showing data and conversation with the FDA and also internally convincing ourselves that this is safe. And now the difference is if we go to other parts of the brain, like visual cortex, which we're interested in as our second product, obviously it's a completely different environment, the cortex is laid out very, very differently.

It's going to be more stimulation focus rather than recording, just kind of creating visual percepts. But in the end, we're using the same thin film array technology, we're using the same robot insertion technology, we're using the same packaging technology. Now it's where the conversation is focused around what are the differences and what are the implication of those differences in safety and efficacy.

Lex Fridman
The way you said second product is both hilarious and awesome to me. That product being restoring sight for blind people. So can you speak to stimulating the visual cortex? I mean, the possibilities there are just incredible to be able to give that gift back to people who don't have sight or even any aspect of that. Can you just speak to the challenges of - there's challenges here -

DJ Seo
Oh, many.

Lex Fridman
One of which is like you said, from recording to stimulation. Just any aspect of that that you're both excited and see the challenges of?

DJ Seo
Yeah, I guess I'll start by saying that we actually have been capable of stimulating through our thin film array as well as other electronics for years. We have actually demonstrated some of that capabilities for reanimating the limb in the spinal cord. Obviously, for the current EFS study, we've hardware disabled that. So that's something that we wanted to embark as a separate journey. And obviously, there are many, many different ways to write information into the brain. The way in which we're doing that is through electrical, passing electrical current, and kind of causing that to really change the local environment so that you can artificially cause the neurons to depolarize in nearby areas. For vision, specifically the way our visual system works, it's both well understood. I mean, anything with kind of brain, there are aspects of it that's well understood, but in the end, we don't really know anything. But the way visual system works is that you have photon hitting your eye, and in your eyes there are these specialized cells called photoreceptor cells that convert the photon energy into electrical signals. And then that then gets projected to your back of your head, your visual cortex. It goes through actually thalamic system called LGN that then projects it out. And then in the visual cortex there's visual area one or V1, and then there's a bunch of other higher level processing layers like V2, V3. And there are actually kind of interesting parallels. And when you study the behaviors of these convolutional neural networks, like what the different layers of the network is detecting, first they're detecting these edges and they're then detecting some more natural curves and then they start to detect objects. Kind of similar thing happens in the brain. And a lot of that has been inspired and also it's been kind of exciting to see some of the correlations there. But things

like from there, where does cognition arise and where's color encoded? There's just not a lot of understanding, fundamental understanding there. So in terms of bringing sight back to those that are blind, there are many different forms of blindness. There's actually million people, 1 million people in the US that are legally blind. That means certain score below in the visual tests. I think it's something like if you can see something at 20 feet distance that normal people can see at 200 feet distance, if you're worse than that, you're legally blind.

Lex Fridman
So fundamental that means you can't function effectively using sight in the world.

DJ Seo
Like to navigate -

Lex Fridman
To navigate.

DJ Seo
- you're environment. And yeah, there are different forms of blindness. There are forms of blindness where there's some degeneration of your retina is photoreceptor cells and rest of your visual processing that I described is intact. And for those types of individuals, you may not need to maybe stick electrodes into the visual cortex. You can actually build retinal prosthetic devices that actually just replaces the function of that retinal cells that are degenerated. And there are many companies that are working on that, but that's a very small slice albeit significance, those smaller slice of folks that are legally blind. If there's any damage along that circuitry, whether it's in the optic nerve or just the LGN circuitry or any break in that circuit, that's not going to work for you. And the source of where you need to actually cause that visual percepts to happen because your biological mechanism not doing that is by placing electrodes in the visual cortex in the back of your head. And the way in which this would work is that you would have an external camera, whether it's something as unsophisticated as a GoPro or some sort of wearable Ray- Ban type glasses that meta is working on that captures a scene. And that scene is then converted to a set of electrical impulses or stimulation pulses that you would activate in your visual cortex through these thin film arrays. And by playing some a concerted kind of orchestra of these stimulation patterns, you can create what's called phosphenes, which are these kind of white yellowish dots that you can also create by just pressing your eyes. You can actually create those percepts by stimulating the visual cortex. And the name of the game is really have many of those and have those percepts, be the phosphenes, be as small as possible so that you can start to tell apart they're the individual pixels of the screen. So if you have many, many of those potentially you'll be able to, in the long term, be able to actually get naturalistic vision. But in the short term to maybe midterm, being able to at least, be able to have object detection algorithms run on your glasses, the pre-processing units, and then being able to at least see the edges of things so you don't bump into stuff.

Lex Fridman
This is incredible. This is really incredible. So you basically would be adding pixels and your brain would start to figure out what those pixels mean with different kinds of assistant signal processing on all fronts.

DJ Seo
Yeah. The thing that actually - so a couple of things. One is obviously if you're blind from birth, the way brain works, especially in the early age, neuroplasticity is really nothing other than your brain and different parts of your brain fighting for the limited territory. And I mean very, very quickly you see cases where people that are - I mean, you also hear about people who are blind that have heightened sense of hearing or some other senses. And the reason for that is because that cortex that's not used just gets taken over by these different parts of the cortex. So for those types of individuals, I mean I guess they're going to have to now map some other parts of their senses into what they call vision, but it's going to be obviously a very, very different conscious experience. Before - so, I think that's an interesting caveat. The other thing that also is important to highlight is that, we're currently limited by our biology in terms of the wavelength that we can see. There's a very, very small wavelength that is a visible light wavelength that we can see with our eyes. But when you have an external camera with this BCI system, you're not limited to that. You can have infrared, you can have UV, you can have whatever other spectrum that you want to see. And whether that gets matched to some sort of weird conscious experience, I've no idea. But oftentimes I talk to people about the goal of Neuralink being going beyond the limits of our biology. That's sort of what I mean.

Lex Fridman
And if you're able to control the kind of raw signal, is that when we use our site, we're getting the photons and there's not much processing on it. If you're being able to control that signal, maybe you can do some kind of processing, maybe you do object detection ahead of time. You're doing some kind of pre-processing and there's a lot of possibilities to explore that. So it's not just increasing thermal imaging, that kind of stuff, but it's also just doing some kind of interesting processing.

DJ Seo
Correct. Yeah. I mean, my theory of how visual system works also is that, I mean, there's just so many things happening in the world and there's a lot of photons that are going into your eye. And it's unclear exactly where some of the pre-processing steps are happening. But I mean, I actually think that just from a fundamental perspective, there's just so much the reality that we're in, if it's a reality, so there's so much data and I think humans are just unable to actually eat enough, actually to process all that information. So there's some sort of filtering that does happen, whether that happens in the retina, whether that happens in different layers of the visual cortex, unclear. But the analogy that I sometimes think about is, if your brain is a CCD camera and all of the information in the world is a sun, and when you

try to actually look at the sun with the CCD camera, it's just going to saturate the sensors because it's an enormous amount of energy. So what you do is you end up adding these filters to just kind of narrow the information that's coming to you and being captured. And I think things like our experiences or our drugs like propofol, anesthetics drug or psychedelics, what they're doing is they're kind of swapping out these filters and putting in new ones or removing older ones and kind of controlling our conscious experience.

Lex Fridman
Yeah, man, not to distract from the topic, but I just took a very high dose of ayahuasca in the Amazon jungle. So yes, it's a nice way to think about it. You're swapping out different experiences and with Neuralink being able to control that, primarily at first to improve function, not for entertainment purposes or enjoyment purposes, but-

DJ Seo
Yeah, giving back loss functions.

Lex Fridman
Giving back loss functions. And there, especially when the function is completely lost, anything is a huge help. Would you implant a Neuralink device in your own brain?

DJ Seo
Absolutely. I mean, maybe not right now, but absolutely.

Lex Fridman
What kind of capability once reached you start getting real curious and almost get a little antsy, jealous of people as you watch them get implanted?

DJ Seo
Yeah, I think even with our early participants, if they start to do things that I can't do, which I think is in the realm of possibility for them to be able to get 15, 20 if not like a hundred BPS. There's nothing that fundamentally stops us from being able to achieve that type of performance. I mean, I would certainly get jealous that they can do that.

Lex Fridman
I should say that watching Noland, I get a little jealous having so much fun, and it seems like such a chill way to play video games.

DJ Seo
Yeah. I mean the thing that also is hard to appreciate sometimes is that, he's doing these things while talking. And I mean, it's multitasking, so it's clearly, it's obviously cognitively intensive. But similar to how when we talk, we move our hands. These are multitasking. I mean, he's able to do that. And you won't be able to do that with other assistive technology.

As far as I am aware, if you're obviously using an eye tracking device, you're very much fixated on that thing that you're trying to do. And if you're using voice control, I mean if you say some other stuff, you don't get to use that.

Lex Fridman
The multitasking aspect of that is really interesting. So it's not just the BPS for the primary task, it's the parallelization of multiple tasks. If you measure the BPS for the entirety of the human organism. So you're talking and doing a thing with your mind and looking around also, I mean, there's just a lot of parallelization that can be happening.

DJ Seo
But I mean, I think at some point for him, if he wants to really achieve those high level BPS, it does require a full attention. And that's a separate circuitry that is a big mystery, how attention works and -

Lex Fridman
Yeah, attention, cognitive load. I've read a lot of literature on people doing two tasks. You have your primary task and a secondary task, and the secondary task is a source of distraction. And how does that affect the performance of the primary task? And depending on the tasks, because there's a lot of interesting - I mean, this is an interesting computational device, and I think there's -

DJ Seo
To say the least.

Lex Fridman
- a lot of novel insights that can be gained from everything. I mean, I personally am surprised that no one's able to do such incredible control of the cursor while talking. And also being nervous at the same time because he's talking like all of us are if you're talking in front of the camera, you get nervous. So all of those are coming into play and he's able to still achieve high performance. Surprising. I mean, all of this is really amazing. And I think just after researching this really in depth, I kind of want a Neuralink.

DJ Seo
Get in the line.

Lex Fridman
And also the safety get in line. Well, we should say the registry is for people who have quadriplegia and all that kind of stuff, so.

DJ Seo
Correct.

Lex Fridman
That'd be a separate line for people. They're just curious like myself. So now that Noland, patient P1 is part of the ongoing prime study, what's the high level vision for P2, P3, P4, P5, and just the expansion into other human beings that are getting to experience this implant?

DJ Seo
Yeah, I mean the primary goal is for our study in the first place is to achieve safety endpoints. Just understand safety of this device as well as the implantation process. And also at the same time understand the efficacy and the impact that it could have on the potential user's lives. And Just because you have, you're living with tetraplegia, it doesn't mean your situation is same as another person living with tetraplegia. It's wildly, wildly varying. And it's something that we're hoping to also understand how our technology can serve not just a very small slice of those individuals, but broader group of individuals and being able to get the feedback to just really build just the best product for them. So there's obviously, also goals that we have. And the primary purpose of the early feasibility study is to learn from each and every participant to improve the device, improve the surgery before we embark on what's called a pivotal study. That then is a much larger trial that starts to look at statistical significance of your endpoints and that's required before you can then market the device. And that's how it works in the US and just generally around the world. That's the process you follow. So our goal is to really just understand from people like Noland, P2, P3, future participants, what aspects of our device needs to improve. If it turns out that people are like, "I really don't like the fact that it lasts only six hours. I want to be able to use this computer for 24 hours." I mean, that is a user needs and user requirements, which we can only find out from just being able to engage with them.

Lex Fridman
So before the pivotal study, there's kind of a rapid innovation based on individual experiences. You're learning from individual people, how they use it, the high resolution details in terms of cursor control and signal and all that kind of stuff, life experience.

DJ Seo
So there's hardware changes, but also just firmware updates. So even when we had that sort of recovery event for Noland, he now has the new firmware that he has been updated with, and similar to how your phones get updated all the time with new firmware for security patches, whatever, new functionality, UI. And that's something that is possible with our implant. It's not a static one-time device that can only do - it's not a static one-time device that can only do the thing that it said it can do. I mean, it's similar to Tesla, you can do over-the-air firmware updates, and now you have completely new user interface and all these bells and whistles and improvements on everything, like the latest. Right? When we say generalized platform, that's what we're talking about.

Lex Fridman
Yeah. It's really cool how the app that Noland is using, there's calibration, all that kind of stuff, and then there's update. You just click and get an update. What other future capabilities are you looking to? You said vision. That's a fascinating one. What about accelerated typing or speech, or this kind of stuff? And what else is there?

DJ Seo
Yeah. Those are still in the realm of movement program. So, largely speaking, we have two programs. We have the movement program and we have the vision program. The movement program currently is focused around the digital freedom. As you can easily guess, if you can control 2D cursor in the digital space, you could move anything in the physical space. So, robotic arms, wheelchair, your environment, or even really, whether it's through the phone or just directly to those interfaces, to those machines. So, we're looking at ways to expand those types of capability, even for Noland. That requires conversation with the FDA and showing safety data for if there's a robotic arm or a wheelchair, that we can guarantee that they're not going to hurt themselves accidentally. Right? It's very different if you're moving stuff in the digital domain versus in the physical space, you can actually potentially cause harm to the participants. So, we're working through that right now. Speech does involve different areas of the brain. Speech prosthetic is very, very fascinating and there's actually been a lot of really amazing work that's been happening in academia. Sergey Stavisky at UC Davis, Jaimie Henderson and late Krishna Shenoy at Stanford, are doing just some incredible amount of work in improving speech neuro-prosthetics. And those are actually looking more at parts of the motor cortex that are controlling these vocal articulators, and being able to, even by mouthing the word or imagine speech, you can pick up those signals. The more sophisticated higher level processing areas like the Broca's area or Wernicke's area, those are still very, very big mystery in terms of the underlying mechanism of how all that stuff works. But I mean, I think Neuralink's eventual goal is to understand those things and be able to provide a platform and tools to be able to understand that and study that.

Lex Fridman
This is where I get to the pothead questions. Do you think we can start getting insight into things like thought? So, speech, there's a muscular component, like you said, there's the act of producing sounds, but then what about the internal things like cognition, like low-level thoughts and high-level thoughts? Do you think we'll start noticing signals that could be picked up, they could be understood, that could be maybe used in order to interact with the outside world?

DJ Seo
In some ways, I guess, this starts to kind of get into the hard problem of consciousness. And I mean, on one hand, all of these are at some point, set of electrical signals that from there maybe it in itself is giving you the cognition or the meaning, or somehow human mind is an incredibly amazing storytelling machine. So, we're telling ourselves and fooling ourselves

that there's some interesting meaning here. But I mean, I certainly think that BCI - really, BCI, at the end of the day is a set of tools that help you study the underlying mechanisms in a both local but also broader sense, and whether there's some interesting patterns of electrical signal that means you're thinking this versus - and you can either learn from many, many sets of data to correlate some of that and be able to do mind reading or not. I'm not sure. I certainly would not rule that out as a possibility, but I think BCI alone probably can't do that. There's probably additional set of tools and framework and also just hard problem of consciousness, at the end of the day, is rooted in this philosophical question of what is the meaning of it all? What's the nature of our existence? Where's the mind emerged from this complex network?

Lex Fridman
Yeah. How does the subjective experience emerge from just a bunch of spikes, electrical spikes?

DJ Seo
Yeah. Yeah. I mean, we do really think about BCI and what we're building as a tool for understanding the mind, the brain. The only question that matters. There actually is some biological existence proof of what it would take to kind of start to form some of these experiences that may be unique. If you actually look at every one of our brains, there are two hemispheres. There's a left-sided brain, there's a right-sided brain. And unless you have some other conditions, you normally don't feel like left legs or right legs, you just feel like one legs, right? So, what is happening there? Right? If you actually look at the two hemispheres, there's a structure that kind of connectorized the two, called the corpus callosum, that is supposed to have around 200 to 300 million connections or axons. So, whether that means that's the number of interface and electrodes that we need to create some sort of mind meld or from that whatever new conscious experience that you can experience. But I do think that there's kind of an interesting existence proof that we all have.

Lex Fridman
And that threshold is unknown at this time?

DJ Seo
Oh, yeah. Everything in this domain is speculation. Right?

Lex Fridman
And then, you'd be continuously pleasantly surprised. Do you see a world where there is millions of people, like tens of millions, hundreds of millions of people walking around with a Neuralink device or multiple Neuralink devices in their brain?

DJ Seo
I do. First of all, there are, if you look at worldwide, people suffering from movement disorders and visual deficits, I mean, that's in the tens if not hundreds of millions of people. So, that alone, I think there's a lot of benefit and potential good that we can do with this type of technology. And once you start to get into psychiatric application, depression, anxiety, hunger or obesity, right? Mood, control of appetite. I mean, that starts to become very real to everyone.

Lex Fridman
Not to mention that most people on Earth have a smartphone, and once BCI starts competing with a smartphone as a preferred methodology of interacting with the digital world, that also becomes an interesting thing.

DJ Seo
Oh, yeah. This is even before going to that, right? There's almost - I mean, the entire world that could benefit from these types of things. And then, if we're talking about next generation of how we interface with machines or even ourselves, in many ways, I think BCI can play a role in that. And some of the things that I also talk about is, I do think that there is a real possibility that you could see 8 billion people walking around with Neuralink.

Lex Fridman
Well, thank you so much for pushing ahead. And I look forward to that exciting future.

DJ Seo
Thanks for having me.

Lex Fridman
Thanks for listening to this conversation with DJ Seo. And now, dear friends, here's Matthew MacDougall, the head neurosurgeon at Neuralink. When did you first become fascinated with the human brain?

Matthew MacDougall
Since forever. As far back as I can remember, I've been interested in the human brain. I mean, I was a thoughtful kid and a bit of an outsider, and you sit there thinking about what the most important things in the world are in your little tiny adolescent brain. And the answer that I came to, that I converged on was that all of the things you can possibly conceive of as things that are important for human beings to care about are literally contained in the skull. Both the perception of them and their relative values and the solutions to all our problems, and all of our problems, are all contained in the skull. And if we knew more about how that worked, how the brain encodes information and generates desires and generates agony and suffering, we could do more about it. You think about all the really great triumphs in human history. You think about all the really horrific tragedies.

You think about the Holocaust, you think about any prison full of human stories, and all of those problems boil down to neurochemistry. So, if you get a little bit of control over that, you provide people the option to do better. In the way I read history, the way people have dealt with having better tools is that they most often, in the end, do better, with huge asterisks. But I think it's an interesting, a worthy, a noble pursuit to give people more options, more tools.

Lex Fridman
Yeah, that's a fascinating way to look at human history. You just imagine all these neurobiological mechanisms, Stalin, Hitler, Genghis Khan, all of them just had a brain, just a bunch of neurons, few times of billions of neurons gaining a bunch of information over a period of time. They have a set of modules that does language and memory and all that. And from there, in the case of those people, they're able to murder millions of people. And all that coming from - there's not some glorified notion of a dictator of this enormous mind or something like this. It's just the brain.

Matthew MacDougall
Yeah. Yeah. I mean, a lot of that has to do with how well people like that can organize those around them.

Lex Fridman
Other brains.

Matthew MacDougall
Yeah. And so, I always find it interesting to look to primatology, look to our closest non-human relatives for clues as to how humans are going to behave and what particular humans are able to achieve. And so, you look at chimpanzees and bonobos, and they're similar but different in their social structures particularly. And I went to Emory in Atlanta and studied under the great Frans de Waal, who was kind of the leading primatologist, who recently died. And his work looking at chimps through the lens of how you would watch an episode of Friends and understand the motivations of the characters interacting with each other. He would look at a chimp colony and basically apply that lens. I'm massively oversimplifying it. If you do that, instead of just saying, "Subject 473 threw his feces at subject 471." You talk about them in terms of their human struggles, accord them the dignity of themselves as actors with understandable goals and drives, what they want out of life. And primarily, it's the things we want out of life, food, sex, companionship, power. You can understand chimp and bonobo behavior in the same lights much more easily. And I think doing so gives you the tools you need to reduce human behavior from the kind of false complexity that we layer onto it with language, and look at it in terms of, oh, well, these humans are looking for companionship, sex, food, power. And I think that that's a pretty powerful tool to have in understanding human behavior.

Lex Fridman
And I just went to the Amazon jungle for a few weeks and it's a very visceral reminder that a lot of life on Earth is just trying to get laid. They're all screaming at each other. I saw a lot of monkeys and they're just trying to impress each other, or maybe if there's a battle for power, but a lot of the battle for power has to do with them getting laid.

Matthew MacDougall
Right. Breeding rights often go with alpha status. And so, if you can get a piece of that, then you're going to do okay.

Lex Fridman
And we'd like to think that we're somehow fundamentally different, and especially when it comes to primates, we really aren't. We can use fancier poetic language, but maybe some of the underlying drives and motivators are similar.

Matthew MacDougall
Yeah, I think that's true.

Lex Fridman
And all of that is coming from this, the brain.

Matthew MacDougall
Yeah.

Lex Fridman
So, when did you first start studying the brain as the biological mechanism?

Matthew MacDougall
Basically, the moment I got to college, I started looking around for labs that I could do neuroscience work in. I originally approached that from the angle of looking at interactions between the brain and the immune system, which isn't the most obvious place to start, but I had this idea at the time that the contents of your thoughts would have a direct impact, maybe a powerful one, on non-conscious systems in your body. The systems we think of as homeostatic automatic mechanisms, like fighting off a virus, like repairing a wound. And sure enough, there are big crossovers between the two. I mean, it gets to kind of a key point that I think goes under-recognized. One of the things people don't recognize or appreciate about the human brain enough, and that is that it basically controls or has a huge role in almost everything that your body does. You try to name an example of something in your body that isn't directly controlled or massively influenced by the brain, and it's pretty hard. I mean, you might say like bone healing or something. But even those systems, the hypothalamus and pituitary end up playing a role in coordinating the endocrine system, that does have a direct influence on say, the calcium level in your blood, that goes to bone

healing. So, non-obvious connections between those things implicate the brain as really a potent prime mover in all of health.

Lex Fridman

One of the things I realized in the other direction too, how most of the systems in the body are integrated with the human brain, they affect the brain also, like the immune system. I think there's just, people who study Alzheimer's and those kinds of things, it's just surprising how much you can understand of that from the immune system, from the other systems that don't obviously seem to have anything to do with the nervous system. They all play together.

Matthew MacDougall

Yeah, you could understand how that would be driven by evolution too. Just in some simple examples, if you get sick, if you get a communicable disease, you get the flu, it's pretty advantageous for your immune system to tell your brain, "Hey, now be antisocial for a few days. Don't go be the life of the party tonight. In fact, maybe just cuddle up somewhere warm, under a blanket, and just stay there for a day or two." And sure enough, that tends to be the behavior that you see both in animals and in humans. If you get sick, elevated levels of interleukins in your blood and TNF-alpha in your blood, ask the brain to cut back on social activity and even moving around, you have lower locomotor activity in animals that are infected with viruses.

Lex Fridman

So, from there, the early days in neuroscience to surgery, when did that step happen? Which is a leap.

Matthew MacDougall

Yeah. It was sort of an evolution of thought. I wanted to study the brain. I started studying the brain in undergrad in this neuroimmunology lab. I, from there, realized at some point that I didn't want to just generate knowledge. I wanted to affect real changes in the actual world, in actual people's lives. And so, after having not really thought about going into medical school, I was on a track to go into a PhD program. I said, "Well, I'd like that option. I'd like to actually potentially help tangible people in front of me." And doing a little digging, found that there exists these MD-PhD programs where you can choose not to choose between them and do both. And so, I went to USC for medical school and had a joint PhD program with Caltech, where I actually chose that program particularly because of a researcher at Caltech named Richard Andersen, who's one of the godfathers of primate neuroscience, and has a macaque lab where Utah arrays and other electrodes were being inserted into the brains of monkeys to try to understand how intentions were being encoded in the brain. So, I ended up there with the idea that maybe I would be a neurologist and study the brain on the side. And then discovered that neurology - again, I'm going to make enemies by saying this, but neurology predominantly and distressingly to me, is the practice of diagnosing a thing and then saying, "Good luck with that. There's not much we can do." And neurosurgery, very differently, it's a powerful lever on taking people that are headed in a bad direction and changing their course in the sense of brain tumors that are potentially treatable or curable with surgery. Even aneurysms in the brain, blood vessels that are going to rupture, you can save lives, really, is at the end of the day what mattered to me. And so, I was at USC, as I mentioned, that happens to be one of the great neurosurgery programs. And so, I met these truly epic neurosurgeons, Alex Khalessi, and Mike Apuzzo, and Steve Giannotta, and Marty Weiss, these epic people that were just human beings in front of me. And so, it kind of changed my thinking from neurosurgeons are distant gods that live on another planet and occasionally come and visit us, to these are humans that have problems and are people, and there's nothing fundamentally preventing me from being one of them. And so, at the last minute in medical school, I changed gears from going into a different specialty and switched into neurosurgery, which cost me a year. I had to do another year of research because I was so far along in the process that to switch into neurosurgery, the deadlines had already passed. So, it was a decision that cost time, but absolutely worth it.

Lex Fridman
What was the hardest part of the training on the neurosurgeon track?

Matthew MacDougall
Yeah, two things. I think that residency in neurosurgery is sort of a competition of pain, of how much pain can you eat and smile? And so, there's work hour restrictions that are not really - they're viewed, I think, internally among the residents as weakness. And so, most neurosurgery residents try to work as hard as they can, and that, I think necessarily means working long hours and sometimes over the work hour limits. We care about being compliant with whatever regulations are in front of us, but I think more important than that, people want to give their all in becoming a better neurosurgeon because the stakes are so high. And so, it's a real fight to get residents to say, go home at the end of their shift and not stay and do more surgery.

Lex Fridman
Are you seriously saying one of the hardest things is literally forcing them to get sleep and rest and all this kind of stuff?

Matthew MacDougall
Historically that was the case.

Lex Fridman
That's hilarious. And that's awesome.

Matthew MacDougall
I think the next generation is more compliant and more self-care -

Lex Fridman
Weaker is what you mean. Alright. I'm just kidding. I'm just kidding.

Matthew MacDougall
I didn't say it.

Lex Fridman
Now I'm making enemies.

Matthew MacDougall
No.

Lex Fridman
Okay, I get it. Wow, that's fascinating. So, what was the second thing?

Matthew MacDougall
The personalities. And maybe the two are connected.

Lex Fridman
So, was it pretty competitive?

Matthew MacDougall
It's competitive, and it's also, as we touched on earlier, primates like power. And I think neurosurgery has long had this aura of mystique and excellence and whatever about it. And so, it's an invitation, I think, for people that are cloaked in that authority. A board certified neurosurgeon is basically a walking fallacious appeal to authority. Right? You have license to walk into any room and act like you're an expert on whatever. And fighting that tendency is not something that most neurosurgeons do well. Humility isn't the forte.

Lex Fridman
Yeah. I have friends who know you and whenever they speak about you that you have the surprising quality for a neurosurgeon of humility, which I think indicates that it's not as common as perhaps in other professions, because there is a kind of gigantic sort of heroic aspect to neurosurgery, and I think it gets to people's head a little bit.

Matthew MacDougall
Yeah. Well, I think that allows me to play well at an Elon company because Elon, one of his strengths, I think, is to just instantly see through fallacy from authority. So, nobody walks into a room that he's in and says, "Well, goddammit, you have to trust me. I'm the guy that

built the last 10 rockets," or something. And he says, "Well, you did it wrong and we can do it better." Or, "I'm the guy that kept Ford alive for the last 50 years. You listen to me on how to build cars." And he says, "No." And so, you don't walk into a room that he's in and say, "Well, I'm a neurosurgeon. Let me tell you how to do it." He's going to say, "Well, I'm a human being that has a brain. I can think from first principles myself. Thank you very much. And here's how I think it ought to be done. Let's go try it and see who's right." And that's proven, I think over and over in his case, to be a very powerful approach.

Lex Fridman
If we just take that tangent, there's a fascinating interdisciplinary team at Neuralink that you get to interact with, including Elon. What do you think is the secret to a successful team? What have you learned from just getting to observe these folks, world experts in different disciplines work together?

Matthew MacDougall
There's a sweet spot where people disagree and forcefully speak their mind and passionately defend their position, and yet, are still able to accept information from others and change their ideas when they're wrong. And so, I like the analogy of how you polish rocks. You put hard things in a hard container and spin it. People bash against each other, and out comes a more refined product. And so, to make a good team at Neuralink, we've tried to find people that are not afraid to defend their ideas passionately and occasionally strongly disagree with people that they're working with, and have the best idea come out on top. It's not an easy balance. Again, to refer back to the primate brain. It's not something that is inherently built into the primate brain to say, "I passionately put all my chips on this position, and now I'm just going to walk away from it and admit you are right." Part of our brains tell us that that is a power loss, that is a loss of face, a loss of standing in the community, and now you're a zeta chump because your idea got trounced. And you just have to recognize that that little voice in the back of your head is maladaptive and it's not helping the team win.

Lex Fridman
Yeah, you have to have the confidence to be able to walk away from an idea that you hold on to. Yeah.

Matthew MacDougall
Yeah.

Lex Fridman
And if you do that often enough, you're actually going to become the best in the world at your thing. I mean, that rapid iteration.

Matthew MacDougall
Yeah, you'll at least be a member of a winning team.

Lex Fridman
Ride the wave. What did you learn - you mentioned there's a lot of amazing neurosurgeons at USC. What lessons about surgery and life have you learned from those folks?

Matthew MacDougall
Yeah. I think working your ass off, working hard while functioning as a member of a team, getting a job done that is incredibly difficult, working incredibly long hours, being up all night, taking care of someone that you think probably won't survive no matter what you do. Working hard to make people that you passionately dislike look good the next morning. These folks were relentless in their pursuit of excellent neurosurgical technique, decade over decade, and I think were well-recognized for that excellence. So, especially Marty Weiss, Steve Giannotta, Mike Apuzzo, they made huge contributions not only to surgical technique, but they built training programs that trained dozens or hundreds of amazing neurosurgeons. I was just lucky to be in their wake.

