

AN INTERVIEW WITH PROFESSOR JAN RABAEY: NEURAL PROSTHETICS AND THEIR FUTURE APPLICATIONS

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BSJ

BSJ interviewed Professor Jan Rabaey to gain insight on his research regarding brain-machine interfaces (BMI) and microscopic implantable devices. Professor Rabaey received his E.E. and Ph.D. degrees in Applied Sciences from the Katholieke Universiteit Leuven, Belgium, in 1978 and 1983 respectively. From 1983-1985, he was a Visiting Research Engineer at UC Berkeley. In 1987, joined the faculty of the Electrical Engineering and Computer Science (EECS) department at UC Berkeley, where he is now holds the Donald O. Pederson Distinguished Professorship. He was the Associate Chair (EE) of the EECS Dept. at Berkeley from 1999 until 2002 and is currently the Scientific co-director of the Berkeley Wireless Research Center (BWRC), as well as the director of the Multiscale Systems Research Center (MuSyC). Professor Rabaey has authored a wide range of papers in the area of signal processing and design automation. He has received numerous scientific awards, including the 1985 IEEE Transactions on Computer Aided Design Best Paper Award (Circuits and Systems Society), the 1989 Presidential Young Investigator award, and the 1994 Signal Processing Society Senior Award. In 1995, he became an IEEE Fellow. He has also be awarded the 2002 ISSCC Jack Raper Award, the 2008 IEEE Circuits and Systems Mac Van Valkenburg Award, the 2009 EDAA Lifetime Achievement Award, and the 2010 Semiconductor Industry Association University Researcher Award. In 2011, he was elected to the Royal Flemish Academy of Arts and Sciences (Belgium).



idea that I should have a lightweight device that connects to a wireless network backbone, that acts as the way to primarily access data, which was 15 to 20 years before the iPad. So I was looking into low power wireless devices. Focusing on limits to what one can accomplish drove me to look at the applications that require small devices and lower energy. So, I was doing a lot of work in the early – late 1990s on sensor nets, little sensor nodes that could have a remote or internal energy source, as well as processing abilities. These could be implemented in all kinds of immersive applications like environmental applications. And then, it happened that we were looking at driving the devices to be smaller and smaller and said hey, if we keep pushing technology further down, we should be able to build innovative devices. Now they're getting as small as the size of a biological cell. Then you could have an electronic sensor that sits next to a cell, and they start talking to each other. Now can you build something with that, and is it really possible to do these things? Where do I get the energy? Biological cells have a way of getting energy, but the electronics need to get it from some other way. These are the questions that we are asking. At that point in time, we hired

BSJ: How did you get involved in your line of research?

Prof. Rabaey: In research, things always go in unexpected ways, and it's always unexpected things that you moved in another direction. I've been working in the field of integrated circuits and wireless for quite a long time. I have been working on low-power mobile devices since the early 1990s. We had a project around 1992 to 1996, which was called InfoPad. It's almost like... It was the

a new faculty member for the department. His name is Jose Carmena. He has an engineering background, and at the time he partially moved out of engineering, into neuroscience. After going to some of his talks, I thought “Hey, that’s kind of cool” and then I started thinking about brain-machine interfaces. Could we build devices that can talk to neurons? So we invited him here. I remember it very well - we had a group meeting and he gave me a talk. At the end of the talk I said, “What can I do for you?” He suggested a head stage. But, that’s boring. Anyone can do that. Give us something harder. He came back to our lab later and said, “Could you build for us little free floating electrodes, localized in the cortical regions, which can wirelessly send information in and out? Could you do that?” My first guess was “This is impossible. This is too hard.” It turned out that since then, which was about 8 years ago, we have been gradually moving into directions of building these devices. Something you start working hard and look at it from all angles, suddenly the impossible becomes possible.

Since this change of direction, we have had more and more faculty added, so we can have a bigger and bigger undertaking. It’s really exciting.

