Oral History of Kwabena Boahen

Interviewed by:
Douglas Fairbairn

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Fairbairn: Okay, we're here at the Computer History Museum. The date is June 22, 2021. I'm Douglas Fairbairn and I'm interviewing Kwabena Boahen, a Professor of Bioengineering and Electrical Engineering at Stanford University. Welcome. We're glad to have you here.

Boahen: Well, nice to be here, Doug.

Fairbairn: So, we like to begin our interviews with delving into the deep past and learning about your family life when you were growing up, especially those elements which impacted your path to the position that you hold today. So, I understand you were born and raised in Ghana.

Boahen: Mm-hmm.

Fairbairn: And so tell me about your early life, where you were born, when you were born and your parents and family and what it was like growing up in Ghana at that time.

Boahen: Yeah. You know, I was born in 1964 in September. I was the second of four kids that my parents had, after my sister who's the eldest and then two younger brothers. And my father was a Professor of History at the University of Ghana, which is just a suburb of the capital city, which is Accra. And the University of Ghana is very much like Stanford. It's built on a hill. It's a sprawling campus. You know, you need your bike to get around. <laughs> Or you can walk 30 minutes to go to see your friend on the other side of campus and so forth. And, you know, very green and lots of trees and so forth. So we spent a lot of time as kids climbing trees. Actually, we had races that we'd do from tree to tree to tree.

Fairbairn: <laughs>

Boahen: Up there in the foliage. But we also did things like building go karts and, you know, racing down the hill and all this kind of stuff. And so we were very--

Fairbairn: Things not too different than American kids perhaps.

Boahen: Yeah, yeah, I guess so. But, you know, I was of the bent of always sort of building something or experimenting and so forth, so I had my little lab, you know, as my parents-- My parents called it kunkaka, [ph?] which is onomatopoeia, right, it's the sound of a hammer breaking something.

Fairbairn: Oh, okay.

Boahen: So they would say, "Oh, he's doing kunkaka," you know.

<laughter>

Boahen: And, yeah, and part of the reason why I got into that is I was a very precocious kid and I was always asking these questions and so forth. And my dad was, like, "Oh, you're too young. You wouldn't understand it," and so forth. So that turned me off. And so, my goal in life was to become the expert at something that he knew nothing about. And then he would come to me to explain it and I would say, "Oh, wait a minute. Well, can you come back later because that's complicated."

<laughter>

Boahen: And so, so yeah, so kind of I went the whole opposite direction, and you know, got into science and math and all that. And you know, would go to the university book store and I would buy, you know, my sister would buy *Archie* and *Tin-Tin* and all these kinds of comic books and I would buy, like, "What Makes It Go?" and, you know, different-- six different projects you can build, like a microscope, electric motor. Yeah, I would buy those kinds of books and I would build the stuff. <laughs> And so, yeah, so I was just like into that kind of thing.

Fairbairn: So I presume your father was a university professor, so education was important, I presume, and--

Boahen: You know, but my father has a very interesting background. He grew up in the village and he always told us, "You know--" I told you it was a sprawling campus like Stanford. So it would be, like, 20 minutes to walk to school or maybe 15 minutes. And so, we'd try and catch him when he was leaving the house and, like, "Hey, Daddy, can you give us a ride to school?" And he'd be like, "You'll be lucky."

<laughter>

Boahen: And the few times you would get lucky, he would point out every kid on the road. He'd be like, "Do you think you're better than that kid? No, you see, they're walking. You know, why can't you walk to school?"

<laughter>

Boahen: And he always reminded us that he used to walk six miles to and from school every day. Because he grew up in this village and the closest school, when he got to primary school, he had to walk that far to the closest one. So, he was very humble, even though he was a professor and moved in all these circles. And you could check out his books in the library at Johns Hopkins where I did my undergrad. He was just the most down to earth person you ever met. So, it was very important to him. He wanted his kids to be humble and he didn't want them to feel they were special in any way or have any kind of privilege and so on.

Fairbairn: Now what about language? Did he speak English or--?

Boahen: Yeah, of course. <laughs> But my parents are from different I prefer the word "nations," right. And they've got different languages that they speak. So, my mom spoke Ga and these indigenous languages, and my dad spoke Akan or Twi. The part of the country we lived in, Accra, was part of my mom's territory. So luckily, they spoke Ga. And so, I spoke a little bit of both as well as English. But, you know, English is like in Europe or whatever, it's the language of instruction and science and all that. so, yeah.

Fairbairn: So you grew up being taught in English and so--

Boahen: Exactly, yeah.

Fairbairn: It was never, it wasn't really a second language, it was almost like your--

Boahen: Yeah. And because my parents spoke different languages, we spoke mostly English at home.

Fairbairn: I see.

Boahen: And so forth, yeah.

Fairbairn: Even between them, it was the common language, huh? <laughs>

Boahen: Yeah.

<laughter>

Fairbairn: How different were their two languages?

Boahen: Oh, they are very different. So, you know, Kwabena, my name, follows the Akan tradition. So if you're a boy that's born on Tuesday, you are called Kwabena. If you're a girl, you're called Abena. And the name of the day is Abenada, Abena's Day. [ph?] And so, all the days are like this. And my mom's folks, their tradition is you're named based on order. If you're the eldest son or if you're the eldest boy and all this, I mean, girl or if you're a twin or whatever, they have all these different names for that, so that's their tradition. Also my mom's people are patrilineal, so you inherit from your father. And my father's people are matrilineal, so you inherit from your mom, so.

<laughter>

Boahen: There you go.

<laughter>

Fairbairn: Amazing complexity in a very small space, huh?

Boahen: Yes.

<laughter>

Fairbairn: So were there any other teachers or mentors that influenced you?

Boahen: Yeah. So after primary school I went to, and this is a relic of the colonial period, we still go to these boarding schools that the British set up far from the cities and they'll send the kids and indoctrinate them basically. <laughs> And we still do that. So, they shipped me off to boarding school, an all-boys boarding school when I was, in '76 when I was 12. The school was founded by the Methodists missionaries back in 1876. And so, I was a freshman or what's called a greenhorn in 1976 when they were celebrating the Centenary. By the way, the same year that Johns Hopkins was founded where I went to undergrad. But, <laughs> anyway, so yeah, a lot of tradition. And in fact, my father wrote the history of the school, which is a very interesting read.

Fairbairn: Wow.

Boahen: And actually, he was commissioned to do it for the Centenary but he didn't finish till 20 years later, but that's another story.