Lex Fridman
What's that like - you mentioned doing a surgery where the person is likely not to survive. Does that wear on you?

Matthew MacDougall
Yeah. It's especially challenging when you - with all respect to our elders, it doesn't hit so much when you're taking care of an 80-year-old, and something was going to get them pretty soon anyway. And so, you lose a patient like that, and it was part of the natural course of what is expected of them in the coming years, regardless. Taking care of a father of two or three, four young kids, someone in their 30s that didn't have it coming, and they show up in your ER having their first seizure of their life, and lo and behold, they've got a huge malignant inoperable or incurable brain tumor. You can only do that, I think, a handful of times before it really starts eating away at your armor. Or, a young mother that shows up that has a giant hemorrhage in her brain that she's not going to survive from. And they bring her four-year-old daughter in to say goodbye one last time before they turn the ventilator off. The great Henry Marsh is an English neurosurgeon who said it best, I think. He says, "Every neurosurgeon carries with them a private graveyard." And I definitely feel that, especially with young parents, that kills me. They had a lot more to give. The loss of those people specifically has a knock-on effect that's going to make the world worse for people for a long time. And it's just hard to feel powerless in the face of that. And that's where I think you have to be borderline evil to fight against a company like Neuralink or to constantly be taking pot shots at us, because what we're doing is to try to fix that stuff. We're trying to give people options to reduce suffering. We're trying to take the pain out of

life that broken brains brings in. And yeah, this is just our little way that we're fighting back against entropy, I guess.

Lex Fridman
Yeah. The amount of suffering that's endured when some of the things that we take for granted that our brain is able to do is taken away, is immense. And to be able to restore some of that functionality is a real gift.

Matthew MacDougall
Yeah. We're just starting. We're going to do so much more.

Lex Fridman
Well, can you take me through the full procedure for implanting, say, the N1 chip in Neuralink?

Matthew MacDougall
Sure. Yeah. It's a really simple, straightforward procedure. The human part of the surgery that I do is dead simple. It's one of the most basic neurosurgery procedures imaginable. And I think there's evidence that some version of it has been done for thousands of years. That there are examples, I think, from ancient Egypt of healed or partially healed trepanations, and from Peru or ancient times in South America where these proto-surgeons would drill holes in people's skulls, presumably to let out the evil spirits, but maybe to drain blood clots. And there's evidence of bone healing around the edge, meaning the people at least survived some months after a procedure. And so, what we're doing is that. We are making a cut in the skin on the top of the head over the area of the brain that is the most potent representation of hand intentions. And so, if you are an expert concert pianist, this part of your brain is lighting up the entire time you're playing. We call it the hand knob.

Lex Fridman
The hand knob. So, it's all the finger movements, all of that is just firing away.

Matthew MacDougall
Yup. There's a little squiggle in the cortex right there. One of the folds in the brain is kind of doubly folded right on that spot. And so, you can look at it on an MRI and say, "That's the hand knob." And then you do a functional test and a special kind of MRI called a functional MRI, fMRI. And this part of the brain lights up when-

Matthew MacDougall
MRI, fMRI, and this part of the brain lights up when people, even quadriplegic people whose brains aren't connected to their finger movements anymore, they imagine finger movements and this part of the brain still lights up. So we can ID that part of the brain in anyone who's preparing to enter our trial and say, okay, that part of the brain we confirm is

your hand intention area. And so I'll make a little cut in the skin, we'll flap the skin open, just like kind of opening the hood of a car, only a lot smaller, make a perfectly round one inch diameter hole in the skull, remove that bit of skull, open the lining of the brain, the covering of the brain, it's like a little bag of water that the brain floats in, and then show that part of the brain to our robot. And then this is where the robot shines. It can come in and take these tiny, much smaller than human hair, electrodes and precisely insert them into the cortex, into the surface of the brain to a very precise depth, in a very precise spot that avoids all the blood vessels that are coating the surface of the brain. And after the robot's done with its part, then the human comes back in and puts the implant into that hole in the skull and covers it up, screwing it down to the skull and sewing the skin back together. So the whole thing is a few hours long. It's extremely low risk compared to the average neurosurgery involving the brain that might, say, open up a deeper part of the brain or manipulate blood vessels in the brain. This opening on the surface of the brain with only cortical micro-insertions carries significantly less risk than a lot of the tumor or aneurysm surgeries that are routinely done.

Lex Fridman
So cortical micro-insertions that are via robot and computer vision are designed to avoid the blood vessels.

Matthew MacDougall
Exactly.

Lex Fridman
So I know you're a bit biased here, but let's compare human and machine. So what are human surgeons able to do well and what are robot surgeons able to do well at this stage of our human civilization and development?

Matthew MacDougall
Yeah. Yeah, that's a good question. Humans are general purpose machines. We're able to adapt to unusual situations. We're able to change the plan on the fly. I remember well a surgery that I was doing many years ago down in San Diego where the plan was to open a small hole behind the ear and go reposition a blood vessel that had come to lay on the facial nerve, the trigeminal nerve, the nerve that goes to the face. When that blood vessel lays on the nerve, it can cause just intolerable, horrific shooting pain that people describe like being zapped with a cattle prod. And so the beautiful, elegant surgery is to go move this blood vessel off the nerve. The surgery team, we went in there and started moving this blood vessel and then found that there was a giant aneurysm on that blood vessel that was not easily visible on the pre-op scans. And so the plan had to dynamically change and that the human surgeons had no problem with that, were trained for all those things. Robots wouldn't do so well in that situation, at least in their current incarnation, fully robotic surgery, like the electrode insertion portion of the neural link surgery, it goes according to a

set plan. And so the humans can interrupt the flow and change the plan, but the robot can't really change the plan midway through. It operates according to how it was programmed and how it was asked to run. It does its job very precisely, but not with a wide degree of latitude in how to react to changing conditions.

Lex Fridman
So there could be just a very large number of ways that you could be surprised as a surgeon? When you enter a situation, there could be subtle things that you have to dynamically adjust to.

Matthew MacDougall
Correct.

Lex Fridman
And robots are not good at that.

Matthew MacDougall
Currently.

Lex Fridman
Currently.

Matthew MacDougall
I think we are at the dawn of a new era with AI of the parameters for robot responsiveness to be dramatically broadened, right? I mean, you can't look at a self-driving car and say that it's operating under very narrow parameters. If a chicken runs across the road, it wasn't necessarily programmed to deal with that specifically, but a Waymo or a self-driving Tesla would have no problem reacting to that appropriately. And so surgical robots aren't there yet, but give it time.

Lex Fridman
And then there could be a lot of semi-autonomous possibilities of maybe a robotic surgeon could say this situation is perfectly familiar, or this situation is not familiar, and in the not familiar case, a human could take over, but basically be very conservative in saying, okay, this for sure has no issues, no surprises, and let the humans deal with the surprises with the edge cases and all that. That's one possibility. So you think eventually you'll be out of the job? Well, you being neurosurgeon, your job being a neurosurgeon. Humans, there will not be many neurosurgeons left on this earth.

Matthew MacDougall
I'm not worried about my job in the course of my professional life. I think I would tell my kids not necessarily to go in this line of work depending on how things look in 20 years.

Lex Fridman
It's so fascinating because if I have a line of work, I would say it's programming. And if you ask me, for the last, I don't know, 20 years, what I would recommend for people, I would tell them, yeah, you'll always have a job if you're a programmer because there's more and more computers and all this kind of stuff and it pays well. But then you realize these large language models come along and they're really damn good at generating code. So overnight you could be surprised like, wow, what is the contribution of the human really? But then you start to think, okay, it does seem that humans have ability, like you said, to deal with novel situations. In the case of programming, it's the ability to come up with novel ideas to solve problems. It seems like machines aren't quite yet able to do that. And when the stakes are very high, when it's life critical as it is in surgery, especially in neurosurgery, then the stakes are very high for a robot to actually replace a human. But it's fascinating that in this case of Neuralink, there's a human robot collaboration.

Matthew MacDougall
Yeah, yeah. I do the parts it can't do and it does the parts I can't do, and we are friends.

Lex Fridman
I saw that there's a lot of practice going on. I mean everything in Neuralink is tested extremely rigorously, but one of the things I saw that there's a proxy on which the surgeries are performed. So this is both for the robot and for the human, for everybody involved in the entire pipeline. What's that like, practicing the surgery?

Matthew MacDougall
It's pretty intense. So there's no analog to this in human surgery. Human surgery is sort of this artisanal craft that's handed down directly from master to pupil over the generations. I mean, literally the way you learn to be a surgeon on humans is by doing surgery on humans. I mean, first you watch your professors do a bunch of surgery, and then finally they put the trivial parts of the surgery into your hands, and then the more complex parts, and as your understanding of the point and the purposes of the surgery increases, you get more responsibility in the perfect condition. Doesn't always go well. In Neuralink's case, the approach is a bit different. We, of course, practiced as far as we could on animals. We did hundreds of animal surgeries. And when it came time to do the first human, we had just an amazing team of engineers build incredibly lifelike models. One of the engineers, Fran Romano in particular, built a pulsating brain in a custom 3-D printed skull that matches exactly the patient's anatomy, including their face and scalp characteristics. And so when I was able to practice that, it's as close as it really reasonably should get to being the real thing in all the details, including having a mannequin body attached to this custom head. And so when we were doing the practice surgeries, we'd wheel that body into the CT scanner and take a mock CT scan and wheel it back in and conduct all the normal safety checks, verbally, "Stop. This patient we're confirming his identification is mannequin number…" Blah, blah, blah. And then opening the brain in exactly the right spot using

standard operative neuro-navigation equipment, standard surgical drills in the same OR that we do all of our practice surgeries in at Neuralink and having the skull open and have the brain pulse, which adds a degree of difficulty for the robot to perfectly precisely plan and insert those electrodes to the right depth and location. And so we kind of broke new ground on how extensively we practiced for this surgery.

Lex Fridman
So there was a historic moment, a big milestone for Neuralink, in part for humanity, with the first human getting a Neuralink implant in January of this year. Take me through the surgery on Noland. What did it feel like to be part of this?

Matthew MacDougall
Yeah. Well, we are lucky to have just incredible partners at the Barrow Neurologic Institute. They are, I think, the premier neurosurgical hospital in the world. They made everything as easy as possible for the trial to get going and helped us immensely with their expertise on how to arrange the details. It was a much more high pressure surgery in some ways. I mean, even though the outcome wasn't particularly in question in terms of our participant's safety, the number of observers, the number of people, there's conference rooms full of people watching live streams in the hospital rooting for this to go perfectly, and that just adds pressure that is not typical for even the most intense production neurosurgery, say, removing a tumor or placing deep brain stimulation electrodes, and it had never been done on a human before. There were unknown unknowns. And so definitely a moderate pucker factor there for the whole team not knowing if we were going to encounter, say, a degree of brain movement that was unanticipated or a degree of brain sag that took the brain far away from the skull and made it difficult to insert or some other unknown unknown problem. Fortunately everything went well and that surgery is one of the smoothest outcomes we could have imagined.

Lex Fridman
Were you nervous?

Matthew MacDougall
Extremely.

Lex Fridman
I mean, you're a bit of a quarterback in the Super Bowl kind of situation.

Matthew MacDougall
Extremely nervous. Extremely. I was very pleased when it went well and when it was over. Looking forward to number two.

Lex Fridman
Even with all that practice, all of that, you've never been in a situation that's so high stakes in terms of people watching. And we should also probably mention, given how the media works, a lot of people may be in a dark kind of way hoping it doesn't go well.

Matthew MacDougall
I think wealth is easy to hate or envy or whatever, and I think there's a whole industry around driving clicks and bad news is great for clicks, and so any way to take an event and turn it into bad news is going to be really good for clicks.

Lex Fridman
It just sucks because I think it puts pressure on people. It discourages people from trying to solve really hard problems because to solve hard problems, you have to go into the unknown. You have to do things that haven't been done before and you have to take risks, calculated risks, you have to do all kinds of safety precautions, but risks nevertheless. I just wish there would be more celebration of that, of the risk taking versus people just waiting on the sidelines waiting for failure and then pointing out the failure. Yeah, it sucks. But in this case, it's really great that everything went just flawlessly, but it's unnecessary pressure, I would say.

Matthew MacDougall
Now that there's a human with literal skin in the game, there's a participant whose well-being rides on this doing well. You have to be a pretty person to be rooting for that to go wrong. And so hopefully people look in the mirror and realize that at some point.

Lex Fridman
So did you get to actually front row seat, watch the robot work? You get to see the whole thing?

Matthew MacDougall
Yeah, because an MD needs to be in charge of all of the medical decision-making throughout the process, I unscrubbed from the surgery after exposing the brain and presenting it to the robot and placed the targets on the robot software interface that tells the robot where it's going to insert each thread. That was done with my hand on the mouse, for whatever that's worth.

Lex Fridman
So you were the one placing the targets?

Matthew MacDougall
Yeah.

Lex Fridman
Oh, cool. So the robot with a computer vision provides a bunch of candidates and you kind of finalize the decision.

Matthew MacDougall
Right. The software engineers are amazing on this team, and so they actually provided an interface where you can essentially use a lasso tool and select a prime area of brain real estate, and it will automatically avoid the blood vessels in that region and automatically place a bunch of targets. That allows the human robot operator to select really good areas of brain and make dense applications of targets in those regions, the regions we think are going to have the most high fidelity representations of finger movements and arm movement intentions.

Lex Fridman
I've seen images of this and for me with OCD, for some reason, are really pleasant. I think there's a Subreddit called Oddly Satisfying.

Matthew MacDougall
Yeah, love that Subreddit.

Lex Fridman
It's oddly satisfying to see the different target sites avoiding the blood vessels and also maximizing the usefulness of those locations for the signal. It just feels good. It's like, ah.

Matthew MacDougall
As a person who has a visceral reaction to the brain bleeding, I can tell you it's extremely satisfying watching the electrodes themselves go into the brain and not cause bleeding.

Lex Fridman
Yeah. Yeah. So you said the feeling was of relief when everything went perfectly?

Matthew MacDougall
Yeah.

Lex Fridman
How deep in the brain can you currently go and eventually go, let's say on the Neuralink side. It seems the deeper you go in the brain, the more challenging it becomes.

Matthew MacDougall
Yeah. So talking broadly about neurosurgery, we can get anywhere. It's routine for me to put deep brain stimulating electrodes near the very bottom of the brain, entering from the top and passing about a two millimeter wire all the way into the bottom of the brain. And that's

not revolutionary, a lot of people do that, and we can do that with very high precision. I use a robot from Globus to do that surgery several times a month. It's pretty routine.

Lex Fridman
What are your eyes in that situation? What are you seeing? What kind of technology can you use to visualize where you are to light your way?

Matthew MacDougall
Yeah, so it's a cool process on the software side. You take a preoperative MRI that's extremely high resolution, data of the entire brain, you put the patient to sleep, put their head in a frame that holds the skull very rigidly, and then you take a CT scan of their head while they're asleep with that frame on and then merge the MRI and the CT in software. You have a plan based on the MRI where you can see these nuclei deep in the brain. You can't see them on CT, but if you trust the merging of the two images, then you indirectly know on the CT where that is, and therefore indirectly know where in reference to the titanium frame screwed to their head those targets are. And so this is sixties technology to manually compute trajectories given the entry point and target and dial in some goofy looking titanium manual actuators with little tick marks on them. The modern version of that is to use a robot. Just like a little Kuka arm you might see building cars at the Tesla factory, this small robot arm can show you the trajectory that you intended from the pre-op MRI and establish a very rigid holder through which you can drill a small hole in the skull and pass a small rigid wire deep into that area of the brain that's hollow, and put your electrode through that hollow wire and then remove all of that except the electrode. So you end up with the electrode very, very precisely placed far from the skull surface. Now, that's standard technology that's already been out in the world for a while. Neuralink right now is focused entirely on cortical targets, surface targets because there's no trivial way to get, say, hundreds of wires deep inside the brain without doing a lot of damage. So your question, what do you see? Well, I see an MRI on a screen. I can't see everything that DBS electrode is passing through on its way to that deep target. And so it's accepted with this approach that there's going to be about one in a hundred patients who have a bleed somewhere in the brain as a result of passing that wire blindly into the deep part of the brain. That's not an acceptable safety profile for Neuralink. We start from the position that we want this to be dramatically maybe two or three orders of magnitude safer than that, safe enough, really, that you or I, without a profound medical problem, might on our lunch break someday say, "Yeah, sure, I'll get that. I'd been meaning to upgrade to the latest version." And so the safety constraints given that are high, and so we haven't settled on a final solution for arbitrarily approaching deep targets in the brain.

Lex Fridman
It's interesting because you have to avoid blood vessels somehow, and you have to - maybe there's creative ways of doing the same thing, like mapping out high resolution geometry of

blood vessels, and then you can go in blind, but how do you map out that in a way that's super stable? There's a lot of interesting challenges there, right?

Matthew MacDougall
Yeah.

Lex Fridman
But there's a lot to do on the surface.

Matthew MacDougall
Exactly. So we've got vision on the surface. We actually have made a huge amount of progress sewing electrodes into the spinal cord as a potential workaround for a spinal cord injury that would allow a brain mounted implant to translate motor intentions to a spine mounted implant that can affect muscle contractions in previously paralyzed arms and legs.

Lex Fridman
That's mind blowing. That's just incredible. So the effort there is to try to bridge the brain to the spinal cord to the peripheral in your nervous - so how hard is that to do?

Matthew MacDougall
We have that working in very crude forms in animals.

Lex Fridman
That's amazing.

Matthew MacDougall
Yeah, we've done -

Lex Fridman
So similar to with Noland where he's able to digitally move the cursor. Here you're doing the same kind of communication, but with the effectors that you have.

Matthew MacDougall
Yeah.

Lex Fridman
That's fascinating.

Matthew MacDougall
So, we have anesthetized animals doing grasp and moving their legs in a sort of walking pattern. Again, early days, but the future is bright for this kind of thing, and people with paralysis should look forward to that bright future. They're going to have options.

Lex Fridman
And there's a lot of sort of intermediate or extra options where you take an optimist robot like the arm, and to be able to control the arm, the fingers and hands of the arm as a prosthetic.

Matthew MacDougall
Exoskeletons are getting better too.

Lex Fridman
Exoskeletons. So that goes hand in hand. Although I didn't quite understand until thinking about it deeply and doing more research about Neuralink how much you can do on the digital side. So this digital telepathy. I didn't quite understand that you can really map the intention, as you described in the hand knob area, that you can map the intention. Just imagine it. Think about it. That intention can be mapped to actual action in the digital world, and now more and more, so much can be done in the digital world that it can reconnect you to the outside world. It can allow you to have freedom, have independence if you're a quadriplegic. That's really powerful. You can go really far with that.

Matthew MacDougall
Yeah, our first participant is - he's incredible. He's breaking world records left and right.

Lex Fridman
And he's having fun with it. It's great. Just going back to the surgery. Your whole journey, you mentioned to me offline you have surgery on Monday, so like you're doing surgery all the time. Yeah. Maybe the ridiculous question, what does it take to get good at surgery?

Matthew MacDougall
Practice, repetitions. Same with anything else. There's a million ways of people saying the same thing and selling books saying it, but you call it 10,000 hours, you call it spend some chunk of your life, some percentage of your life focusing on this, obsessing about getting better at it. Repetitions, humility, recognizing that you aren't perfect at any stage along the way, recognizing you've got improvements to make in your technique, being open to feedback and coaching from people with a different perspective on how to do it, and then just the constant will to do better. That, fortunately, if you're not a sociopath, I think your patients bring that with them to the office visits every day. They force you to want to do better all the time.

Lex Fridman
Yeah, just step up. I mean, it's a real human being, a real human being that you can help.

Matthew MacDougall
Yeah.

Lex Fridman
So every surgery, even if it's the same exact surgery, is there a lot of variability between that surgery in a different person?

Matthew MacDougall
Yeah. A fair bit. A good example for us is the angle of the skull relative to the normal plane of the body axis of the skull over hand knob is pretty wide variation. Some people have really flat skulls and some people have really steeply angled skulls over that area, and that has consequences for how their head can be fixed in sort of the frame that we use and how the robot has to approach the skull. Yeah, people's bodies are built as differently as the people you see walking down the street, as much variability and body shape and size as you see there. We see in brain anatomy and skull anatomy, there are some people who we've had to exclude from our trial for having skulls that are too thick or too thin or scalp that's too thick or too thin. I think we have the middle 97% or so of people, but you can't account for all human anatomy variability.

Lex Fridman
How much mushiness and mess is there? Because taking biology classes, the diagrams are always really clean and crisp. Neuroscience, the pictures of neurons are always really nice and very - but whenever I look at pictures of like real brains, they're all - I don't know what is going on.

Matthew MacDougall
Yeah.

Lex Fridman
So, how much our biological systems, in reality - like how hard is it to figure out what's going on?

Matthew MacDougall
Not too bad. Once you really get used to this, that's where experience and skill and education really come into play is if you stare at a thousand brains, it becomes easier to kind of mentally peel back the, say, for instance, blood vessels that are obscuring the sulci and gyri, know kind of the wrinkle pattern of the surface of the brain. Occasionally when you're first starting to do this and you open the skull, it doesn't match what you thought you were going to see based on the MRI. And with more experience, you learn to kind of peel

back that layer of blood vessels and see the underlying pattern of wrinkles in the brain and use that as a landmark for where you are.

Lex Fridman
The wrinkles are a landmark?

Matthew MacDougall
Yeah. So, I was describing hand knob earlier. That's a pattern of the wrinkles in the brain. It's sort of this Greek letter, omega shaped area of the brain.

Lex Fridman
So, you could recognize the hand knob area. If I show you a thousand brains and give you one minute with each, you'd be like, "Yup, that's that."

Matthew MacDougall
Sure.

Lex Fridman
And so there is some uniqueness to that area of the brain in terms of the geometry, the topology of the thing.

Matthew MacDougall
Yeah.

Lex Fridman
Where is it about in the -

Matthew MacDougall
So, you have this strip of brain running down the top called the primary motor area, and I'm sure you've seen this picture of the homunculus laid over the surface of the brain, the weird little guy with huge lips and giant hands. That guy sort of lays with his legs up at the top of the brain and face arm areas farther down, and then some kind of mouth, lip, tongue areas farther down. And so the hand is right in there, and then the areas that control speech, at least on the left side of the brain in most people are just below that. And so any muscle that you voluntarily move in your body, the vast majority of that references that strip or those intentions come from that strip of brain, and the wrinkle for hand knob is right in the middle of that.

Lex Fridman
And vision is back here?

Matthew MacDougall
Yup.

Lex Fridman
Also close to the surface.

Matthew MacDougall
Vision's a little deeper. And so this gets to your question about how deep can you get. To do vision, we can't just do the surface of the brain. We have to be able to go in, not as deep as we'd have to go for DBS, but maybe a centimeter deeper than we're used to for hand insertions. And so that's work in progress. That's a new set of challenges to overcome.

Lex Fridman
By the way, you mentioned the Utah Array and I just saw a picture of that and that thing looks terrifying.

Matthew MacDougall
Yeah. The nails.

Lex Fridman
It's because it's rigid and then if you look at the threads, they're flexible. What can you say that's interesting to you about that kind of approach of the flexible threads to deliver the electrodes next to the neurons?

Matthew MacDougall
Yeah. I mean, the goal there comes from experience. I mean, we stand on the shoulders of people that made Utah Arrays and used Utah Arrays for decades before we ever even came along. Neuralink arose, partly this approach to technology arose out of a need recognized after Utah Arrays would fail routinely because the rigid electrodes, those spikes that are literally hammered using an air hammer into the brain, those spikes generate a bad immune response that encapsulates the electrode spikes in scar tissue essentially. And so one of the projects that was being worked on in the Anderson Lab at Caltech when I got there was to see if you could use chemotherapy to prevent the formation of scars. Things are pretty bad when you're jamming a bed of nails into the brain, and then treating that with chemotherapy to try to prevent scar tissue, it's like, maybe we've gotten off track here, guys. Maybe there's a fundamental redesign necessary. And so Neuralink's approach of using highly flexible, tiny electrodes avoids a lot of the bleeding, avoids a lot of the immune response that ends up happening when rigid electrodes are pounded into the brain. And so what we see is our electrode longevity and functionality and the health of the brain tissue immediately surrounding the electrode is excellent. I mean, it goes on for years now in our animal models.

Lex Fridman
What do most people not understand about the biology of the brain? We will mention the vasculature. That's really interesting.

Matthew MacDougall
I think the most interesting maybe underappreciated fact is that it really does control almost everything. I don't know, for an out of the blue example, imagine you want a lever on fertility. You want to be able to turn fertility on and off. There are legitimate targets in the brain itself to modulate fertility, say blood pressure. You want to modulate blood pressure, there are legitimate targets in the brain for doing that. Things that aren't immediately obvious as brain problems are potentially solvable in the brain. And so I think it's an under-explored area for primary treatments of all the things that bother people.

Lex Fridman
That's a really fascinating way to look at it. There's a lot of conditions we might think have nothing to do with the brain, but they might just be symptoms of something that actually started in the brain. The actual source of the problem, the primary source is something in the brain.

Matthew MacDougall
Yeah. Not always. I mean, kidney disease is real, but there are levers you can pull in the brain that affect all of these systems.

Lex Fridman
There's knobs.

Matthew MacDougall
Yeah.

Lex Fridman
On-off switches and knobs in the brain from which this all originates. Would you have a Neuralink chip implanted in your brain?

Matthew MacDougall
Yeah. I think use case right now is use a mouse, right? I can already do that, and so there's no value proposition. On safety grounds alone, sure. I'll do it tomorrow.

Lex Fridman
You know, when you say the use case of the mouse, is it -

Lex Fridman
The use case of the mouse is after researching all this and part of it's just watching Nolan have so much fun. If you can get that bits per second look really high with the mouse, being able to interact, because if you think about the way on the smartphone, the way you swipe, that was transformational. How we interact with the thing, it's subtle, you don't realize it, but to be able to touch a phone and to scroll with your finger, that changed everything. People were sure you need a keyboard to type. There's a lot of HCI aspects to that that changed how we interact with computers, so there could be a certain rate of speed with the mouse that would change everything. You might be able to just click around a screen extremely fast. I can't see myself getting a Neuralink for much more rapid interaction with the digital devices.

Matthew MacDougall
Yeah, I think recording speech intentions from the brain might change things as well, the value proposition for the average person. A keyboard is a pretty clunky human interface, requires a lot of training. It's highly variable in the maximum performance that the average person can achieve. I think taking that out of the equation and just having a natural word to computer interface might change things for a lot of people.

Lex Fridman
It'd be hilarious if that is the reason people do it. Even if you have speech to text, that's extremely accurate. It currently isn't, but it'd say you've gotten super accurate. It'd be hilarious if people went for Neuralink. Just so you avoid the embarrassing aspect of speaking, looking like a douchebag speaking to your phone in public, which is a real, that's a real constraint.

Matthew MacDougall
I mean with a bone conducting case, that can be an invisible headphone, say, and the ability to think words into software and have it respond to you. That starts to sound sort of like embedded super intelligence. If you can silently ask for the Wikipedia article on any subject and have it read to you without any observable change happening in the outside world. For one thing, standardized testing is obsolete.

Lex Fridman
If it's done well in the UX side, it could change, I don't know if it transforms society, but it really can create a kind of shift in the way we interact with digital devices in the way that a smartphone did. Just having to look into the safety of everything involved, I would totally try it. So it doesn't have to go to some incredible thing where you have, it connects your vision or to some other, it connects all over your brain. That could be just connecting to the hand knob. You might have a lot of interesting interaction, human computer interaction possibilities. That's really interesting.

Matthew MacDougall
And the technology on the academic side is progressing at light speed here. There was a really amazing paper out of UC Davis at Sergey Stavisky's lab that basically made an initial solve of speech decode. It was something like 125,000 words that they were getting with very high accuracy, which is-

Lex Fridman
So, you're just thinking the word?

Matthew MacDougall
Yeah.

Lex Fridman
Thinking the word and you're able to get it?

Matthew MacDougall
Yeah.

Lex Fridman
Oh, boy. You have to have the intention of speaking it. So do the inner voice. Man, it's so amazing to me that you can do the intention, the signal mapping. All you have to do is just imagine yourself doing it. And if you get the feedback that it actually worked, you can get really good at that. Your brain will first of all adjust and you develop, like any other skill, like touch typing. You develop in that same kind of way. To me, it's just really fascinating to be able to even to play with that, honestly, I would get a Neuralink just to be able to play with that, just to play with the capacity, the capability of my mind to learn this skill. It's like learning the skill of typing and learning the skill of moving a mouse. It's another skill of moving the mouse, not with my physical body, but with my mind.

Matthew MacDougall
I can't wait to see what people do with it. I feel like we're cavemen right now. We're banging rocks with a stick and thinking that we're making music. At some point when these are more widespread, there's going to be the equivalent of a piano that someone can make art with their brain in a way that we didn't even anticipate. Looking forward to it.

Lex Fridman
Give it to a teenager. Anytime I think I'm good at something I'll always go to - I don't know. Even with the bits per second and playing a video game, you realize you give it to a teenager, you give a Neuralink to a teenager. Just a large number of them, the kind of stuff they get good at stuff, they're going to get hundreds of bits per second. Even just with the current technology.

Matthew MacDougall
Probably. Probably.

Lex Fridman
Because it's also addicting, the number go up aspect of it of improving and training. It is almost like a skill and plus there's the software on the other end that adapts to you, and especially if the adapting procedure algorithm becomes better and better and better. You're like learning together.

Matthew MacDougall
Yeah, we're scratching the surface on that right now. There's so much more to do.

Lex Fridman
So on the complete other side of it, you have an RFID chip implanted in you?