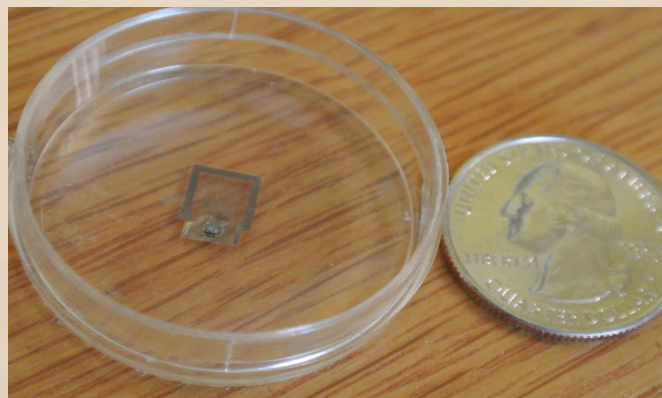
BSJ: Yes, definitely. That’s kind of our interviews team right here - two of us are biology majors and two are electrical engineering and computer science majors.

“Could you build for us little free floating electrodes, localized in the cortical regions, which can wirelessly send information in and out? Could you do that?”

Prof. Rabaey: Exactly! And that’s where you exchange information, when you learn from other spaces, and you see opportunities. Absolutely!

BSJ: We came across your research on neural dusts, with shrinking components smaller and smaller. We understand that they’re used in the BMIs. How do you power such a small device?

Prof. Rabaey: That’s the right question to ask. This is the powering problem. There are little passive elements that are free-floating, little cubes. When you power them, the way you get back the data is that you take the incoming waveform, and you



Microsensor integrated within organic polymer circuit board that can be implanted within the human body. Quarter is used as a reference for size.

modulate data back on the reflected waveform, just like how RFID works - you send an RF frequency at it. It’s a sine wave. And the RFID tag just modulates the impedance and superimposes information back on the reflected waveform. And that’s the way you can read it. We did the math, and wrote a little proposal. After two months we came to the conclusion that it’s impossible. We looked at the physics analysis and saw that sending the largest amount of power within regulation didn’t have enough to power it. We cannot have a huge amount of power pounding on your head, that’s not very healthy. We got basically 2 nano-watts for a single node of 50 micrometers. That’s nothing - you can’t do anything with it. That was the problem. We couldn’t get enough sensitivity. So

we thought, that’s it.

We gave up, until about two years later, when we revisited the idea, and asked: What if I would use acoustic sound instead of electromagnetics? Basically, use an acoustic wave to power it. The advantage of acoustic waves is that they have a much smaller wavelength. And it’s all about that - it’s all about impedance matching. When you have a little node, and the wave is too big, you don’t have good coupling between the two. So in tissues, acoustic wave fronts propagate a lot more effectively and efficiently, not like magnetics. That was the solution. Suddenly we got three orders of

magnitude of more power for the same node size. And that's a lot! You don't get this easily. In science, sometimes you get 2 or 3 times more. Three orders of magnitude is a big win.

Basically, it says, that we should go for acoustics, and generating acoustics is not hard to do. You have piezoelectric material that allow you put in an electric waveform, acoustic waveform coming out, and then it hits the little node. Acoustics really go well through tissue; acoustics don't go well through bone. For example, I couldn't put an acoustic generator here (pointing on the head) and hope I can talk through skull. That doesn't work very well, because of the scattering of the signal through the skull. Electromagnetics are much better, so for that purpose, we indeed use electromagnetics and an antenna as an intermediate stage. We send an electromagnetic wave through the skull to power an intermediate stage, which powers amplifiers, supplies energy to de-converters, and generates an acoustic wave to send to the small neural dust nodes. The intermediate stage then takes the refracted acoustic wave coming back from the neural dust, demodulates it and sends it back out of the skull on an electromagnetic wave. So you need to combine them all. That's engineering. Engineering is not just focused on one problem. It focuses on big systems with all the components. You have to put them together and it all has to fit in the end.

BSJ: What kind of circuits are present on each neural dust node?

Prof. Rabaey: Neural dust node has one transistor, and it's mostly passive. You have a power waveform coming in, you turn it into a power signal, and that powers the single transistor. You need some amplification, which is provided by that single transistor. The transistor modulates information back onto the piezo element, making it move, which scatters the information backwards. However, I need something that generates a waveform and decodes the information coming back from the neural dust- something like a radar, which is not easy. A radar has several antennas, where one can set a beam with different phase shifts for the different antenna elements. When the data comes back, it comes from a whole bunch of antennas, the neural dust, and you have to take them apart. Signal processing is required on the intermediate stage and that will require more power. But, fortunately, with the intermediate stage, you're not

very deep in the tissue, and we have area. Area matters. If I have more area, I can have more power. The amount of power and energy a small node can get really depends on the size of the node. On the top of cortex, the intermediate stage can have a little membrane spread out that has quite a large aperture in terms of antenna size, electronics and processing.

