**NPBH 2024 Transcript- (Day 2) Intro**

00:35 → 01:25

**Ralph Etienne-Cummings:** Good morning, everyone. I hope you had a lovely evening and got to enjoy the city a little bit, you know the waterfront. At any rate, it was a beautiful night, I thought, you know, so I hope you got a chance to walk around and, yeah, and chat and speak about the day yesterday. I think it was quite lively. Lots of good discussion, and I'll and hopefully that will also generate, you know, a lot of fodder for our position paper when the time comes. So we are looking forward to an additional day of even more, and you know more controversial perspectives and discussions, and so on. This is very important to the process, I believe. So to begin this morning. We're gonna have Ali from the Nsf. Give us a little bit of an introduction, but let me turn it over to Grace to introduce her and move forward.

01:30 → 02:33

**Grace Hwang:** I'm delighted to introduce Dr. Ale Lukashev, who is a co-sponsor of this workshop.She's currently a director at Nsf's engineering directorate. She runs the Eccs program, and her interest encompasses the boundary between classical and quantum communications, sensing computing AI and next generation computing before she joined the Nsf. She was a program manager at Darpa, where she also led multidisciplinary programs covering novel, classical and quantum devices. She's also developed efforts for hardware for the next generation. AI. And many interactions between Dod DOE, Nsf. And NASA. She is the Abs fellow and an Osa. Senior member and Cottrell scholar. We regretfully missed Ali during our funders panel yesterday, so she'll have an opportunity to tell us more about herself, and also her interest in this space and some funding opportunities.

03:38 → 09:41

**Ale Lukaszew:** Thank you so much, Grace, and I regret that I can't be there in person. But at least we have this opportunity to do things via zoom. So thank you for your kind introduction. So you already cover who I am, so we can go to the one after that. We already told who I am, and I appreciate your candid remarks. So yeah, why am I here? So this is more important. And this is because the collaboration with Grace actually started at Nsf when she developed her program in 2021. The brain inspired dynamics for engineering energy, efficient circuits and artificial intelligence or braid. And the goal behind this particular program was that it was recognized that brain-inspired engineering efforts so far had focused on highly simplified concepts from neuroscience, and there was significantly more that was done and has and continues to be done in neuroscience. And so brave proposals were aimed to need to demonstrate how principles of biological intelligence can be translated to engineering learning systems in the context of situated relationships between brain, body and environment, by drawing from models and knowledge of theoretical neuroscience and the expectations was that the proposal should dwell into a close interaction between theory and algorithms or theory and hardware, and all of them should definitely have strong component in neuroscience.So this particular program braid led to 16 ongoing awards for a total of in excess of 20 million dollars up to date. Next slide, please, Grace. So I want to tell you about ongoing Nsf engineering investments in neuromorphic slash brain inspired applications. So if you do a search on the awards that are current, the engineering directorate and those 2 concepts there is of the order of 585 million dollars on brain inspired research on more than 879 awards. I'm sorry. 875 awards in the order of 37 million on neuromorphic related research, with more than 65 ongoing awards. My particular division, which is the electrical Communication and Service Systems Division has of the order of 107 million dollars in brain inspired research. More than 225 awards and 19 million dollars in neuromorphic related research, with more than 50 awards. Next slide, please. So ongoing efforts right now. Well, there is the particular new every program on via biocomputing through engineering organoid intelligence. And so far there are 7 projects awarded for more than 11 million dollars. So I'm going to be very quick now. And what we're doing right now is brainstorming about a possible future program around novel concepts, incorporating. Of course, New Brian inspired brain, inspired understanding and mathematical model, and this has been inspired by some very interesting research that started many, many years ago with the work of Pentican urban at Stanford, and then Berkeley on, for example, high dimensional vector algebra trying to identify some of the processes in in brain thinking. And so there were a lot of inspirational remarks. Yesterday, for example, it was said that at the beginning of air flight there were a number of concepts that were trying to mimic birds too closely, and they were not successful, and it was only when we were actually able to capture the fundamentals behind air flight that we were able to conquer the airspace. So I believe that that will apply also to the next generation of brain inspired computing, and that we definitely need to further understand what is really going on at brain level in order to improve upon what we have since, as Pauline mentioned, current efforts in computing are definitely not going to be sustainable in the energy landscape. We are definitely using much more resources and will be available in the future for computing needs.So this is an important part of neuromorphic or brain inspired research that needs to be addressed. Another concept that was brought up yesterday in conversations was that we don't need to necessarily mimic exactly how things are happening at the brain, because the evolution of the brain came about a particular collection of materials that were available for nature to work with which are not necessary and necessarily representing the materials that are available today. So we have said that, as I said. You know, I think, that we still need to try to capture what is the fundamental mathematical fabric behind neuromorphic and brain inspired approaches for computing and try to see if we can understand that better and incorporate that into the new design of computer systems. And that's all I have to say. So thank you for being here, and I am very, very excited about participating in this workshop. Thank you very much, Grace. Back to you.