Matthew MacDougall
Yeah.

Lex Fridman
So I hear.

Matthew MacDougall
Nice.

Lex Fridman
So this is -

Matthew MacDougall
Little subtle thing.

Lex Fridman
It's a passive device that you use for unlocking a safe with top secrets or what do you use it for? What's the story behind it?

Matthew MacDougall
I'm not the first one. There's this whole community of weirdo biohackers that have done this stuff, and I think one of the early use cases was storing private crypto wallet keys and whatever. I dabbled in that a bit and had some fun with it.

Lex Fridman
You have some Bitcoin implanted in your body somewhere. You can't tell where. Yeah, yeah.

Matthew MacDougall
Actually, yeah. It was the modern day equivalent of finding change in the sofa cushions after I put some orphaned crypto on there that I thought was worthless and forgot about it for a few years. Went back and found that some community of people loved it and had propped up the value of it, and so it had gone up fifty-fold, so there was a lot of change in those cushions.

Lex Fridman
That's hilarious.

Matthew MacDougall
But the primary use case is mostly as a tech demonstrator. It has my business card on it. You can scan that in by touching it to your phone. It opens the front door to my house, whatever, simple stuff.

Lex Fridman
It's a cool step. It's a cool leap to implant something in your body. I mean, perhaps it's a similar leap to a Neuralink because for a lot of people, that kind of notion of putting something inside your body, something electronic inside a biological system is a big leap.

Matthew MacDougall
We have a kind of mysticism around the barrier of our skin. We're completely fine with knee replacements, hip replacements, dental implants, but there's a mysticism still around the inviolable barrier that the skull represents, and I think that needs to be treated like any other pragmatic barrier. The question isn't how incredible is it to open the skull? The question is what benefit can we provide?

Lex Fridman
So, from all the surgeries you've done, from everything you understand the brain, how much does neuroplasticity come into play? How adaptable is the brain? For example, just even in the case of healing from surgery or adapting to the post-surgery situation.

Matthew MacDougall
The answer that is sad for me and other people of my demographic is that plasticity decreases with age. Healing decreases with age. I have too much gray hair to be optimistic about that. There are theoretical ways to increase plasticity using electrical stimulation. Nothing that is totally proven out as a robust enough mechanism to offer widely to people. But yeah, I think there's cause for optimism that we might find something useful in terms of say, an implanted electrode that improves learning. Certainly there's been some really amazing work recently from Nicholas Schiff, Jonathan Baker and others who have a cohort of patients with moderate traumatic brain injury who have had electrodes placed in the deep nucleus in the brain called the central median nucleus or just near central median

nucleus, and when they apply small amounts of electricity to that part of the brain, it's almost like electronic caffeine. They're able to improve people's attention and focus. They're able to improve how well people can perform a task. I think in one case, someone who was unable to work, after the device was turned on, they were able to get a job. And that's sort of one of the holy grails for me with Neuralink and other technologies like this is from a purely utilitarian standpoint, can we make people able to take care of themselves and their families economically again? Can we make it so someone who's fully dependent and even maybe requires a lot of caregiver resources, can we put them in a position to be fully independent, taking care of themselves, giving back to their communities? I think that's a very compelling proposition and what motivates a lot of what I do and what a lot of the people at Neuralink are working for.

Lex Fridman
It's just a cool possibility that if you put a Neuralink in there, that the brain adapts the other part of the brain adapts too and integrates it. The capacity of the brain to do that is really interesting. Probably unknown to the degree to which you can do that, but you're now connecting an external thing to it, especially once it's doing stimulation. The biological brain and the electronic brain outside of it working together, the possibilities there are really interesting. It's still unknown, but interesting. It feels like the brain is really good at adapting to whatever, but of course it is a system that by itself is already, everything serves a purpose and so you don't want to mess with it too much.

Matthew MacDougall
Yeah, it's like eliminating a species from an ecology. You don't know what the delicate interconnections and dependencies are. The brain is certainly a delicate, complex beast, and we don't know every potential downstream consequence of a single change that we make.

Lex Fridman
Do you see yourself doing, so you mentioned P1, surgeries of P2, P3, P4, P5? Just more and more and more humans.

Matthew MacDougall
I think it's a certain kind of brittleness or a failure on the company's side if we need me to do all the surgeries. I think something that I would very much like to work towards is a process that is so simple and so robust on the surgery side that literally anyone could do it. We want to get away from requiring intense expertise or intense experience to have this done and make it as simple and translatable as possible. I mean, I would love it if every neurosurgeon on the planet had no problem doing this. I think we're probably far from a regulatory environment that would allow people that aren't neurosurgeons to do this, but not impossible.

Lex Fridman
Alright, I'll sign up for that. Did you ever anthropomorphize the robot R1? Do you give it a name? Do you see it as a friend as working together with you?

Matthew MacDougall
I mean, to a certain degree it's -

Lex Fridman
Or an enemy who's going to take your job?

Matthew MacDougall
To a certain degree, yeah. It's complex relationship.

Lex Fridman
All the good relationships are.

Matthew MacDougall
It's funny when in the middle of the surgery, there's a part of it where I stand basically shoulder to shoulder with the robot, and so if you're in the room reading the body language, it's my brother in arms there. We're working together on the same problem. Yeah, I'm not threatened by it.

Lex Fridman
Keep telling yourself that. How have all the surgeries that you've done over the years, the people you've helped and the stakes, the high stakes that you've mentioned, how has that changed your understanding of life and death?

Matthew MacDougall
Yeah, it gives you a very visceral sense, and this may sound trite, but it gives you a very visceral sense that death is inevitable. On one hand, as a neurosurgeon, you're deeply involved in these, just hard to fathom tragedies, young parents dying, leaving a four-year-old behind, say. And on the other hand, it takes the sting out of it a bit because you see how just mind-numbingly universal death is. There's zero chance that I'm going to avoid it. I know techno-optimists right now and longevity buffs right now would disagree on that 0.000% estimate, but I don't see any chance that our generation is going to avoid it. Entropy is a powerful force and we are very ornate, delicate, brittle, DNA machines that aren't up to the cosmic ray bombardment that we're subjected to. So on the one hand, every human that has ever lived died or will die. On the other hand, it's just one of the hardest things to imagine inflicting on anyone that you love is having them gone. I mean, I'm sure you've had friends that aren't living anymore and it's hard to even think about them. And so I wish I had arrived at the point of nirvana where death doesn't have a sting, I'm not worried about it. But I can at least say that I'm comfortable with the certainty of it, if not having

found out how to take the tragedy out of it. When I think about my kids either not having me or me not having them or my wife.

Lex Fridman
Maybe I've come to accept the intellectual certainty of it, but it may be the pain that comes with losing the people you love. But I don't think I've come to understand the existential aspect of it, that this is going to end, and I don't mean in some trite way. I mean, it certainly feels like it's not going to end. You live life like it's not going to end. And the fact that this light that's shining, this consciousness is going to no longer be in one moment, maybe today. It fills me when I really am able to load all that in with Ernest Becker's terror. It is a real fear. I think people aren't always honest with how terrifying it is. I think the more you are able to really think through it, the more terrifying it is. It's not such a simple thing, "Oh, well, it's the way life is." If you really can load that in, it's hard, but I think that's why the Stoics did it, because it helps you get your shit together and be like, "The moment, every single moment you're alive is just beautiful" and it's terrifying that it's going to end, and it's almost like you're shivering in the cold, a child helpless. This kind of feeling, And then it makes you, when you have warmth, when you have the safety, when you have the love to really appreciate it. I feel like sometimes in your position when you mentioned armor just to see death, it might make you not be able to see that, the finiteness of life because if you kept looking at that, it might break you. So it is good to know that you're kind of still struggling with that. There's the neurosurgeon and then there's a human, and the human is still able to struggle with that and feel the fear of that and the pain of that.

Matthew MacDougall
Yeah, it definitely makes you ask the question of how many of these can you see and not say, "I can't do this anymore"? But I mean you said it well, I think it gives you an opportunity to just appreciate that you're alive today and I've got three kids and an amazing wife, and I am really happy. Things are good. I get to help on a project that I think matters. I think it moves us forward. I'm a very lucky person.

Lex Fridman
It's the early steps of a potentially gigantic leap for humanity. It's a really interesting one. And it's cool because you read about all this stuff in history where it's like the early days. I've been reading, before going to the Amazon, I would read about explorers that would go and explore even the Amazon jungle for the first time. It's just those are the early steps or early steps into space, early steps in any discipline in physics and mathematics, and it's cool because on the grand scale, these are the early steps into delving deep into the human brain, so not just observing the brain but be able to interact with the human brain. It's going to help a lot of people, but it also might help us understand what the hell's going on in there.

Matthew MacDougall
Yeah. I think ultimately we want to give people more levers that they can pull. You want to give people options. If you can give someone a dial that they can turn on how happy they are, I think that makes people really uncomfortable. But now talk about major depressive disorder. Talk about people that are committing suicide at an alarming rate in this country, and try to justify that queasiness in that light of, you can give people a knob to take away suicidal ideation, suicidal intention. I would give them that knob. I don't know how you justify not doing that.

Lex Fridman
You can think about all the suffering that's going on in the world, every single human being that's suffering right now. It'll be a glowing red dot. The more suffering, the more it's glowing, and you just see the map of human suffering and any technology that allows you to dim that light of suffering on a grand scale is pretty exciting. Because there's a lot of people suffering and most of them suffer quietly, and we look away too often, and we should remember those are suffering because once again, most of them are suffering quietly.

Matthew MacDougall
Well, and on a grander scale, the fabric of society. People have a lot of complaints about how our social fabric is working or not working, how our politics is working or not working. Those things are made of neurochemistry too in aggregate, right? Our politics is composed of individuals with human brains, and the way it works or doesn't work is potentially tunable in the sense that, I don't know, say remove our addictive behaviors or tune our addictive behaviors for social media or our addiction to outrage, our addiction to sharing the most angry political tweet we can find. I don't think that leads to a functional society, and if you had options for people to moderate that maladaptive behavior, there could be huge benefits to society. Maybe we could all work together a little more harmoniously toward useful ends.

Lex Fridman
There's a sweet spot, like you mentioned. You don't want to completely remove all the dark sides of human nature. Those are somehow necessary to make the whole thing work, but there's a sweet spot.

Matthew MacDougall
Yeah, I agree. You got to suffer a little, just not so much that you lose hope.

Lex Fridman
Yeah. When you, all the surgeries you've done, have you seen consciousness in there ever? Was there a glowing light?

Matthew MacDougall
I have this sense that I never found it, never removed it like a Dementor in Harry Potter. I have this sense that consciousness is a lot less magical than our instincts want to claim it is. It seems to me like a useful analog for about what consciousness is in the brain is that we have a really good intuitive understanding of what it means to say, touch your skin and know what's being touched. And I think consciousness is just that level of sensory mapping applied to the thought processes in the brain itself. So what I'm saying is, consciousness is the sensation of some part of your brain being active, so you feel it working. You feel the part of your brain that thinks of red things or winged creatures or the taste of coffee. You feel those parts of your brain being active, the way that I'm feeling my palm being touched, and that sensory system that feels the brain working is consciousness.

Lex Fridman
That's so brilliant. It's the same way. It's the sensation of touch when you're touching a thing. Consciousness is the sensation of you feeling your brain working, your brain thinking, your brain perceiving.

Matthew MacDougall
Which isn't like a warping of space-time or some quantum field effect, right? It's nothing magical. People always want to ascribe to consciousness something truly different, and there's this awesome long history of people looking at whatever the latest discovery in physics is to explain consciousness because it's the most magical, the most out there thing that you can think of, and people always want to do that with consciousness. I don't think that's necessary. It's just a very useful and gratifying way of feeling your brain work.

Lex Fridman
And as we said, it's one heck of a brain. Everything we see around us, everything we love, everything that's beautiful came from brains like these.

Matthew MacDougall
It's all electrical activity happening inside your skull.

Lex Fridman
And I, for one, am grateful there's people like you that are exploring all the ways that it works and all the ways it can be made better.

Matthew MacDougall
Thanks, Lex.

Lex Fridman
Thank you so much for talking today.

Matthew MacDougall
It's been a joy.

Lex Fridman
Thanks for listening to this conversation with Matthew MacDougall. Now, dear friends, here's Bliss Chapman, brain interface software lead at Neuralink. You told me that you've met hundreds of people with spinal cord injuries or with ALS, and that your motivation for helping at Neuralink is grounded in wanting to help them. Can you describe this motivation?

Bliss Chapman
Yeah. First, just a thank you to all the people I've gotten a chance to speak with for sharing their stories with me. I don't think there's any world really in which I can share their stories as powerful way as they can, but just I think to summarize at a very high level, what I hear over and over again is that people with ALS or severe spinal cord injury in a place where they basically can't move physically anymore, really at the end of the day are looking for independence. And that can mean different things for different people. For some folks, it can mean the ability just to be able to communicate again independently without needing to wear something on their face, without needing a caretaker to be able to put something in their mouth. For some folks, it can mean independence to be able to work again, to be able to navigate a computer digitally, efficiently enough to be able to get a job, to be able to support themselves, to be able to move out and ultimately be able to support themselves after their family maybe isn't there anymore to take care of them. And for some folks, it's as simple as just being able to respond to their kid in time before they run away or get interested in something else. And these are deeply personal and very human problems. And what strikes me again and again when talking with these folks is that this is actually an engineering problem. This is a problem that with the right resources, with the right team, can make a lot of progress on. And at the end of the day, I think that's a deeply inspiring message and something that makes me excited to get up every day.

Lex Fridman
So it's both an engineering problem in terms of a BCI, for example, that can give them capabilities where they can interact with the world, but also on the other side, it's an engineering problem for the rest of the world to make it more accessible for people living with quadriplegia?

Bliss Chapman
Yeah. And actually, I'll take a broad view lens on this for a second. I think I'm very in favor of anyone working in this problem space. So beyond BCI, I'm happy and excited and willing to support any way I can, folks working on eye tracking systems, working on speech to text systems, working on head trackers or mouse sticks or quad sticks. And I've met many engineers and folks in the community that do exactly those things. And I think for the people we're trying to help, it doesn't matter what the complexity of the solution is as long

as the problem is solved. And I want to emphasize that there can be many solutions out there that can help with these problems. And BCI is one of a collection of such solutions. So BCI in particular, I think offers several advantages here. And I think the folks that recognize this immediately are usually the people who have spinal cord injury or some form of paralysis. Usually you don't have to explain to them why this might be something that could be helpful. It's usually pretty self-evident, but for the rest of us folks that don't live with severe spinal cord injury or who don't know somebody with ALS, it's not often obvious why you would want a brain implant to be able to connect and navigate a computer. And it's surprisingly nuanced, and to the degree that I've learned a huge amount just working with Noland in the first Neuralink clinical trial and understanding from him and his words why this device is impactful for him, and it's a nuanced topic. It can be the case that even if you can achieve the same thing, for example, with a mouse stick when navigating a computer, he doesn't have access to that mouse stick every single minute of the day. He only has access when someone is available to put it in front of him. And so a BCI can really offer a level of independence and autonomy that, if it wasn't literally physically part of your body, it'd be hard to achieve in any other way.

Lex Fridman
So there's a lot of fascinating aspects to what it takes to get Noland to be able to control a cursor on the screen with his mind. You texted me something that I just love. You said, "I was part of the team that interviewed and selected P1, I was in the operating room during the first human surgery monitoring live signals coming out of the brain. I work with the user basically every day to develop new UX paradigms, decoding strategies, and I was part of the team that figured out how to recover useful BCI to new world record levels when the signal quality degraded." We'll talk about, I think every aspect of that, but just zooming out, what was it like to be a part of that team and part of that historic, I would say, historic first?

Bliss Chapman
Yeah. I think for me, this is something I've been excited about for close to 10 years now. And so to be able to be even just some small part of making it a reality is extremely exciting. A couple maybe special moments during that whole process that I'll never really truly forget. One of them is entering the actual surgery. At that point in time, I know Noland quite well. I know his family. And so I think the initial reaction when Noland is rolled into the operating room is just an "Oh, shit" kind of reaction. But at that point, muscle memory kicks in and you sort of go into, you let your body just do all the talking. And I have the lucky job in that particular procedure to just be in charge of monitoring the implant. So my job is to sit there, to look at the signals coming off the implant, to look at the live brain data streaming off the device as threads are being inserted into the brain and just to basically observe and make sure that nothing is going wrong or that there's no red flags or fault conditions that we need to go and investigate or pause the surgery to debug. And because I had that sort of spectator view of the surgery, I had a slightly removed perspective than I think most folks in the room. I got to sit there and think to myself, "Wow, that brain is moving a lot." When you

look inside the craniectomy that we stick the threads in, one thing that most people don't realize is the brain moves. The brain moves a lot when you breathe, your heart beats, and you can see it visibly. So that's something that I think was a surprise to me and very, very exciting to be able to see someone's brain who you physically know and have talked with that length, actually pausing and moving inside their skull.

Lex Fridman
And they used that brain to talk to you previously, and now it's right there moving.

Bliss Chapman
Yup.

Lex Fridman
Actually, I didn't realize that in terms of the thread sending, so the Neuralink implant is active during surgery and one thread at a time, you're able to start seeing the signal?

Bliss Chapman
Yeah.

Lex Fridman
So, that's part of the way you test that the thing is working?

Bliss Chapman
Yeah. So actually in the operating room, right after we sort of finished all the thread insertions, I started collecting what's called broadband data. So broadband is basically the most raw form of signal you can collect from a Neuralink electrode. It's essentially a measurement of the local fuel potential or the voltage essentially measured by that electrode. And we have a certain mode in our application that allows us to visualize where detected spikes are. So it visualizes where in the broadband signal and it's very, very raw form of the data, a neuron is actually spiking. And so one of these moments that I'll never forget as part of this whole clinical trial is seeing live in the operating room while he's still under anesthesia, beautiful spikes being shown in the application, just streaming live to a device I'm holding in my hand.

Lex Fridman
So this is no signal processing the raw data, and then the signals processing is on top of it, you're seeing the spikes detected?

Bliss Chapman
Right.

Lex Fridman
And that's a UX too, that looks beautiful as well.

Bliss Chapman
During that procedure, there was actually a lot of cameramen in the room, so they also were curious and wanted to see, there's several neurosurgeons in the room who were all just excited to see robots taking their job, and they were all crowded around a small little iPhone watching this live brain data stream out of his brain.

Lex Fridman
What was that like seeing the robot do some of the surgery? So the computer vision aspect where it detects all the spots that avoid the blood vessels, and then obviously with the human supervision, then actually doing the really high precision connection of the threads to the brain?

Bliss Chapman
That's a good question. My answer is going to be pretty lame here, but it was boring. I've seen it so many times.

Lex Fridman
The way you want it to be.

Bliss Chapman
Yeah, that's exactly how you want surgery to be. You want it to be boring. I've seen it so many times. I've seen the robot do the surgery literally hundreds of times, and so it was just one more time.

Lex Fridman
Yeah, all the practice surgeries and the proxies, and this is just another day.

Bliss Chapman
Yeah.

Lex Fridman
So what about when Noland woke up? Do you remember a moment where he was able to move the cursor, not move the cursor, but get signal from the brain such that it was able to show that there's a connection?

Bliss Chapman
Yeah. Yeah. So we are quite excited to move as quickly as we can, and Noland was really, really excited to get started. He wanted to get started, actually the day of surgery, but we waited until the next morning very patiently. It's a long night - we waited until the next

morning very patiently. So a long night. And the next morning in the ICU where he was recovering, he wanted to get started and actually start to understand what kind of signal we can measure from his brain. And maybe for folks who are not familiar with the Neuralink system, we implant the Neuralink system or the Neuralink implant in the motor cortex. So the motor cortex is responsible for representing things like motor intent. If you imagine closing and opening your hand, that kind of signal representation would be present in the motor cortex. If you imagine moving your arm back and forth or wiggling a pinky, this sort of signal can be present in the motor cortex. So one of the ways we start to map out what kind of signal do we actually have access to, in any particular individual's brain, is through this task called body mapping. And body mapping is where you essentially present a visual to the user and you say, "Hey, imagine doing this," and their visual is a 3D hand opening, closing or index finger modulating up and down. And you ask the user to imagine that, and obviously you can't see them do this, because they're paralyzed, so you can't see them actually move their arm. But while they do this task, you can record neural activity and you can basically offline model and check, "Can I predict, or can I detect the modulation corresponding with those different actions?" And so we did that task and we realized, "Hey, there's actually some modulation associated with some of his hand motion," which was a first indication that, "okay, we can potentially use that modulation to do useful things in the world." For example, control a computer cursor. And he started playing with it, the first time we showed him it. And we actually just took the same live view of his brain activity and put it in front of him and we said, "Hey, you tell us what's going on? We're not you. You're able to imagine different things, and we know that it's modulating some of these neurons, so you figure out for us, what that is actually representing." And so he played with it for a bit. He was like, "I don't quite get it yet." He played for a bit longer and he said, "Oh, when I move this finger, I see this particular neuron start to fire more." And I said, "Okay, prove it. Do it again." And so he said, "Okay, three, two, one," boom. And the minute he moved, you can see instantaneously this neuron is firing, single neuron. I can tell you the exact channel number if you're interested. It's stuck in my brain now forever. But that single channel firing was a beautiful indication that it was behaved really modulated, neural activity, that could then be used for downstreaming tasks, like decoding a computer cursor.

Lex Fridman
And when you say single channel, is that associated with a single electrode?

Bliss Chapman
Yeah. Channel and electrode are interchangeable.

Lex Fridman
And there's a 1,024 of those?

Bliss Chapman
1,024. Yeah.

Lex Fridman
That's incredible that, that works. When I was learning about all this and loading it in, it was just blowing my mind that the intention, you can visualize yourself moving the finger. That can turn into a signal, and the fact that you can then skip that step and visualize the cursor moving, or have the intention of the cursor moving. And that leading to a signal that can then be used to move the cursor? There is so many exciting things there to learn about the brain, about the way the brain works, the very fact of there existing signal that can be used, is really powerful.

Bliss Chapman
Yup.

Lex Fridman
But it feels like that's just the beginning of figuring out how that signal could be used really, really effectively? I should also just, there's so many fascinating details here, but you mentioned the body mapping step. At least in the version I saw, that Noland was showing off, there's a super nice interface, a graphical interface, but it just felt like I was in the future. I guess it visualizes you moving the hand, and there's a very sexy polished interface that, "Hello," I don't know if there's a voice component, but it just felt like when you wake up in a really nice video game, and this is the tutorial at the beginning of that video game. This is what you're supposed to do. It's cool.

Bliss Chapman
No, I mean the future should feel like the future.

Lex Fridman
But it's not easy to pull that off. I mean, it needs to be simple, but not too simple.

Bliss Chapman
Yeah. And I think the UX design component here is underrated for BCI development in general. There's a whole interaction effect between the ways in which you visualize an instruction to the user, and the kinds of signal you can get back. And that quality of your behavioral alignment to the neural signal, is a function of how good you are at expressing to the user what you want them to do. And so yeah, we spend a lot of time thinking about the UX, of how we build our applications, of how the decoder actually functions, the control surfaces it provides to the user. All these little details matter a lot.

Lex Fridman
So maybe it'd be nice to get into a little bit more detail of what the signal looks like, and what the decoding looks like?

Bliss Chapman
Yup.

Lex Fridman
So there's a N1 implant that has, like we mentioned, 1,024 electrodes, and that's collecting raw data, raw signal. What does that signal look like? And what are the different steps along the way before it's transmitted, and what is transmitted? All that kind of stuff.

Bliss Chapman
Yup. This is going to be a fun one.

Lex Fridman
Let's go.

Bliss Chapman
So maybe before diving into what we do, it's worth understanding what we're trying to measure, because that dictates a lot of the requirements for the system that we build. And what we're trying to measure is really individual neurons, producing action potentials. And action potential is, you can think of it like a little electrical impulse that you can detect, if you're close enough. And by being close enough, I mean within let's say 100 microns of that cell. And 100 microns is a very, very tiny distance. And so the number of neurons that you're going to pick up with any given electrode, is just a small radius around that electrode. And the other thing worth understanding about the underlying biology here, is that when neurons produce an action potential, the width of that action potential is about one millisecond. So from the start of the spike, to the end of the spike, that whole width of that characteristic feature, of a neuron firing, is one millisecond wide. And if you want to detect that an individual spike is occurring or not, you need to sample that signal, or sample the local fuel potential nearby that a neuron - much more frequently than once a millisecond. You need to sample many, many times per millisecond, to be able to detect that this is actually the characteristic waveform of a neuron producing an action potential. And so we sample across all 1,024 electrodes, about 20,000 times a second. 20,000 times a second means for any given one millisecond window, we have about 20 samples that tell us what that exact shape of that actual potential looks like. And once we've sort of sampled at super high rate the underlying electrical field nearby these cells, we can process that signal into just where do we detect a spike, or where do we not? Sort of a binary signal, one or zero. Do we detect a spike in this one millisecond or not? And we do that because the actual information carrying subspace of neural activity, is just when our spikes occurring. Essentially everything that we care about for decoding can be captured or represented in the frequency characteristics of spike trains. Meaning, how often are spikes firing in any given window of time. And so that allows us to do sort of a crazy amount of compression, from this very rich high-density signal, to something that's much, much more sparse and

compressible, that can be sent out over a wireless radio. Like a Bluetooth communication for example.

Lex Fridman
Quick tangents here. You mentioned electrode neuron, there's a local neighborhood of neurons nearby. How difficult is it to isolate from where the spike came from?

Bliss Chapman
So there's a whole field of academic neuroscience work on exactly this problem, of basically given a single electrode, or given a set of electrodes measuring a set of neurons. How can you sort, spike sort, which spikes are coming from what neuron? And this is a problem that's pursued in academic work, because you care about it for understanding what's going on in the underlying neuroscience of the brain. If you care about understanding how the brain's representing information, how that's evolving through time, then that's a very, very important question to understand. For the engineering side of things, at least at the current scale, if the number of neurons per electrode is relatively small, you can get away with basically ignoring that problem completely. You can think of it like a random projection of neurons to electrodes, and there may be in some cases more than one neuron per electrode. But if that number is small enough, those signals can be thought of as sort of a union of the two. And for many applications, that's a totally reasonable trade-off to make, and can simplify the problem a lot. And as you sort of scale out channel count, the relevance of distinguishing individual neurons becomes less important. Because you have more overall signal, and you can start to rely on correlations or covariate structure in the data to help understand when that channel is firing - what does that actually represent? Because you know that when that channel's firing in concert with these other 50 channels, that means move left. But when that same channel's firing with concert with these other 10 channels, that means move right.

Lex Fridman
Okay. So you have to do this kind of spike detection onboard, and you have to do that super efficiently? So fast, and not use too much power, because you don't want to be generating too much heat, so it'd have to be a super simple signal processing step?

Bliss Chapman
Yup.

Lex Fridman
Is there some wisdom you can share about what it takes to overcome that challenge?

Bliss Chapman
Yeah. So we've tried many different versions of basically turning this raw signal into a feature that you might want to send off the device. And I'll say that I don't think we're at the

final step of this process, this is a long journey. We have something that works clearly today, but there can be many approaches that we find in the future that are much better than what we do right now. So some versions of what we do right now, and there's a lot of academic heritage to these ideas, so I don't want to claim that these are original Neuralink ideas or anything like that. But one of these ideas is basically to build sort of like a convolutional filter almost, if you will. That slides across the signal and looks for a certain template to be matched. That template consists of how deep the spike modulates, how much it recovers, and what the duration and window of time is for that, the whole process takes. And if you can see in the signal that, that template is matched within certain bounds, then you can say, "Okay, that's a spike." One reason that approach is super convenient, is that you can actually implement that extremely efficiently in hardware. Which means that you can run it in low power across 1,024 channels all at once. Another approach that we've recently started exploring, and this can be combined with the spike detection approach, is something called spike band power. And the benefits of that approach are that you may be able to pick up some signal from neurons that are maybe too far away to be detected as a spike, because the farther away you are from an electrode, the weaker that actual spike waveform will look like on that electrode. So you might be able to pick up population level activity of things that are maybe slightly outside the normal recording radius - what neuroscientists sometimes refer to as the hash of activity, the other stuff that's going on. And you can look at across many channels how that background noise is behaving, and you might be able to get more juice out of the signal that way. But it comes at a cost. That signal is now a floating point representation, which means it's more expensive to send out over a power. It means you have to find different ways to compress it, that are different than what you can apply to binary signals. So there's a lot of different challenges associated with these different modalities.

Lex Fridman
So also in terms of communication, you're limited by the amount of data you can send?

Bliss Chapman
Yeah.

Lex Fridman
And also because you're currently using the Bluetooth protocol, you have to batch stuff together? But you have to also do this, keeping the latency crazy low? Crazy low? Anything to say about the latency?

Bliss Chapman
Yeah. This is a passion project of mine. So I want to build the best mouse in the world. I don't want to build the Chevrolet Spark or whatever of electric cars. I want to build the Tesla Roadster version of a mouse. And I really do think it's quite possible that within five to 10 years that most eSports competitions are dominated by people with paralysis. This is a very

real possibility for a number of reasons. One is that they'll have access to the best technology to play video games effectively. The second is they have the time to do so. So those two factors together are particularly potent for eSport competitors.

Lex Fridman
Unless, people without paralysis are also allowed to implant N1?

Bliss Chapman
Right.

Lex Fridman
Which, it is another way to interact with a digital device, and there's something to that, if it's a fundamentally different experience, more efficient experience? Even if it's not like some kind of full-on high bandwidth communication, if it's just the ability to move the mouse 10x faster, like the bits per second? If I can achieve a bits per second at 10x what I can do with a mouse, that's a really interesting possibility of what that can do? Especially as you get really good at it. With training.