BSJ: You mentioned just now that the neural dust nodes are mostly passive. Could you explain a little bit about the passive and active states and what those mean?

Prof. Rabaey: A passive device is a device similar to a resistor or capacitor something that doesn't perform any gain, so they don't have any amplifiers. If I basically take a resistor, I put a voltage across it, I get a response. It's a pure response to an active waveform. Now let's use a very simple example. Suppose I have an RFID tag, I put a sine wave in, and I modulate the information back down. There is no need to do anything active with the device, there is no energy stored, per se, in the device. The energy is conserved, and I modulate the information back out on that energy beam. If I want to do computation, I'm going to need an energy source. An energy source means I have to take the wave coming in, rectify it in some way or another, make sure it becomes DC, and store it in some energy resource like a battery or capacitor. I use that energy to perform computation, which puts the data back into the oncoming waveform. Active components require that you have some extra components that do some individual computation; while with passive components, you react to what's coming in, change it a little bit and send it back.

BSJ: Because the neural dust nodes are so small, I would imagine that it's very hard to control the direction of the nodes, which comes back to the incoming word. Does it matter for the output signal?

Prof. Rabaey: That is definitely a good point, directionality matters. You have a little cube that consists of piezoelectric material and two electrodes. The rotations will definitely change the way it's going to refract. That is why, ultimately, you don't look at it as a single transmitter-receiver-reflector type system. To use it, you really need an array of interrogating elements. So, basically, you put in one wave, and it scatters back in different directions. The directional information can be used

to identify individual nodes. So, the signal will definitely be impacted by how deep the nodes are, and how the nodes are oriented, but you can learn those things. Once you learn those things, the nodes don't move much. They might move a couple of microns occasionally, but that's it. For example, every time my heart beats, I pump blood into the brain, and the brain expands and contracts continuously. You might have some micro motion but the nodes can be considered to be generally static in location. That is kind of an assumption that we are making. If we say they are moving all over the place the problem becomes much harder.

BSJ: Building off of that question, how exactly do you deliver neural dust into the cortex of the brain?

Prof. Rabaey: Ah, good question. What apparatus you choose to use, this is not trivial at all. Obviously, you have to have surgery first. Surgery, hopefully, can be done by having a little burr hole. You try to avoid taking the whole skull off. You make a little hole in skull, about a centimeter wide that goes through the dura and into the cortical material. There are some apparatus that allow you to push material in to do this. You can actually build surgical tools; people have been doing this for a variety of devices that help you to put the nodes into the system. What you are trying to do is minimize the amount of damage to the surrounding tissue when you push something in, as you have all of the arteries and capillaries around there.

That's a good question; we haven't really gotten into massive deployment of these things yet. We have a lot to learn. These are really tiny, tiny little devices, manipulating these type of things is not trivial. But, we do have some experience with this. We are not doing this just with neural dust, we have many other devices that we are working with, which are ECoG based devices. These are flexible membranes with electrodes that you put on top of the cortex. It's like EEG, but ECoG electrodes are placed below the skull, because that is much more efficient in terms of information gathering. Your skull is a low pass filter and an attenuator. With EEG you don't get much information -- everything above 50 Hz is gone. But if you go below the skull, you can go up to 300 Hz and get a lot more information. There are, however, some packaging issues. For example, how do you make it flexible, how do you make it compliant, and all these types of things.

Another method we use is to push little needles, almost in the shape of an octopus, into the cortex. These needles are flexible and connect to a central platform, where a radio and power generator sit. You use a special apparatus to push this device into the cortex. There are a variety of tools that people have built. If you can make small things, you can also make very small apparatus.

BSJ: I'm guessing these devices are meant to be chronic. This seems like a very difficult task. What are some tradeoffs and challenges that you had to address to make these devices chronic?