09:43 → 10:03

**Grace Hwang:** Thank you, Ale. Are there any questions for her? Oh. I think there's a question from Don Juanch. Could you repeat the question? I didn't quite hear it

10:04 → 10:08

**Don Juanch:** Any chance for a workshop on that brainstorming?

10:10 → 10:11

**Grace Hwang:** You're referring to Ale's new idea.

10:12 → 10:28

**Ale Lukaszew:** Yeah, we're thinking about it. We are still in a very early stage of idea, idea of how this is gonna go. But, Don, you're definitely going to be called upon for that. Thank you. Thank you for the question.

10:30→ 10:36

**Grace Hwang:** If there are no other questions. I'm gonna turn this over to Ralph, and we're back on schedule.

10:28 → 12:56

**Ralph Etienne-Cummings:** Thank you so much, Ali. So today, the next item on the agenda is the next keynote speaker who is gonna be Dr. Zhenan Bao. It's rare that we have somebody who's so accomplished. To give us a keynote. So Dr. Bau is one of these individuals who, in academic life, is basically an egot winner. Right? She's in four national academies, you know. That is an accomplishment you know is quite an accomplishment. In addition to that, she's a professor at Stanford University. She's currently in the Kk. Lee professor in chemical engineering with courtesy appointments in chemistry and material science and engineering. She has been department chair and also started the Stanford Wearable Electronics initiative which, where she currently, who she currently directs. She is also affiliated with a faculty member of the Pre-court Institute Woods Institute and the Chemical H and the Biox Institutes as well. She received the degrees in Chemistry from University of Chicago and Material Science, and Material Science department. She has spent some time at Bell Labs. A lot of our great scientists have done so in the past. Fortunate to have a person in my department, Jim West, who also spent some time, who you probably know very well, and she has published a large number of papers and been recognized with a lot of patents as well as her work has been highly cited. In addition to you know, the members being members of the National Academies. She's also a fellow of the Uhcs, Mrs. Spi, A/C, and so on and so forth. So clearly, you know. She's very well accomplished, and we are, you know, very fortunate to have her coming. Give us her presentation please.