Bliss Chapman
It's definitely the case that you have a higher ceiling performance, because you don't have to buffer your intention through your arm, through your muscle. You get just by nature of having a brain implant at all, like 75 millisecond lead time on any action that you're actually trying to take. And there's some nuance to this, there's evidence that the motor cortex, you can sort of plan out sequences of actions, so you may not get that whole benefit all the time. But for reaction time style games, where you just want to - somebody's over here, snipe them, that kind of thing? You actually do have just an inherent advantage, because you don't need to go through muscle. So the question is, just how much faster can you make it? And we're already faster than what you would do if you're going through muscle from a latency point of view, and we're in the early stages of that. I think we can push it. So our end to end latency right now from brain spike to cursor movement, it's about 22 milliseconds. If you think about the best mice in the world, the best gaming mice, that's about five milliseconds ish of latency, depending on how you measure, depending how fast your screen refreshes, there's a lot of characteristics that matter there. And the rough time for a neuron in the brain to actually impact your command of your hand is about 75 milliseconds. So if you look at those numbers, you can see that we're already competitive and slightly faster than what you'd get by actually moving your hand. And this is something that if you ask Noland about it, when he moved the cursor for the first time - we asked him about this, it was something I was super curious about. "What does it feel like when you're modulating a click intention, or when you're trying to just move the cursor to the right?" He said it moves before he is actually intending it to. Which is kind of a surreal thing, and something that I would love to experience myself one day, what is that like to have the thing just be so

immediate, so fluid, that it feels like it's happening before you're actually intending it to move?

Lex Fridman
Yeah. I suppose we've gotten used to that latency, that natural latency that happens. So is currently the bottleneck, the communication? So the Bluetooth communication? What's the actual bottleneck? I mean there's always going to be a bottleneck, what's the current bottleneck?

Bliss Chapman
Yeah. A couple things. So kind of hilariously, Bluetooth low-energy protocol has some restrictions on how fast you can communicate. So the protocol itself establishes a standard of the most frequent sort of updates you can send, are on the order of 7.5 milliseconds. And as we push latency down to the level of individual spikes impacting control, that level of resolution, that kind of protocol is going to become a limiting factor at some scale. Another sort of important nuance to this, is that it's not just the Neuralink itself that's part of this equation. If you start pushing latency below the level of how fast you're going to refresh, then you have another problem. You need your whole system to be able to be as reactive as the limits of what the technology can offer.

Lex Fridman
Yes.

Bliss Chapman
120 hertz just doesn't work anymore, if you're trying to have something respond at something that's at the level of one millisecond.

Lex Fridman
That's a really cool challenge. I also like that for a t-shirt, the best mouse in the world. Tell me on the receiving end, so the decoding step? Now we figured out what the spikes are, we've got them all together, now we're sending that over to the app. What's the decoding step look like?

Bliss Chapman
Yeah. So maybe first, what is decoding? I think there's probably a lot of folks listening that just have no clue what it means to decode brain activity.

Lex Fridman
Actually, even if we zoom out beyond that, what is the app? So there's an implant that's wirelessly communicating with any digital device that has an app installed.

Bliss Chapman
Yup.

Lex Fridman
So, maybe can you tell me at high-level what the app is, what the software is outside of the brain?

Bliss Chapman
So maybe working backwards from the goal. The goal is to help someone with paralysis. In this case, Noland. Be able to navigate his computer independently. And we think the best way to do that, is to offer them the same tools that we have to navigate our software. Because we don't want to have to rebuild an entire software ecosystem for the brain, at least not yet. Maybe someday you can imagine there's UXs that are built natively for BCI, but in terms of what's useful for people today, I think most people would prefer to be able to just control mouse and keyboard inputs, to all the applications that they want to use for their daily jobs, for communicating with their friends, etc. And so the job of the application is really to translate this wireless stream of brain data, coming off the implant, into control of the computer. And we do that by essentially building a mapping from brain activity to sort of the HID inputs, to the actual hardware. So HID is just the protocol for communicating like input device events, so for example, move mouse to this position or press this key down. And so that mapping is fundamentally what the app is responsible for. But there's a lot of nuance of how that mapping works, and we spent a lot of time to try to get it right, and we're still in the early stages of a long journey to figure out how to do that optimally. So one part of that process is decoding. So decoding is this process of taking the statistical patterns of brain data, that's being channeled across this Bluetooth connection to the application. And turning it into, for example, a mouse movement. And that decoding step, you can think of it in a couple of different parts. So similar to any machine learning problem, there's a training step and there's an inference step. The training step in our case is a very intricate behavioral process where the user has to imagine doing different actions. So for example, they'll be presented a screen with a cursor on it, and they'll be asked to push that cursor to the right. Then imagine pushing that cursor to the left, push it up, push it down. And we can basically build up a pattern or using any sort of modern ML method of mapping of given this brain data, and then imagine behavior, map one to the other. And then at test time you take that same pattern matching system. In our case it's a deep neural network, and you run it and you take the live stream of brain data coming off their implant, you decode it by pattern matching to what you saw at calibration time, and you use that for a control of the computer. Now a couple sort of rabbit holes that I think are quite interesting. One of them has to do with how you build that best template matching system. Because there's a variety of behavioral challenges and also debugging challenges when you're working with someone who's paralyzed. Because again, fundamentally you don't observe what they're trying to do, you can't see them attempt to move their hand. And so you have to figure out a way to instruct the user to do something, and validate that they're doing it correctly, such that

then you can downstream, build with confidence, the mapping between the neural spikes and the intended action. And by doing the action correctly, what I really mean is, at this level of resolution of what neurons are doing. So if, in ideal world, you could get a signal of behavioral intent that is ground truth accurate at the scale of one millisecond resolution, then with high confidence, I could build a mapping from my neural spikes, to that behavioral intention. But the challenge is again, that you don't observe what they're actually doing. And so there's a lot of nuance to how you build user experiences, that give you more than just a course on average correct representation of what the user's intending to do. If you want to build the world's best mouse, you really want it to be as responsive as possible. You want it to be able to do exactly what the user's intending, at every step along the way, not just on average be correct, when you're trying to move it from left to right. And building a behavioral calibration game, or our software experience, that gives you that level of resolution, is what we spend a lot of time working on.

Lex Fridman
So, the calibration process, the interface, has to encourage precision. Meaning whatever it does, it should be super intuitive that the next thing the human is going to likely do, is exactly that intention that you need, and only that intention?

Bliss Chapman
Yeah.

Lex Fridman
And you don't have any feedback except that may be speaking to you afterwards, what they actually did, you can't - oh, yeah.

Bliss Chapman
Right.

Lex Fridman
So that's fundamentally, that is a really exciting UX challenge. Because that's all on the UX, it's not just about being friendly or nice or usable.

Bliss Chapman
Yup.

Lex Fridman
It's like -

Bliss Chapman
User experience is how it works.

Lex Fridman
- it's how it works, for the calibration. And calibration, at least at this stage of Neuralink is fundamental to the operation of the thing? And not just calibration, but continued calibration essentially?

Bliss Chapman
Yeah.

Lex Fridman
Wow, yeah.

Bliss Chapman
You said something that I think is worth exploring there a little bit. You said it's primarily a UX challenge, and I think a large component of it is, but there is also a very interesting machine learning challenge here. Which is given some dataset, including some on average correct behavior, of asking the user to move up, or move down, move right, move left, and given a dataset of neural spikes. Is there a way to infer, in some kind of semi-supervised, or entirely unsupervised way, what that high resolution version of their intention is? And if you think about it, there probably is, because there are enough data points in the dataset, enough constraints on your model. That there should be a way with the right sort of formulation, to let the model figure out itself, for example - at this millisecond, this is exactly how hard they're pushing upwards, and at this millisecond, this is how hard they're trying to push upwards.

Lex Fridman
It's really important to have very clean labels, yes? So the problem becomes much harder from the machine learning perspective if the labels are noisy?

Bliss Chapman
That's correct.

Lex Fridman
And then to get the clean labels, that's a UX challenge?

Bliss Chapman
Correct. Although clean labels, I think maybe it's worth exploring what that exactly means. I think any given labeling strategy will have some number of assumption to make, about what the user is attempting to do. Those assumptions can be formulated in a loss function, or they can be formulated in terms of heuristics that you might use, to just try to estimate or guesstimate what the user's trying to do. And what really matters is, how accurate are those assumptions? For example, you might say, "Hey, user, push upwards and follow the speed of this cursor." And your heuristic might be that they're trying to do exactly what that cursor is

trying to do. Another competing heuristic might be, they're actually trying to go slightly faster at the beginning of the movement and slightly slower at the end. And those competing heuristics may or may not be accurate reflections of what the user is trying to do. Another version of the task might be, "Hey, user, imagine moving this cursor a fixed offset." So rather than follow the cursor, just try to move it exactly 200 pixels to the right. So here's the cursor, here's the target, okay, cursor disappears, try to move that now invisible cursor, 200 pixels to the right. And the assumption in that case would be that the user can't actually modulate correctly that position offset. But that position offset assumption might be a weaker assumption, and therefore potentially, you can make it more accurate, than these heuristics that are trying to guesstimate at each millisecond what the user's trying to do. So you can imagine different tasks that make different assumptions about the nature of the user intention. And those assumptions being correct is what I would think of as a clean label.

Lex Fridman
For that step, what are we supposed to be visualizing? There's a cursor, and you want to move that cursor to the right, or the left, or up and down, or maybe move them by a certain offset. So that's one way. Is that the best way to do calibration? So for example, an alternative crazy way that probably is playing a role here, is a game like WEG Grid. Where you're just getting a very large amount of data, the person playing a game. Where if they're in a state of flow, maybe you can get clean signal as a side effect?

Bliss Chapman
Yup.

Lex Fridman
Or is that not an effective way for initial calibration?

Bliss Chapman
Yeah. Great question. There's a lot to unpack there. So the first thing I would draw a distinction between is, open loop versus closed loop. So open loop, what I mean by that is, the user is sort of going from zero to one. They have no model at all, and they're trying to get to the place where they have some level of control, at all. In that setup, you really need to have some task that gives the user a hint of what you want them to do, such that you can build its mapping again, from brain data to output. Then once they have a model, you could imagine them using that model and actually adapting to it, and figuring out the right way to use it themself. And then retraining on that data to give you sort of a boost in performance. There's a lot of challenges associated with both of these techniques, and we can rabbit hole into both of them if you're interested. But the sort of challenge with the open loop task is that the user themself doesn't get proprioceptive feedback about what they're doing. They don't necessarily perceive themself or feel the mouse under their hand, when they're trying to do an open loop calibration. They're being asked to perform something – imagine if you

sort of had your whole right arm numbed, and you stuck it in a box and you couldn't see it, so you had no visual feedback and you had no proprioceptive feedback, about what the position or activity of your arm was. And now you're asked, "Okay, given this thing on the screen, that's moving from left to right, match that speed?" And you basically can try your best to invoke whatever that imagined action is in your brain, that's moving the cursor from left to right. But in any situation, you're going to be inaccurate and maybe inconsistent in how you do that task. And so that's sort of the fundamental challenge of open loop. The challenge with closed loop is that once the user's given a model, and they're able to start moving the mouse on their own, they're going to very naturally adapt to that model. And that coadaptation between the model learning what they're doing, and the user learning how to use the model, may not find you the best sort of global minima. And maybe that your first model was noisy in some ways, or maybe just had some quirk. There's some part of the data distribution, it didn't cover super well, and the user now figures out, because they're a brilliant user like Noland, they figure out the right sequence of imagined motions, or the right angle they have to hold their hand at to get it to work. And they'll get it to work great, but then the next day they come back to their device, and maybe they don't remember exactly all the tricks that they used the previous day. And so there's a complicated sort of feedback cycle here that can emerge, and can make it a very, very difficulty debugging process.

Lex Fridman
Okay. There's a lot of really fascinating things there. Actually, just to stay on the closed loop - I've seen situations, this actually happened watching psychology grad students. They used a piece of software and they don't know how to program themselves. They used a piece of software that somebody else wrote, and it has a bunch of bugs, and they've been using it for years. They figure out ways to walk around, "Oh, that just happens." Nobody considers, "Maybe we should fix this." They just adapt. And that's a really interesting notion, that we're really good at it adapting, but that might not be the optimal?

Bliss Chapman
Yeah.

Lex Fridman
Okay. So how do you solve that problem? Do you have to restart from scratch every once in a while, kind of thing?

Bliss Chapman
Yeah. It's a good question. First and foremost, I would say this is not a solve problem. And for anyone who's listening in academia who works on BCIs, I would also say this is not a problem that's solved by simply scaling channel count. So maybe that can help, and you can get sort of richer covariant structures that you can use to exploit, when trying to come up with good labeling strategies. But if you're interested in problems that aren't going to be solved

inherently by scaling channel count, this is one of them. Yeah. So how do you solve it? It's not a solve problem. That's the first thing I want to make sure it gets across. The second thing is, any solution that involves closed loop is going to become a very difficult debugging problem. And one of my general heuristics for choosing what prompts to tackle is, that you want to choose the one that's going to be the easiest to debug. Because if you can do that, even if the ceiling is lower, you're going to be able to move faster, because you have a tighter iteration loop debugging the problem. In the open loop setting, there's not a feedback cycle to debug with the user in the loop. And so there's some reason to think that, that should be an easier debugging problem. The other thing that's worth understanding is that even in the closed loop setting, there's no special software magic of how to infer what the user is truly attempting to do. In the closed loop setting, although they're moving the cursor on the screen, they may be attempting something different than what your model is outputting. So what the model is outputting is not a signal that you can use to retrain if you want to be able to improve the model further. You still have this very complicated guestimation, or unsupervised problem of figuring out what is the true user intention underlying that signal? And so the open loop problem has the nice property of being easy to debug, and the second nice property of, it has all the same information and content as the closed loop scenario. Another thing I want to mention and call out, is that this problem doesn't need to be solved in order to give useful control to people. Even today with the solutions we have now, and that academia has built up over decades, the level of control that can be given to a user today, is quite useful. It doesn't need to be solved to get to that level of control. But again, I want to build the world's best mouse. I want to make it so good that it's not even a question that you want it. And to build the world's best mouse, the superhuman version, you really need to nail that problem. And a couple maybe details of previous studies that we've done internally, that I think are very interesting to understand, when thinking about how to solve this problem. The first is that even when you have ground-truth data of what the user's trying to do, and you can get this with an able-bodied monkey, a monkey that has a Neuralink device implanted, and moving a mouse to control a computer. Even with that ground-truth dataset, it turns out that the optimal thing to predict to produce high performance BCI, is not just the direct control of the mouse. You can imagine building a dataset of what's going on in the brain, and what is the mouse exactly doing on the table? And it turns out that if you build the mapping from neurospikes to predict exactly what the mouse is doing, that model will perform worse, than a model that is trained to predict higher level assumptions about what the user might be trying to do. For example, assuming that the monkey is trying to go in a straight line to the target, it turns out that making those assumptions is actually more effective in producing a model, than actually predicting the underlying hand movement.

Lex Fridman
So the intention, not the physical movement, or whatever?

Bliss Chapman
Yeah.

Lex Fridman
There's obviously a really strong correlation between the two, but the intention is a more powerful thing to be chasing?

Bliss Chapman
Right.

Lex Fridman
Well, that's also super interesting. I mean, the intention itself is fascinating because yes, with the BCI here in this case with the digital telepathy, you're acting on the intention, not the action. Which is why there's an experience of feeling like it's happening before you meant for it to happen? That is so cool. And that is why you could achieve superhuman performance problem, in terms of the control of the mouse? So for open loop, just to clarify, so whenever the person is tasked to move the mouse to the right, you said there's not feedback, so they don't get to get that satisfaction of actually getting it to move? Right?

Bliss Chapman
So you could imagine giving the user feedback on a screen, but it's difficult, because at this point you don't know what they're attempting to do. So what can you show them that would basically give them a signal of, "I'm doing this correctly or not correctly?" So let's take a very specific example. Maybe your calibration task looks like you're trying to move the cursor, a certain position offset. So your instructions to the user are, "Hey, the cursor's here. Now when the cursor disappears, imagine you're moving it 200 pixels from where it was, to the right to be over this target." In that kind of scenario, you could imagine coming up with some sort of consistency metric that you could display to the user of, "Okay, I know what the spike trend looks like on average when you do this action to the right. Maybe I can produce some sort of probabilistic estimate of how likely is that to be the action you took, given the latest trial or trajectory that you imagined?" And that could give the user some sort of feedback of how consistent are they, across different trials. You could also imagine that if the user is prompted with that kind of consistency metric, that maybe they just become more behaviorally engaged to begin with, because the task is kind of boring when you don't have any feedback at all. And so there may be benefits to the user experience of showing something on the screen, even if it's not accurate. Just because it keeps the user motivated to try to increase that number, or push it upwards.

Lex Fridman
So there's this psychology element here?

Bliss Chapman
Yeah. Absolutely.

Lex Fridman
And again, all of that is UX challenge? How much signal drift is there hour-to-hour, day-to-day, week-to-week, month-to-month? How often do you have to recalibrate because of the signal drift?

Bliss Chapman
Yeah. So this is a problem we've worked on both with NHP, non-human primates, before our clinical trial, and then also with Noland during the clinical trial. Maybe the first thing that's worth stating is what the goal is here. So the goal is really to enable the user to have a plug and play experience - well, I guess they don't have to plug anything in, but a play experience where they can use the device whenever they wanted, however they want to. And that's really what we're aiming for. And so there can be a set of solutions that get to that state without considering this non-stationary problem. So maybe the first solution here that's important, is that they can recalibrate whenever they want. This is something that Noland has the ability to do today, so he can recalibrate the system at 2:00am, in the middle of the night without his caretaker, or parents or friends around, to help push a button for him. The other important part of the solution is that when you have a good model calibrated, that you can continue using that without needing to recalibrate it. So how often he has to do this recalibration to-date, depends really on his appetite for performance. We observe sort of a degradation through time, of how well any individual model works, but this can be mitigated behaviorally by the user adapting their control strategy. It can also be mitigated through a combination of software features that we provide to the user. For example, we let the user adjust exactly how fast the cursor is moving. We call that the gain, for example, the gain of how fast the cursor reacts to any given input intention. They can also adjust the smoothing, how smooth the output of that cursor intention actually is. That can also adjust the friction, which is how easy is it to stop and hold still? And all these software tools allow the user a great deal of flexibility and troubleshooting mechanisms to be able to solve this problem for themselves.

Lex Fridman
By the way, all of this is done by looking to the right side of the screen, selecting the mixer. And the mixer you have, it's -

Bliss Chapman
Like DJ mode. DJ mode for your BCI.

Lex Fridman
I mean, it's a really well done interface. It's really, really well done. And so there's that bias that there's a cursor drift that Noland talked about in a stream. Although he said that you

guys were just playing around with it with him, and then constantly improving. So that could have been just a snapshot of that particular moment, a particular day, where he said that there was this cursor drift and this bias that could be removed by him. I guess, looking to the right side of the screen, or left side of the screen, to adjust the bias?

Bliss Chapman
Yeah, yeah.

Lex Fridman
That's one interface action, I guess, to adjust the bias?

Bliss Chapman
Yeah. So this is actually an idea that comes out of academia. There is some prior work with BrainGate clinical trial participants where they pioneered this idea of bias correction. The way we've done it, I think is, it's very prioritized, very beautiful user experience. Where the user can essentially flash the cursor over to the side of the screen, and it opens up a window, where they can actually adjust or tune exactly the bias of the cursor. So bias, maybe for people who aren't familiar, is just sort of what is the default motion of the cursor, if you're imagining nothing? And it turns out that, that's one of the first sort - and it turns out that that's one of the first quality of the cursor control experience that's impacted by neuron non-stationarity.

Lex Fridman
Quality of the cursor experience.

Bliss Chapman
I mean, I don't know how else to describe it. I'm not the guy moving thing.

Lex Fridman
It's very poetic. I love it. The quality of the cursor experience. Yeah, I mean it sounds poetic, but it is deeply true. There is an experience. When it works well, it is a joyful - a really pleasant experience. And when it doesn't work well, it's a very frustrating experience. That's actually the art of UX, you have the possibility to frustrate people, or the possibility to give them joy.

Bliss Chapman
And at the end of the day, it really is truly the case that UX is how the thing works. And so it's not just what's showing on the screen, it's also, what control surfaces does a decoder provide the user? We want them to feel like they're in the F1 car, not like some minivan. And that really truly is how we think about it. Noland himself is an F1 fan. We refer to ourself as a pit crew, he really is truly the F1 driver. And there's different control surfaces that different kinds of cars and airplanes provide the user, and we take a lot of inspiration from that when

designing how the cursor should behave. And maybe one nuance of this is, even details like when you move a mouse on a MacBook trackpad, the sort of response curve of how that input that you give the trackpad translates to cursor movement is different than how it works with a mouse. When you move on the trackpad, there's a different response function, a different curve to how much a movement translates to input to the computer than when you do it physically with a mouse. And that's because somebody sat down a long time ago, when they're designing the initial input systems to any computer, and they thought through exactly how it feels to use these different systems. And now we're designing the next generation of this, input system to a computer, which is entirely done via the brain, and there's no proprioceptive feedback, again, you don't feel the mouse in your hand, you don't feel the keys under your fingertips, and you want a control surface that still makes it easy and intuitive for the user to understand the state of the system, and how to achieve what they want to achieve. And ultimately the end goal is that that UX is completely - it fades in the background, it becomes something that's so natural and intuitive that it's subconscious to the user, and they just should feel like they have basically direct control over the cursor, just does what they want it to do. They're not thinking about the implementation of how to make it do what they want it to do, it's just doing what they want it to do.

Lex Fridman
Is there some kind of things along the lines of like Fitt's Law, where you should move the mouse in a certain kind of way that maximizes your chance to hit the target? I don't even know what I'm asking, but I'm hoping the intention of my question will land on a profound answer. No. Is there some kind of understanding of the laws of UX when it comes to the context of somebody using their brain to control it that's different than with a mouse?

Bliss Chapman
I think we're in the early stages of discovering those laws, so I wouldn't claim to have solved that problem yet, but there's definitely some things we've learned that make it easier for the user to get stuff done. And it's pretty straightforward when you verbalize it, but it takes a while to actually get to that point, when you're in the process of debugging the stuff in the trenches. One of those things is that any machine learning system that you build has some number of errors, and it matters how those errors translate to the downstream user experience. For example, if you're developing a search algorithm in your photos, if you search for your friend, Joe, and it pulls up a photo of your friend, Josephine, maybe that's not a big deal, because the cost of an error is not that high. In a different scenario, where you're trying to detect insurance fraud or something like this, and you're directly sending someone to court because of some machine learning model output, then the errors make a lot more sense to be careful about, you want to be very thoughtful about how those errors translate to downstream effects. The same is true in BCI. So for example, if you're building a model that's decoding a velocity output from the brain, versus an output where you're trying to modulate the left click for example, these have sort of different trade-offs of how precise you need to be before it becomes useful to the end user. For velocity, it's okay to be on

average correct, because the output of the model is integrated through time. So if the user's trying to click at position A, and they're currently position B, they're trying to navigate over time to get between those two points. And as long as the output of the model is on average correct, they can sort of steer it through time, with the user control loop in the mix, they can get to the point they want to get to. The same is not true of a click. For a click, you're performing it almost instantly, at the scale of neurons firing. And so you want to be very sure that that click is correct, because a false click can be very destructive to the user. They might accidentally close the tab that they're trying to do something in, and lose all their progress. They might accidentally hit some send button on some text that there's only half composed and reads funny after. So there's different sort of cost functions associated with errors in this space, and part of the UX design is understanding how to build a solution that is, when it's wrong, still useful to the end user.

Lex Fridman
It's so fascinating, assigning cost to every action when an error occurs. So every action, if an error occurs, has a certain cost, and incorporating that into how you interpret the intention, mapping it to the action is really important. I didn't quite, until you said it, realize there's a cost to sending the text early. It's a very expensive cost.

Bliss Chapman
Yeah, it's super annoying if you accidentally - imagine if your cursor misclicked every once in a while. That's super obnoxious. And the worst part of it is, usually when the user's trying to click, they're also holding still, because they're over the target they want to hit, and they're getting ready to click, which means that in the datasets that we build, on average is the case that sort of low speeds, or desire to hold still, is correlated with when the user's attempting to click.

Lex Fridman
Wow, that is really fascinating.

Bliss Chapman
People think that, "Oh, a click is a binary signal, this must be super easy to decode." Well, yes, it is, but the bar is so much higher for it to become a useful thing for the user. And there's ways to solve this. I mean, you can sort of take the compound approach of, "Well, let's take five seconds to click. Let's take a huge window of time, so we can be very confident about the answer." But again, world's best mouse. The world's best mouse doesn't take a second to click, or 500 milliseconds to click, it takes five milliseconds to click or less. And so if you're aiming for that kind of high bar, then you really want to solve the underlying problem.

Lex Fridman
So maybe this is a good place to ask about how to measure performance, this whole bits per second. Can you explain what you mean by that? Maybe a good place to start is to talk about Webgrid as a game, as a good illustration of the measurement of performance.

Bliss Chapman
Yeah. Maybe I'll take one zoom out step there, which is just explaining why we care to measure this at all. So again, our goal is to provide the user the ability to control the computer as well as I can, and hopefully better. And that means that they can do it at the same speed as what I can do, it means that they have access to all the same functionality that I have, including all those little details like command tab, command space, all this stuff, they need to be able to do it with their brain, and with the same level of reliability as what I can do with my muscles. And that's a high bar, and so we intend to measure and quantify every aspect of that to understand how we're progressing towards that goal. There's many ways to measure BPS by the way, this isn't the only way, but we present the user a grid of targets, and basically we compute a score which is dependent on how fast and accurate they can select, and then how small are the targets. And the more targets that are on the screen, the smaller they are, the more information you present per click. And so if you think about it from information theory point of view, you can communicate across different information theoretic channels, and one such channel is a typing interface, you can imagine, that's built out of a grid, just like a software keyboard on the screen. And bits per second is a measure that's computed by taking the log of the number of targets on the screen. You can subtract one if you care to model a keyboard, because you have to subtract one for the delete key on the keyboard. But log of the number of targets on the screen, times the number of correct selections, minus incorrect, divided by some time window, for example, 60 seconds. And that's sort of the standard way to measure a cursor control task in academia. And all credit in the world goes to this great professor, Dr. Shenoy of Stanford who came up with that task, and he's also one of my inspirations for being in the field. So all the credit in the world to him for coming up with a standardized metric to facilitate this kind of bragging rights that we have now to say that Noland is the best in the world at this task with this BCI. It's very important for progress that you have standardized metrics that people can compare across. Different techniques and approaches, how well does this do? So big kudos to him and to all the team at Stanford. Yeah, so for Noland, and for me playing this task, there's also different modes that you can configure this task. So the Webgrid task can be presented as just sort of a left click on the screen, or you could have targets that you just dwell over, or you could have targets that you left, right click on, you could have targets that are left, right click, middle click, scrolling, clicking and dragging. You can do all sorts of things within this general framework, but the simplest, purest form is just blue targets show up on the screen, blue means left click. That's the simplest form of the game. And the sort of prior records here in academic work and at Neuralink internally with NHPs have all been matched or beaten by Noland with his Neuralink device. So prior to Neuralink, the world record for a human using device is somewhere between 4.2 to 4.6 BPS, depending on

exactly what paper you read and how you interpret it. Noland's current record is 8.5 BPS. and again, this sort of median Neuralinker performance is 10 BPS. So you can think of it roughly as, he's 85% the level of control of a median Neuralinker using their cursor to select blue targets on the screen. I think there's a very interesting journey ahead to get us to that same level of 10 BPS performance. It's not the case that the tricks that got us from 4 to 6 BPS, and then 6 to 8 BPS are going to be the ones that get us from 8 to 10. And in my view, the core challenge here is really the labeling problem. It's how do you understand, at a very, very fine resolution, what the user's attempting to do? And I highly encourage folks in academia to work on this problem.

Lex Fridman
What's the journey with Noland on that quest of increasing the BPS on Webgrid? In March, you said that he selected 89,285 targets in Webgrid. So he loves this game, he's really serious about improving his performance in this game. So what is that journey of trying to figure out how to improve that performance? How much can that be done on the decoding side? How much can that be done on the calibration side? How much can that be done on the Noland side of figuring out how to convey his intention more cleanly?

Bliss Chapman
Yeah. No, this is a great question. So in my view, one of the primary reasons why Noland's performance is so good is because of Noland. Noland is extremely focused and very energetic. He'll play Webgrid sometimes for four hours in the middle of the night. From 2:00am To 6:00am he'll be playing Webgrid, just because he wants to push it to the limits of what he can do. This is not us asking him to do that, I want to be clear. We're not saying, " Hey, you should play Webgrid tonight." We just gave him the game as part of our research, and he is able to play it independently, and practice whenever he wants, and he really pushes hard to push it, the technology's absolute limit. And he views that as his job, really, to make us be the bottleneck. And boy, has he done that well. And so the first thing to acknowledge is that he's extremely motivated to make this work. I've also had the privilege to meet other clinical trial participants from BrainGate and other trials, and they very much shared the same attitude of, they viewed this as their life's work to advance the technology as much as they can. And if that means selecting targets on the screen for four hours from 2:00am to 6:00am, then so be it. And there's something extremely admirable about that that's worth calling out. Okay, so then how do you get from where he started, which is no cursor control to eight BPS? I mean, when he started, there's a huge amount of learning to do on his side and our side to figure out what's the most intuitive control for him. And the most intuitive control for him is, you have to find the set intersection of, "Do we have the signal to decode?" So we don't pick up every single neuron in the motor cortex, which means we don't have representation for every part of the body. So there may be some signals that we have better decode performance on than others. For example, on his left hand, we have a lot of difficulty distinguishing his left ring finger from his left middle finger, but on his right hand, we have a good control and good modulation detected from the

neurons that were able to record for his pinky, and his thumb, and his index finger. So you can imagine how these different subspaces of modulated activity intersect with what's the most intuitive for him. And this has evolved over time, so once we gave him the ability to calibrate models on his own, he was able to go and explore various different ways to imagine controlling the cursor. For example, he can imagine controlling the cursor by wiggling his wrist side to side, or by moving his entire arm, by - I think at one point he did his feet. He tried a whole bunch of stuff to explore the space of what is the most natural way for him to control the cursor, that at the same time, it's easy for us to decode-

Lex Fridman
Just to clarify, it's through the body mapping procedure there, you're able to figure out which finger he can move?