Prof. Rabaey: If I want to put this in a human, for whatever purpose, it could be used to address motor dysfunction or any other type of neural disease. Once you do an implant you want to make sure it stays there for a long time. People typically talk about ten years minimum for these devices. It's hard. No one has really done it in the neural space because there are a whole bunch of problems that emerge over time. However, not everything has to be chronic. There are certain implants that could be used for short term implant and explant. A very good example is neural implants for stroke patients. If somebody has stroke, the stroke basically destroys certain regions of the brain. It turns out that many stroke patients afterwards are capable of remapping some functionality, so if they have motor issues, they can remap some of those motor functions to other regions in the neighborhood that are not damaged. Same thing works with speech. Stroke patients initially have a hard time speaking, but then they can recover



Prof. Rabaey demonstrates implantation of microsensor within the brain.

some speech. We hope to use BMI to help them rehabilitate. If someone has a stroke and cannot move their hand, what they do now is that they have an exoskeleton that moves the hand for them. What you hope is that by moving the hand, things start linking up and they start rebuilding some neural connectivity. It would be even better if I had that exoskeleton with an implant. You have electrodes that drive that exoskeleton, and you have a linkage between a region in the brain and what's happening. You do this for a couple of months, and when you are done you explant the device. So, not everything has to be chronic.

If it is chronic, there are a bunch of failure mechanisms you have to address; for example materials and scar tissue. It turns out that a lot of the implants that people do today with humans, monkeys, rats, and other animals is that when you put electrodes in the brain, after a certain period of time, you see the sensitivity of the electrodes goes down. The signals get weaker and weaker, and suddenly they disappear. No signal anymore. The main reason for this is scar tissue. You have created damage. If you put something big in there, ranging from 100 microns to 2mm long, the body reacts to it. The other thing that happens, is when you move your head, there is micro motion. The electrode is fixed, but your brain is moving, so you create more damage. You see glial tissue growing around it and you lose connection to the neuron in that neighborhood.

That's why we thought of neural dust. Neural dust is free floating, so it moves with the brain. The reason we go after a 50 micron size is because it has been shown, by a number of groups, that if you make an object smaller than 50 microns and you put it in the body, the body basically ignores it. It considers this object to be normal. It's only if it's bigger it reacts to it. That's one of the reasons we want to make neural dust very tiny.

The other issue involves the materials that you are using. The brain is a vicious environment, there several types of fluids there. For example, if you have two materials that fit perfectly well together, say you have a polymer and a titanium wire on top of that, you have a perfect connection. However, in the presence of liquids and certain acids, they might delaminate over time. Water gets in there, and suddenly a wire might come loose. So, the right choice of material is very important.

The other thing which becomes very important is the possibility of infections. Today, most of the implants are done via burr hole surgery. Every time you have a hole through tissue, at some point in time, you will surely get an infection. That is why we are so insistent on wireless connectivity. With our system, you can close the skull back up, with the implant below, and you have reduced all sources of infection.

BSJ: So if you have problems with the neural dust, is there any way to remove them, or get at them and change how they work at all. Or is it that once they are in, you are unable to modify them at all?

Prof. Rabaey: You have hit on a very important issue. You can implant them, but explanting them is almost impossible. You are not going to start fishing after nodes that are 50 microns in size. You can composition them with some imaging strategy, but that's it. The idea is that they are there for life. But, they don't matter as they can get absorbed by the tissue. In general, the idea is, and dust says it all, that you sprinkle many of them, more than you need. If I really want to do listhetic or prosthetic control, I can talk to a certain set of neurons, say 50 or 100 neurons, and that should have enough connectivity. To make it robust over time, as some of those nodes might not work anymore or the neuron might not be operational, we put plenty of them in. The idea is that we sprinkle more than a hundred, we sprinkle hundreds to thousands of nodes, so that you have redundancy. Now you have a very wide bandwidth. If some disappear, no problem, you have another one now. That's kind of the mindset. You can imagine getting these things to regulation is not going to be a trivial thing. So initially we are looking at this for rats, monkeys, and other animals. It's going to take a lot of water to go to the sea before you can really put this in a human. For humans, we use more standard technologies, which you can do step by step.