13:57 → 1:00:51

**Zhenan Bao:** Okay, all right. It's such an honor for me to be here. Thanks, Ralph, for such a kind introduction and the grace for the invitation. It was really humble to hear from those yesterday who have taken devices actually to clinical application, and the kind of requirements and restrictions one have to meet for me. I come more from the chemistry and materials aspect. So our goal is to understand the materials, design, and the materials which will ultimately lead to certain applications, but then the application is more of. I see our feedback, and to provide us with an understanding of what may be good about the material or devices, what may be the limitations, so that we can make them better. So in terms of whether they are suitable for a particular application, then we try to find out from those who know about it, and we are perfectly happy if you tell me there are criticisms about the limitations, because my principle is, I rather know that early on, instead of going down a wrong path. So from my point of view, we talked a lot about neuromorphic yesterday. And actually, I felt, after the discussions, I felt more confused about what it really means. But anyway, I will talk about basically our learning from skiing as an organism that has certain materials, functions, and also signal processing capabilities. And some of it might be neuromorphic according to certain definitions. So as material scientists. When we think about designing things, we like to have inspiration from natural systems because it allows us to have imagination of how to design them. To me skiing has been fascinating, because as a material, it's not only flexible but also stretchable, biodegradable and also self- healing all at the same time. And this type of materials are not naturally occurring, especially if we want such electronic materials, they are not naturally occurring, so it provides us a large playground to work with. But here I also want to differentiate flexible material versus skin, inspired or skin-like material. There are materials such as Polyamide, or even silicon, that can be flexible when you make them really thin. But the modulus of such material remains very. And if you make them thin enough, potentially, they won't cause tissue damage, it's still arguably, or it's still to be determined for the long-term effect for ultra thin materials, because in one dimension the thin material has very low, bending stiffness. But then this is two-dimensional material. Still, the high modulus potentially can cut into tissue. But that's still to be decided. So the type of materials that we are interested in is soft, low modulus material, with modulus comparable to that of tissue. And the other thing that I'm really fascinated about skin is its way of processing signals right after sensing. So our mechanoreceptors respond to external stimuli by generating spike train signals in terms of action potential that can travel through the nerve. Okay, thank you. Can travel through the nerve without losing the information. There are different types of mechanoreceptors, but all of them use frequency encoded signals to communicate. And basically, you can see that in this case, some signal processing is actually done right at the sensing front. And then all the signals finally come to our brain, which is the central processor that gives us instruction after receiving the information. So this is also part of the reason that humans can operate at very low energy consumption using this kind of distributed sensing system. So, our thought is, if we can learn from skin in terms of both the materials, property as well as its functionality. As a sensing system. Potentially, we can change the current paradigm for diagnosis and monitoring devices to make them closer, getting closer to the human body to extract information signals more precisely, and also make them to be these devices to be less invasive. Well, you, you might say. Well, wait a minute. Silicon is so advanced you can now integrate so many functions, sensors, signal processing, or signal conditioning. All in such a small form factor, this can be an implantable device and wirelessly controlled. What's wrong with it? Well, there's nothing wrong with it. This is very advanced. But I see the difference is that whether you have the data conditioning, signal conditioning, or some preprocessing done up front and versus having all the kind of signal processing at the silicon end and then depending on what is the application that's desirable if we are measuring things that's sensing information that's very localized near the silicon chip, then the lowercase would work very well. But if we have a large number of sensors which require a lot of processing of the data potentially, the system design that's similar to how skiing processes data could be desirable. So the 1st one is what we try to explore. And in this case, we want to see if we through materials design, we want to see if it's possible to make the 1st scenario happen. Basically, this is what we call E-skin, which contains the sensors and signal processing, all in the form factor that's similar to human skin. Another approach led by John Rogers and many others, is taking rigid components, but then embedded them into the soft matrix, and in this case more localized sensing would be the case. So this gives us the driver for materials development, because such kinds of electronic materials that are as soft as jelly, but with good electronic properties as good as silicon or the lower performing form of silicon, or as good as metal, did not exist before. So this becomes our overarching kind of fundamental study that we perform in my group. For some of you who may have followed the development of organic electronics. You may also think that. Well, organic. What's the difference? Organic electronics have been going on for a long time. What's new here? Indeed, this field has been going on for quite a number of years since the initial discovery of conducting Polymer, that basically the discovery suggested that having these kinds of conjugated structure with very rigid structure would lead to good conductivity, and also quite a long time ago, when I was in Bell Labs, we discovered that for semiconductors again, we need this kind of rigid molecular structure to be able to transport charges along the polymer chain, and also allow charges to go across the chain. And this field has developed for a long time with organic light emitting diodes being the current used products and some anti-static applications for polymer coatings. But the main limitation for a lot of these materials is that these polymers, even though they can conduct electricity. But there are a lot of conformational defects where the polymer backbone can have twisting.Also, when polymer molecules are very long in high molecular weight. They will have this banded structure, and all of these are charge traps that have been limiting the electrical performance of these materials for decades. So in our case, we made a very important discovery that actually now allows us to boost the charge transport, and also at the same time being able to incorporate a number of skin like functionalities that we wanted to add into the material. Mainly, we found that actually, we can induce these kinds of confined structures, where the diameter of the molecule of the structure is much lower compared to that of the persistent lens of the polymer. What it does is, it forces the polymer to adapt to a planar and a more linear structure in this Nano confined structure. And the beauty is that we can induce this by using a matrix material that can add all the skin-like functionalities that we need. Then this way, we get the actual, to our surprise, when we 1st did this, we found that the charge transport mobility which determines how fast transistors can operate or can switch. In this case, when we have the nano confined structure, we have a boost in charge transport compared to that of the pure semiconductor. So basically, these nanostructures could be seen in these. We have these molecules aligned very nicely in the confinement along these kinds of fiber, like larger structures instead of in the neat semiconductor, they are very highly disordered. That's what we typically have observed, which limits the charge transfer. But this became the foundation to allow us to now have a collection of skin like materials, not only just stretchable soft semiconductors, but also biodegradable conductors using matrix that's biodegradable and semiconductor. That's degradable. Or they can become self-healable. Using again, the similar approach, and then, importantly, for neural interface or bar interface, we need conductors that are very high in conductivity, but also at the same time have low impedance when in contact with tissue. So this version of the conducting polymer, with our introducing of the Nano confinement effect using a specially designed matrix allows us to get these photo patternable electrodes made of conducting polymer that are transparent, similar to indium, tin oxide, and also with conductivity similar to that of traditional transparent inorganic material, but at the same time you can see the impedance in contact with tissue is many orders of magnitude lower in impedance compared to using metal for comparison, and this type of electrode now allows us to directly perform direct photo patterning and allow us to test stimulation and the recording in situations that previously was difficult, for example, implanting at the brain stem region where the spinal cord and brain intersect. In that region, we could perform single nuclei stimulation with 50 micron electrodes and also high resolution emg and single neuron recording in the mouse brain. So with this understanding, then, we can, and the development of a collection of conductors, semiconductors. Then we