Bliss Chapman
Yes. Yeah, that's one way to do it. Maybe one nuance of the - when he's doing it, he can imagine many more things than we represent in that visual on the screen. So we show him, sort of abstractly, "Here's a cursor. You figure out what works the best for you." And we obviously have hints about what will work best from that body mapping procedure, of, "We know that this particular action we can represent well." But it's really up to him to go and explore and figure out what works the best.

Lex Fridman
But at which point does he no longer visualize the movement of his body, and is just visualizing the movement of the cursor?

Bliss Chapman
Yeah.

Lex Fridman
How quickly does he get there?

Bliss Chapman
So this happened on a Tuesday. I remember this day very clearly, because at some point during the day, it looked like he wasn't doing super well, it looked like the model wasn't performing super well, and he was getting distracted, but actually, it wasn't the case. What actually happened was, he was trying something new, where he was just controlling the cursor, so he wasn't imagining moving his hand anymore, he was just imagining - I don't know what it is, some abstract intention to move the cursor on the screen, and I cannot tell you what the difference between those two things are, I truly cannot. He's tried to explain it to me before, I cannot give a first-person account of what that's like. But the expletives that he uttered in that moment were enough to suggest that it was a very qualitatively different experience for him to just have direct neural control over a cursor.

Lex Fridman
I wonder if there's a way through UX to encourage a human being to discover that, because he discovered it - like you said to me, that he's a pioneer. So he discovered that on his own through all of this, the process of trying to move the cursor with different kinds of intentions. But that is clearly a really powerful thing to arrive at, which is to let go of trying to control the fingers and the hand, and control the actual digital device with your mind.

Bliss Chapman
That's right. UX is how it works. And the ideal UX is one that the user doesn't have to think about what they need to do in order to get it done, it just does it.

Lex Fridman
That is so fascinating. But I wonder, on the biological side, how long it takes for the brain to adapt. So is it just simply learning high level software, or is there a neuroplasticity component where the brain is adjusting slowly?

Bliss Chapman
Yeah. The truth is, I don't know. I'm very excited to see with sort of the second participant that I implant, what the journey is like for them, because we'll have learned a lot more, potentially, we can help them understand and explore that direction more quickly. This wasn't me prompting Noland to go try this, he was just exploring how to use his device and figured it out himself. But now that we know that that's a possibility, that maybe there's a way to, for example, hint the user, "Don't try super hard during calibration, just do something that feels natural." Or, "Just directly control the cursor. Don't imagine explicit action." And from there, we should be able to hopefully understand how this is for somebody who has not experienced that before. Maybe that's the default mode of operation for them, you don't have to go through this intermediate phase of explicit motions.

Lex Fridman
Or maybe if that naturally happens for people, you can just occasionally encourage them to allow themselves to move the cursor.

Bliss Chapman
Right.

Lex Fridman
Actually, sometimes, just like with a four-minute mile, just the knowledge that that's possible -

Bliss Chapman
Yes, pushes you to do it.

Lex Fridman
Yeah.

Bliss Chapman
Yeah.

Lex Fridman
Enables you to do it, and then it becomes trivial. And then it also makes you wonder, this is the cool thing about humans, once there's a lot more human participants, they will discover things that are possible.

Bliss Chapman
Yes. And share their experiences probably with each other.

Lex Fridman
Yeah, and share. And that because of them sharing it, they'll be able to do it. All of a sudden that's unlocked for everybody, because just the knowledge sometimes is the thing that enables you to do it.

Bliss Chapman
Yeah. Just to comment on that too, we've probably tried 1,000 different ways to do various aspects of decoding, and now we know what the right subspace is to continue exploring further. Again, thanks to Noland and the many hours he's put into this. And so even just that, help constraints, or the beam search of different approaches that we could explore really helps accelerate for the next person the set of things that we'll get to try on day one, how fast we hopefully get them to use for control, how fast we can enable them to use it independently, and to get value out of the system. So massive hats off to Noland and all the participants that came before to make this technology a reality.

Lex Fridman
So, how often are the updates to the decoder? 'Cause Noland mentioned, "Okay, there's a new update that we're working on." In the stream he said he plays the snake game, because it's super hard, it's a good way for him to test how good the update is. And he says sometimes the update is a step backwards, it's a constant iteration. What does the update entail? Is it mostly on the decoder side?

Bliss Chapman
Yeah. Couple of comments. So, one, it's probably worth drawing distinction between research sessions where we're actively trying different things to understand what the best approach is, versus independent use, where we wanted to have ability to just go use the device how anybody would want to use their MacBook. So what he's referring to is, I think, usually in the context of a research session, where we're trying many, many different

approaches to - even unsupervised approaches, like we talked about earlier, to try to come up with better ways to estimate his true intention, and more accurately decoded. And in those scenarios, we try, in any given session - he'll sometimes work for eight hours a day, and so that can be hundreds of different models that we would try in that day. A lot of different things. Now, it's also worth noting that we update the application he uses quite frequently, I think sometimes up to 4 or 5 times a day, we'll update his application with different features, or bug fixes, or feedback that he's given us. He's a very articulate person who is part of the solution, he's not a complaining person, he says, "Hey, here's this thing that I've discovered is not optimal in my flow. Here's some ideas how to fix it. Let me know what your thoughts are, let's figure out how to solve it." And it often happens that those things are addressed within a couple of hours of him giving us his feedback, that's the kind of iteration cycle we'll have. And so sometimes at the beginning of the session, he'll give us feedback, and at the end of the session he's giving us feedback on the next iteration of that process or that setup.

Lex Fridman
That's fascinating, 'cause one of the things you mentioned that there was 271 pages of notes taken from the BCI sessions, and this was just in March. So one of the amazing things about human beings that they can provide - especially ones who are smart, and excited, and all positive and good vibes like Noland, that they can provide feedback, continuous feedback.

Bliss Chapman
Yeah. Just to brag on the team a little bit, I work with a lot of exceptional people, and it requires the team being absolutely laser-focused on the user, and what will be the best for them. And it requires a level of commitment of, "Okay, this is what the user feedback was. I have all these meetings, we're going to skip that today, and we're going to do this." That level of focus and commitment is, I would say, underappreciated in the world. And also, you obviously have to have the talent to be able to execute on these things effectively, and we have that in loads.

Lex Fridman
Yeah, and this is such an interesting space of UX design, because there's so many unknowns here. And I can tell UX is difficult because of how many people do it poorly. It's just not a trivial thing.

Bliss Chapman
Yeah. UX is not something that you can always solve by just constant iterating on different things. Sometimes you really need to step back and think globally, "Am I even in the right sort of minima to be chasing down for a solution?" There's a lot of problems in which sort of fast iteration cycle is the predictor of how successful you'll be. As a good example, like in an RL simulation for example, the more frequently you get reward, the faster you can progress. It's just an easier learning problem the more frequently you get feedback. But UX is not that

way, I mean, users are actually quite often wrong about what the right solution is, and it requires a deep understanding of the technical system, and what's possible, combined with what the problem is you're trying to solve. Not just how the user expressed it, but what the true underlying problem is to actually get to the right place.

Lex Fridman
Yeah, that's the old stories of Steve Jobs rolling in there, like, "Yeah, the user is a useful signal, but it's not a perfect signal, and sometimes you have to remove the floppy disc drive." Or whatever the - I forgot all the crazy stories of Steve Jobs making wild design decisions. But there, some of it is aesthetic, that some of it is about the love you put into the design, which is very much a Steve Jobs, Johnny Ive type thing, but when you have a human being using their brain to interact with it, it also is deeply about function, it's not just aesthetic. And that, you have to empathize with a human being before you, while not always listening to them directly. You have to deeply empathize. It's fascinating. It's really, really fascinating. And at the same time, iterate, but not iterate in small ways, sometimes a complete - like rebuilding the design. Noland said in the early days the UX sucked, but you improved quickly. What was that journey like?

Bliss Chapman
Yeah, I mean, I'll give you one concrete example. So he really wanted to be able to read manga. This is something that he - I mean, it sounds like a simple thing, but it's actually a really big deal for him, and he couldn't do it with his mouse stick. It wasn't accessible, you can't scroll with the mouse stick on his iPad on the website that he wanted to be able to use to read the newest manga, and so -

Lex Fridman
Might be a good quick pause to say the mouth stick is the thing he's using. Holding a stick in his mouth to scroll on a tablet.

Bliss Chapman
Right. Yeah. You can imagine it's a stylus that you hold between your teeth. Yeah, it's basically a very long stylus.

Lex Fridman
It's exhausting, it hurts, and it's inefficient.

Bliss Chapman
Yeah. And maybe it's also worth calling out, there are other alternative assisted technologies, but the particular situation Noland's in, and this is not uncommon, and I think it's also not well-understood by folks, is that he's relatively spastic, so he'll have muscle spasms from time to time. And so any assistive technology that requires him to be positioned directly in front of a camera, for example, an eye tracker, or anything that

requires him to put something in his mouth just is a no-go, 'cause he'll either be shifted out of frame when he has a spasm, or if he has something in his mouth, it'll stab him in the face if he spasms too hard. So these kinds of considerations are important when thinking about what advantages a BCI has in someone's life. If it fits ergonomically into your life in a way that you can use it independently when your caretakers not there, wherever you want to, either in the bed or in the chair, depending on your comfort level and your desire to have pressure source, all these factors matter a lot in how good the solution is in that user's life. So one of these very fun examples is scroll. So, again, manga is something he wanted to be able to read, and there's many ways to do scroll with a BCI. You can imagine different gestures, for example, the user could do that would move the page. But scroll is a very fascinating control surface, because it's a huge thing on the screen in front of you. So any sort of jitter in the model output, any sort of air in the model output causes an earthquake on the screen. You really don't want to have your mango page that you're trying to read be shifted up and down a few pixels just because your scroll decoder is not completely accurate. And so this was an example where we had to figure out how to formulate the problem in a way that the errors of the system, whenever they do occur, and we'll do our best to minimize them, but whenever those errors do occur, that it doesn't interrupt the quality, again, of the experience that the user is having. It doesn't interrupt their flow of reading their book. And so what we ended up building is this really brilliant feature. This is a teammate named Bruce who worked on this really brilliant work called Quick Scroll. And Quick Scroll basically looks at the screen, and it identifies where on the screen are scroll bars. And it does this by deeply integrated with macOS to understand where are the scroll bars actively present on the screen, using the sort of accessibility tree that's available to macOS apps. And we identified where those scroll bars are, and we provided a BCI scroll bar, and the BCI scroll bar looks similar to a normal scroll bar, but it behaves very differently, in that once you move over to it, your cursor sort of morphs onto it, it sort of attaches or latches onto it. And then once you push up or down, in the same way that you'd use a push to control the normal cursor, it actually moves the screen for you. So it's basically like remapping the velocity to a scroll action. And the reason that feels so natural and intuitive is that when you move over to attach to it feels like magnetic, so you're sort of stuck onto it, and then it's one continuous action, you don't have to switch your imagined movement, you sort of snap onto it, and then you're good to go. You just immediately can start pulling the page down or pushing it up. And even once you get that right, there's so many little nuances of how the scroll behavior works to make it natural and intuitive. So one example is momentum. When you scroll a page with your fingers on the screen, you actually have some flow, it doesn't just stop right when you lift your finger up. The same is true with BCI scroll, so we had to spend some time to figure out, "What are the right nuances when you don't feel the screen under your fingertip anymore? What is the right sort of dynamic, or what's the right amount of page give, if you will, when you push it to make it flow the right amount for the user to have a natural experience reading their book?" I could tell you there's so many little minutia of how exactly that scroll works, that we spent probably a month getting right, to make that feel extremely natural and easy for the user to navigate.

Lex Fridman
I mean, even the scroll on a smartphone with your finger feels extremely natural and pleasant, and it probably takes an extremely long time to get that right. And actually, the same kind of visionary UX design that we were talking about, don't always listen to the users, but also listen to them, and also have visionary, big, like throw everything out, think from first principles, but also not. Yeah, yeah. By the way, it just makes me think that scroll bars on the desktop probably have stagnated, and never taken that - 'cause the snap, same as snap to grid, snap to scroll bar action you're talking about is something that could potentially be extremely useful in the desktop setting, even just for users to just improve the experience. 'Cause the current scroll bar experience in the desktop is horrible.

Bliss Chapman
Yup. Agreed.

Lex Fridman
It's hard to find, hard to control, there's not a momentum, there's - and the intention should be clear, when I start moving towards a scroll bar, there should be a snapping to the scroll bar action, but of course - maybe I'm okay paying that cost, but there's hundreds of millions of people paying that cost non-stop, but anyway. But in this case, this is necessary, because there's an extra cost paid by Noland for the jitteriness, so you have to switch between the scrolling and the reading. There has to be a face shift between the two, like when you're scrolling, you're scrolling.

Bliss Chapman
Right, right. So that is one drawback of the current approach. Maybe one other just sort of case study here. So, again, UX is how it works, and we think about that holistically, from the - even the feature detection level of what we detect in the brain, to how we design the decoder, what we choose to decode, to then how it works once it's being used by the user. So another good example in that sort of how it works once they're actually using the decoder, the output that's displayed on the screen is not just what the decoder says, it's also a function of what's going on on the screen. So we can understand, for example, that when you're trying to close a tab, that very small, stupid little X that's extremely tiny, which is hard to get precisely hit, if you're dealing with a noisy output of the decoder, we can understand that that is a small little X you might be trying to hit, and actually make it a bigger target for you. Similar to how when you're typing on your phone, if you are used to the iOS keyboard for example, it actually adapts to target size of individual keys based on an underlying language model. So it'll actually understand if I'm typing, "Hey, I'm going to see L." It'll make the E key bigger because it knows Lex is the person I'm going to go see. And so that kind of predictiveness can make the experience much more smooth, even without improvements to the underlying decoder or feature detection part of the stack. So we do that with a feature called magnetic targets, we actually index the screen, and we understand, "Okay, these are the places that are very small targets that might be difficult to

hit. Here's the kind of cursor dynamics around that location that might be indicative of the user trying to select it. Let's make it easier. Let's blow up the size of it in a way that makes it easier for the user to sort of snap onto that target." So all these little details, they matter a lot in helping the user be independent in their day-to-day living.

Lex Fridman
So how much of the work on the decoder is generalizable to P2, P3, P4, P5 PM? How do you improve the decoder in a way that's generalizable?

Bliss Chapman
Yeah, great question. So the underlying signal we're trying to decode is going to look very different in P2 than in P1. For example, channel number 345 is going to mean something different in user one than it will in user two, just because that electrode that corresponds with channel 345 is going to be next to a different neuron in user one to person user two. But the approach is the methods, the user experience of how do you get the right behavioral pattern from the user to associate with that neural signal. We hope that will translate over multiple generations of users. And beyond that, it's very, very possible, in fact, quite likely that we've overfit to Noland's user experience, desires and preferences. And so what I hope to see is that when we get a second, third, fourth participant, that we find what the right wide minimums are that cover all the cases that make it more intuitive for everyone. And hopefully, there's a crosspollination of things, where, "Oh, we didn't think about that with this user because they can speak. But with this user who just can fundamentally not speak at all, this user experience is not optimal." Those improvements that we make there should hopefully translate then to even people who can speak but don't feel comfortable doing so because we're in a public setting, like their doctor's office.

Lex Fridman
So the actual mechanism of open-loop labeling, and then closed-loop labeling would be the same, and hopefully can generalize across the different users -

Bliss Chapman
Correct.

Lex Fridman
- as they're doing the calibration step? And the calibration step is pretty cool. I mean, that in itself. The interesting thing about Webgrid, which is closed-loop, it's fun. I love it when there's - they used to be kind of idea of human computation, which is using actions a human would want to do anyway to get a lot of signal from. And Webgrid is that, a nice video game that also serves as great calibration.

Bliss Chapman
It's so funny, I've heard this reaction so many times. Before the first user was implanted, we had an internal perception that the first user would not find this fun. And so we thought really quite a bit actually about, "Should we build other games that are more interesting for the user, so we can get this kind of data and help facilitate research that's for long duration and stuff like this?" Turns out that people love this game. I always loved it, but I didn't know that that was a shared perception.

Lex Fridman
Yeah. And just in case it's not clear, Webgrid is - there's a grid of let's say 35 by 35 cells and one of them lights up blue and you have to move your mouse over that and click on it. And if you miss it, it's red, and -

Bliss Chapman
I've played this game for so many hours, so many hours.

Lex Fridman
And what's your record you said?

Bliss Chapman
I think I have the highest at Neuralink right now. My record's 17 BPS.

Lex Fridman
17 BPS?

Bliss Chapman
If you imagine that 35 by 35 grid, you're hitting about 100 trials per minute. So 100 correct selections in that one minute window. So you're averaging about between 500-600 milliseconds per selection.

Lex Fridman
So one of the reasons I think I struggle with that game is I'm such a keyboard person, so everything is done with via keyboard. If I can avoid touching the mouse, it's great. So how can you explain your high performance?

Bliss Chapman
I have a whole ritual I go through when I play Webgrid. There's actually like a diet plan associated with this. It's a whole thing.

Lex Fridman
That's great.

Bliss Chapman
The first thing is -

Lex Fridman
"I have to fast for five days, I have to go up to the mountains."

Bliss Chapman
I mean, the fasting thing is important. So this is like -

Lex Fridman
Focuses the mind, yeah. It's true, it's true.

Bliss Chapman
So what I do is, I - actually, I don't eat for a little bit beforehand, and then I'll actually eat a ton of peanut butter right before I play, and I get -

Lex Fridman
This is a real thing?

Bliss Chapman
This is a real thing, yeah. And then it has to be really late at night, this is, again, a night owl thing I think we share, but it has to be midnight - 2:00am kind of time window. And I have a very specific physical position I'll sit in, which is - I was homeschooled growing up, and so I did most of my work on the floor, just in my bedroom or whatever. And so I have a very specific situation-

Lex Fridman
On the floor?

Bliss Chapman
- on the floor, that I sit and play. And then you have to make sure there's not a lot of weight on your elbow when you're playing so you can move quickly. And then I turn the gain of the cursor, so the speed of the cursor way, way up, so it's small motions that actually move the cursor.

Lex Fridman
Are you moving with your wrist, or you're - you're never -

Bliss Chapman
I move with my fingers. So my wrist is almost completely still, I'm just moving my fingers.

Lex Fridman
You know those - just on a small tangent -

Bliss Chapman
Yeah.

Lex Fridman
- the - which I've been meaning to go down this rabbit hole of people that set the world record in Tetris. Those folks, they're playing - there's a way to - did you see this?

Bliss Chapman
I've seen it. All the fingers are moving?

Lex Fridman
Yeah, you could find a way to do it where it's using a loophole, like a bug that you can do some incredibly fast stuff. So it's along that line, but not quite. But you do realize there'll be a few programmers right now listening to this who'll fast and eat peanut butter, and be like-

Bliss Chapman
Yeah, please track my record. I mean, the reason I did this literally was just because I wanted the bar to be high for the team. The number that we aim for should not be the median performance, it should be able to beat all of us at least, that should be the minimum bar.

Lex Fridman
What do you think is possible, like 20?

Bliss Chapman
Yeah, I don't know what the limits- I mean, the limits, you can calculate just in terms of screen refresh rate and cursor immediately jumping to the next target. I mean, I'm sure there's limits before that with just sort of reaction time, and visual perception, and things like this. I would guess it's below 40, but above 20, somewhere in there is probably the right - that I'd never to be thinking about. It also matters how difficult the task is. You can imagine some people might be able to do 10,000 targets on the screen, and maybe they can do better that way. So there's some task optimizations you could do to try to boost your performance as well.

Lex Fridman
What do you think it takes for Noland to be able to do above 8.5, to keep increasing that number? You said every increase in the number - to keep increasing that number. You said every increase in the number might require different improvements in the system.

Bliss Chapman
Yeah. The first answer that's important to say is, I don't know. This is edge of the research so, again, nobody's gotten to that number before, so what's next is going to be a heuristic guess from my part. What we've seen historically is that different parts of the stack can compile next to different time points. So when I first joined Neuralink, three years ago or so, one of the major problems was just the latency of the Bluetooth connection. The radio in the device wasn't super good, it was an early revision of the implant. And it just, no matter how good your decoder was, if your thing is updating every 30 milliseconds or 50 milliseconds, it's just going to be choppy. And no matter how good you are, that's going to be frustrating and lead to challenges. So at that point, it was very clear that the main challenge is just get the data off the device in a very reliable way such that you can enable the next challenge to be tackled. And then at some point it was actually the modeling challenge of how do you just build a good mapping, like the supervised learning problem of, you have a bunch of data and you have a label you're trying to predict, just what is the right neural decoder architecture and hyperparameters to optimize that? And that was the problem for a bit, and once you solve that, it became a different bottleneck. I think the next bottleneck after that was actually just software stability and reliability. If you have widely varying inference latency in your system or your app just lags out every once in a while, it decreases your ability to maintain and get in a state of flow, and it basically just disrupts your control experience. And so there's a variety of different software bugs and improvements we made that basically increased the performance of the system, made it much more reliable, much more stable and led to a state where we could reliably collect data to build better models with. So that was a bottleneck for a while, it was just the software stack itself. If I were to guess right now, there's two major directions you could think about for improving VPS further. The first major direction is labeling. So labeling is, again, this fundamental challenge of given a window of time where the user is expressing some behavioral intent, what are they really trying to do at the granularity of every millisecond? And that again, is a task design problem, it's a UX problem, it's a machine learning problem, it's a software problem. It touches all those different domains. The second thing you can think about to improve BPS further is either completely changing the thing you're decoding or just extending the number of things that you're decoding. So this is serving the direction of functionality, basically, you can imagine giving more clicks. For example, a left click, a right click, a middle click, different actions like click-and-drag for example, and that can improve the effective bit rate of your communication processes. If you're trying to allow the user to express themselves through any given communication channel, you can measure that with bits per second. But what actually is measured at the end of the day is how effective are they at navigating their computer? So from the perspective of the downstream tasks that you care about, functionality and extending functionality is something we're very interested in, because not only can it improve the number of BPS, but it can also improve the downstream independence that the user has and the skill and efficiency with which they can operate their computer.

Lex Fridman
Would the number of threads increasing also potentially help?

Bliss Chapman
Yes. Short answer is: Yes. It's a bit nuanced how that manifests in the numbers. So what you'll see is that if you plot a curve of number of channels that you're using for decode versus either the offline metric of how good you are at decoding or the online metric of in practice how good is the user at using this device, you see roughly a log curve. So as you move further out in number of channels, you get a corresponding logarithmic improvement in control quality and offline validation metrics. The important nuance here is that each channel corresponds with a specific represented intention in the brain. So for example, if you have a channel 254, it might correspond with moving to the right. Channel 256, might mean move to the left. If you want to expand the number of functions you want to control, you really want to have a broader set of channels that covers a broader set of imagined movements. You can think of it like Mr. Potato Man actually, if you had a bunch of different imagined movements you could do, how would you map those imagined movements to input to a computer? You could imagine handwriting to output characters on the screen. You could imagine just typing with your fingers and have that output text on the screen. You could imagine different finger modulations for different clicks. You can imagine wiggling your big nose for opening some menu or wiggling your big toe to have command tab occur or something like this. So it's really the amount of different actions you can take in the world depends on how many channels you have on the information content that they carry.

Lex Fridman
Right, so that's more about the number of actions. So actually as you increase the number of threads, that's more about increasing the number of actions you're able to perform.

Bliss Chapman
But one other nuance there that is worth mentioning. So again, our goal is really to enable a user with paralyzes to control the computer as fast as I can, so that's BPS, with all the same functionality I have, which is what we just talked about, but then also as reliably as I can. And that last point is very related to channel account discussion. So as you scale out number of channels, the relative importance of any particular feature of your model input to the output control of the user diminishes, which means that if the neural non-stationarity effect is per channel, or if the noise is independent such that more channels means on average less output effect, then your reliability of your system will improve. So one core thesis that at least I have is that scaling channel account should improve the reliability system without any work on the decoder itself.

Lex Fridman
Can you linger on the reliability here? So first of all, when you say non-stationarity of the signal, which aspect are you referring to?

Bliss Chapman
Yeah, so maybe let's talk briefly what the actual underlying signal looks like. So again, I spoke very briefly at the beginning about how when you imagine moving to the right or imagine moving to the left, neurons might fire more or less, and the frequency content that signal, at least in the motor cortex, it's very correlated with the output intention, the behavioral task that the user is doing. You can imagine actually this is not obvious that rate coding, which is the name of that phenomenon, is the only way the brain could represent information. You can imagine many different ways in which the brain could encode intention, and there's actually evidence in bats for example, that there's temporal codes. So timing codes of exactly when particular neurons fire is the mechanism of information representation. But at least in the motor cortex, there's substantial evidence that it's rate coding or at least first order of effect is that it's rate coding. So then if the brain is representing information by changing the frequency of a neuron firing, what really matters is the delta between the baseline state of the neuron and what it looks like when it's modulated. And what we've observed and what has also been observed in academic work is that that baseline rate, if you're to target the scale, if you imagine that analogy for measuring flour or something when you're baking, that baseline state of how much the pot weighs is actually different day to day. So if what you're trying to measure is how much rice is in the pot, you're going to get a different measurement different days because you're measuring with different pots. So that baseline rate shifting is really the thing that at least from a first order description of the problem is what's causing this downstream bias. There can be other effects, not linear effects on top of that, but at least at a very first order description of the problem. That's what we observed day to day is that the baseline firing rate of any particular neuron or observed on a particular channel is changing.

Lex Fridman
So can you just adjust to the baseline to make it relative to the baseline nonstop?

Bliss Chapman
Yeah, this is a great question. So with monkeys, we have found various ways to do this. One example way to do this is you ask them to do some behavioral tasks like play the game with a joystick, you measure what's going on in the brain. You compute some mean of what's going on across all the input features, and you subtract that on the input when you're doing your BCI session, works super well. For whatever reason, that doesn't work super well with Noland. I actually don't know the full reason why, but I can imagine several explanations. One such explanation could be that the context effect difference between some open-loop task and some closed-loop task is much more significant with Noland than it is with the monkey. Maybe in this open-loop task, he's watching the Lex Fridman Podcast while he's doing the task or he's whistling and listening to music and talking with his friend and ask his mom what's for dinner while he's doing this task. So the exact difference in context between those two states may be much larger and thus lead to a bigger generalization gap between

the features that you're normalizing at open-loop time and what you're trying to use at closed-loop time.

Lex Fridman
That's interesting. Just on that point, it's incredible to watch Noland be able to multitask, to do multiple tasks at the same time, to be able to move the mouse cursor effectively while talking and while being nervous because he's talking in front of -

Bliss Chapman
Kicking my ass and chest too, yeah.

Lex Fridman
Kicking your ass and talk trash while doing it -

Bliss Chapman
Yes.

Lex Fridman
- so all at the same time. And yes, if you are trying to normalize to the baseline, that might throw everything off. Boy, is that interesting?

Bliss Chapman
Maybe one comment on that too. For folks that aren't familiar with assistive technology, I think there's a common belief that, well, why can't you just use an eye tracker or something like this for helping somebody move a mouse on the screen? It's really a fair question and one that I actually was not confident before Sir Noland that this was going to be a profoundly transformative technology for people like him. And I'm very confident now that it will be, but the reasons are subtle. It really has to do with ergonomically how it fits into their life, even if you can just offer the same level of control as what they would have with an eye tracker or with a mouse stick, but you don't need to have that thing in your face. You don't need to be positioned a certain way. You don't need your caretaker to be around to set it up for you. You can activate it when you want, how you want, wherever you want. That level of independence is so game-changing for people. It means that they can text a friend at night privately without their mom needing to be in the loop. It means that they can open up and browse the internet at 2:00am when nobody's around to set their iPad up for them. This is a profoundly game-changing thing for folks in that situation, and this is even before we start talking about folks that may not be able to communicate at all or ask for help when they want to. This can be potentially the only link that they have to the outside world. And yeah, that one doesn't, I think, need explanation of why that's so impactful.

Lex Fridman
You mentioned NeuroDecodeR. How much machine learning is in the decoder, how much magic, how much science, how much art? How difficult is it to come up with a decoder that figures out what these sequence of spikes mean?