BSJ: What kind of packaging do you have to put the neural dust into? You mentioned that you have to choose your materials wisely to make sure that it doesn't interact with the brain at all, so what do you have to do to guarantee this?

Prof. Rabaey: It all depends on what you're talking about, and how complex the nodes are. Neural dust is fairly simple, and the only thing you really need to have is something that can measure voltage. You need two electrodes that are exposed metal;

the rest of the node is a tiny piezoelectric layer and a transistor that can be built on the same platform. You use the two exposed electrodes to measure voltage. That's the risk factor. The rest of the dust, the piezoelectric layer and transistor, can just be put in a blob of silicon dioxide, a relatively resistant and inert material. In general the silicon dioxide doesn't react with any chemical processes. However, a problem arises when something gets past the silicon dioxide covering of the node. Over time, this could destroy the node. However, neural dust encapsulation is easy. For instance, cochlear implants are a little more complicated – they use a titanium box in which everything is encapsulated. Again, you have to be careful where the electrode comes out, which is where you have the weak spots.

We just started a large project with UCSF on these next generation implant devices. We work with Livermore Labs, which do the biocompatibility encapsulation – they have a lot of experience in that space. It is something that you have to build. You have to know what works and what doesn't work.

BSJ: Is there any reason why the neural dust is expected to stay in its place? Does it have any attractive interactions with cells?

Prof. Rabaey: That's a good question. Obviously the key thing we're doing is sending acoustics through the system. In itself, you might say that piezomaterial is going to stand and go in. Now if you compute how much motion there is, you'll find that it's extremely small. However, one thing we have been worried about is that if I transmit a large acoustic wave, could I create electric waves that, in one way or another, start interfering with the operation itself? Would that basically create stimulation? Now stimulation, in itself, is a useful thing to have. What neural dust does right now is to read out of the brain – it looks at a neuron and information comes out. But for a number of applications, you would like to write into the brain. You want to, basically, add some electric current, and you stimulate a neuron to fire. That's exactly the way cochlear implants work: they stimulate the nerves. A deep brain stimulation, for Parkinson's disease, involves long electrodes, with which they inject small electric currents. Amazingly, people who have extreme Parkinson's, where they cannot control their limbs, can start writing. Often, when you have reading of material, you don't want to

have unintentional writing in the body. We've been looking at that, and we're convinced that the amount of acoustic power we put in is much smaller than the amount that would lead to stimulation.

BSJ: When you are reading these signals from the brain and transmitting them, how do you target the signals you want without interference from other signals, and how do you interpret the data?

Prof. Rabaey: The beauty of the brain is that it's an extremely plastic environment – it's a platform that can be configured, and reconfigured. It's not a fixed computational system. If you look at a lot of the BMI systems, you want to control prosthetic limbs. To do that, first, you have to map the brain. Every human is a little different, so where exactly the function lies depends on the size of the brain, and other factors. Using imaging techniques, you can figure out where the auditory controls, motor controls, and other functions are. You're not going to randomly choose. However, you don't have to be too precise. You basically have a specific neuron, and you get signals, which you feed into a controller. The device takes in the inputs, and conducts computation and filtering. That translates into signals that go into the prosthetic device. If that was the whole story, though, this would never work. The first time you tried it, the arm would go left, and right, and all over the place, because that neuron has no clue about what's happening. Fortunately, you have eyes – feedback. Feedback comes into the game. I have tactile feedback, visual feedback, which gets put back into the system. It then finds its way to that particular neuron. The brain is really densely connected. So you start reprogramming that neuron, and the pathways between various neurons. After a number of trials, it gets better. Then in the end, after hundreds of trials, they get 95% agreement in the experiment. If the brain wasn't plastic and flexible, you wouldn't be able to do this. That's why you don't have to know exactly what you're shooting at.

BSJ: So how do you convert these signals that you're getting? Inherently, they're just electric impulses, so how do you convert them into something meaningful?