can start to build circuits. Our goal is not to build circuits just kind of for the sake of making circuits. We want to use these high performance materials to build circuits that can start to have performance that's comparable to that of either amorphous silicon or polysilicon. I don't think we can get to that crystalline silicon level of speed and performance. But for the distributed sensing and signal processing, amorphous silicon or polysilicon level of performance would be already potentially sufficient. And also the photolithography patterning. We leverage the process that's already developed by the semiconductor industry, but adapt our material for these processing so that we can make integrated circuits with high resolution. For example, this is our recent version of a 50 by 20 transistor array. Here a thousand transistors basically fit into a small kind of 1 by 1 area region. So this could be used as the matrix switching matrix to sense, to use, combined with sensors and reduce the number of wires that are needed, and this is the largest circuit that we have been able to build. Now in with the stretchable, soft, substrate, and all the stretchable materials. So here is a circuit with more than a thousand transistors. With the switching frequency up to Megahertz range. With this type of circuit. So now with Megahertz, which for bio signal sensing the highest frequency, would be Kilohertz. So we think this could be potentially usable. Together with bioelectronics, application, and then the more recent unpublished result is the previous one, are all based on p-type transistors, with the highest performance comparable to polysilicon. The most recent one would be Cmos. So the advantage of Cmos is that it will have lower power consumption. That's what's used in industry for most of the integrated circuits, and also the footprint would be half of the Pmos based footprint. So this, we hope, will allow us to further miniaturize the devices. So the example of sensing arrays that can potentially be built. That's what we're working towards. It's partially done. So here you see a kind of a hybrid system. Basically, here we are putting the signal conditioning blocks together with the sensors. So the sensor, then simple amplifier and filter. And also we build the amplitude to time, domain, conversion, but then the rest are placed in the silicon, the rigid domain. So we envision that on the sensing patch there will be a race of sensors and multiplexer, all to reduce the number of wirings to the rigid component. And then there will be one indeed, still one rigid component. But this kind of design hopefully will allow us to maintain the high quality of the signal when they travel over longer distances, especially for large area sensing based applications. So now I want to talk a little bit about sensors, and then come together to come back to the system that's inspired by the human skin. So for sensors, if we want to mimic human skin, then sense pressure and the force would be required. This is the sensor that we have invented. Basically this pyramid is a small pyramid structure to overcome the issue with the typical rubber material. When they are compressed they can deform. But the issue is, there's a significant hysteresis, and the sensor does not bounce back to their original shape, making the signal inaccurate. And then, oh, it's my own phone. That's sorry about okay? All right. Finally, more recently, we are able to take the fabrication into the whole hand level. So these sensor arrays contain several 100 sensor nodes. And then, with this kind of form factor, they can be easily attached onto humans to explore how humans would interact with the surroundings. So now we start collecting data of basically someone wearing this kind of sensing array to manipulate objects. This could be interesting in teaching robots to or program robots more easily, and this is the type of signal that we would be obtaining. For example, grabbing an apple, you can see a lot of the sensor will light up, and then cantaloupe is much heavier, so we have to use the palm to grab it. So you see a lot more sensors on the palm. Many more fingers are being used. And then for something really tiny. These seats, right? Only a tiny region of the fingers are activated. So having more sensors can indeed, potentially make the job of AI easier. And here, even by my own eye, looking at this signal, I can see the difference in manipulating different kinds of objects. But, on the other hand, if we are building these kinds of electronic skin, we can also think about going beyond human capability. For example, in terms of resolution. The previous study suggested that the smallest spatial resolution are finger can actually differentiate is 0 point 9 8 from that paper. And here we use features that are 500 micron in the spatial width, and here the image recognition can be done very readily with these high resolution sensors, and also, I find it interesting that, actually using AI accuracy. We can use this as a way to determine what kind of design or sensor layout could be the most desirable to give us the highest accuracy, maybe for a certain task. We don't need to have as many sensors to conserve power, and here you can see with different numbers of fingers. Of course, with the full hand, we have the highest accuracy in recognizing objects, while with just one finger still some level of recognition, but much lower accuracy. So this could be useful to allow us to think about what's the best layout for the sensing array. This is another example of trying to push the limit of sensing resolution. This is using the transistor array that we built to read a whole ward. This is a braille pattern for skin. It's read with 2 by 3 area instead of. And this, again, this kind of resolution is not differentiable by human skin. So basically, many sensors are being developed. We have been focusing in my group on those physiological sensors, such as touch sensors, temperature sensors. There are many, many different sensors being developed by others in the field and in the skin. Like a version of sensors. Currently, high resolution, electrical physiological recording is already possible. With beating heart on the beating heart movement, moving muscle as well as in the brain, and also neurotransmitter sensors that are in the form factor. Again, in this kind of soft string, like devices are possible. So here are dopamine and serotonin sensors that we built with a specially modified graphene to allow them to be sensitive enough, and also selective enough for dopamine versus serotonin. The experiment we did here is to try to use the take advantage of the soft, soft form factor of our strain, like sensor neurostrain, so that we can implant ones in the gut, which at which location, if anything is rigid, will cause discomfort to the animal, but this is done with a weak animal, but at the same time we also implanted a neural strain in the brain, so that we can simultaneously measure the neurotransmitter generation in the brain and also later in the gut. Here, the experiment is not a neuroscience experiment. It's just to show that we can actually measure in 2 locations in a weak animal. When we give the mouse chocolate, we see a different timeline to observe the dopamine spike versus the serotonin in the gut. So with all these sensors, then the natural question that arises is, How do we process all the data? And what do we do about these wiring? So again, I think, Skin give us some ideas about how we might approach this problem with some signal preprocessing and also with the spike train type of signal. It has been shown previously using spike train signals and combined with amplitude for stimulation. This is work by Machera in Epfl. It shows that it can induce more natural sensation for tactile function, and also work done by Luke and Nitesh that these kinds of spike train encoded signals can allow patients to differentiate touch, sensation versus pain induced by these kinds of sharp objects. So we have been trying to see how we can kind of generate this kind of spike train signal. And can we use this to directly stimulate our nerves? Hopefully, it can induce sensation directly. Maybe we don't need the complex microprocessor. And here, basically, we use a simple circuit. It's an oscillator ring. Then the sensor will modulate the oscillation frequency depending on the received sensing information, the magnitude of the sensor so frequency increases as the pressure increases. So when we just couple the sensor with a few transistor based circuits, and then we use the edge detector to sharpen the signal. And then here we use the optogenetics in this stimulation to see if the brain will respond to this kind of naive thinking of just pulse waves. And here this is work done with Carl Desraff, and it's shown that indeed, the brain slice can fire according to the frequency used for stimulation. And then next, we want to see well, what happens if we have multiple sensors, basically to mimic the function of our synapse where different branches of sensors or clusters of sensors can have information all projected into them through the synapse. And then this will also generate when the synapse reaches a certain threshold, then it will create firing. So here again the ring oscillator generates the spike train signal. So here you can see low frequency, high frequency, which correspond to different pressures. So that's a frequency encoded signal. And then, in the lower part. You can see, as we increase the frequency for stimulation, then, in the synaptic transistor, which is a transistor. That's ion gated to mimic how our biological synapse works. In that case the higher frequency stimulation resulted in the higher current output through these depending on the frequency. So that means higher amplitude than more current injection and also longer duration of