<laughter>

Boahen: But they shipped me off and because I like to build stuff, one of my favorite subjects was metalwork and technical drawing. You have your T-square and your protractor and you can draw these things and you can do 3D sections, all this stuff. I love doing that stuff. And metalwork, you go in the shop. We had lathes. We had files. You would build stuff. So, I think in my third year, me and a friend of mine, we designed a corn planting machine which was I think was more similar to a wheelbarrow. It had these two wheels and then it had this handle. But, you know, two main wheels and then it had two little, you know, castor wheels in the back, right. And you would push the thing along in the field. And what we had done is we had measured the space at which they plant corn, in this way and that way. So we had two spikes in the front axle that would come in and make holes. And there was a little hopper you would fill with seeds on both sides. And then there was this drum that would line up with the hopper and release a few seeds which will then shoot into the hole the spike just made and there were little flaps in the back which would come and just cover it up.

Fairbairn: Cover it up.

Boahen: So. <laughs> So that was the thing. And we won the National Science Fair competition.

Fairbairn: Wow. Very creative.

Boahen: And so, the government sent us to the West Africa-Wide Competition. So I got my passport when I was, like, 14 and flew on a plane for the first time and landed in Lagos, which is the Nigerian capital, for this competition. Yeah.

Fairbairn: So you were building this-- You did this in metal shop at school and--?

Boahen: Yeah, yeah. Yeah.

Fairbairn: Interesting.

Boahen: Yeah.

Fairbairn: And so what happened to you-- So, well, let me-- You continued there until what grade did you graduate or what was the--?

Boahen: Yeah, so, okay, so the way it works is you do O levels, Ordinary levels, and this is the West Africa-world Exam. And that's the first five years. And then there's what's called Sixth Form, which is two years and then you do A levels. And by the time you finish Sixth Form you are kind of, like, you finished freshman year in college here and university is three years, right, over there. And so, so I finished my O levels. I was Valedictorian of my high school. And then I went to Sixth Form in Accra, actually just right near Legon, actually, where there was a school that specialized in science and math, right. It's kind of, I guess a magnet school or something you would call it. So then I was the top of that class. I think there were four or five of us in that year who had perfect scores in the final exam. So then, you had to do National Service, so I did National Service for a year. Those two, three years I was applying to all these schools in the States every year. MIT at that time, Stanford wasn't so-- Everybody wanted to go to MIT.

<laughter>

Boahen: And getting rejected. And my dad wasn't supportive of that because he said his theory was that if you didn't get your first degree in Ghana, you would never come back. He wanted me to get my first degree and then maybe go for graduate study abroad. I was into electronics and this kind of stuff and he was into history. I'm like, "Yeah, you can do world class history in Ghana, but, you know, we can't do that--"

<laughter>

Boahen: But anyway, I finished a year of National Service, which was actually an interesting period I could come back to in a second. But then I started a year of university at the University of Science & Technology which is in Kumasi which is 200 miles north of the capital. And that year, my dad did a sabbatical at Johns Hopkins University in Baltimore because Johns Hopkins, if you know, Hopkins has the School of Oriental & African Studies. Actually, the School of Oriental & African Studies is in London. That's where he got his Ph.D. But they have the School of SIAS, School of International & African Studies or something in Georgetown, which is administered by Hopkins. So they had a very strong history program and he was collaborating with some people there who hosted him and so forth. And they found out that, "Wow, your son has perfect grades and he invented this, <laughs> this complex machine and this and that. And, you know, why don't you-- We'll nominate him for a scholarship. You should have him apply."

Fairbairn: <laughs>

Boahen: And you know, he couldn't afford the fees, so that was the only way. But anyway, so that's how I ended up at Hopkins.

Fairbairn: I see.

Boahen: Yeah, yeah. But the part of the story that's relevant here is the sabbatical before that-- oh, I don't think it was a sabbatical-- but he was in London and he brought home, so this was kind of while I was doing my National Service or maybe before that, so it's probably '82 or so, he brought home one of these BBC microcomputers, right.

Fairbairn: Oh, yeah.

Boahen: It had a Z80 processor. It was a glorified kind of, you know, it looked like a pocket calculator but bigger, right. And it had these sort of rubber keys on it, so the keyboard was built into it. It had a little LCD display, but that's not what you used. You had to basically just hook it up to your television and you used your television as the monitor and then you hook it up to your cassette recorder and use that as your tape drive. And, you know, so you could play games like, yeah, Pong on it with the paddles and stuff. And, you know, you could program in Basic. So you were able to program on this thing. And it was really, really exciting.

Fairbairn: So how old were you when you got your hands on that?

Boahen: This was '82, so I was, 16 or 17-- 17. Yeah. And so of course I was too intimidated to take this thing apart. <laughs> So, I went in the library, you know. Yeah, at that time, I was doing my National Service at the Center for Scientific and Industrial Research, which was just in the neighborhood that we lived. We were now living in a different part of the town. But anyway, I went in the library they had there. In fact, you know, I was learning a lot about op-amps and transistors, and I was building these-- It was really fun because they had oscilloscopes, they had power supplies, they had a whole thing I could-- I was playing with all these electronics. So, then I pulled out the book they had there on computers and so then I figured out, oh, wow. So this is how it works. You know, you have a program counter. It points at an instruction. You load it. You read the memory. You send it to the ALU. You have these logic things that can add and subtract and stuff. If you want to do a branch instruction, then you just overwrite the program counter with the new address and then it branches and all this stuff. And I'm like, "This is so stupid."

<laughter>

Boahen: You know? You start out with, like, a bunch of “and’s” and “or’s” and by the time you're able to multiply two numbers, you need all this complexity. It was, like, huge, it was like so brute force. And then you have to do all these instructions like clock the thing so fast and do all this work. And so I just, I wasn't impressed.

<laughter>

Boahen: Yeah.

Fairbairn: There's got to be a more efficient way, right?

Boahen: Exactly.

<laughter>

Fairbairn: So you wound up going to Johns Hopkins.

Boahen: Yes. I went to Johns Hopkins Electrical and Computer Engineering program. I was a freshman in 1985 when I was-- No, sorry. <laughs> Yeah, in '85 when I was 21-years-old because of, you know, not being able to get <laughs> into a college in the U.S. But anyway, so then it was fabulous. So I prided myself, again, going back to the beginning of the story, in mastering something that my dad didn't know anything about. I kind of viewed history as memorization and stuff like that, and I prided myself in being able to derive everything from first principles. So, you could set me on a <laughs> desert island, I could just come up-- yeah, reconstruct everything I knew. So, then his counter to that was that, actually, no. <laughs> He was good at math and science, but his uncle told him that, he should study history. He could become a lawyer and he could make a lot of money. And that's why he went into history.