Bliss Chapman
Yeah, good question. There's a couple of different ways to answer this, so maybe I'll zoom out briefly first and then I'll go down one of the rabbit holes. So the zoomed out view is that building the decoder is really the process of building the dataset plus compiling it into the weights, and each of those steps is important. The direction I think of further improvement is primarily going to be in the dataset side of how do you construct the optimal labels for the model. But there's an entirely separate challenge of then how do you compile the best model? And so I'll go briefly down the second rabbit hole. One of the main challenges with designing the optimal model for BCI is that offline metrics don't necessarily correspond to online metrics. It's fundamentally a control problem. The user is trying to control something on the screen and the exact user experience of how you output the intention impacts their ability to control. So for example, if you just look at validation loss as predicted by your model, there can be multiple ways to achieve the same validation loss. Not all of them are equally controllable by the end user. And so it might be as simple as saying, oh, you could just add auxiliary loss terms that help you capture the thing that actually matters. But this is a very complex nuanced process. So how you turn the labels into the model is more of a nuanced process than just a standard supervised learning problem. One very fascinating anecdote here, we've tried many different neural network architectures that translate brain data to velocity outputs, for example. And one example that's stuck in my brain from a couple of years ago now is at one point, we were using just fully-connected networks to decode the brain activity. We tried A-B test where we were measuring the relative performance in online control sessions of one deconvolution over the input signal. So if you imagine per channel you have a sliding window that's producing some convolved feature, for each of those input sequences for every single channel simultaneously, you can actually get better validation metrics, meaning you're fitting the data better and it's generalizing better in offline data if you use this convolutional architecture. You're reducing parameters. It's a standard procedure when you're dealing with time series data. Now it turns out that when using that model online, the controllability was worse, was far worse, even though the offline metrics were better, and there can be many ways to interpret that. But what that taught me at least was that, hey, it's at least the case right now that if you were to just throw a bunch of compute at this problem and you were trying to hyperparameter optimize or let some GPT model hard code or come up with or invent many different solutions, if you were just optimizing for loss, it would not be sufficient, which means that there's still some inherent modeling gap here. There's still some artistry left to be uncovered here of how to get your model to scale with more compute, and that may be fundamentally a labeling problem, but there may be other components to this as well.

Lex Fridman
Is it data constraint at this time, which is what it sounds like? How do you get a lot of good labels?

Bliss Chapman
Yeah, I think it's data quality constrained, not necessarily data quantity constrained.

Lex Fridman
But even just the quantity 'cause it has to be trained on the interactions. I guess there's not that many interactions.

Bliss Chapman
Yeah, so it depends what version of this you're talking about. So if you're talking about, let's say, the simplest example of just 2D velocity, then I think, yeah, data quality is the main thing. If you're talking about how to build a multi-function output that lets you do all the inputs the computer that you and I can do, then it's actually a much more sophisticated nuanced modeling challenge because now you need to think about not just when the users are left clicking, but when you're building the left click model, you also need to be thinking about how to make sure it doesn't fire when they're trying to right click or when they're trying to move the mouse. So one example of an interesting bug from week one of BCI with Noland was when he moved the mouse, the click signal dropped off a cliff and when he stopped, the click signal went up. So again, there's a contamination between the two inputs. Another good example was at one point he was trying to do a left click and drag, and the minute he started moving, the left click signal dropped off a cliff. So again, 'cause some contamination between the two signals, you need to come up with some way to either in the dataset or in the model build robustness against this kind of, you think of it like overfitting, but really it's just that the model has not seen this kind of variability before. So you need to find some way to help the model with that.

Lex Fridman
This is super cool 'cause it feels like all of this is very solvable, but it's hard.

Bliss Chapman
Yes, it is fundamentally an engineering challenge. This is important to emphasize, and it's also important to emphasize that it may need fundamentally new techniques, which means that people who work on let's say unsupervised speech classification using CTC loss for example, with internal to Siri, they could potentially have very applicable skills to this.

Lex Fridman
So what things are you excited about in the future development of the software stack on Neuralink? So everything we've been talking about, the decoding, the UX?

Bliss Chapman

I think there's something I'm excited about from the technology side and some I'm excited about for understanding how this technology is going to be best situated for entering the world, so I'll work backwards. On the technology entering the world side of things, I'm really excited to understand how this device works for folks that cannot speak at all, that have no ability to bootstrap themselves into useful control by voice command, for example, and are extremely limited in their current capabilities. I think that will be an incredibly useful signal for us to understand really, what is an existential threat for all startups, which is product market fit. Does this device have the capacity and potential to transform people's lives in the current state? And if not, what are the gaps? And if there are gaps, how do we solve them most efficiently? So that's what I'm very excited about for the next year or so of clinical trial operations. On the technology side, I'm quite excited about basically everything we're doing. I think it's going to be awesome. The most prominent one I would say is scaling channel account. So right now we have a 1,000-channel device. The next version we'll have between 3 and 6,000 channels, and I would expect that curve to continue in the future. And it's unclear what set of problems will just disappear completely at that scale and what set of problems will remain and require for their focus. And so I'm excited about the clarity of gradient that gives us in terms of the user experiences we choose to focus our time and resources on. And then also in terms of even things as simple as non-stationarity, does that problem just completely go away at that scale? Or do we need to come up with new creative UXes still even at that point? And also when we get to that time point, when we start expanding out dramatically the set of functions that you can output from one brain how to deal with all the nuances of both the user experience of not being able to feel the different keys under your fingertips, but still needing to be able to modulate all of them in synchrony to achieve the thing you want. And again, you don't have that appropriate set of feedback loop, so how can you make that intuitive for a user to control a high dimensional control surface without feeling the thing physically? I think that's going to be a super interesting problem. I'm also quite excited to understand do these scaling laws continue? As you scale channel count, how much further out do you go before that saturation point is truly hit? And it's not obvious today. I think we only know what's in the interpolation space. We only know what's between 0 and 1,024, but we don't know what's beyond that. And then there's a whole range of interesting neuroscience and brain questions, which is, when you stick more stuff in the brain in more places, you get to learn much more quickly about what those brain regions represent. And so I'm excited about that fundamental neuroscience learning, which is also important for figuring out how to most efficiently insert electrodes in the future. So yeah, I think all those dimensions I'm really, really excited about. And that doesn't even get close to touching the software stack that we work on every single day and what we're working on right now.

Lex Fridman

Yeah, it seems virtually impossible to me that 1,000 electrodes is where it saturates. It feels like this would be one of those silly notions in the future where obviously you should have millions of electrodes and this is where the true breakthroughs happen. You tweeted, “Some thoughts are most precisely described in poetry.” Why do you think that is?

Bliss Chapman
I think it’s because the information bottleneck of language is pretty steep, and yet you’re able to reconstruct on the other person’s brain more effectively without being literal. If you can express a sentiment such that in their brain they can reconstruct the actual true underlying meaning and beauty of the thing that you’re trying to get across, the generator function in their brain is more powerful than what language can express. And so the mechanism of poetry is really just to feed or seed that generator function.

Lex Fridman
So being literal sometimes is a suboptimal compression for the thing you’re trying to convey.

Bliss Chapman
That right. And it’s actually in the process of the user going through that generation that they understand what you mean. That’s the beautiful part. It’s also like when you look at a beautiful painting, it’s not the pixels of the painting that are beautiful, it’s the thought process that occurs when you see that, the experience of that, that actually is the thing that matters.

Lex Fridman
Yeah, it’s resonating with some deep thing within you that the artist also experienced and was able to convey that through the pixels.

Bliss Chapman
Right. Right.

Lex Fridman
And that’s actually going to be relevant for full-on telepathy. It’s like if you just read the poetry literally, that doesn’t say much of anything interesting. It requires a human to interpret it. So it’s the combination of the human mind and all the experiences that a human being has within the context of the collective intelligence of the human species that makes that poem make sense and they load that in. So in that same way, the signal that carries from human to human meaning may seem trivial, but may actually carry a lot of power because of the complexity of the human mind and the receiving end. Yeah, that’s interesting. Who was it? I think Joscha Bach on my first podcast said something about, "All the people that think we’ve achieved AGI. Explain why humans like music."

Bliss Chapman
Oh, yeah.

Lex Fridman
And until the AGI likes music, you haven't achieved AGI or something like this.

Bliss Chapman
Do you not think that's some next token entropy surprise kind of thing going on there?

Lex Fridman
I don't know.

Bliss Chapman
I don't know either. I listen to a lot of classical music and also read a lot of poetry and yeah, I do wonder if there is some element of the next token surprise factor going on there.

Lex Fridman
Yeah, maybe.

Bliss Chapman
Cause a lot of the tricks in both poetry and music are basically you have some repeated structure and then you do a twist. It's like, okay, clause 1, 2, 3 is one thing and then clause four is like, "Okay, now we're onto the next theme," and they play with exactly when the surprise happens and the expectation of the user. And that's even true through history as musicians evolve in music, they take some known structure that people are familiar with and they just tweak it a little bit. They tweak it and add a surprising element. This is especially true in classical music heritage, but that's what I'm wondering. Is it all just entropy?

Lex Fridman
So breaking structure or breaking symmetry is something that humans seem to like. Maybe it's as simple as that.

Bliss Chapman
Yeah, and great artists copy and knowing which rules to break is the important part, and fundamentally, it must be about the listener of the piece. Which rule is the right one to break? It's about the audience member perceiving that as interesting.

Lex Fridman
What do you think is the meaning of human existence?

Bliss Chapman
There's a TV show I really like called The West Wing, and in The West Wing there's a character, he's the President of the United States who's having a discussion about the Bible with one of their colleagues. And the colleague says something about the Bible says X, Y,

and Z, and the President says, "Yeah, but it also says A, B, C." The person says, "Well, do you believe the Bible to be literally true?" And the President says, "Yes, but I also think that neither of us are smart enough to understand it." I think the analogy here for the meaning of life is that largely we don't know the right question to ask. So I think I'm very aligned with the Hitchhiker's Guide to the Galaxy version of this question, which is basically, if we can ask the right questions, it's much more likely we find the meaning of human existence. So in the short term as a heuristic in the search policy space, we should try to increase the diversity of people asking such questions or generally of consciousness and conscious beings asking such questions. So again, I think I will take the I don't know card here, but say I do think there are meaningful things we can do that improve the likelihood of answering that question.

Lex Fridman
It's interesting how much value you assign to the task of asking the right questions. That's the main thing, it's not the answers, it's the questions.

Bliss Chapman
This point, by the way, is driven home in a very painful way when you try to communicate with someone who cannot speak, because a lot of the time, the last thing to go is they have the ability to somehow wiggle a lip or move something that allows them to say yes or no. And in that situation, it's very obvious that what matters is, are you asking them the right question to be able to say yes or no to?

Lex Fridman
Wow, that's powerful. Well, Bliss, thank you for everything you do, and thank you for being you, and thank you for talking today.

Bliss Chapman
Thank you.

Lex Fridman
Thanks for listening to this conversation with Bliss Chapman. And now, dear friends, here's Noland Arbaugh, the first human being to have a Neuralink device implanted in his brain. You had a diving accident in 2016 that left you paralyzed with no feeling from the shoulders down. How did that accident change your life?

Noland Arbaugh
It was a freak thing that happened. Imagine you're running into the ocean, although this is a lake, but you're running into the ocean and you get to about waist high, and then you dive in, take the rest of the plunge under the wave or something. That's what I did, and then I just never came back up. Not sure what happened. I did it running into the water with a couple of guys, and so my idea of what happened is really just that I took a stray fist, elbow, knee,

foot, something to the side of my head. The left side of my head was sore for about a month afterwards, so I must've taken a pretty big knock, and then they both came up and I didn't. And so I was face down in the water for a while. I was conscious, and then eventually just realized I couldn't hold my breath any longer and I keep saying took a big drink. People, I don't know if they like that I say that. It seems like I'm making light of it all, but it's just how I am, and I don't know. I am a very relaxed stress-free person. I rolled with the punches for a lot of this. I took it in stride. It's like, "Alright, well, what can I do next? How can I improve my life even a little bit on a day-to-day basis?" At first, just trying to find some way to heal as much of my body as possible to try to get healed, to try to get off a ventilator, learn as much as I could so I could somehow survive once I left the hospital. And then thank God I had my family around me. If I didn't have my parents, my siblings, then I would've never made it this far. They've done so much for me, more than I can ever thank them for, honestly, and a lot of people don't have that. A lot of people in my situation, their families either aren't capable of providing for them or honestly just don't want to, and so they get placed somewhere in some sort of home. So thankfully, I had my family. I have a great group of friends, a great group of buddies from college who have all rallied around me, and we're all still incredibly close. People always say if you're lucky, you'll end up with one or two friends from high school that you keep throughout your life. I have about 10 or 12 from high school that have all stuck around, and we still get together, all of us twice a year. We call it the spring series and the fall series. This last one we all did, we dressed up X-Men, so I did a -

Lex Fridman
Nice.

Noland Arbaugh
- Professor Xavier, and it was freaking awesome. It was so good. So yeah, I have such a great support system around me, and so being a quadriplegic isn't that bad. I get waited on all the time. People bring me food and drinks, and I get to sit around and watch as much TV and movies and anime as I want. I get to read as much as I want. It's great.

Lex Fridman
It's beautiful to see that you see the silver lining in all of this. Just going back, do you remember the moment when you first realized you were paralyzed from the neck down?

Noland Arbaugh
Yup. I was face down in the water when I - whatever, something hit my head. I tried to get up and I realized I couldn't move, and it just clicked. I'm like, "Alright, I'm paralyzed, can't move. What do I do? If I can't get up? I can't flip over, can't do anything, then I'm going to drown eventually." And I knew I couldn't hold my breath forever, so I just held my breath and thought about it for maybe 10-15 seconds. I've heard from other people that on lookers, I guess the two girls that pulled me out of the water were two of my best friends. They were lifeguards, and one of them said that it looked like my body was shaking in the water like I

was trying to flip over and stuff, but I knew. I knew immediately, and I realized that that's what my situation was from here on out. Maybe if I got to the hospital, they'd be able to do something.When I was in the hospital right before surgery, I was trying to calm one of my friends down. I had brought her with me from college to camp, and she was just bawling over me, and I was like, "Hey, it's going to be fine. Don't worry." I was cracking some jokes to try to lighten the mood. The nurse had called my mom, and I was like, "Don't tell my mom. She's just going to be stressed out. Call her after I'm out of surgery 'cause at least she'll have some answers then, whether I live or not, really." And I didn't want her to be stressed through the whole thing, but I knew. And then when I first woke up after surgery, I was super drugged up. They had me on fentanyl three ways, which was awesome. I don't recommend it, but I saw some crazy stuff on that fentanyl, and it was still the best I've ever felt on drugs, medication, sorry, on medication. I remember the first time I saw my mom in the hospital, I was just bawling. I had ventilator in. I couldn't talk or anything, and I just started crying because it was more like seeing her - the whole situation obviously was pretty rough, but it was just seeing her face for the first time was pretty hard. But yeah, I never had a moment of, "Man, I'm paralyzed. This sucks. I don't want to be around anymore." It was always just, "I hate that I have to do this, but sitting here and wallowing isn't going to help."

Lex Fridman
So immediate acceptance.

Noland Arbaugh
Yeah. Yeah.

Lex Fridman
Has there been low points along the way?

Noland Arbaugh
Yeah, yeah, sure. There are days when I don't really feel like doing anything. Not so much anymore. Not for the last couple of years I don't really feel that way. I've more so just wanted to try to do anything possible to make my life better at this point. But at the beginning, there were some ups and downs. There were some really hard things to adjust to. First off, just the first couple months, the amount of pain I was in was really, really hard. I remember screaming at the top of my lungs in the hospital because I thought my legs were on fire, and obviously I can't feel anything, but it's all nerve pain. And so that was a really hard night. I asked them to give me as much pain meds as possible, but they're like, "You've had as much as you can have, so just deal with it. Go to a happy place," sort of thing. So that was a pretty low point. And then every now and again, it's hard realizing things that I wanted to do in my life that I won't be able to do anymore. I always wanted to be a husband and father, and I just don't think that I could do it now as a quadriplegic. Maybe it's possible, but I'm not sure I would ever put someone I love through that, having to take care of me and stuff. Not being able to go out and play sports, I was a huge athlete growing up, so that was pretty hard.

Little things too, when I realized I can't do them anymore. There's something really special about being able to hold a book and smell a book, the feel, the texture, the smell as you turn the pages, I just love it and I can't do it anymore, and it's little things like that. The two-year mark was pretty rough. Two years is when they say you will get back basically as much as you're ever going to get back as far as movement and sensation goes. And so for the first two years, that was the only thing on my mind was try as much as I can to move my fingers, my hands, my feet, everything possible to try to get sensation and movement back. And then when the two-year mark hit, so June 30, 2018, I was really sad that that's where I was, and then just randomly here and there, but I was never depressed for long periods of time. Just it never seemed worthwhile to me.

Lex Fridman
What gave you strength?

Noland Arbaugh
My faith. My faith in God was a big one. My understanding that it was all for purpose, and even if that purpose wasn't anything involving Neuralink, even if that purpose was - there's a story in the Bible about Job, and I think it's a really, really popular story about how Job has all of these terrible things happen to him, and he praises God throughout the whole situation. I thought, and I think a lot of people think for most of their lives that they are Job, that they're the ones going through something terrible, and they just need to praise God through the whole thing and everything will work out. At some point after my accident, I realized that I might not be Job, that I might be one of his children that gets killed or kidnapped or taken from him. And so it's about terrible things that happen to those around you who you love. So maybe in this case, my mom would be Job and she has to get through something extraordinarily hard, and I just need to try and make it as best as possible for her because she's the one that's really going through this massive trial. She's the one that's really going through this massive trial and that gave me a lot of strength, and obviously my family. My family and my friends, they give me all the strength that I need on a day-to-day basis. So it makes things a lot easier having that great support system around me.

Lex Fridman
From everything I've seen of you online, your streams and the way you are today, I really admire, let's say your unwavering positive outlook on life. Has that always been this way?

Noland Arbaugh
Yeah, yeah. I mean, I've just always thought I could do anything I ever wanted to do. There was never anything too big. Whatever I set my mind to, I felt like I could do it. I didn't want to do a lot. I wanted to travel around and be sort of like a gypsy and go work odd jobs. I had this dream of traveling around Europe and being like, I don't know, a shepherd in Wales or Ireland, and then going and being a fisherman in Italy, doing all of these things for a year. It's such cliche things, but I just thought it would be so much fun to go and travel and do

different things. And so I've always just seen the best in people around me too, and I've always tried to be good to people. And growing up with my mom too, she's like the most positive energetic person in the world, and we're all just people people. I just get along great with people. I really enjoy meeting new people, and so I just wanted to do everything. This is kind of just how I've been.

Lex Fridman
It's just great to see that cynicism didn't take over given everything you've been through.

Noland Arbaugh
Yeah.

Lex Fridman
Was that a deliberate choice you made, that you're not going to let this keep you down?

Noland Arbaugh
Yeah, a bit. Also, it's just kind of how I am. I just, like I said, I roll with the punches with everything. I always used to tell people I don't stress about things much, and whenever I'd see people getting stressed, I would just say, "It's not hard just don't stress about it and that's all you need to do. And they're like, "That's not how that works." I'm like, "It works for me. Just don't stress and everything will be fine. Everything will work out." Obviously not everything always goes well, and it's not like it all works out for the best all the time, but I just don't think stress has had any place in my life since I was a kid.

Lex Fridman
What was the experience like of you being selected to be the first human being to have a Neuralink device implanted in your brain? Were you scared? Excited?

Noland Arbaugh
No, no. It was cool. I was never afraid of it. I had to think through a lot. Should I do this? Be the first person? I could wait until number two or three and get a better version of the Neuralink. The first one might not work. Maybe it's actually going to kind of suck. It's going to be the worst version ever in a person, so why would I do the first one? I've already kind of been selected? I could just tell them, "Okay, find someone else, and then I'll do number two or three." I'm sure they would let me, they're looking for a few people anyways, but ultimately I was like, I don't know? There's something about being the first one to do something. It's pretty cool. I always thought that if I had the chance that I would like to do something for the first time, this seemed like a pretty good opportunity. And I was never scared. I think my faith had a huge part in that. I always felt like God was preparing me for something. I almost wish it wasn't this, because I had many conversations with God about not wanting to do any of this as a quadriplegic. I told Him, "I'll go out and talk to people. I'll go out and travel the world and talk to stadiums, thousands of people, give my testimony. I'll do all of it, but heal

me first. Don't make me do all of this in a chair. That sucks." And I guess He won that argument. I didn't really have much of a choice. I always felt like there was something going on. And to see how, I guess easily I made it through the interview process and how quickly everything happened, how the stars sort of aligned with all of this. It just told me as the surgery was getting closer, it just told me that it was all meant to happen. It was all meant to be, and so I shouldn't be afraid of anything that's to come. And so I wasn't. I kept telling myself like, "You say that now, but as soon as the surgery comes, you're probably going to be freaking out. You're about to have brain surgery." And brain surgery is a big deal for a lot of people, but it's an even bigger deal for me. It's all I have left. The amount of times I've been like, "Thank You, God, that you didn't take my brain and my personality and my ability to think, my love of learning, my character, everything. Thank You so much. As long as You left me that, then I think I can get by." And I was about to let people go root around in there like, "Hey, we're going to go put some stuff in your brain. Hopefully it works out." And so it was something that gave me pause, but like I said, how smoothly everything went. I never expected for a second that anything would go wrong. Plus the more people I met on the Barrow side and on the Neuralink side, they're just the most impressive people in the world. I can't speak enough to how much I trust these people with my life and how impressed I am with all of them. And to see the excitement on their faces, to walk into a room and, roll into a room and see all of these people looking at me like, "We're so excited. We've been working so hard on this and it's finally happening." It's super infectious and it just makes me want to do it even more. And to help them achieve their dreams, I don't know, it's so rewarding and I'm so happy for all of them, honestly.

Lex Fridman

What was the day of surgery like? When did you wake up? What'd you feel? Minute-by-minute. Were you freaking out?

Noland Arbaugh

No, no. I thought I was going to, but as surgery approached the night before, the morning of, I was just excited. I was like, "Let's make this happen." I think I said that, something like that to Elon on the phone. Beforehand we were FaceTiming, and I was like, "Let's rock and roll." And he's like, "Let's do it." I don't know. I wasn't scared. So we woke up. I think we had to be at the hospital at 5:30am. I think surgery was at 7:00am So we woke up pretty early. I'm not sure much of us slept that night. Got to the hospital 5:30, went through all the pre-op stuff. Everyone was super nice. Elon was supposed to be there in the morning, but something went wrong with his plane, so we ended up FaceTiming. That was cool. I had one of the greatest one-liners of my life after that phone call. Hung up with him. There were 20 people around me and I was like, "I just hope he wasn't too starstruck talking to me."

Lex Fridman

Nice.

Noland Arbaugh
And yeah, it was good.

Lex Fridman
Well done. Well done. Did you write that ahead of time it just came to you?

Noland Arbaugh
No. No, it just came to me. I was like, "This seems right." Went into surgery. I asked if I could pray right beforehand, so I prayed over the room. I asked God if He would be with my mom in case anything happened to me and just to calm her nerves out there. Woke up, played a bit of a prank on my mom. I don't know if you've heard about it?

Lex Fridman
Yeah, I read about it.

Noland Arbaugh
Yeah, she was not happy.

Lex Fridman
Can you take me through the prank?

Noland Arbaugh
Yeah. This is something -

Lex Fridman
Do you regret doing that now?

Noland Arbaugh
No, no. Not one bit. It was something I had talked about ahead of time with my buddy Bane. I was like, "I would really like to play a prank on my mom." Very specifically, my mom. She's very gullible. I think she had knee surgery once even, and after she came out of knee surgery, she was super groggy. She's like, "I can't feel my legs." And my dad looked at her. He was like, "You don't have any legs. They had to amputate both your legs." And we just do very mean things to her all the time. I'm so surprised that she still loves us. But right after surgery, I was really worried that I was going to be too groggy, not all there. I had had anesthesia once before and it messed me up. I could not function for a while afterwards. And I said a lot of things that - I was really worried that I was going to start, I don't know, dropping some bombs and I wouldn't even know. I wouldn't remember. So I was like, "Please God, don't let that happen, and please let me be there enough to do this to my mom." And so she walked in after surgery. It was the first time they had been able to see me after surgery, and she just looked at me. She said, "Hi, how are you? How are you doing? How do you feel?" And I looked at her and this very, I think the anesthesia helped, very groggy, sort of

confused look on my face. It's like, "Who are you?" And she just started looking around the room at the surgeons, at the doctors like, "What did you do to my son? You need to fix this right now." Tears started streaming. I saw how much she was freaking out. I was like, "I can't let this go on." And so I was like, "Mom, mom, I'm fine. It's alright." And still, she was not happy about it. She still says she's going to get me back someday, but I mean, I don't know. I don't know what that's going to look like.

Lex Fridman
It's a lifelong battle, man.

Noland Arbaugh
Yeah, but it was good.

Lex Fridman
In some sense it was a demonstration that you still got - still had a sense of humor.

Noland Arbaugh
That's all I wanted it to be. That's all I wanted it to be. And I knew that doing something super mean to her like that would show her.

Lex Fridman
To show that you're still there, that you love her.

Noland Arbaugh
Yeah, exactly. Exactly.

Lex Fridman
It's a dark way to do it, but I love it.

Noland Arbaugh
Yeah.

Lex Fridman
What was the first time you were able to feel that you can use the Neuralink device to affect the world around you?

Noland Arbaugh
The first little taste I got of it was actually not too long after surgery. Some of the Neuralink team had brought in a little iPad, a little tablet screen, and they had put up eight different channels that were recording some of my neuron spikes and they put it in front of me. They're like, "This is real time your brain firing." I was like, "That's super cool." My first thought was, "I mean, if they're firing now, let's see if I can affect them in some way." So I

started trying to wiggle my fingers and I just started scanning through the channels, and one of the things I was doing was moving my index finger up and down, and I just saw this yellow spike on top row, third box over or something. I saw this yellow spike every time I did it, and I was like, "Oh, that's cool." And everyone around me was just like, "What are you seeing?" I was like, "Look at this one. Look at this top row, third box over this yellow spike. That's me right there, there, there." And everyone was freaking out. They started clapping. I was like, "That's super unnecessary." This is what's supposed to happen, right?

Lex Fridman
So you're imagining yourself moving each individual finger one at a time, and then seeing that you can notice something. And then when you did the index finger, you're like, "Oh, cool."

Noland Arbaugh
Yeah, I was wiggling all of my fingers to see if anything would happen. There was a lot of other things going on, but that big yellow spike was the one that stood out to me. I'm sure that if I would've stared at it long enough, I could have mapped out maybe a hundred different things. But the big yellow spike was the one that I noticed.

Lex Fridman
Maybe you could speak to what it's like to wiggle your fingers, to imagine the cognitive effort required to wiggle your index finger, for example. How easy is that to do?

Noland Arbaugh
Pretty easy for me. It's something that at the very beginning, after my accident, they told me to try and move my body as much as possible. Even if you can't, just keep trying because that's going to create new neural pathways or pathways in my spinal cord to reconnect these things to hopefully regain some movement someday.

Lex Fridman
That's fascinating.

Noland Arbaugh
Yeah, I know. It's bizarre.

Lex Fridman
That's part of the recovery process is to keep trying to move your body.

Noland Arbaugh
Yup. Every day as much as you can.

Lex Fridman
And the nervous system does its thing. It starts reconnecting.

Noland Arbaugh
It'll start reconnecting for some people, some people it never works. Some people they'll do it. For me, I got some bicep control back, and that's about it. If I try enough, I can wiggle some of my fingers, not on command. It's more like if I try to move, say my right pinky, and I just keep trying to move it, after a few seconds it'll wiggle. So I know there's stuff there. I know, and that happens with a few different of my fingers and stuff. But yeah, that's what they tell you to do. One of the people at the time when I was in the hospital came in and told me for one guy who had recovered most of his control, what he thought about every day was actually walking, like the act of walking just over and over again. So I tried that for years. I tried just imagining walking, which is, it's hard. It's hard to imagine all of the steps that go into, well, taking a step. All of the things that have to move, all of the activations that have to happen along your leg in order for one step to occur.

Lex Fridman
But you're not just imagining, you're doing it, right?

Noland Arbaugh
I'm trying. Yeah. So it's imagining over again what I had to do to take a step, because it's not something any of us think about. We just, you want to walk and you take a step. You don't think about all of the different things that are going on in your body. So I had to recreate that in my head as much as I could, and then I practice it over, and over, and over again.

Lex Fridman
So it's not like a third-person perspective, it's a first-person perspective. It's not like you're imagining yourself walking. You're literally doing everything, all the same stuff as if you're walking.

Noland Arbaugh
Yeah, which was hard. It was hard at the beginning.

Lex Fridman
Frustrating hard, or actually cognitively hard, which way?

Noland Arbaugh
It was both. There's a scene in one of the Kill Bill movies, actually, oddly enough, where she is paralyzed, I don't know, from a drug that was in her system. And then she finds some way to get into the back of a truck or something, and she stares at her toe and she says, "Move," like move your big toe. And after a few seconds on screen, she does it. And she did that with every one of her body parts until she can move again. I did that for years, just stared at my

body and said, “Move your index finger, move your big toe.” Sometimes vocalizing it out loud, sometimes just thinking it. I tried every different way to do this to try to get some movement back. And it’s hard because it actually is taxing, physically taxing on my body, which is something I would’ve never expected. It’s not like I’m moving, but it feels like there’s a buildup of, the only way I can describe it is there are signals that aren’t getting through from my brain down, because there’s that gap in my spinal cord, so brain down, and then from my hand back up to the brain. And so it feels like those signals get stuck in whatever body part that I’m trying to move, and they just build up, and build up, and build up until they burst. And then once they burst, I get this really weird sensation of everything dissipating back out to level, and then I do it again. It’s also just a fatigue thing, like a muscle fatigue, but without actually moving your muscles. It’s very, very bizarre. And then if you try to stare at a body part or think about a body part and move for two, three, four, sometimes eight hours, it’s very taxing on your mind. It takes a lot of focus. It was a lot easier at the beginning because I wasn’t able to control a TV in my room or anything. I wasn’t able to control any of my environment. So for the first few years, a lot of what I was doing was staring at walls. And so, obviously I did a lot of thinking and I tried to move a lot just over, and over, and over again.

Lex Fridman
So you never gave up hope there?

Noland Arbaugh
No.

Lex Fridman
Just training hard essentially.

Noland Arbaugh
Yeah. And I still do it. I do it subconsciously, and I think that that helped a lot with things with Neuralink, honestly. It’s something that I talked about the other day at the All Hands that I did at Neuralink’s Austin facility.