stimulation, also more current injection. So what that means is that when we apply higher pressure, then this pressure will lead to higher current you generated for stimulation of, say, muscle. So this is the kind of simple experiment that we did to show that. Okay, you can indeed use the pressure and then synaptic sensors to be able to process such signals. And the other function of this synaptic device is that they can potentially combine the sensing information in one single device. So instead of having a processor to generate these patterns of signal as a function of time, then these pulse train signals could with 2 different pressures, you can see, then they generate a pattern that basically is the stacking of the sensing amplitude from 2 different sensors. But then you can see both the high frequency and the low frequency all observed from this single synaptic device and if you use the same type of sensor, all going to the 2 branches sensing the same pressure, then the frequency is unchanged. So here the synaptic transistor will only respond to different frequencies of stimulation. So here, maintaining the same frequency, still will give us the same amount of current generation in this synaptic transistor. Additionally, we can also use this kind of device to be able to easily recognize certain patterns and also the direction of movement of patterns without complex kinds of computing algorithms. So on the top. You're looking at 2 pressure sensors. The yellow bars are pressure sensors.Both these branches are going into the ring oscillator. And then the synaptic transistor. So then, we use the transistor. We just measure the transistor output. When this bar is rolling against these 2 pressure sensors, it will arrive at the one on the left, first, at the one on the right has no signal.So frequent, even though there are 2 branches. So we only see in the time domain, the firing that comes from one transistor. But then, at the longer time duration, the bar moves to the second pressure sensor. Then we will see the signal again, all from the synaptic device. But we can see essentially the pattern of how this bar arrives at different sensors at different times, using a very simple setup. And then, in the case of pattern recognition, we also learn from the tactile sensing case in the skin where multiple inputs are going to be projected through synapse to the same neuron to increase the accuracy of sensors. So here we have each of the pressure sensors. 2 pressure sensors will go to one synaptic junction, and we found that this kind of biomimetic arrangement of design actually gives us a higher accuracy in predicting the Brill pattern. Using this kind of structure.So our latest electronic skin, we actually call it neuromorphic electronic skin, mainly because of the frequency encoded signal that's generated with the circuit that we are able to build. Now the sensor and circuits are all integrated in one monolithically integrated sensing sheet where we encode the pressure information or could be temperature information. The amplitude is converted to frequency, and then our synaptic device here, as the frequency used for stimulation is increased, then the current increases, and that causes the change in the movement of the muscle that's controlled by the pressure that we sense. So the previous version of the circuit is quite large. This one mechanoreceptor, one sensor and circuit you can see, occupy almost the whole finger with the current development we expect with the Cmos circuit development. Then we should be able to make each of the artificial mechanoreceptors to have a comparable size to the size of the mechanoreceptor, the actual biological mechanoreceptor. So this could be quite interesting to think about building more sophisticated electronic skin and combined with the synaptic transistors to see how this can be used to process data more efficiently, and for the implantables. The neural string is the type of platform we're working with. The challenge is to really get a lot of sensors onto this one-dimensional structure. But taking advantage of the materials, we develop all the electronic materials we develop and the circuits are strain tolerant. So then we can basically build this kind of one-dimensional sensing system with many sensors for the gut probe, we incorporated 150 sensors in 250 diameter, over 10Â cm long structure, and for the brain probe the 150 micron diameter, 1Â cm long can incorporate more than 300 recording sites for single unit brain recording. So here, the interconnects and here are sensors. Some sensors are embedded and some sensors are on the surface, so when they are rolled up, then the interconnect, and also some sensors which do not have for electrophysiology recording. We need the sensor to be on the surface, but for sensing movement and pressure and strain. Sensors are embedded in the middle, so after they are rolled up. This is the probe, and then that's the interconnect we bound to the flexible PCB. To take the signal. So here this is what we use now to perform implantation into the gut or inside the brain, as multifunctional bioelectronic fiber, which can take advantage of the skin-like electronic sensors and circuits. Yeah, for this one there are tens of sensors, but the one that the largest number we have built for the gut sensor is 150 sensors. It depends on the resolution that we pattern for this version. Not yet. We connect. But our vision is to have our circuits also built near these sensors. Yeah, especially for the very long sensors to have the signal processing incorporated into this form factor. All right. So for this kind of signal processing, I'm not the only group working on it. The organic electrochemical sensors that I talked about transistors that I talked about for synaptic processing of signals also have been leveraged for use for wearable devices. You will hear this from actually showing in the afternoon for these devices, for on body signal processing also, there are a large community now actually exploring the ion gated transistors to also generate spike train signal, and potentially, these transistors are sensitive to sodium ions or calcium ions, or could be dopamine ions, so that then the circuit can be directly linked to the spike train signal firing so that can provide additional dimensions, that combining sensing and the signal conditioning. So this is basically the type of system design we're pursuing. The question is, what kind of application maybe this kind of scheme, like electronics, might be uniquely suited for, especially for clinical applications. So I welcome here are a few thoughts for this type of design where we separate some of the signal processing signal conditioning at the sensing front. Maybe in some cases it could be a direct biointerface to reduce the complexity of the overall circuit design that's needed for large area electrophysiological sensing. Maybe for emg, there could be emg over a much larger area, and also Eeg, where the signal is very weak. Potentially, the amplifier and analog to digital conversion can happen at the sensing front, and also the ability for these circuits to subtract the noise directly at the sensing front for measurement moving subject that could be a possibility, for where the application be also the tactile sensing function for humanoid robots. Maybe in that case I talked to my colleagues who work on robots. They mentioned that the noise issue from sensors traveling over long distances might be an issue to overcome. So these are some of the vacations that I'm seeing. But if there are suggestions. I really welcome that to summarize here, the type of electronics that we are developing is what we call ski inspired sensors and integrated systems. I think the main attributes for these electronics are, they have soft, low modulus, and are compatible with tissue. They could be used for large area sensing, but could have a high resolution at the same time, a lot of time. We compromise the resolution when we go to larger sizes. But in this case I don't think we need to compromise that, and the various sensing functionalities are possible, and also high level of circuit. Fabrication and functions are starting to emerge, and they are very, very new. So still, a lot of development is needed. But these functions I can see should be possible and also potentially manufacturable. What are the needs? I think these performances over a long time is still unknown, and also, more importantly, the long term biocompatibility. That's an area that there's not much research so far. And also there's a challenge for prototyping these devices for clinical application, because all the materials are non-conventional. So each material we use we have to figure out how to really pattern them or integrate into devices specifically for that material. But most importantly, I think there is a need to use applications to help us to understand what may be the pros and cons for the hybrid design, because in terms of energy consumption. It's really hard to know, unless you actually do the system level integration and know the energy consumption from each part. And then we may see that for a certain scenario this might be advantageous. Other scenarios this may not be. Silicon is perfectly good for those applications, so I think it will be interesting to have a kind of a target application, as the studying example for those of us from different field, to really get together to understand what are the strengths and the limitations for different kinds of approach, and that kind of funding usually is not easily available, because it has to cross so many different communities. Finally, I'd like to thank my research group and funding agencies for their support. I still need to figure out how to get to Nih funding, and also many collaborators for their collaboration over the years. And thanks again for your attention.