<laughter>

Boahen: But in fact, anyway, it's a different story. But he-- It's not memorization. <laughs>

Fairbairn: <laughs>

Boahen: But anyway, the rest of the story is that the way that biology was taught in, secondary school and primary school was like memorization. It was like natural history. You draw the plot and you label all the parts and then you describe what's going on and stuff. And so, I hated biology. I had I felt like there was a more elegant way to compute, but I didn't know anything about the brain. I didn't have a different example. So, when I was I think a sophomore, I went to a talk by a guy called Terry Sejnowski. Carver [Mead of Caltech] actually knows him. He's at the Salk [Institute]. But at that time, he was at Johns Hopkins in the Biophysics Department. And so, he gave this talk about this neural network that he developed called NETtalk. And what NETtalk did was that it just had one hidden layer, then it had an input layer and an output layer. And you presented it with text, letters, and it would generate the phonemes that correspond to those parts of the word and--

Fairbairn: So what year was this?

Boahen: '86-'87.

Fairbairn: Early in the neural network world. <laughs>

Boahen: Yeah. This was, we had come out of the winter and then neural networks had started to take off again, so that was that previous wave of neural networks, yeah.

Fairbairn: Yeah.

Boahen: And so he was kind of one of the pioneers in that. And so, Terry was a terrific showman because he had a demo where not only was he training this network on the computer, he was taking these phonemes and he was using something called a vocoder. He was using something called a vocoder that would vocalize the phonemes.

Fairbairn: Okay.

Boahen: So, so he would show you, he would play the phonemes he was getting early on in the training, and it sounded like a baby babbling. You couldn't make any sense of it. And then, yeah, a little bit later, he would give an example and you know, it sounded like that baby talk that the parent can understand what the baby is saying but nobody else <laughs> can--

Fairbairn: Nobody else can.

Boahen: Can understand it. And eventually it was like, "Wow. This thing's reading." It's like, yeah! I'm like, "Wow." So then I was just really impressed by that. I said, "Wow. This is the way to go." I mean, you don't even know how to solve the problem and you just take this network and you show it examples and it figures out the algorithm by itself. And it's so elegant. So I got excited about that. Then I took a VLSI class in my junior year and I designed my first…it wasn't called neuromorphic in those days, but. <laughs> You know, we were trying to take these neural network models and we were trying to implement them on a chip. And so--

Fairbairn: You mean in digital or in analog?

Boahen: No. Analog, of course. <laughs> I mean, the brain is analog. <laughs> And so it was this. Anyway, it took binary inputs because these were vectors you were going to store in memory. But then it, this was the Hopfield model, which John Hopfield had developed this sort of analog way. Just a dynamical system. It's all continuous time and continuous values would just emerge and grow over time in such a way that when you initialized it with some piece of the memory, of a few bits, it would complete the rest. And so that was the principle.

And so we're taking that and we were using analog circuits to implement all these operations and it will present the… And so the chip worked, and I had my first journal paper, in '89 in my senior year. But, Carver shows up in this before then. Because in my sophomore year, I took an integrated electronics lab. So you go into lab and you prototype stuff and you build it and you do this thing. And my TA was a guy called Andreas Andreou, who was a Ph.D. student. He was finishing up his Ph.D. in device physics in the Department and he's now a Professor, and in fact Chair of the Department, there now. He stayed at Hopkins. But he was my TA then. And so, me and my teammate in the lab, Philippe Pouliquen, who was the same year, but he was a Biomedical Engineering student, we were kind of the best students in the class. So Andreas recruited us to come down in the basement and work in the lab with him. And he presented us with, this was back in, so, in '90 it's like-- I always get these sort of dates-- You know, I'm not the historian in the family, but--

<laughter>

Boahen: This was like '86 or so. You know, '85 I was a freshman, so '86, '87 or something, you know, the first year I worked in a Biomedical Engineering Department down in the Hospital, East Baltimore. But the second year, I was working in Andreas's lab. It was actually where Roger Westgate was actually the PI. So Andreas had gotten a set, so this was, like, '86, '87, the summer of '87, had gotten a set of, you know, lab assignments from Carver's analog VLSI class. So every week we would do an experiment on a particular circuit that they had come up with for building these sort of neuron-like things.

I don't think we had a copy of the book… So, we had these lab handouts <laughs> . And so, Andreas was like, "Hey. You guys, you should do these things. Like, this is a new thing coming out of Caltech. It's really exciting stuff." So we looked at them and we were like, "Oh. Wow…sub-threshold. It's like, yeah, we'll measure pico-amps, okay." I was like, "Andreas, how do we do that?" He's like, "Oh, you should just build something to measure that." I'm like, "Okay. Sure." <laughs> So, we didn't have money to go buy a $5,000 dollar Keithley electrometer and stuff, so. So, I was the hardware guy and Philippe was the software guy. So I found out that Analog Devices made an op-amp that had like, a 45 femtoamp input leakage current, so we could use that.

So, I was like, "Hey, Andreas, we should get these things. We can build something with this to measure those pico-amps." And he goes, "Just call them up. Ask for a sample." So I called them up and they sent me samples. <laughs> So then I put them in this whole thing and so we had built this little box here. To measure pico-amps you can't use a PCB. You have to have Teflon standoffs in holes in sort of a copper board and individually wire them. And then you put, like, giga-ohm resistors, which were glass-encased and all that stuff. And you would wire up everything and so forth and it had relays in there. So, you could change the range. You could make measure the different currents. And then Philippe had, yeah, we had a DEC 350 computer which was like a personal computer. It sat on the desk. We program that and everything.

And so we were like, "Okay. So what about these chips that they are using at Caltech? We need to measure these chips." And it's like, "Oh. We don't have any of those chips." <laughs> I'm like, "Okay. So what do we do?" "Oh," so Andreas was like, "Oh. There's this thing called CA3600. It's just an array of, like, 6 MOSFETs on a chip. You know, like these TTL chips." And then, like, "Yeah, get a couple of those and then you can just look at the diagram and you can build it out of those MOSFET and operate them some thresholds." So we were like, <laughs> actually building the things that, you know, because in Carver's lab what they would design a chip with all these individual circuits on it with a printout that you then work on through the quarter to, like, you know, characterize these circuits and learn about all that. And so, we make the circuit and then we'll test it and we'll get all the data. And it was really tremendous fun. When we would run an experiment and something would break, I would be like, "Mmm. It's the software."

Fairbairn: <laughs>

Boahen: And Philippe would be like, "No, it's the hardware." <laughs> And then but when we got, you know, IV characteristics for a transistor on the screen, we knew every single thing that happened the whole system. Because we built the whole thing. <laughs>

Fairbairn: That's a great experience.

Boahen: Yeah.

Fairbairn: So, you finished master's degree at Johns Hopkins?