Prof. Rabaey: This is a question about neural codes. How is the information encoded into those signals? So you look in any single neuron, and you put an electrode to measure voltage in the neighborhood of the neuron. Firstly, you have to

measure the neuron itself. The neuron basically contains many impulses that build up, reach a threshold, and then fires. That propagates down the axon and connects to all the neurons that are involved in the connection. That's the electric field you're measuring, from which you'll get a voltage signal. Most of the time you may measure two or three neurons, not just one. However, they all look different – some of them are further away, or closer, and the shape of the pulse is different. There's also other information there because there are thousands of neurons in this neighborhood that are all firing back and forth. So you can imagine that somewhere, you'll have a combination of those signals. Now it turns out that you would expect to get a whole bunch of noise. But in reality, neurons are connected. One neuron fires, then the next one fires, then the next one. You'll get phase coherence within different neurons, from which you get a waveform. This is where all the EEG signals come from. All the alpha, beta, and gamma waves are resolved of many neurons acting in synchronization. That's the other information you get, which you can measure.

After this, it depends what you want to do. You can filter it, or you can process it. Most of the BMI folks that work on prosthetics so far have been using spikes. When you find the spikes, you can figure out how often the neuron fires, on the average. That's the key information that most BMIs use. If I use EEG, you don't have spikes. You look at the low frequency waveforms, which I described, and you look at them in the frequency domains. You may have delta waves, which are very low frequency, along with alpha, beta, lower gamma, and upper gamma waves. If you divide these into frequency units, and do spectral analysis, you'll observe not the energy itself, but how it changes. If I am active, I am going to see the energy shifted to gamma waves. If I am not active, the energy shift will be seen at lower frequencies. So this sort of spectral information can be used for BMI as well. People have been using this for doing speech synthesis among other things. But in the end that's what you get is some metric, be it energy change or spike rates. And that's what inputs to my model. I try to build a model, an adaptive model, or a stochastic model that learns and adjusts the parameters in a given situation to give the best possible response. So that's a lot of signal processing, machine learning, all these things come into the game.

BSJ: What are some near future applications for neural dust?

Prof. Rabaey: We just got a large grant from UCSF that's looking at neuro-psychiatric diseases. There are many of soldiers coming back from Afghanistan, and a lot of them have neural conditions such as depression, stress, and posttraumatic stress disorder. It's a big fraction of our society, so can I learn about why these things happen, and what causes depression? Can I do something about it? Right now it's drugs - you basically have overdoses of some chemicals that are being created and you put in a drug which suppresses it. But maybe I can learn. If it turns out these are neurons that start firing an open loop, I can stimulate that region. For instance I have a discussion going on right now with a cardiologist in Poland. He came here with a group of people, so we heard his presentation. There is a beautiful application in this field, too. People who have coronary diseases, basically have clogging of the arteries. They put a stent, which is a flexible device that keeps the artery open. The blood has to come in and out. And what typically happens with someone with clogging, is this makes the whole tissue, the whole cellular membrane, stiff. If doesn't move anymore, the arteries will get clogged up. Then, when you put in the stent, you hope that the artery will start recovering and become flexible again. So, the new idea we had is that the acoustic power and integration of the neural dust would be really beautiful if it could actually be a pressure sensor instead. The pressure sensor basically something that's flexible, that can measure strain and stress. Then, since piezoelectric anyhow, I can interrogate it again with my acoustic wave from the outside and basically on a database figure out if things are getting better, how fast are they evolve and things like that. So the idea of monitoring devices is possible. Peripheral neural is something we haven't talked about - it's really anything in the nervous system, where there are a lot of signals which you can tap into. I might be able to drive prosthetic devices as well. So there is a set of applications that seems to be coming. It's all very interesting, but obviously when you have a small group, you have to focus on research; you cannot just say well I am going to take everything on. If you want to get some results, you have to focus on specific things and topics and say this is what I'm going do first, and I'll see what's happening later.

BSJ: Where do you see this research taking in you 5-10 years? There are a lot of neuro-inspired applications that BMI has. What are a few things we can look forward to in the news in upcoming years?