1:00:57 → 1:01:50

**Ralph** **Etienne-Cummings:** Thank you! Wonderful! We would love to have some questions. Please go to the microphone so folks can ask questions. But you know, as the moderator, I get to answer the first question, if that's okay. So I noticed that you used a lot of the terms of art in neuroscience synapses, neurons and so on. Even though I would argue that maybe the circuits that you're using are not exactly mimicking the particular functions. So, coming back to your original point of saying, Hey, you know, I'm still a little confused about what neuromorphic is to me. That's exactly what neuromorphic is. And you are getting the form, maybe not the form, but at least the function of a particular. You know, we're having this agreement, the function that you're trying to implement. And you're mimicking. Maybe some functions of neurons and synapses. So what's your comment on?

1:01:51 → 01:03:23

**Xinan Chen:** Yeah, yeah. And I think the reason I feel a little bit confused was that when I read the papers which made neurons or artificial neurons. Then these kinds of circuits are trying to mimic exactly the action potential profile right? And my kind of naive take of well, what we mimic is basically the spike train. And now we did not really kind of try to mimic all the exact profiles. And I'm not sure because I'm not a circuit designer. I'm not sure whether it's really needed to have the exact output to look at, to be like a biological neuron. So we are just taking the simplistic kind of understanding of neuron and synapse. And then that perhaps that's because of that simplistic kind of take of what these functional blocks actually mean, then our design as a result, is also very simple, not so complex. Also, partly because we're limited by the capability of the type of devices we're able to make. And over time I think that will get. You know, more sophisticated, so to speak.

01:03:25 → 01:03:38

**Audience:** Hi! I have 2 questions. So the 1st one is, how do you make different parts of the skin conduct versus insulative? And the second question is, how strong is the skin?