Boahen: Yeah. So I did a master's and a bachelor's in four years. Because I had one year of classes from the University in Ghana, I managed to transfer some of those credits. And they had what at the time was called a co-term program and this was called a concurrent master's-bachelor's program, so.

Fairbairn: Just like Stanford.

Boahen: Yeah, yeah. It's like a Stanford co-term. So I finished that and of course then <laughs> I knew about Carver and so I wanted to go to Caltech to do my Ph.D., so that's how I ended up there.

Fairbairn: So how did you find, when you moved to Johns Hopkins. You'd been outside of Ghana but not outside of Africa, right? What was it like coming to America then? What was your first impressions, experiences there?

Boahen: Okay, well, we could have a whole show about that, but. <laughs> The way I like to put it is that it's very interesting, right. So it's kind of like the rest of the world is exposed to Western culture. You know, we watch your movies which … my sister watched all those things. I didn't care about it. <laughs> So were just immersed in this Western culture. But you guys don't know about us, <laughs> you know. So it's like a very asymmetrical thing. But I think we actually kind of fool ourselves that we know about American culture, because when I came here, and I was looking around and things. The way I put it was that I had “over-fit” my model. My model was making predictions that didn't generalize.

Fairbairn: Right.

Boahen: And I just spent, like, three years just reprogramming and relearning my model--

Fairbairn: <laughs>

Boahen: To really build to understand or predict what was happening, you know. So, so, yeah, so it's really quite a--

Fairbairn: That's a great analogy, over-fitting the model. <laughs>

Boahen: Yeah. Totally over-fit. Totally because it wouldn't generalize. Yeah. And it also then gives you insight into, okay, this is how Ghana is different and this is-- It's just, yeah. So I really encourage people to travel. You really have to, you know. It's, yeah--

Fairbairn: Yeah. The movies are a very narrow window to point to. <laughs>

Boahen: Exactly, yeah.

<laughter>

Fairbairn: Into unreality.

Boahen: Yeah, exactly. Yeah. <laughs>

Fairbairn: So were there any other notable events you want to mention or learnings that you wanted to mention in Johns Hopkins? And then--

Boahen: You know--

Fairbairn: How did you get in touch with Carver Mead?

Boahen: I had friends who were Indian, Chinese, African-American and so forth. Of course, there were no other Africans around, so, you know.

<laughter>

Boahen: I heard that, you know, I was into music. I used to be a DJ when I was back home in university and stuff. And we used to listen to all these tapes, mix tapes and things like that, that people would record from WBLS, Worlds Best and Latest Music or something.

<laughter>

Boahen: In New York or whatever. <laughs> And there was KISS-FM and other stuff. And the way they talked and all that stuff. And then it was hip hop and Sugar Hill Gang and all that stuff. We were into that kind of stuff. So, I heard that this woman called Shannon and Alexander O'Neal who is more like a crooner R&B guy, were playing at Morgan State University. Shannon had this hit called "Let The Music Play." It was, like, a disco, or whatever. And so, I was telling my friends, "Hey, we should go check this out. They're playing in town and stuff like that." And they were like, "Who?" <laughs> And I was like, "Yeah. You know what, this is, well, you should listen to it. You don't know this music?" We thought we were listening to American music in Ghana but we were actually listening to African-American music!

<laughter>

Boahen: And so, I think my African-American friends knew who those guys were. We ended up going with two of my African-American friends. And we get to Morgan State University, and it was like we were in Africa. It was like a sea of just Black people. I was like, "Oh, shit."

<laughter>

Boahen: You know, if these people wanted to go to school with all Black people. Why didn't they stay in Africa? What's the point to come to America and to be--?"

<laughter>

Boahen: It's like the model totally didn't predict that. <laughs>

Fairbairn: So, yeah, so you--

Boahen: This is where my father would have told you exactly what's going on. He's an historian, of course he could-- <laughs> He understands the history. He could tell you why it's like this. But, you know, I'm using first principles and it doesn't work.

<laughter>

Fairbairn: So, speaking of your dad, did he ever come to visit you in Caltech or--? [ph?]

Boahen: Oh, yeah. Oh, yeah. Yeah. Not in those days, you know, I had a Ghanaian student over at my house for dinner. He took my class last quarter and so I invited him over. And we're chatting and he was, like, "Oh, Stanford has this program where, you know--" He's on a scholarship but Stanford has this program where they'll provide him money so he can travel. It gives a thousand-something bucks to travel and fly back to Africa, back and forth. And so, from '85 when I was a freshman till '92, my second year in graduate school, I never went home. I just couldn't afford it, <laughs> you know.

Fairbairn: Right. Yeah.

Boahen: And when I went in '92, I had to sort of borrow money to do that. But now they have this program so he can go home every year. So what was the question you asked? And because I brought this up, but--

Fairbairn: I asked you if your father ever came to visit you.

Boahen: So of course, yeah, I never saw them and he never saw me. He couldn't afford it, you know. Like, somebody would have to sponsor him. So, no, there was none of that. But he did come to visit in graduate school at Caltech at some point. He had something at UCLA with one of his colleagues, a collaboration, and so was in town and he met Carver and all that. And I remember walking with him across the campus at Caltech. And it was nice and sunny and nice out. And he was like, "Where are all the people?" And I'm like--

Fairbairn: <laughs>

Boahen: Back then of course, there was a lot of studying! There was nobody around. <laughs> You know, it's like, "Wow, this is weird." <laughs> So, yeah. <laughs> And then the other time, after graduate school, I taught and my first faculty position was at University of Pennsylvania in Philadelphia. He came and visited out there, so this must have been … I started in '96.

Fairbairn: So in doing your studies, was your path always to academia? Was that what you had in mind?

Boahen: I grew up in a university. <laughs>I'm like a creature of academia. I'm totally comfortable there. I thought I was forging my own path because I was like, "Ah, I'm not going to study history. I'm going to go do something he knows nothing about it." But at 30,000 feet, I'm just like my dad.

Fairbairn: You're still the same. <laughs>

Boahen: Yeah, like, a professor. I write all these papers. I never had any kind of imposter syndrome or had any kind of….. Yeah, it's just natural. It feels comfortable.

Fairbairn: Yeah.

Boahen: Yeah. <laughs>

Fairbairn: So, you got your Ph.D. And tell me a little bit about your Ph.D. research and what you focused on there.

Boahen: Oh, but I was going to say, the other thing about…

Fairbairn: Oh, okay.

Boahen: In Philadelphia when my dad came to visit, we were walking around Center City and everything like that. He's like, "Oh. This is where you guys have the Liberty Bell here." And I was like, "Dad…" And said, "Oh, this is where--" He knows more about the city, you know….