Lex Fridman
Welcome to Austin, by the way.

Noland Arbaugh
Yeah. Hey, thanks man. I went to school -

Lex Fridman
Nice hat.

Noland Arbaugh
Hey, thanks. Thanks, man. The Gigafactory was super cool. I went to school at Texas A&M. So, I've been around before.

Lex Fridman
So, you should be saying welcome to me. Welcome to Texas, Lex.

Noland Arbaugh
Yeah.

Lex Fridman
I get you.

Noland Arbaugh
But yeah, I was talking about how a lot of what they've had me do, especially at the beginning, well, I still do it now, is body mapping. So there will be a visualization of a hand or an arm on the screen, and I have to do that motion, and that's how they train the algorithm to understand what I'm trying to do. And so it made things very seamless for me I think.

Lex Fridman
That's really, really cool. So it's amazing to know. I've learned a lot about the body mapping procedure with the interface and everything like that. It's cool to know that you've been essentially training to be world-class at that task.

Noland Arbaugh
Yeah. Yeah. I don't know if other quadriplegics, other paralyzed people give up. I hope they don't. I hope they keep trying, because I've heard other paralyzed people say, "Don't ever stop." They tell you two years, but you just never know. The human body's capable of amazing things. So I've heard other people say, "Don't give up." I think one girl had spoken to me through some family members and said that she had been paralyzed for 18 years, and she'd been trying to wiggle her index finger for all that time, and she finally got it back 18 years later. So I know that it's possible, and I'll never give up doing it. I do it when I'm lying down watching TV. I'll find myself doing it just almost on its own. It's just something I've gotten so used to doing that I don't know. I don't think I'll ever stop.

Lex Fridman
That's really awesome to hear. I think it's one of those things that can really pay off in the long term. It is training. You're not visibly seeing the results of that training at the moment, but there's that Olympic level nervous system getting ready for something.

Noland Arbaugh
Which honestly was something that I think Neuralink gave me that I can't thank them enough for. I can't show my appreciation for it enough, was being able to visually see that what I'm doing is actually having some effect. It's a huge part of the reason why I know now that I'm going to keep doing it forever. Because before Neuralink, I was doing it every day and I was just assuming that things were happening. It's not like I knew. I wasn't getting back any mobility or sensation or anything. So I could have been running up against a brick wall for all I knew. And with Neuralink, I get to see all the signals happening real time, and I get to see that what I'm doing can actually be mapped. When we started doing click calibrations and stuff, when I go to click my index finger for a left click, that it actually recognizes that. It changed how I think about what's possible with retraining my body to move. And so yeah, I'll never give up now.

Lex Fridman
And also just the signal that there's still a powerhouse of a brain there that's like, and as the technology develops, that brain is, I mean, that's the most important thing about the human body is the brain, and it can do a lot of the control. So what did it feel like when you first could wiggle the index finger and saw the environment respond? Like that little thing - where everybody is just being "way too dramatic" according to you.

Noland Arbaugh
Yeah, it was very cool. I mean, it was cool, but I keep telling this to people. It made sense to me. It made sense that there are signals still happening in my brain, and that as long as you had something near it that could measure those, that could record those, then you should be able to visualize it in some way. See it happen. And so that was not very surprising to me. I was just like, "Oh, cool. We found one, we found something that works." It was cool to see that their technology worked and that everything that they had worked so hard for was going to pay off. But I hadn't moved a cursor or anything at that point. I hadn't interacted with a computer or anything at that point. So it just made sense. It was cool. I didn't really know much about BCI at that point either, so I didn't know what sort of step this was actually making. I didn't know if this was a huge deal, or if this was just like, "Okay, this is, it's cool that we got this far, but we're actually hoping for something much better down the road." It's like, "Okay." I just thought that they knew that it turned on. So I was like, "Cool, this is cool."

Lex Fridman
Well, did you read up on the specs of the hardware you get installed, the number of threads, all this kind of stuff.

Noland Arbaugh
Yeah, I knew all of that, but it's all Greek to me. I was like, "Okay, 64 threads, 16 electrodes, 1,024 channels. Okay, that math checks out."

Lex Fridman
Sounds right.

Noland Arbaugh
Yeah.

Lex Fridman
When was the first time you were able to move a mouse cursor?

Noland Arbaugh
I know it must have been within the first maybe week, a week or two weeks that I was able to first move the cursor. And again, it kind of made sense to me. It didn't seem like that big of a deal. It was like, okay, well, how do I explain this? When everyone around you starts clapping for something that you've done, it's easy to say, "Okay, I did something cool." That was impressive in some way. What exactly that meant, what it was hadn't really set in for me. So again, I knew that me trying to move a body part and then that being mapped in some sort of machine learning algorithm to be able to identify my brain signals and then take that and give me cursor control, that all kind of made sense to me. I don't know all the ins and outs of it, but I was like, "There are still signals in my brain firing. They just can't get through because there's a gap in my spinal cord, and so they can't get all the way down and back up, but they're still there." So when I moved the cursor for the first time, I was like, "That's cool, but I expected that that should happen." It made sense to me. When I moved the cursor for the first time with just my mind, without physically trying to move. So I guess I can get into that just a little bit. The difference between attempted movement, and imagine movement.

Lex Fridman
Yeah, that's a fascinating difference - the leap from from one to the other.

Noland Arbaugh
Yeah, yeah, yeah. So attempted movement is me physically trying to attempt to move, say my hand. I try to attempt to move my hand to the right, to the left, forward and back. And that's all attempted. Attempt to lift my finger up and down, attempt to kick or something. I'm physically trying to do all of those things, even if you can't see it. This would be me attempting to shrug my shoulders or something. That's all attempted movement. That's what I was doing for the first couple of weeks when they were going to give me cursor control. When I was doing body mapping, it was attempt to do this, attempt to do that. When Nir was telling me to imagine doing it, it kind of made sense to me, but it's not something that people practice. If you started school as a child and they said, "Okay, write your name with this pencil," and so you do that. Like, "Okay, now imagine writing your name with that pencil." Kids would think, "Uh, I guess that kind of makes sense," and they would do it. But that's not something we're taught, it's all how to do things physically. We think about

thought experiments and things, but that's not a physical action of doing things. It's more what you would do in certain situations. So imagine movement, it never really connected with me. I guess you could maybe describe it as a professional athlete swinging a baseball bat or swinging a golf club. Imagine what you're supposed to do. But then you go right to that and physically do it. Then you get a bat in your hand, and then you do what you've been imagining. And so I don't have that connection. So telling me to imagine something versus attempting it, there wasn't a lot that I could do there mentally. I just kind of had to accept what was going on and try. But the attempted moving thing, it all made sense to me. If I try to move, then there's a signal being sent in my brain, and as long as they can pick that up, then they should be able to map it to what I'm trying to do. And so when I first moved the cursor like that, it was just like, "Yes, this should happen. I'm not surprised by that."

Lex Fridman
But can you clarify, is there supposed to be a difference between imagine movement and attempted movement?

Noland Arbaugh
Yeah, just that in imagine movement, you're not attempting to move at all. So it's -

Lex Fridman
You're visualizing what you're doing.

Noland Arbaugh
- visualizing.

Lex Fridman
And then theoretically, is that supposed to be a different part of the brain that lights up in those two different situations?

Bliss Chapman
Yeah, not necessarily. I think all these signals can still be represented in motor cortex, but the difference I think, has to do with the naturalness of imagining something versus -

Lex Fridman
Got it.

Bliss Chapman
- attempting it. The fatigue of that over time.

Lex Fridman
And by the way, on the mic is Bliss. So this is just different ways to prompt you to kind of get to the thing that you arrived at.

Noland Arbaugh
Yeah, yeah.

Lex Fridman
Attempted movement does sound like the right thing. Try.

Noland Arbaugh
Yeah. I mean, it makes sense to me.

Lex Fridman
Because imagine, for me, I would start visualizing, in my mind, visualizing. Attempted I would actually start trying to - I did combat sports my whole life, like wrestling. When I'm imagining a move, see, I'm moving my muscle.

Noland Arbaugh
Exactly.

Lex Fridman
There is a bit of an activation almost versus visualizing yourself, like a picture doing it.

Noland Arbaugh
Yeah. It's something that I feel like naturally anyone would do. If you try to tell someone to imagine doing something, they might close their eyes and then start physically doing it, but it just -

Lex Fridman
Just didn't click.

Noland Arbaugh
Yeah, it's hard. It was very hard at the beginning.

Lex Fridman
But attempted worked.

Noland Arbaugh
Attempted worked. It worked just like it should. Worked like a charm.

Bliss Chapman
Remember there was one Tuesday we were messing around and I think, I forget what swear word you used, but there's a swear word that came out of your mouth when you figured out you could just do the direct cursor control.

Noland Arbaugh
Yeah, it blew my mind, no pun intended. Blew my mind when I first moved the cursor just with my thoughts and not attempting to move. It's something that I found over the couple of weeks building up to that, that as I get better cursor controls, the model gets better, then it gets easier for me to - I don't have to attempt as much to move it. And part of that is something that I'd even talked with them about when I was watching the signals of my brain one day. I was watching when I attempted to move to the right and I watched the screen as I saw the spikes. I was seeing the spike, the signal was being sent before I was actually attempting to move. I imagine just because when you go to say, move your hand or any body part, that signal gets sent before you're actually moving, has to make it all the way down and back up before you actually do any sort of movement. So there's a delay there. And I noticed that there was something going on in my brain before I was actually attempting to move that my brain was anticipating what I wanted to do, and that all started sort of, I don't know, percolating in my brain. It was just there always in the back like, "That's so weird that it could do that. It kind of makes sense, but I wonder what that means as far as using the Neuralink." And then as I was playing around with the attempted movement and playing around with the cursor, and I saw that as the cursor control got better, that it was anticipating my movements and what I wanted it to do, like cursor movements, what I wanted it to do a bit better and a bit better. And then one day I just randomly, as I was playing Webgrid, I looked at a target before I had started attempting to move, I was just trying to get over, train my eyes to start looking ahead, like, "Okay, this is the target I'm on, but if I look over here to this target, I know I can maybe be a bit quicker getting there." And I looked over and the cursor just shot over. It was wild. I had to take a step back. I was like, "This should not be happening." All day I was just smiling. I was so giddy. I was like, "Guys, do you know that this works? I can just think it and it happens." Which they'd all been saying this entire time like, "I can't believe you're doing all this with your mind." I'm like, "Yeah, but is it really with my mind. I'm attempting to move and it's just picking that up so it doesn't feel like it's with my mind." But when I moved it for the first time like that, it was, oh man. It made me think that this technology, that what I'm doing is actually way, way more impressive than I ever thought. It was way cooler than I ever thought, and it just opened up a whole new world of possibilities of what could possibly happen with this technology and what I might be able to be capable of with it.

Lex Fridman
Because you had felt for the first time like this was digital telepathy. You're controlling a digital device with your mind.

Noland Arbaugh
Yup.

Lex Fridman
I mean, that's a real moment of discovery. That's really cool. You've discovered something. I've seen scientists talk about a big aha moment, like Nobel Prize winning. They'll have this like, "Holy crap." Like, "Whoa."

Noland Arbaugh
That's what it felt like. I felt like I had discovered something, but for me, maybe not necessarily for the world-at-large or this field-at-large, it just felt like an aha moment for me. Like, "Oh, this works." Obviously it works. And so that's what I do all the time now. I kind of intermix the attempted movement and imagine movement. I do it all together because I've found that - I do it all together because I've found that there is some interplay with it that maximizes efficiency with the cursor. So it's not all one or the other. It's not all just, I only use attempted or I only use imagined movements. It's more I use them in parallel and I can do one or the other. I can just completely think about whatever I'm doing, but I don't know, I like to play around with it. I also like to just experiment with these things. Every now and again, I'll get this idea in my head, I wonder if this works and I'll just start doing it, and then afterwards I'll tell them, "By the way, I wasn't doing that like you guys wanted me to. I thought of something and I wanted to try it and so I did. It seems like it works, so maybe we should explore that a little bit."

Lex Fridman
So I think that discovery's not just for you, at least from my perspective. That's a discovery for everyone else who ever uses a Neuralink that this is possible. I don't think that's an obvious thing that this is even possible. It's like I was saying to Bliss earlier, it's like the four-minute mile. People thought it was impossible to run a mile in four minutes and once the first person did it, then everyone just started doing it. So just to show that it's possible, that paves the way to anyone can now do it. That's the thing that's actually possible. You don't need to do the attempted movement, you can just go direct.

Noland Arbaugh
Yeah. Yeah.

Lex Fridman
That's crazy.

Noland Arbaugh
It is crazy. It is crazy. Yeah.

Lex Fridman
For people who don't know, can you explain how the Link app works? You have an amazing stream on the topic. Your first stream, I think, on X describing, the app. Can you just describe how it works?

Noland Arbaugh
Yeah, so it's just an app that Neuralink created to help me interact with the computer. So on the Link app there are a few different settings, and different modes, and things I can do on it. So there's the body mapping, which we kind of touched on. There's a calibration. Calibration is how I actually get cursor control, so calibrating what's going on in my brain to translate that into cursor control. So it will pop out models. What they use, I think, is time. So it would be five minutes and calibration will give me so good of a model, and then if I'm in it for 10 minutes and 15 minutes, the models will progressively get better. And so the longer I'm in it, generally, the better the models will get.

Lex Fridman
That's really cool because you often refer to the models. So the model's the thing that's constructed once you go through the calibration step.

Noland Arbaugh
Yeah.

Lex Fridman
And then you also talked about sometimes you'll play a really difficult game like Snake just to see how good the model is.

Noland Arbaugh
Yeah. Yeah, so Snake is kind of like my litmus test for models. If I can control a snake decently well then I know I have a pretty good model. So yeah, the Link app has all of those. It has Webgrid in it now. It's also how I connect to the computer just in general. So they've given me a lot of voice controls with it at this point. So I can say, "Connect," or, "Implant disconnect," and as long as I have that charger handy, then I can connect to it. So the charger is also how I connect to the Link app to connect to the computer. I have to have the implant charger over my head when I want to connect, to have it wake up, because the implant's in hibernation mode always when I'm not using it. I think there's a setting to wake it up every so long, so we could set it to half an hour, or five hours, or something, if I just want it to wake up periodically. So, yeah. I'll connect to the Link app and then go through all sorts of things, calibration for the day, maybe body mapping. I made them give me a little homework tab because I am very forgetful and I forget to do things a lot. So I have a lot of data collection things that they want me to do.

Lex Fridman
Is the body mapping part of the data collection or is that also part of the calibration?

Noland Arbaugh
Yeah, it is. It's something that they want me to do daily, which I've been slacking on because I've been doing so much media and traveling so much. So, I've been - I've been -

Lex Fridman
You've gotten super famous.

Noland Arbaugh
Yeah, I've been a terrible first candidate for how much I've been slacking on my homework. But yeah, it's just something that they want me to do every day to track how well the Neuralink is performing over time and to have something to give, I imagine, to give to the FDA to create all sorts of fancy charts and stuff, and show like, hey, this is what the Neuralink - this is how it's performing day 1, versus day 90, versus day 180, and things like that.

Lex Fridman
What's the calibration step like? Is it move left, move right?

Noland Arbaugh
It's a bubble game. So there will be yellow bubbles that pop up on the screen. At first, it is open loop. So open loop, this is something that I still don't fully understand, the open loop and closed loop thing.

Lex Fridman
The me and Bliss talked for a long time about the difference between the two on the technical side.

Noland Arbaugh
Okay, yeah.

Lex Fridman
So, it'd be great to hear your -

Noland Arbaugh
Okay, so open -

Lex Fridman
- your side of the story.

Noland Arbaugh
Open loop is basically I have no control over the cursor. The cursor will be moving on its own across the screen and I am following, by intention, the cursor to different bubbles. And then the algorithm is training off of what the signals it's getting are as I'm doing this. There are a couple of different ways that they've done it. They call it center-out targets. So there will be a bubble in the middle and then eight bubbles around that, and the cursor will go from the middle to one side. So say, middle to left, back to middle, to up, to middle, up, right, and

they'll do that all the way around the circle. And I will follow that cursor the whole time, and then it will train off of my intentions, what it is expecting my intentions to be throughout the whole process.

Lex Fridman
Can you actually speak to, when you say follow -

Noland Arbaugh
Yes.

Lex Fridman
- you don't mean with your eyes, you mean with your intentions?

Noland Arbaugh
Yeah, so generally for calibration, I'm doing attempted movements because I think it works better. I think the better models, as I progress through calibration, make it easier to use imagined movements.

Lex Fridman
Wait. Wait, wait, wait. So calibrated on attempted movement will create a model that makes it really effective for you to then use the force.

Noland Arbaugh
Yes. I've tried doing calibration with imagined movement and it just doesn't work as well for some reason. So that was the center-out targets. There's also one where a random target will pop up on the screen and it's the same. I just move, I follow along wherever the cursor is, to that target all across the screen. I've tried those with imagined movement and for some reason the models just don't, they don't give as high level as quality when we get into closed loop. I haven't played around with it a ton, so maybe the different ways that we're doing calibration now might make it a bit better. But what I've found is there will be a point in calibration where I can use imagined movement. Before that point, it doesn't really work. So if I do calibration for 45 minutes, the first 15 minutes, I can't use imagined movement. It just doesn't work for some reason. And after a certain point, I can just feel it, I can tell. It moves different. That's the best way I can describe it. It's almost as if it is anticipating what I am going to do again, before I go to do it. And so using attempted movement for 15 minutes, at some point, I can tell when I move my eyes to the next target that the cursor is starting to pick up. It's starting to understand, it's learning what I'm going to do.

Lex Fridman
So first of all, it's really cool that, you are a true pioneer in all of this. You're exploring how to do every aspect of this most effectively and there's just, I imagine, so many lessons learned from this. So thank you for being a pioneer in all these kinds of different super technical

ways. And it's also cool to hear that there's a different feeling to the experience when it's calibrated in different ways because I imagine your brain is doing something different and that's why there's a different feeling to it. And then trying to find the words and the measurements to those feelings would be also interesting. But at the end of the day, you can also measure your actual performance, on whether it's Snake or Webgrid, you could see what actually works well. And you're saying, for the open loop calibration, the attempted movement works best for now.

Noland Arbaugh
Yup. Yup.

Lex Fridman
So the open loop, you don't get the feedback that you did something.

Noland Arbaugh
Yeah. I just -

Lex Fridman
Is that frustrating? Or -

Noland Arbaugh
No, no. It makes sense to me. We've done it with a cursor and without a cursor in open loop. So sometimes it's just, say for the center out, you'll start calibration with a bubble lighting up and I push towards that bubble, and then when it's pushed towards that bubble for, say, three seconds, a bubble will pop and then I come back to the middle. So I'm doing it all just by my intentions. That's what it's learning anyway. So it makes sense that as long as I follow what they want me to do, follow the yellow brick road, that it'll all work out.

Lex Fridman
You're full of great references. Is the bubble game fun?

Noland Arbaugh
Yeah, they always feel so bad making me do calibration like, oh, we're about to do a 40-minute calibration. I'm like, "Alright, do you guys want to do two of them?" I'm always asking to - whatever they need, I'm more than happy to do. And it's not bad. I get to lie there or sit in my chair and do these things with some great people. I get to have great conversations. I can give them feedback. I can talk about all sorts of things. I could throw something on, on my TV in the background, and split my attention between them. It's not bad at all. I don't mind it.

Lex Fridman
Is there a score that you get?

Noland Arbaugh
No.

Lex Fridman
Can you do better on a bubble game?

Noland Arbaugh
No, I would love that.

Lex Fridman
Yeah.

Noland Arbaugh
Yeah, I would love a -

Lex Fridman
Writing down suggestions from Noland.

Noland Arbaugh
That -

Lex Fridman
Make it more fun, gamified.

Noland Arbaugh
Yeah, that's one thing that I really, really enjoy about Webgrid is because I'm so competitive. The higher the BPS, the higher the score, I know the better I'm doing, and so if I - I think I've asked at one point, one of the guys, if he could give me some sort of numerical feedback for calibration. I would like to know what they're looking at. Like, oh, we see this number while you're doing calibration, and that means, at least on our end, that we think calibration is going well. And I would love that because I would like to know if what I'm doing is going well or not. But then they've also told me, yeah, not necessarily one to one. It doesn't actually mean that calibration is going well in some ways. So it's not like a hundred percent and they don't want to skew what I'm experiencing or want me to change things based on that, if that number isn't always accurate to how the model will turn out or the end result,. That's at least what I got from it. One thing I have asked them, and something that I really enjoy striving for, is towards the end of calibration, there is a time between targets. And so I like to keep, at the end, that number as low as possible. So at the beginning it can be four or five, six seconds between me popping bubbles, but towards the end I like to keep it below 1.5 or if I could get it to one second between bubbles. Because in my mind, that translates really nicely to something like Webgrid, where I know if I can hit a target, one every second, that I'm doing real, real well.

Lex Fridman
There you go. That's a way to get a score on the calibrations, like the speed. How quickly can you get from bubble to bubble?

Noland Arbaugh
Yeah.

Lex Fridman
So there's the open loop and then it goes to the closed loop.

Noland Arbaugh
Closed loop.

Lex Fridman
And the closed loop can already start giving you a sense because you're getting feedback of how good the model is.

Noland Arbaugh
Yeah. Yeah. So closed loop is when I first get cursor control, and how they've described it to me, someone who does not understand this stuff, I am the dumbest person in the room every time I'm with any of those guys.

Lex Fridman
I love the humility. I appreciate it.

Noland Arbaugh
Yeah, is that I am closing the loop. So I am actually now the one that is finishing the loop of whatever this loop is. I don't even know what the loop is. They've never told me. They just say there is a loop and at one point it's open and I can't control, and then I get control and it's closed. So I'm finishing the loop.

Lex Fridman
So how long the calibration usually take? You said 10-15 minutes?

Noland Arbaugh
Well, yeah. They're trying to get that number down pretty low. That's what we've been working on a lot recently, is getting that down is low as possible. So that way, if this is something that people need to do on a daily basis or if some people need to do on a every-other-day basis or once a week, they don't want people to be sitting in calibration for long periods of time. I think they've wanted to get it down seven minutes or below, at least where we're at right now. It'd be nice if you never had to do calibration. So we'll get there at some point, I'm sure, the more we learn about the brain, and I think that's the dream. I think

right now, for me to get really, really good models, I'm in calibration 40 or 45 minutes. And I don't mind, like I said, they always feel really bad, but if it's going to get me a model that can break these records on Webgrid, I'll stay in it for flipping two hours.

Lex Fridman
Let's talk business. So Webgrid, I saw a presentation where Bliss said by March you selected 89,000 targets in Webgrid. Can you explain this game? What is Webgrid and what does it take to be a world-class performer in Webgrid, as you continue to break world records?

Noland Arbaugh
Yeah.

Lex Fridman
It's like a gold medalist talk. Well, where do I begin?

Noland Arbaugh
Yeah, I'd like thank -

Lex Fridman
Yeah, exactly.

Noland Arbaugh
- everyone who's helped me get here, my coaches, my parents, for driving me to practice every day at 5:00 in the morning. I like to thank God and just overall my dedication to my craft.

Lex Fridman
Yeah, the interviews with athletes, they're always like that exact -

Noland Arbaugh
Yeah.

Lex Fridman
It's that template.

Noland Arbaugh
Yeah, so -

Lex Fridman
So, Webgrid is a -

Noland Arbaugh
Webgrid is a -

Lex Fridman
- grid of cells.

Noland Arbaugh
Yeah, it's literally just a grid. They can make it as big or small as you can make a grid. A single box on that grid will light up and you go and click it. And it is a way for them to benchmark how good a BCI is. So it's pretty straightforward. You just click targets.

Lex Fridman
Only one blue cell appears and you're supposed to move the mouse to there and click on it.

Noland Arbaugh
Yup. So I like playing on bigger grids because the bigger the grid, the more BPS, it's bits per second, that you get every time you click one. So I'll say I'll play on a 35 by 35 grid, and then one of those little squares, a cell, you can call it, target, whatever, will light up. And you move the cursor there, and you click it, and then you do that forever.

Lex Fridman
And you've been able to achieve, at first, eight bits per second, then you've recently broke that.

Noland Arbaugh
Yeah. Yeah, I'm at 8.5 right now. I would've beaten that literally the day before I came to Austin. But I had a - I don't know - a five-second lag right at the end and I just had to wait until the latency calmed down, and then I kept clicking. But I was at 8.01, and then five seconds of lag, and then the next three targets I clicked all stayed at 8.01. So if I would've been able to click during that time of lag, I probably would've hit, I don't know, I might've hit nine. So I'm there. I'm really close, and then this whole Austin trip has really gotten in the way of my Webgrid playing ability.

Lex Fridman
It's frustrating.

Noland Arbaugh
Yeah, it's -

Lex Fridman
So, that's all -

Noland Arbaugh
I've been itching.

Lex Fridman
- you've thinking about right now?

Noland Arbaugh
Yeah, I know. I just want to do better.

Lex Fridman
At 9.

Noland Arbaugh
I want to do better. I want to hit 9, I think, well, I know 9 is very, very achievable. I'm right there. I think 10 I could hit, maybe in the next month. I could do it probably in the next few weeks if I really push.

Lex Fridman
I think you and Elon are basically the same person because last time I did a podcast with him, he came in extremely frustrated that he can't beat Uber Lilith as a Druid. That was a year ago, I think, I forget, solo. And I could just tell there's some percentage of his brain, the entire time was thinking, "I wish I was right now attempting…"

Noland Arbaugh
Yeah. I think he did it that night.

Lex Fridman
He did it that night.

Noland Arbaugh
Yeah.

Lex Fridman
He stayed up and did it that night -

Noland Arbaugh
Yeah.

Lex Fridman
- which is crazy to me. In a fundamental way, it's really inspiring and what you're doing is inspiring in that way because it's not just about the game. Everything you're doing there has impact. By striving to do well on Webgrid, you're helping everybody figure out how to create

the system all along the decoding, the software, the hardware, the calibration, all of it. How to make all of that work so you can do everything else really well.

Noland Arbaugh
Yeah, it's just really fun.

Lex Fridman
Well, that's also, that's part of the thing, is that making it fun.

Noland Arbaugh
Yeah, it's a addicting. I've joked about what they actually did when they went in and put this thing in my brain. They must've flipped a switch to make me more susceptible to these kinds of games, to make me addicted to Webgrid or something.

Lex Fridman
Yeah.

Noland Arbaugh
Do you know Bliss's high score?

Lex Fridman
Yeah, he said like 14 or something.

Noland Arbaugh
17.

Lex Fridman
Oh, boy.

Noland Arbaugh
17.1 or something. 17.01?

Bliss Chapman
17 on the dot.

Noland Arbaugh
17.

Bliss Chapman
17.01.

Noland Arbaugh
Yeah.

Lex Fridman
He told me he does it on the floor with peanut butter and he fasts. It's weird. That sounds like cheating. Sounds like performance-enhancing -

Bliss Chapman
Noland, the first time Noland played this game, he asked how good are we at this game? And I think you told me right then, you're going to try to beat me.

Noland Arbaugh
I'm going to get there someday.

Bliss Chapman
Yeah, I fully believe you.

Noland Arbaugh
I think I can. I think I can. I think -

Bliss Chapman
I'm excited for that.

Noland Arbaugh
Yeah. So I've been playing, first off, with the dwell cursor, which really hampers my Webgrid playing ability. Basically I have to wait 0.3 seconds for every click.

Lex Fridman
Oh, so you can't do the click. So you click by dwelling, you said 0.3.

Noland Arbaugh
0.3 seconds, which sucks. It really slows down how high I'm able to get. I still hit 50, I think I hit 50-something net trials per minute in that, which was pretty good because I'm able to - one of the settings is also how slow you need to be moving in order to initiate a click, to start a click. So I can tell, sort of, when I'm on that threshold, to start initiating a click just a bit early. So I'm not fully stopped over the target when I go to click, I'm doing it on my way to the targets a little, to try to time it just right.

Lex Fridman
Oh, wow.

Noland Arbaugh
Yeah.

Lex Fridman
So, you're slowing down.

Noland Arbaugh
Yeah, just a hair, right before the targets.

Lex Fridman
This is like elite performance. Okay, but that's still - it sucks that there's a ceiling of the 0.3.

Noland Arbaugh
Well, I can get down to 0.2 and 0.1. 0.1's what I've -

Lex Fridman
0.2.

Noland Arbaugh
Yeah, and I've played with that a little bit too. I have to adjust a ton of different parameters in order to play with 0.1, and I don't have control over all of that on my end yet. It also changes how the models are trained. If I train a model, like in Webgrid, I bootstrap on a model, which basically is them training models as I'm playing Webgrid based off of the Webgrid data that I'm - so if I play Webgrid for 10 minutes, they can train off that data specifically in order to get me a better model. If I do that with 0.3 versus 0.1, the models come out different. The way that they interact, it's just much, much different. So I have to be really careful. I found that doing it with 0.3 is actually better in some ways. Unless I can do it with 0.1 and change all of the different parameters, then that's more ideal, because obviously 0.3 is faster than 0.1. So I could get there. I can get there.

Lex Fridman
Can you click using your brain?

Noland Arbaugh
For right now, it's the hover clicking with the dwell cursor. Before all the thread retraction stuff happened, we were calibrating clicks, left click, right click. That was my previous ceiling, before I broke the record again with the dwell cursor, was I think on a 35 by 35 grid with left and right click. And you get more BPS, more bits per second, using multiple clicks because it's more difficult.

Lex Fridman
Oh, because what is it, you're supposed to do either a left click or a right click?

Noland Arbaugh
Yes.

Lex Fridman
Is a different colors, something like this?

Noland Arbaugh
Different colors.

Lex Fridman
Cool. Cool.