01:03:39 → 01:05:20

**Xinan Chen:** So for the conductive part, we design those conducting polymer materials which are low modulus, and also can stretch at the same time. And then for insulators, there are a vast amount of materials to choose from, but of course, we need to pick the ones that have appropriate mechanical properties as well as the insulating property for either electronic application or for encapsulation requirements. So did that answer your question about how we make it insulating or conductive? All right. Yeah. But of course, the materials all need to be patterned into the right geometry and the size. So there we use a photolithography process to pattern them. And then how strong are the skin? So basically, that depends on the substrate and the encapsulation material that we use. So a lot of the materials that we develop can have a very high toughness, meaning that even when we have a cut on the material, intentional cut, normally material will just tear along the cut, but our materials are designed so that even if there's a cut you can still repeatedly stretch without having the crack propagation.

01:05:23 → 01:05:24

**Ralph** **Etienne-Cummings:** Thank you. Please state your name and ask your question.

01:05:25 → 01:06:46

**Pamela:** Okay, Pamela Abshaw University of Maryland College Park. Thank you for a fantastic talk that was really inspiring. I think, like, I want to make a comment, and then I'll ask a question if that's okay. The comment is, I think that your work highlights something that I like, an idea that I hadn't previously had, which is that it's sometimes hard to figure out. And then there was a lot of semantic discussion yesterday. It's hard to figure out what is the value of neuromorphic, this or that. But your work is really interesting in that, like neuromorphic is good for low power. It's good for a kind of minimal circuit. You need minimal circuits. Right? You're making circuits. It's really hard to get dozens of transistors in your technology. And so you need to make the circuit with 3 transistors. And that's what neuromorphic is really good for in your case, I think so. That's how neuromorphic is really well, particularly well matched to your technology. So that's pretty cool. The question that I wanted to ask is. I'm guessing that your transistors aren't that great? They're probably pretty. They're not very power efficient. And so I'm wondering if you could talk about like, do these skins heat up like? Are there power issues in the deployment on a skin like, can you fill it heating up self heating as they're operating? Because I'm imagining they're much less power efficient than crystalline silicon, for example.

01:06:47 → 01:07:31

**Xinan Chen:** Yeah, their charge carrier mobility is much lower than crystalline silicon. So the amount of current that passed through also is much lower, so they don't heat up as much in our case. But, on the other hand, these circuits are built on materials that are poor heat conductors. So we don't know yet what issues we may encounter, because we have not kind of realized the level of computing that will generate so much heat in our case.

01:07:33 → 01:07:57

**Audience:** Hi, great talk. I have a question about possible applications. Have you thought about using this as a skin to skin communicator similar to if you and I shake hands, I will see whether your hand is hot, soft, more sweaty than mine? Do you foresee any issues with using that as a communication modality in terms of crosstalk between this enormous amount of devices that you have?

01:07:58 → 01:08:27

**Xinan Chen:** Yeah, that we have not thought about it. Well, I guess if people are willing to wear something for this new form of communication, I think. There, there, then, there are even more possibilities. Actually, lots of things, functionalities can be potentially integrated into this platform, you know. That's an interesting idea. Thank you.

01:08:29 → 01:09:49

**Timmer Horiucci:** Please state your name. Nope. I'm Timmer Horiucci. I'm at the University of Maryland. Ece. Wonderful, inspiring talk. I think it was absolutely wonderful. Some notes about neuromorphic. I have taken it aside. I'm certainly on the side more like what Sunny is interested in. I think neuromorphic is really about using principles for computation that neurons or the brain. And so, for example, spikes. In your specific case. The reason to go to spikes should be motivated by what's coming downstream. So the processing not necessarily, you know, I believe that for the most part the spikes are not the shape of the spikes are not important, nor is the duration aside from. If you're going to use that principle downstream, the timing again, if it's going to be used in encoding information which in many cases it is. So yeah, I'm gonna weigh in with Sunny about this against Ralph. We have disagreed for long times. So the specific question about the pressure sensor in your skin. Is that so? It seemed to be modeled as a resistive element. Is that true?

01:09:50 → 01:10:42

**Xinan Chen:** For the circuit based? E-skiing? Yes, we use a resistive sensor because it can couple into the circuit much easier, and also the trend of pressure versus frequency is exactly the same as our mechanoreceptors. But for the whole hand, currently, that was the capacitive sensor. So potentially, there's some potential options for doing amplification of that initial sensing signal as well as modeling the different kinds of, you know, Petunion sensors and the different filtering functions. Right? That's right. Yeah, yeah, those are the type of circuits we are building to couple with the sensors. Yeah, okay, great. Thank you very much. Thank you.

01:10:45 → 01:11:05

**Grace Hwang:** Thank you for the wonderful talk. I'm Grace Huang from the Nih. I have a couple of questions. I couldn't help but notice that you had accuracy data for braille reading. and I was wondering if that was computed by working with persons who actually use Brail. And how is your technique, compared to the state of the art in terms of speed?