<laughter>

Boahen: I had been living there for a couple of years and he's, like, "You didn't tell me all this. Like, oh, we should go--" Yeah, I'm like, "Okay." <laughs> You know? <laughs> So I was really impressed. Wow, this is a very historical city! I didn't know.

<laughter>

Boahen: …Because, the Constitution and all this stuff.

Fairbairn: Yeah. Sure.

Boahen: And the Declaration of Independence was signed there and everything. He went to see a couple and all that. I didn't know any of this, so I'm like, "Oh, wow." Anyway….

<laughter>

Boahen: But he knew all that. So I get to Caltech, I had to wait a year. Carver said he didn't have any room and I had all this debt I had to pay off, so I worked for a year in the Applied Physics Lab, which was part of Hopkins.

Fairbairn: Right.

Boahen: And, Andreas had some collaborations with them and so forth, so I was able to get paid out of there, while I was working in the same lab in the basement. <laughs>

Fairbairn: So as a result of the work that you were doing at Johns Hopkins, Carver knew of you and knew the kind of stuff you were doing?

Boahen: Yeah, yeah. So, I had my, a journal paper out and I also got a paper accepted in the-- I don't know whether you know about this. There was the Caltech Conference for Advanced Research in VLSI. And so it used to be the CI. [ph?][1] So, I presented there in '89. At the '89 conference, I had had a paper in that.

Fairbairn: And I think that was started back in when I was working with Carver, but I wasn't still involved in 1989.

Boahen: Yeah. So this is VLSI. All these were talks -- mostly academia and everything like that, yeah.

Fairbairn: Right.

Boahen: I was nervous as all hell. I'm sure nobody understood anything I said. <laughs> Until it got to the questions and answers part there where I was like, "OH, relax." I'm like, "Oh, yeah, sure. Yeah."

[1] Interviewer was not able to solve it.

<laughter>

Boahen: But anyway, So that's where I met with Carver for lunch or something afterwards and everything like that. And so I have a nickname that I got when I was three or two where my dad was doing a sabbatical in London. That's where we lived for a year. Me and my sister were born then, and she was four and I was three or something, and we had a nanny that looked after us, a British woman. So, she nicknamed me Buster, and it stuck. This is what all my siblings, everyone calls me in high school, secondary school and stuff. And of course, I get to America and nobody can pronounce Kwabena. So it stuck, so they're calling me Buster. So, I'm going to Caltech and I'm determined right now I'm going to get everybody to call me Kwabena. So, I meet Carver. He's like, "Buster, I'm so excited to meet you. I heard so much about you." <laughs> <Inaudible 00:35:41> and I'm like...

Fairbairn: Oh well.

Boahen: Yeah, exactly. You going to tell Carver Mead to call you Kwabena? <laughs> Yeah. You know how he is, like very outgoing, very Californian, so we just ran with it. Yeah.

Fairbairn: Interesting. So you arrived at Caltech. What did you think of California and Pasadena and...?

Boahen: Yeah. I mean, by that time, my model was generalized, so not much.

Fairbairn: It wasn't much of a change.

Boahen: It wasn't much-- just like California is great, because it's not cold. The weather is nice. It doesn't get dark too early and all that and there's no winter. So all this was fantastic and so yeah. No, so I loved LA, and I actually drove across the country. I bought a car and drove across the country with one of my closest friends. It took two weeks to drive across, and then, because California, you got to drive so yeah. No, it was great.

Fairbairn: So what year did you enter Caltech?

Boahen: I started in '90, and then I got my Ph.D. in '96.

Fairbairn: So how did you decide on your research topics and...?

Boahen: Yeah. So, this is the thing. One of the reasons I hit it off with Carver, he was just like my father. "Whatever you want to do, fine." So, he just left me to do my own thing, which is just like my dad, and so I was very comfortable with that. So, it's actually interesting. Even though I did my Ph.D. with Carver, a lot of people think that I did my Ph.D. at Johns Hopkins because I got papers published with Andreas. I don't have a paper published with Carver and me.

Fairbairn: Is that right?

Boahen: Yeah, because Carver would be like, "You did this thing all on your own. These are your ideas. So no, that's fine. You don't have to." Yeah, it would be good to have a paper with Carver, but we'll see. Anyway, at Hopkins, I had come up with my own way of doing things. So the Caltech folks and Carver were designing these, what I call voltage mode circuits. So, the idea was the information was represented by a voltage and these circuits have voltages coming in and they put out a voltage, so they transformed voltages into voltages.

But, I was enamored with the current mode approach, so my inputs were coming as current. I merely converted voltages to currents. Because remember, we are dealing with these random, linsnear devices down in subthreshold, where there’s an exponential relationship between the voltage and the current. So to do voltage mode, you had to do all kinds of things to try and hide this nonlinear behavior and try and get some kind of linear, reasonable, not-too-nonlinear input-output relationship. If you just did sort of a log and then took the antilog—you take the current in there, you get the log, and then you put it through another device, you get the antilog—that gives you a linear. So your relationship can go to current mirror, and it's perfectly linear, current in, current out. If you wanted to square the current, you put it through two stacked transistors, so you added the log of the two currents and you put it in there. So you get the multiplication of the two currents or the square and so you can do these kind of nonlinear operations in a very controlled way and you can build any kind of … So we were...

Fairbairn: Now, is it also a characteristic of the brain or what goes on there has these nonlinear characteristics?

Boahen: Yeah. That's a whole different story. Yeah.

Fairbairn: Sorry. We don't have to go there.

Boahen: So Carver made this point about Boltzmann energy distribution, the way the concentration of electrons depends on the potential. This exponential relationship is true for any kind of drift-diffusion balance, that's established. It will give you this kind of exponential distribution of densities or concentrations. And so that applies to an ion channel and applies equally well to a transistor. It's just physics. These forces of drift balance the forces of diffusion, and you get that. Carver made a point of that, so by that analogy, we can do a lot of stuff, really biophysically, with transistors.

Very few people ended up using that. Taking charges and combining-- this is happening at the individual transistor level. You think about your transistors, then combine them into an opamp, you lose that property. So a lot of those things are based on these transconductance amplifiers that are coming from traditional opamp circuit design. I really wanted to explore that full richness that opens up if you move away. So I think partly it was Andreas's influence, because Andreas was really a device physicist and so he wasn't a circuits guy and so he encouraged that approach. So, sort of, I was combining these influences, although Carver was also a physics guy.

Fairbairn: I was about to say, he's a device physicist himself.