Prof. Rabaey: There are many interesting directions we could go in, right? The things I am interested in, on one side, is part of this whole process in learning about how the brain works. The Obama initiative is about mapping the brain, understanding brain functionality, and so on and so forth. It's cool, because the brain is a decent machine. It has 20 Watts of power - that's not a lot, its about as much a little light bulb - and that's the total power it takes on the average, and it does a lot of good computation. We're darn good as humans in doing things like multitasking, taking time, and doing pattern recognition. It's really amazing, that we do all of this in such a small brain. Now we say, could we learn from the brain, to build better computers? That's one thinking process. So Moore's Law is slowing down a little bit. The question is, "What's coming up after that, if silicon based computing basically plateaus out?" Could you not learn from the brain to build computers that are a little bit different, that are good in certain tasks like pattern recognition, synthesis, ordering, decision making? These are processes that computers are not very good at right now. So you start looking at the brain with this perspective. Why does the brain work the way it does? 1. It's not a digital machine. The brain doesn't work on 1s and 0s, (analog coding) 2. It has plenty of concurrence and parallels. It's a giant parallel machine. Only certain fractions work at any point in time. If everything was firing at all the time, your head would explode. We would explode. From an energetic, and thermal perspective, you would be unable to maintain it. 3. It's very redundant. If I kill one neuron, take one neuron away, functionality wouldn't be impacted in a major way, even though that neuron would be trained for a very specific task. For example, you have these grandmother neurons or Mona Lisa neurons, named after the concept of seeing the Mona Lisa and having this one neuron fire like crazy. Now if I take that Mona Lisa neuron away, I would still recognize the Mona Lisa, but I might have to a bit more inference involved in the process of recognizing the painting. So, there are several good properties of the brain that can be used to build better computers. Computers that are energy efficient and that can be built on your cell phone, can help you have more precise and exact functionality.

The other way I am looking at this is that with BMI is that neural diseases are huge in humans. I already mentioned spinal cord injury, stroke, epilepsy, stress, depression, and a whole range of neuropsychiatric diseases. The impact of this slew of diseases attacking humanity is huge. Looking at technology and how you can address some of these illnesses or resolve them, or at least aid them, is very noble goal.

At the same time, now, wait a second, once I have indeed a connection into the brain, could I do a lot more with this? Its not purely trying to address neural disease, but could I also use it for the brain-machine interfaces' controlling function. Basically, I could have a cyber wall, a more close-linked channel, high linked channel between the two. So, this is an interesting question that, obviously, we're far away from this. I can put an EEG helmet on and say go left, go right. You can do about 3-4 things. It's good for one day and then it's really boring, so that's not really efficient. You can imagine that as technology evolves, the purpose will change. This is one part of what you can call "human augmentation". Now people don't want to speculate about this very dangerous topic to speculate about. Augmentation from an ethical standpoint has a ton of questions. But they can imagine that there are many other ways of augmentation in our body. So we turn to wearable devices: you have a watch, you have bangles, dongles, and all kinds of electronics that people can wear. That could be interesting. If I start putting those things into a network, I can start building what I call the "Human Intranet" - a network that parallels the network that's inside your body. Inside your body you have your nervous system, which is a data information network, and you have your arterial network, which is basically energy, provision, and nutrients. So if something gets attacked, could I not replace it, but complement it with a network that is sitting on my skin outside my body? You can imagine that I have a set of

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sensors on my brain and inside my brain, that act as the control faction, and I could use this for instance to drive an exoskeleton. Once I have an exoskeleton I want to run faster, or for example I want to drive my bicycle or car. So, obviously those networks have to have sensors and energy. That's why the placement of the arterial networks is so important as well. How do you get the energy to power these sensors? Well you need a network of energy distribution. It could be wireless, it could be acoustic, or it could be infrared. So this whole mindset involves thinking about how to evolve this whole variable world. If you start thinking about having that link to the brain as well, it's really intriguing. Now is this 5-10 years? Probably not. But it's good to have the thought that somewhere this might be possible. Then you can start questioning, is this something I want, is something that is acceptable, is this something that's safe? A lot of discussion these days is also about if it's wireless, people can hack into it. Suddenly you have security issues. You have privacy issues. If someone can start reading your brain activity, can he start snooping on you? Can you imagine NSA in your head? That's pretty scary, right? So we have to start thinking about this, and start thinking, maybe I should put security in this wireless device or I should add some encryption. There are many different angles and we don't know where it's going to go. That's the nice thing about research - you speculate. And you go forward, and at the same time you see all these possibilities which you can explore.

BSJ: BSJ would like to thank you for your time.

Layout by: Lucy Zhang