01:11:06 → 01:11:39

**Xinan:** Oh, so we did not. It's more the accuracy. We know what this real reading is supposed to be, and then we use our sensor to to do kind of to to touch and then determine what it is. The inclusion of users who would actually use this potential device was not part of your research. No, right? There wasn't any human study. Yeah, yeah. I mean, I thought that might be, you know, if you wanted to interact with the Nih, those kinds of conversations might be useful.

01:11:40 → 01:11:55

**Grace Hwang:** The other thought I had was, I think it's really wonderful that you mentioned that you can improve the spatial, tactile, spatial sensation of humans. And I just can't help but wonder if there could be a myriad of applications, even maybe in athletics that would benefit from this enhancement.

01:11:56 → 01:12:22

**Xinan Chen:** Potentially. Yeah, I can only think about robots. It might be useful. But music, yeah maybe. See how? How? Yeah, how someone plays a certain instrument or manipulates certain objects, you know.

01:12:27 → 01:13:24

**Brian:** Hello, Professor Paul, I'm Brian from Johns Hopkins, I have been closely following your work over the past 2 years, and I've been really, really fascinated by like how the novel materials you have developed has enabled the very advanced designs, especially in neurointerfacing, like endovascular, endovascular electrodes and ultra, like no low immunogenic cortical arrays. And I'm very curious as to how driven like it is based on the superior properties of these materials that you have developed . What would you imagine as the next step, the next form factor that could enable the next generation of pretty much interfacing. For example, like, I don't know. Maybe it's maybe it would enable, like combining deep neural arrays with cortical arrays like these kinds of form factor designs. What might be next? The next thing that's coming up?

01:13:25 → 01:15:07

**Xinan Chen:** Well in the brain. I'm not so sure that we have a big advantage, as neural pixels work with ultra thin silicon and really high density. Electrical recording electrodes are already kind of commercially available. And then we also hear the closed loop. Closed loop Dbs and also neurotransmitter sensors for the brain that all have been developed and in the brains. Still, I guess it's up to debate whether something that's a soft kind of tissue level modulus is really needed. And so there we are, trying to see, maybe for the human brain where we need a long probe and also high density electrical recording. Maybe our soft probe could be useful for that. That's what we are exploring the area we are exploring. More is in the gut where we need, where the gut does not tolerate anything rigid. So there we can have the serotonin sensing and also the muscle signal sensing movement sensing. And also we're trying to see if we can sense the neurons in the gut, using our one dimensional probe. So those are the areas we're looking to.

01:15:08 → 01:15:11

**Ralph Etienne-Cummings:** Maybe we have 2 more questions. I guess I'd say, because yeah.

01:15:12 → 01:16:26

**Sunny Bains:** This is maybe too, off the wall. But it's maybe a cyberpunk kind of question. But it suddenly occurred to me that the technology you're working on could enable ports in the body. So ports for plugging in your prosthetics for upgrading on a regular basis electronics that you might need to have. So, for instance, we all worry about the ethics of implanting something that may become obsolete. I know this has happened with some retinal implants that they've become obsolete over the years, and it just occurred to me that you could kind of pierce things. You could have an open piece of skin that's covered by your synthetic skin, and then that could be easily replaced without having to cut the patient over and over, and then you could have access to nerves, so that you know you could put on your new probe. You know the upgraded probe without having to do a new operation. It just seems to me that having a kind of synthetic skin would open up just a huge number of applications that it never occurred to me to really think about except as a science fiction thing before.

01:16:27 → 01:16:36

**Zhenan Bao:** Oh, I never thought about it, too, but that sounds very cool. Thank you.

01:16:37 → 01:17:25

**Audience:** I will wrap up really quick, so great to talk, I really enjoyed it. So my question is, you showed the resolution is even smaller than what a human can tell with a fingertip. It's a very static measurement. Have you tried to tell like texture so like its dynamics, right? So you're touching things like our fingers. Could you know just by touch, we know how smooth the material is or what the texture is, so that just by one question, and then the other one is a multimodality. So you talk about the sensing. Could it be motion? Could it be? You know the electrical signals? Are they using the same sensor mechanism? If so, how did you tell? You know that you know what? Exactly you're measuring?

01:17:26 → 01:18:35

**Xinan Chen:** Yeah, it's interesting. Yeah. You mentioned texture. We have not studied that. Now, we finally can build a system that can have real time readouts. Then we can start to explore some of these aspects. Certainly we found that when we have many sensors and also large arrays, then we can get a lot more information compared to previously possible to just have a few sensors place the object on, and we see very dynamic signal change. So I think the texture should be possible. And then the second question is the multimodality like, Oh, multi, yeah. So these different kinds of sensors are based on different mechanisms. Yeah, so then, we can differentiate on the same material, though. For the well that's yet to be integrated. That by itself is a material challenge.

01:18:36 → 01:19:05

**Ralph** **Etienne-Cummings:** Well, let us thank our speaker. Thank you so much. Dr. Bau’s wonderful. So Dr. Bau's talk fits very nicely into the next 2 sessions. The one that comes right afterwards is on devices and architectures and material science essentially, is a big part of it, and the last part, the last session this afternoon will be on wearables and analysis and imaging. So again. It's very nice within this context. So coffee, come back at 10:30, please.