Boahen: Yeah, yeah, yeah. Yeah, but you see, so I think Carver had that insight. But most circuits people who were taking more traditional EE stuff immediately drifted away from it. I think Andreas really appreciated that insight, because he was also coming from essentially the same place Carver was coming from. So that's just my way of saying that, so we were doing these current-mode circuits and if you did that and you looked at it very carefully, you're talking about silicon retina.

So to build a silicon retina, you have to model these, what are called gap junctions. They are basically resistors or conductors that go directly between neighboring cells in the retina, both the photoreceptors and the horizontal cells. And they compute the spatial average of the signals, local spatial average. So the guys at Caltech-- Misha was working on this project but I think it was Massimo Sivilotti who came up with what was called HRes circuit. It was like eight transistors to model one of these gap junctions. By pushing for this current-mode approach and this analogy, I was able to replace that whole thing with just one transistor, so then I developed this next-generation circuit, I mean way simplified, and it worked much better because the more devices you have, the more the mismatch compounds and so yeah.

Fairbairn: Okay. So I was asking you about your interest on the bio side, and we've been talking about the engineering side, the electrical engineering side. What kind of study and work had you done in terms of understanding the function of the brain or whatever previous to coming to Caltech, for example?

Boahen: Yeah. So like I said, it started with Terry's talk when I was a sophomore or something about NetTalk. And then I would be reading about this Hopfield network and these neural networks, that generation of neural networks, and deciding to design a chip that did relate slightly different from the Hopfield network but basically the same idea-- with, actually, Philippe. When we took the VLSI class, there was a chip project, and we submitted a chip to MOSIS. It came back. We tested it, and it worked and so forth. So then we got a publication on that, but it didn't work so well. <laughs>

It was what's called a heteroassociative memory. So it's believed that the way that you recall somebody's name is, I see your face and there's some connections from those face neurons to some other neurons in sort of maybe the language area that represent Doug. So when the face comes in, I can just activate those neurons and then I'll recall this is Doug and so that's called heteroassociation, two different things associated. You also have autoassociation, which is you just show me the bottom part of your face, and I'm able to fill it in and say, "That's Doug." So that's autoassociation, relating a thing back to itself, and that was what the Hopfield network did. But you could generalize it to this heteroassociative model and that's what we implemented. Then, now you have two layers. You have this layer that's storing your face and you have this layer storing your name and you can present either one and recall the other one and you can also correct errors within them. So we could store these patterns which were up to 16 bits, 0, 1 patterns and 16 bits here, and we could present patterns to sort of memorize it by changing the connection strands which was all part of the chip. Then, we could then test it by presenting this and seeing whether it recalled the right thing. And I really only worked with two pairs and the pairs were actually complements of each other, like the negation of the other guy. There was theory to show that, for 16 neurons, you expect to be able to store something like one-sixth or one-seventh, so that's maybe like 2.

So, I realized these things are actually not that efficient and also they are really susceptible to any kind of variability and heterogeneity and noise and things like that. My understanding was that the neurons in the brain are very noisy. They are very heterogenous and all this stuff, and so there had to be something we were missing. And this is where I started to appreciate Carver's approach. In fact, Carver, Hopfield, and Feynman-- I'm sure you covered this-- taught this Physics of Computation class together. I think it was '81 or '82 when he was beginning to explore moving away from the VLSI side, starting to explore...

Fairbairn: All right. Yeah. I remember hearing about that. Yeah.

Boahen: Yeah. He started to explore these ideas, and it was very interesting because Hopfield came up with these mathematically formulated Hopfield networks. In that class, he was talking about these kinds of things, and it was like he treated it like sort of a physical system but by minimizing the energy in the system, setting up connections in such a way that those memories you are trying to store were energy minima of the system. Then naturally, when you initialized it, it would just go to those. It would recall. So there was a nice physical insight there.

Then Feynman was coming up with quantum computing. He was saying, "Hey, we should use these Qbits," and showing that yeah, these make a much more powerful computer. And then, Carver was talking about the retina and so on and so forth. So these are all very different approaches. Feynman is talking about, fundamentally in a computing system, it is the primitives, these “ands” and “ors” that I thought were so brute force that you had to combine to do a multiply. It's those primitives and your signal representations, like the bits. You're using these classical binary bits. That's what fundamentally determines how powerful the computer is, so a quantum computer, by replacing those computational primitives, ands and ors with entanglement and superposition and replacing those binary signals or binary bits with quantum bits, you could show that something that was exponentially hard for a classical computer would be polynomially easy for a quantum computer. So that's a really deep insight. That's coming at it, really, from the instruction set architecture, the way they think about it now.

Then, Hopfield was talking about there's a Hamiltonian for the system, any physical system described by some energy function and the action is going to minimize that. So we can just exploit that to do computation because there's a lot of problems where we're trying to minimize something. You're trying to find which route you should take so that with the least distance you can hit all the cities that you need to go to and stuff. That's an optimization problem, and so you can actually do that in a physical system.

Then, Carver was saying that this is all good, but when you try to implement these things, they don't work, which is what I was discovering. <laughs> So why don't we be a little bit less pretentious and go look at something that actually works? I don't know what it was that he said, but this is how you look at it. He took the approach that, okay, so what is the part of the brain that we understand the best? In other words, we know what the cells are. We know how they're connected. We know what they are doing, and we can control the ins and outs. We can check exactly that it's doing what we think it's doing, and that's retina. It tends to be a very accessible part of the brain and it is part of the brain that grows in to the inside cover of the eyeball.

So he had been talking to these neurobiologists and they were telling him what the cell types are and how they're connected by these gap junctions and these kinds of synapses and so forth, and based on that, working with Misha Mahowald, who was actually a biology major, undergrad, at Caltech. So she understood the biology, and he understood the circuits and so they were working together to do this.

So, after my experience with trying to implement this kind of Hopfield-inspired model and it not working so robustly, I said, "There should be something"-- I knew the brain was doing something different. So that's how I got interested in the biology because I was like, "Wow. I want to build something that works." So yeah, when I got to Carver’s lab, I was initially CS because it was the CS department but then they set up this computation and neural systems program, which then they brought in Christof Koch to be the director of. It's not really a chair. So then, I switched to that major, and so I was taking actual neurobiology classes. I took my first Intro to Neurobiology with a new assistant professor then called Gilles Laurent who has now moved back to Germany. He's actually French. Gilles, the way GIles taught neurobiology was just awesome. It wasn't like we were taught biology in secondary school. He would show you some traces that he had recorded from some nerve cell with his oscilloscope, and it was doing this and then he would apply this blocker to this channel to shut down these channels and it would change to this and that. Then, you would have to explain, "Okay. Why is it doing that?" So it was just taught from the point of view of figuring out how something works like a machine, like debugging it and this kind of stuff.