Noland Arbaugh
Yeah, blue targets for left click, orange targets for right click is what they had done.

Lex Fridman
Got it.

Noland Arbaugh
So, my previous record of 7.5 -

Lex Fridman
Was with the two clicks.

Noland Arbaugh
- was with the blue and the orange targets, yeah, which I think if I went back to that now, doing the click calibration, I would be able to - and being able to initiate clicks on my own, I think I would break that 10 ceiling in a couple days, max.

Lex Fridman
Yeah, you would start making Bliss nervous about his 17.

Noland Arbaugh
Yeah, he should be.

Bliss Chapman
Why do you think we haven't given him the -

Noland Arbaugh
Yeah.

Lex Fridman
Exactly. Exactly. So what did it feel like with the retractions, that some of the threads are retracted?

Noland Arbaugh
It sucked. It was really, really hard. The day they told me was the day of my big Neuralink tour at their Fremont facility. They told me right before we went over there. It was really hard to hear. My initial reaction was, alright, go in, fix it. Go in, take it out and fix it. The first surgery was so easy. I went to sleep, a couple hours later I woke up and here we are. I didn't feel any pain, didn't take any pain pills or anything. So I just knew that if they wanted to, they could go in and put in a new one next day if that's what it took because I wanted it to be better and I wanted not to lose the capability. I had so much fun playing with it for a few weeks, for a month. It had opened up so many doors for me. It had opened up so many more possibilities that I didn't want to lose it after a month. I thought it would've been a cruel twist of fate if I had gotten to see the view from the top of this mountain and then have it all come crashing down after a month. And I knew, I say the top of the mountain, but how I saw it was I was just now starting to climb the mountain and there was so much more that I knew was possible. And so to have all of that be taken away was really, really hard. But then on the drive over to the facility, I don't know, five minute drive, whatever it is, I talked with my parents about it. I prayed about it. I was just like, I'm not going to let this ruin my day. I'm not going to let this ruin this amazing tour that they have set up for me. I want to go show everyone how much I appreciate all the work they're doing. I want to go meet all of the people who have made this possible, and I want to go have one of the best days of my life, and I did. And it was amazing, and it absolutely was one of the best days I've ever been privileged to experience. And then for a few days I was pretty down in the dumps, but for the first few days afterwards, I didn't know if it was ever going to work again. And then I made the decision that, even if I lost the ability to use the Neuralink, even if I lost out on everything to come, if I could keep giving them data in any way, then I would do that. If I needed to just do some of the data collection every day or body mapping every day for a year, then I would do it because I know that everything I'm doing helps everyone to come after me, and that's all I wanted. Just the whole reason that I did this was to help people, and I knew that anything I could do to help, I would continue to do, even if I never got to use the cursor again, then I was just happy to be a part of it. And everything that I had done was just a perk. It was something that I got to experience, and I know how amazing it's going to be for everyone to come after me. So might as well just keep trucking along.

Lex Fridman
Well, that said, you were able to get to work your way up, to get the performance back. So this is like going from Rocky I to Rocky II. So when did you first realize that this is possible, and what gave you the strength, the motivation, the determination to do it, to increase back up and beat your previous record?

Noland Arbaugh
Yeah, it was within a couple weeks like -

Lex Fridman
Again, this feels like I'm interviewing an athlete. This is great. I'd like thank my parents.

Noland Arbaugh
The road back was long and hard -

Lex Fridman
Yeah, it's like a movie.

Noland Arbaugh
- fraught with many difficulties. There were dark days. It was a couple weeks, I think, and then there was just a turning point. I think they had switched how they were measuring the neuron spikes in my brain, the - Bliss help me out.

Bliss Chapman
Yeah, the way in which we were measuring the behavior of individual neurons.

Noland Arbaugh
Yeah.

Bliss Chapman
So we're switching from individual spike detection to something called spike band power, which if you watch the previous segments with either me or DJ, you probably have some context.

Noland Arbaugh
Yeah, okay.

Lex Fridman
Mmhmm.

Noland Arbaugh
So when they did that, it was like a light over the head, light bulb moment, like, oh, this works and this seems like we can run with this. And I saw the uptick in performance immediately. I could feel it when they switched over. I was like, "This is better. This is good. Everything up until this point," for the last few weeks, last, whatever, three or four weeks because it was before they even told me, "Everything before this sucked. Let's keep doing what we're doing now." And at that point it was not like, oh, I know I'm still only at, say in Webgrid terms, four or five BPS compared to my 7.5 before, but I know that if we keep doing

this, then I can get back there. And then they gave me the dwell cursor and the dwell cursor sucked at first. It's obviously not what I want, but it gave me a path forward to be able to continue using it and hopefully to continue to help out. And so I just ran with it, never looked back. Like I said, I'm just kind of person, I roll with the punches anyway. So-

Lex Fridman
What was the process? What was the feedback loop on the figuring out how to do the spike detection in a way that would actually work well for Noland?

Bliss Chapman
Yeah, it's a great question. So maybe just to describe first how the actual update worked. It was basically an update to your implant. So we just did an over-the-air software update to his implants, same way you'd update your Tesla or your iPhone. And that firmware change enabled us to record averages of populations of neurons nearby individual electrodes. So we have less resolution about which individual neuron is doing what, but we have a broader picture of what's going on nearby an electrode overall. And that feedback loop, basically as Noland described it, it was immediate when we flipped that switch. I think the first day we did that, you had three or four BPS right out of the box, and that was a light bulb moment for, okay, this is the right path to go down. And from there, there's a lot of feedback around how to make this useful for independent use. So what we care about ultimately is that you can use it independently to do whatever you want. And to get to that point, it required us to re-engineer the UX, as you talked about with the dwell cursor, to make it something that you can use independently without us needing to be involved all the time. And yeah, this is obviously the start of this journey still. Hopefully we get back to the places where you're doing multiple clicks and using that to control, much more fluidly, everything, and much more naturally the applications that you're trying to interface with.

Lex Fridman
And most importantly, get that Webgrid number up.

Noland Arbaugh
Yup.

Bliss Chapman
Yes.

Noland Arbaugh
Yeah.

Lex Fridman
So how is - on the hover click - do you accidentally click stuff sometimes?

Noland Arbaugh
Yup.

Lex Fridman
How hard is it to avoid accidentally clicking?

Noland Arbaugh
I have to continuously keep it moving, basically. So like I said, there's a threshold where it will initiate a click. So if I ever drop below that, it'll start and I have 0.3 seconds to move it before it clicks anything.

Lex Fridman
Oh.

Noland Arbaugh
And if I don't want it to ever get there, I just keep it moving at a certain speed and just constantly doing circles on screen, moving it back and forth, to keep it from clicking stuff. I actually noticed, a couple weeks back, that when I was not using the implant, I was just moving my hand back and forth or in circles. I was trying to keep the cursor from clicking and I was just doing it while I was trying to go to sleep. And I was like, "Okay, this is a problem."

Lex Fridman
To avoid the clicking. I guess, does that create problems when you're gaming, accidentally click a thing? Like -

Noland Arbaugh
Yeah. Yeah. It happens in chess.

Lex Fridman
Accidental, yeah.

Noland Arbaugh
I've lost a number of games because I'll accidentally click something.

Bliss Chapman
I think the first time I ever beat you was because of an accidental click.

Noland Arbaugh
Yeah, a misclick. Yeah.

Lex Fridman
It's a nice excuse, right? You can always -

Noland Arbaugh
Yeah, it's - it's -

Lex Fridman
- anytime you lose - you could just say, "That was accidental."

Noland Arbaugh
Yeah. Yeah.

Lex Fridman
You said the app improved a lot from version one when you first started using it. It was very different. So can you just talk about the trial and error that you went through with the team? 200 plus pages of notes. What's that process like of going back and forth and working together to improve the thing?

Noland Arbaugh
It's a lot of me just using it day in and day out and saying, "Hey, can you guys do this for me? Give me this. I want to be able to do that. I need this." I think a lot of it just doesn't occur to them maybe, until someone is actually using the app, using the implant. It's just something that they just never would've thought of or it's very specific to even me, maybe what I want. It's something I'm a little worried about with the next people that come is maybe they will want things much different than how I've set it up or what the advice I've given the team, and they're going to look at some of the things I've - they've added for me. Like, "That's a dumb idea. Why would he ask for that?" And so I'm really looking forward to get the next people on because I guarantee that they're going to think of things that I've never thought of. They're going to think of improvements something like, wow, that's a really good idea. I wish I would've thought of that. And then they're also going to give me some pushback about, yeah, what you are asking them to do here, that's a bad idea. Let's do it this way. And I'm more than happy to have that happen, but it's just a lot of different interactions with different games or applications, the internet, just with the computer in general. There's tons of bugs that end up popping up, left, right, center. So it's just me trying to use it as much as possible and showing them what works and what doesn't work, and what I would like to be better. And then they take that feedback and they usually create amazing things for me. They solve these problems in ways I would've never imagined. They're so good at everything they do, and so I'm just really thankful that I'm able to give them feedback and they can make something of it, because a lot of my feedback is really dumb. It's just like, "I want this, please do something about it," and it'll come back, super well-thought-out, and it's way better than anything I could have ever thought of or implemented myself. So they're just great. They're really, really cool.

Lex Fridman
As the BCI community grows, would you like to hang out with the other folks with Neuralinks? What relationship, if any, would you want to have with them? Because you said they might have a different set of ideas of how to use the thing.

Noland Arbaugh
Yeah.

Lex Fridman
Would you be intimidated by their Webgrid performance?

Noland Arbaugh
No. No. I hope -

Lex Fridman
Compete.

Noland Arbaugh
I hope, day one, they wipe the floor with me. I hope they beat it and they crush it, double it if they can, just because on one hand it's only going to push me to be better because I'm super competitive. I want other people to push me. I think that is important for anyone trying to achieve greatness is they need other people around them who are going to push them to be better. And I even made a joke about it on X once, once the next people get chosen, cue buddy cop music. I'm just excited to have other people to do this with and to share experiences with. I'm more than happy to interact with them as much as they want, more than happy to give them advice. I don't know what kind of advice I could give them. But if they have - give them advice? I don't know what advice I could give them. But if they have questions, I'm more than happy.

Lex Fridman
What advice would you have for the next participant in the clinical trial?

Noland Arbaugh
That they should have fun with this, because it is a lot of fun, and that I hope they work really, really hard because it's not just for us, it's for everyone that comes after us. And come to me if they need anything. And to go to Neuralink if they need anything. Man, Neuralink moves mountains. They do absolutely anything for me that they can, and it's an amazing support system to have. It puts my mind at ease for so many things that I have had questions about or so many things I want to do, and they're always there, and that's really, really nice. And so I would tell them not to be afraid to go to Neuralink with any questions that they have, any concerns, anything that they're looking to do with this. And any help that

Neuralink is capable of providing, I know they will. And I don't know. I don't know. Just work your ass off because it's really important that we try to give our all to this.

Lex Fridman
So have fun and work hard.

Noland Arbaugh
Yeah. Yeah. There we go. Maybe that's what I'll just start saying to people. Have fun, work hard.

Lex Fridman
Now you're a real pro athlete. Just keep it short. Maybe it's good to talk about what you've been able to do now that you have a Neuralink implant, the freedom you gain from this way of interacting with the outside world. You play video games all night and you do that by yourself, and that's the freedom. Can you speak to that freedom that you gain?

Noland Arbaugh
Yeah. It's what all - I don't know, people in my position want. They just want more independence. The more load that I can take away from people around me, the better. If I'm able to interact with the world without using my family, without going through any of my friends, needing them to help me with things, the better. If I'm able to sit up on my computer all night and not need someone to sit me up, say, on my iPad, in a position where I can use it, and then have to have them wait up for me all night until I'm ready to be done using it, it takes a load off of all of us and it's really all I can ask for. It's something that I could never thank Neuralink enough for, and I know my family feels the same way. Just being able to have the freedom to do things on my own at any hour of the day or night, it means the world to me and - I don't know.

Lex Fridman
When you're up at 2:00am playing Webgrid by yourself, I just imagine it's darkness and there's just a light glowing and you're just focused. What's going through your mind? Or you were in a state of flow where it's like the mind is empty like those Zen masters.

Noland Arbaugh
Yeah. Generally, it is me playing music of some sort. I have a massive playlist, and so I'm just rocking out to music. And then it's also just a race against time, because I'm constantly looking at how much battery percentage I have left on my implant, like, "Alright. I have 30%, which equates to X amount of time, which means I have to break this record in the next hour and a half or else it's not happening tonight." And so it's a little stressful when that happens. When it's above 50%, I'm like, "Okay, I got time." It starts getting down to 30, and then 20 it's like, "Alright, 10%, a little popup is going to pop up right here, and it's going to really screw my Webgrid flow. It's going to tell me that - the low battery popup comes up and I'm like, "It's

really going to screw me over. So if I'm going to break this record, I have to do it in the next 30 seconds," or else that popup is going to get in the way, cover my Webgrid. And then after that, I go click on it, go back into Webgrid, and I'm like, "Alright, that means I have 10 minutes left before this thing's dead." That's what's going on in my head, generally. That and whatever song's playing. And I want to break those records so bad. It's all I want when I'm playing Webgrid. It has become less of like, "Oh, this is just a leisurely activity. I just enjoy doing this because it just feels so nice and it puts me at ease." It is, "No. Once I'm in Webgrid, you better break this record or you're going to waste five hours of your life right now." And I don't know. It's just fun. It's fun, man.

Lex Fridman
Have you ever tried Webgrid with two targets and three targets? Can you get higher BPS with that?

Noland Arbaugh
Can you do that?

Bliss Chapman
You mean different colored targets or you mean -

Lex Fridman
Oh, multiple targets. Does that change the thing?

Bliss Chapman
Yeah. So BPS is a log of number of targets times correct minus incorrect, divided by time. And so you can think of different clicks as basically double the number of active targets.

Lex Fridman
Got it.

Bliss Chapman
So basically higher BPS, the more options there are, the more difficult the task. And there's also Zen mode you've played in before, which is infinite -

Noland Arbaugh
Yeah. Yeah. It covers the whole screen with a grid and - I don't know -

Lex Fridman
And so you can go - that's insane.

Noland Arbaugh
Yeah.

Bliss Chapman
He doesn't like it because it didn't show BPS, so -

Noland Arbaugh
I had them put in a giant BPS in the background, so now it's the opposite of Zen mode. It's super hard mode, just metal mode. If it's just a giant number in the back counting.

Bliss Chapman
We should renamed that. "Metal mode" is a much better name now.

Lex Fridman
So you also play Civilization VI.

Noland Arbaugh
I love Civ VI. Yeah.

Lex Fridman
You usually go with Korea, you said?

Noland Arbaugh
I do. Yeah. So the great part about Korea is they focus on science tech victories, which was not planned. I've been playing Korea for years, and then all of the Neuralink stuff happened, so it kind of aligned. But what I've noticed with tech victories is if you can just rush tech, rush science, then you can do anything. At one point in the game, you'll be so far ahead of everyone technologically that you'll have musket men, infantrymen, planes sometimes, and people will still be fighting with bows and arrows. And so if you want to win a domination victory, you just get to a certain point with the science, and then go and wipe out the rest of the world. Or you can just take science all the way and win that way, and you're going to be so far ahead of everyone because you're producing so much science that it's not even close. I've accidentally won in different ways just by focusing on science.

Lex Fridman
Accidentally won by focusing on science -

Noland Arbaugh
Yeah. I was playing only science, obviously. Just science all the way, just tech. And I was trying to get every tech in the tech tree and stuff, and then I accidentally won through a diplomatic victory, and I was so mad. I was so mad because it just ends the game one turn. It was like, "Oh, you won. You're so diplomatic." I'm like, "I don't want to do this. I should have declared war on more people or something." It was terrible. But you don't need giant civilizations with tech, especially with Korea. You can keep it pretty small. So I generally just

get to a certain military unit and put them all around my border to keep everyone out, and then I will just build up. So very isolationist.

Lex Fridman
Nice.

Noland Arbaugh
Yeah.

Lex Fridman
Just work on the science and the tech.

Noland Arbaugh
Yup, that's it.

Lex Fridman
You're making it sound so fun.

Noland Arbaugh
It's so much fun.

Lex Fridman
And I also saw a Civilization VII trailer.

Noland Arbaugh
Oh, man. I'm so pumped.

Lex Fridman
And that's probably coming out -

Noland Arbaugh
Come on Civ VII, hit me up. All alpha, beta tests, whatever.

Lex Fridman
Wait, when is it coming out?

Noland Arbaugh
2025.

Lex Fridman
Yeah, yeah, next year. Yeah. What other stuff would you like to see improved about the Neuralink app and just the entire experience?

Noland Arbaugh
I would like to, like I said, get back to the click on demand, the regular clicks. That would be great. I would like to be able to connect to more devices. Right now, it's just the computer. I'd like to be able to use it on my phone or use it on different consoles, different platforms. I'd like to be able to control as much stuff as possible, honestly. An Optimus robot would be pretty cool. That would be sick if I could control an Optimus robot. The Link app itself, it seems like we are getting pretty dialed in to what it might look like down the road. It seems like we've gotten through a lot of what I want from it, at least. The only other thing I would say is more control over all the parameters that I can tweak with my cursor and stuff. There's a lot of things that go into how the cursor moves in certain ways, and I have - I don't know. Three or four of those parameters, and there might-

Lex Fridman
Gain and friction and all that.

Noland Arbaugh
Gain and friction, yeah. And there's maybe double the amount of those with just velocity and then with the actual dwell cursor. So I would like all of it. I want as much control over my environment as possible, especially -

Lex Fridman
So you want advanced mode. There's usually this basic mode, and you're one of those folks, the power-user, advanced -

Noland Arbaugh
Yeah. Yeah.

Lex Fridman
Got it.

Noland Arbaugh
That's what I want. I want as much control over this as possible. So, yeah, that's really all I can ask for. Just give me everything.

Lex Fridman
Has speech been useful? Just being able to talk also in addition to everything else?

Noland Arbaugh
Yeah, you mean while I'm using it?

Lex Fridman
While you're using it? Speech-to-text?

Noland Arbaugh
Oh, yeah.

Lex Fridman
Or do you type - because there's also a keyboard -

Noland Arbaugh
Yeah, yeah, yeah. So there's a virtual keyboard. That's another thing I would like to work more on is finding some way to type or text in a different way. Right now, it is a dictation basically and a virtual keyboard that I can use with the cursor, but we've played around with finger spelling, sign language finger spelling, and that seems really promising. So I have this thought in my head that it's going to be a very similar learning curve that I had with the cursor where I went from attempted movement to imagine movement at one point. I have a feeling, this is just my intuition, that at some point, I'm going to be doing finger spelling and I won't need to actually attempt to finger spell anymore, that I'll just be able to think the letter that I want and it'll pop up.

Lex Fridman
That would be epic. That's challenging. That's hard. That's a lot of work for you to take that leap, but that would be awesome.

Noland Arbaugh
And then going from letters to words is another step. Right now, it's finger spelling of just the sign language alphabet, but if it's able to pick that up, then it should be able to pick up the whole sign language language, and so then if I could do something along those lines, or just the sign language spelled word, if I can spell it at a reasonable speed and it can pick that up, then I would just be able to think that through and it would do the same thing. After what I saw with the cursor control, I don't see why it wouldn't work, but we'd have to play around with it more.

Lex Fridman
What was the process in terms of training yourself to go from attempted movement to imagined movement? How long did that take? So how long would this process take?

Noland Arbaugh
Well, it was a couple weeks before it just happened upon me. But now that I know that that was possible, I think I could make it happen with other things. I think it would be much, much simpler.

Lex Fridman
Would you get an upgraded implant device?

Noland Arbaugh
Sure, absolutely. Whenever they'll let me.

Lex Fridman
So you don't have any concerns for you with the surgery experience? All of it was no regrets?

Noland Arbaugh
No.

Lex Fridman
So everything's been good so far?

Noland Arbaugh
Yup.

Lex Fridman
You just keep getting upgrades.

Noland Arbaugh
Yeah. I mean, why not? I've seen how much it's impacted my life already, and I know that everything from here on out, it's just going to get better and better. So I would love to get the upgrade.

Lex Fridman
What future capabilities are you excited about? So beyond this telepathy, is vision interesting? So for folks, for example, who are blind, so Neuralink enabling people to see, or for speech.

Noland Arbaugh
Yeah, there's a lot that's very, very cool about this. I mean, we're talking about the brain, so this is just motor cortex stuff. There's so much more that can be done. The vision one is fascinating to me. I think that is going to be very, very cool. To give someone the ability to see for the first time in their life would just be - I mean, it might be more amazing than even helping someone like me. That just sounds incredible. The speech thing is really interesting. Being able to have some real-time translation and cut away that language barrier would be really cool. Any actual impairments that it could solve with speech would be very, very cool. And then also, there are a lot of different disabilities that all originate in the brain, and you would be able to hopefully be able to solve a lot of those. I know there's already stuff to help people with seizures that can be implanted in the brain. I imagine the same thing. And so you could do something like that. I know that even someone like Joe Rogan has talked about the possibilities with being able to stimulate the brain in different ways. I'm not sure how

ethical a lot of that would be. That's beyond me, honestly. But I know that there is a lot that can be done when we're talking about the brain and being able to go in and physically make changes to help people or to improve their lives. So I'm really looking forward to everything that comes from this. And I don't think it's all that far off. I think a lot of this can be implemented within my lifetime, assuming that I live a long life.

Lex Fridman
What you were referring to is things like people suffering from depression or things of that nature, potentially getting help.

Noland Arbaugh
Yeah, flip a switch like that, make someone happy. I think Joe has talked about it more in terms of you want to experience what a drug trip feels like. You want to experience what it'd be like to be on mushrooms or something like that, DMT. You can just flip that switch in the brain. My buddy, Bain, has talked about being able to wipe parts of your memory and re-experience things for the first time, like your favorite movie or your favorite book, just wipe that out real quick, and then re-fall in love with Harry Potter or something. I told him, I was like, "I don't know how I feel about people being able to just wipe parts of your memory. That seems a little sketchy to me." He's like, "They're already doing it."

Lex Fridman
Sounds legit. I would love memory replay. Just actually high resolution, replay of old memories.

Noland Arbaugh
Yeah. I saw an episode of Black Mirror about that once, so I don't think I want it.

Lex Fridman
Yeah, so Black Mirror always considers the worst case, which is important. I think people don't consider the best case or the average case enough. I don't know what it is about us humans. We want to think about the worst possible thing. We love drama. It's like how is this new technology going to kill everybody? We just love that. Again like, "Yes, let's watch."

Noland Arbaugh
Hopefully people don't think about that too much with me. It'll ruin a lot of my plans.

Lex Fridman
Yeah, I assume you're going to have to take over the world. I mean, I love your Twitter. You tweeted, "I'd like to make jokes about hearing voices in my head since getting the Neuralink, but I feel like people would take it the wrong way. Plus the voices in my head told me not to."

Noland Arbaugh
Yeah.

Lex Fridman
Yeah.

Noland Arbaugh
Yeah.

Lex Fridman
Please never stop. So you were talking about Optimus. Is that something you would love to be able to do to control the robotic arm or the entirety of Optimus?

Noland Arbaugh
Oh, yeah. For sure. For sure. Absolutely.

Lex Fridman
You think there's something fundamentally different about just being able to physically interact with the world?

Noland Arbaugh
Yeah. Oh, 100%. I know another thing with being able to give people the ability to feel sensation and stuff too, by going in with the brain and having a Neuralink maybe do that, that could be something that could be transferred through the Optimus as well. There's all sorts of really cool interplay between that. And then also, like you said, just physically interacting. I mean, 99% of the things that I can't do myself, obviously, I need a caretaker for, someone to physically do things for me. If an Optimus robot could do that, I could live an incredibly independent life and not be such a burden on those around me, and it would change the way people like me live, at least until whatever this is gets cured. But being able to interact with the world physically, that would just be amazing. And not just for having it be a caretaker or something, but something like I talked about. Just being able to read a book. Imagine an Optimus robot just being able to hold a book open in front of me. I get that smell again. I might not be able to feel it at that point, or maybe I could, again, with the sensation and stuff. But there's something different about reading a physical book than staring at a screen or listening to an audiobook. I actually don't like audiobooks. I've listened to a ton of them at this point, but I don't really like them. I would much rather read a physical copy.

Lex Fridman
So, one of the things you would love to be able to experience is opening the book, bringing it up to you, and to feel the touch of the paper.

Noland Arbaugh
Yeah. Oh, man. The touch, the smell. I mean, it's just something about the words on the page. And they've replicated that page color on the Kindle and stuff. Yeah, it's just not the same. Yeah. So just something as simple as that.

Lex Fridman
So, one of the things you miss is touch?

Noland Arbaugh
I do. Yeah. A lot of things that I interact with in the world, like clothes or literally any physical thing that I interact within the world, a lot of times what people around me will do is they'll just come rub it on my face. They'll lay something on me so I can feel the weight. They will rub a shirt on me so I can feel fabric. There's something very profound about touch, and it's something that I miss a lot and something I would love to do again. We'll see.

Lex Fridman
What would be the first thing you do with a hand that can touch? Give your mom a hug after that, right?

Noland Arbaugh
Yeah. I know. It's one thing that I've asked God for basically every day since my accident was just being able to one day move, even if it was only my hand, so that way, I could squeeze my mom's hand or something just to show her how much I care and how much I love her and everything. Something along those lines. Being able to just interact with the people around me. Handshake, give someone a hug. I don't know. Anything like that. Being able to help me eat. I'd probably get really fat, which would be a terrible, terrible thing.

Lex Fridman
Also, beat Bliss in chess on a physical board.

Noland Arbaugh
Yeah. Yeah. I mean, there were just so many upsides. And any way to find some way to feel like I'm bringing Bliss down to my level because he's just such an amazing guy, and everything about him is just so above and beyond, that anything I can do to take him down a notch, I'm more than happy-

Lex Fridman
Yeah. Yeah, humble him a bit. He needs it.

Noland Arbaugh
Yeah.

Lex Fridman
Okay. As he's sitting next to me. Did you ever make sense of why God puts good people through such hardship?

Noland Arbaugh
Oh, man. I think it's all about understanding how much we need God. And I don't think that there's any light without the dark. I think that if all of us were happy all the time, there would be no reason to turn to God ever. I feel like there would be no concept of good or bad, and I think that as much of the darkness and the evil that's in the world, it makes us all appreciate the good and the things we have so much more. And I think when I had my accident, one of the first things I said to one of my best friends was - and this was within the first month or two after my accident, I said, "Everything about this accident has just made me understand and believe that God is real and that there really is a God, basically. And that my interactions with him have all been real and worthwhile." And he said, if anything, seeing me go through this accident, he believes that there isn't a God. And it's a very different reaction, but I believe that it is a way for God to test us, to build our character, to send us through trials and tribulations, to make sure that we understand how precious He is and the things that He's given us and the time that He's given us, and then to hopefully grow from all of that. I think that's a huge part of being here, is to not just have an easy life and do everything that's easy, but to step out of our comfort zones and really challenge ourselves because I think that's how we grow.

Lex Fridman
What gives you hope about this whole thing we have going on human civilization?

Noland Arbaugh
Oh, man. I think people are my biggest inspiration. Even just being at Neuralink for a few months, looking people in the eyes and hearing their motivations for why they're doing this, it's so inspiring. And I know that they could be other places, at cushier jobs, working somewhere else, doing X, Y, or Z, that doesn't really mean that much. But instead, they're here and they want to better humanity, and they want to better just the people around them. The people that they've interacted with in their life, they want to make better lives for their own family members who might have disabilities, or they look at someone like me and they say, "I can do something about that. So I'm going to." And it's always been what I've connected with most in the world are people. I've always been a people person and I love learning about people, and I love learning how people developed and where they came from, and to see how much people are willing to do for someone like me when they don't have to, and they're going out of their way to make my life better. It gives me a lot of hope for just humanity in general, how much we care and how much we're capable of when we all get together and try to make a difference. And I know there's a lot of bad out there in the world, but there always has been and there always will be. And I think that that is - it shows human resiliency and it shows what we're able to endure and how much we just want to be there

and help each other, and how much satisfaction we get from that, because I think that's one of the reasons that we're here is just to help each other, and - I don't know. That always gives me hope, is just realizing that there are people out there who still care and who want to help.

Lex Fridman
And thank you for being one such human being and continuing to be a great human being through everything you've been through and being an inspiration to many people, to myself, for many reasons, including your epic, unbelievably great performance on Webgrid. I'll be training all night tonight to try to catch up.

Noland Arbaugh
Hey, man. You can do it. You can do it.

Lex Fridman
And I believe in you that once you come back - so sorry to interrupt with the Austin trip, once you come back, eventually beat Bliss.

Noland Arbaugh
Yeah, yeah, for sure. Absolutely.

Lex Fridman
I'm rooting for you, though. The whole world is rooting for you.

Noland Arbaugh
Thank you.

Lex Fridman
Thank you for everything you've done, man.

Noland Arbaugh
Thanks. Thanks, man.

Lex Fridman
Thanks for listening to this conversation with Nolan Arbaugh, and before that, with Elon Musk, DJ Seo, Matthew McDougall, and Bliss Chapman. To support this podcast, please check out our sponsors in the description. And now, let me leave you with some words from Aldous Huxley in The Doors of Perception. "We live together. We act on and react to one another. But always, and in all circumstances, we are by ourselves. The martyrs go hand in hand into the arena. They are crucified alone. Embrace the lovers desperately tried to fuse their insulated ecstasies into a single self-transcendence in vain. But it's very nature, every embodied spirit is doomed to suffer and enjoy its solitude, sensations, feelings, insights,

fancies, all these are private, and except through symbols and a secondhand incommunicable. We can pool information about experiences, but never the experiences themselves. From family to nation, every human group is a society of island universes." Thank you for listening and hope to see you next time.