So I was like, "Wow. I love this stuff." So then, I was able to get more and more into the biology, and so after my first year at Caltech, I actually came and spent the summer because Carver had been talking to these retina folks. He connected me with a guy called Frank Werblin, who was a professor at Berkeley in the MCB, Molecular and Cellular Biology Department. So I spent the summer in his lab actually recording from the retinas of tiger salamander, juvenile tiger salamanders. So we had a tank of these little things swimming around and every morning you got in, you would catch a couple of them and you would enucleate the eye and you would open it up and you would have this little eye cup sitting underneath your microscope, but then you also have to make all your electrodes from scratch and all this stuff. You could go record, and you had a little speaker. You'd come down with the electrode and you'd have a little projector that was moving some light across it and if you had a successful recording, you'd hear, "Pop, pop, pop, pop, pop." The spikes would be playing through the speaker, and you're like, "Okay. I'm good." So I spent that whole summer… So I really got into the biology...

Fairbairn: That's how you got into the retina, silicon retina project. Were you doing this out of just pure interest and curiosity? You ever have dreams of, gee, we'd like to be able to replace, fix people's eyesight or whatever? Define your motivation here.

Boahen: No, I think that motivation here is just like I was 10-year-old. I tell my students, "You need to go back to the two-year-old program. You take any two-year-old, he's curious, and you can even explain it to him and be like, "No, this is how it works," and so forth. Then he looks at you and then, as soon as you leave, he'll go do his own thing and he'll try and figure it out because he's got some hypothesis and he doesn't want to, when he runs into a problem, have to come and ask you. I mean, come on. It's like, figure it out. So, I'm just driven by curiosity. I like to figure things out and everything it takes to make it work; I'm interested. I find every time I run into trouble because I have some preconceived notion as to how it should work, and I have these blind spots. So, I'm constantly trying to uncover them.

Fairbairn: So you complete your work at Caltech, and then you ended up going to University of Pennsylvania. Tell me, is that the next path is...?

Boahen: Yeah. So, I finished. I ended up working on a bunch of things. I took over this silicon retina project from Misha Mahowald then, but there's a lot of infrastructure you had to build going around it. I think you asked about this. So Carver, you know from his history, had done VLSI and all that and really, in a sense, democratized chip design. Everybody could do it now. And he really expected people to take this new power that they had and go do wonderful things. Just be the spur of creativity but it never happened. Everybody's designing some processor. It just became the big guy, but anyway, so he was like, "Okay." He had done this whole Moore's law projection and all that and predict the ultimate scaling and he had compared it with the brain and he realized that there's no way we're going to build something as powerful and efficient as the brain, even with this approach[2]. So that's how he got interested in this physics of computation and exploiting some of the actual physics of the devices, which is a more analog style for computing.

So in those early days, it was really sort of a dogma. Like I said, whenever we think something doesn't matter, we run into trouble. There's this dogma that analog is good and digital is bad. But you started running into limitations when you have to build a system bigger than one chip, which the digital guys do all the time. We had Chuck Seitz, and these guys had supercomputers that were whole rooms on campus like the Intel Paragon and stuff. I said, "How are you going to build such a large system? You can't send analog signal around. They just get corrupted by noise and so forth. Even the brain doesn't do that. When you have to go more than a millimeter, it sends a spike. So there was these more sort of digital-oriented guys who were saying that, look, this is the way you solve this problem. You can't just send these analog signals out. You don't have enough wires and so forth, so you have to multiplex. Just run faster and send the same thing and all these signals with a smaller set of wires. So I developed, initially, just to get the signals out when the number of outputs of the retina chip or pixels became bigger than the number of pins on the chips. You needed some kind of solution like this. So Misha, as part of her thesis, and Mass Sivilotti, a more digital-oriented guy, had worked out a solution, which is multiplex but in an asynchronous way. There was no round-robin pooling of all the signals. It was just, if a neuron became active, it generated a spike, and that would initiate the whole process of its address being sent out of the chip on a bus, which was shared by all the other neurons. Misha used this to really hook up her retina to other chips that were combining inputs from two retinas and doing stereo and all that.

So there was all this infrastructure that went into it. It was just like the first prototype was really hard to use and very flaky and all this stuff, so then I took that over and just redesigned all that from scratch. I took a class in asynchronous digital design with Alain Martin, who was also at Caltech, and so I can do this. We were doing seat-of-the-pants analog circuit design to do these things, and it wasn't quite correct by construction. So we each applied our methodology to it, which was great but yeah. So that was part--

[2] [Interviewer's note] ultimate chip technology.

and so by maybe late '90s, these address event representation circuits in thesechips, transmitters and receivers for encoding and decoding these address events, were starting to work well and we could now start to build bigger systems. So, I published tutorials and review papers on this and shared the design so that people could use them and so forth. So then it sort of became a standard for building larger neuromorphic systems.

So when I got to Penn—actually, I had offers from all these top places and everything like that, but I picked Penn because Penn is sort of similar to Stanford in that respect in that it really has got this collaborative, multidisciplinary environment. Partly because the hospital, the engineering school, the college, all this stuff, they are all concentrated on the same campus, and so forth. One of my mentors who was on my thesis committee was a guy named Peter Sterling who I had met at these retina meetings and so he was the neurobiologist on the committee. We still talk and he's still really involved. So that's the other reason. He was at Penn, so that was attractive. So the early days of my lab at Penn, it was very much modeled after Carver's lab, which one of my students described as an artists' colony. <laughs> Everybody had their little art form they were perfecting.

I was the retina guy, and my first student, who now has his own lab, he was MD-Ph.D., and he's got a lab at the NIH in Bethesda, and he actually records from temporal lobe of human patients and studies how they represent memories and things like that. So, he built the mother of all silicon retinas, which basically replicated the four main types of ganglion cell outputs on the retina. It's like 90 percent of your optic nerve is these four main types. And they are sending four different movies that emphasize different aspects, different features simultaneously into the brain. So that's it really, and then all the nonlinear stuff the retina does.

Anyway, so that was the retina story, and there was another student who worked on, once the retina gets into the brain, one of the first places where we understand how that circuit develops and matures is something called the tectum, which can self-organize itself, its connections from the retina to the tectum such that you've almost got a topographic map. It's not scrambled anymore. You start in random locations, and they sort themselves out. So, he worked on that and then we had people working on the thalamus where you can relay the information to the cortex, and you can control what inputs get in and what don't and stuff, then the cortex. We were also working on the cochlear and the cochlear nucleus and stuff. So everybody had his own little chip that did something completely different, and if you build all these things together, maybe we could build a brain or something. <laughs> So it was really fun and so in 2005 I had a cover story that I wrote for Scientific American on neuromorphic chips that showed the kind of stuff we were doing.

Fairbairn: So what year did you get to Penn, and how long did you stay there?

Boahen: So yeah. Actually, I finished in '96, but then I went and spent three months on vacation in Ghana and then I started at Penn in '97 and then I moved to Stanford in 2005.

Fairbairn: And what was the motivation for that?

Boahen: So, like I said, I was very appreciative of a multidisciplinary environment, and one of the other attractive things about Penn, because it's got a traditional kind of approach, was they were trying to formalize that by setting up something called the Institute of Medicine and Engineering. So the idea was that these folks who were in medical school, folks from engineering, based on intellectual interest, like if I'm doing some robotic and some guy's an orthopedic surgeon and stuff like that and we are possibly interested in biomechanics or something, we would have our labs next to each other, based on this structure. You would be thinking Bio-X at Stanford, but this was way before Bio-X. This was like in '96, '97, and so they built this building and it ended up being one floor of this building which I think probably in '98 had started and I think it was probably like 2000 or '99 when Jim Clark donated money for Bio-X, the Clark Center [at Stanford].

Anyway, so they were ahead of the time in that, but what happened was it ended up being just kind of like 7000 square feet, one floor of a building, and it was enough to-- maybe it was 15,000 square feet—enough to house like seven labs or something like that. It ended up being focused basically, based on the guy they hired as director, in the cardiovascular engineering area, tissue engineering area. So yeah. So then this Bio-X thing happened and Stanford also set up a bioengineering department in 2002 or so and they were initially housed in the Clark Center. A guy I knew from Caltech, Steve Quake, who was starting there as an assistant professor when I was leaving and stuff like that, moved from Caltech to bioengineering at Stanford, so then I called up Steve and I'm like, "Hey, what's going on?" So, then I told him I was thinking about moving and seeing what they did, and it was really exciting. So that was the pull.

Fairbairn: Cumulation of events.

Boahen: Yeah. So when I came in 2005, Carver was still living up in Woodside. He would come to the lab meetings and stuff, and we would see each other and so on and so forth.

Fairbairn: So you got there-- in one of the talks that I listened to, you talked about-- I hope this provides a framework in terms of guiding the future discussion-- our evolution of understanding of the brain. That we've gone through three different models or understandings of what's really going on or what's important, and then that is reflected in the engineering or work that you're doing. Can you-- is that reasonable framework to...?

Boahen: Yeah, yeah, yeah. That's what I came up with but yeah. So, the way I like to describe it is, and you put it just right. One of the things that's really just true about nature and biology and all that is just the sheer complexity and the sheer amount of detail and there's no way we can ever replicate all that complexity or all that detail. So, we're always faced with a choice that we have to make. Which parts do we take, and which parts do we throw out? In making that choice, we don't want to throw out the baby with the bath water, so it's tough. Which one is it? Maybe it's everything. Then, we're screwed. <laughter> I don't know how you approach these problems. It's intuition. It's trying things and learning your lessons, whatever, and so kind of like with that. Then, it's also a moving target because the biologists are discovering new things every day. When I started learning neurobiology when I was at Caltech and I was thinking that over the years things would become much more clear, like what's going on. What's actually true, over the years, it becomes more complicated, what's going on, because we know so much more that we didn't know.

Fairbairn: Just keep peeling it back and it keeps getting more complicated.

Boahen: Yeah, that we didn't know. So it's very interesting, but that makes it interesting. So anyway, if you look at it over the last 60 years, abstraction, your conception of how the brain computes has evolved and the stuff we keep, the stuff we drop, it's changing. So, these neural networks you see all around, this deep learning, all this kind of stuff.

They go back to the multilayer perceptron, Rosenblatt's multilayer perceptron, which says that what a neuron does is that it's connected to all these other neurons and they send in inputs and it applies a different weight to each input. Then, it sums the thing, and then based on whether that result exceeds some threshold or not, it's activated or not activated. It may be activated in proportion to how much you exceed that threshold, and so then it will send that information down to the guys it's connected to. Then, the parameters that you change to get this, going back to Terry's talk, is you tweak these weights that are on these connections and then you can get it to do different things, to learn different things.

So I call this a synaptocentric view of the brain, because the only thing we're taking from the brain is that synapses, which are these connections between the neurons, have a strength. They can be weaker or stronger and we capture that in these deep neural networks. But this is 60 years old. Over those 60 years, we know so much more about the brain and so part of when we went through this, and if you just look at the stuff because it's just weighted real numbers, you just represent those real numbers by some integers or by some analog signals, whatever. There's nothing like a spike. There's nothing discrete about it, and it's just sort of math. So, part of the problem we run into when we're trying to build these systems and try to enlarge them and send these analog signals around which are easily corrupted by noise, we realize that, no, we have to convert to digital to communicate.

So this is what I talk about later, and that's actually what a neuron does. A neuron doesn't actually send some amount of stuff. When you exceed the threshold, it fires a spike, and it resets. It dumps all that input and then it starts accumulating input again and <inaudible 01:08:10> spikes, so it's sending this discrete thing. It's just a pulse, waveform, full amplitude, very thin width, and it sends that down its axon and then it hits a bunch of synapses and then it generates some analog input. So you go back down a little. Anyway, so this part here, when we say, "We actually have this axon, and it's sending these pulses," this has to be incorporated into the neuromorphic chips. That's the main difference between these neuromorphic chips that you hear about which came out of Carver's work, the work Carver pioneered and the more traditional neural networks. So I called that the axocentric view. Now we think <inaudible 01:08:58>[3], and that's what we...

Fairbairn: So you have the synapse-centric and then the axion...

[3] Interviewer was not able to resolve this inaudible.

Boahen: Axon-centric, axocentric.

Fairbairn: Axocentric.

Boahen: Yeah. So that's what we've been doing more recently, or actually over the last past 20 years, this evolution to analog and then mixed-signal neuromorphic system. Now, at least I am beginning to recognize the limitations of this approach, and at the same time, the biologists tend to understand much more about the fact that the dendrite does some very sophisticated things and this is something that Carver always insinuated. He thought, these dendrites, I think that's where the power is, but we didn't know enough. So in the axocentric view, you take this elaborate dendritic tree and you throw it out and you just deliver all the inputs directly to the cell body.

This elaborate structure that the dendritic tree has, we are finding that it can do its own computation. It's not just a sum. In other words, this little segment of dendrite can get a bunch of inputs, and if the input's coming this way, do, re, me, this is me, re, do, it will trigger a regenerative potential, like a dendritic spike, and it can even sit there. It can switch into an UP state, so it has a memory over seconds that that thing happened. Then, the next segment of dendrite is primed to look for another sequence of spikes and if that comes in, eventually we can just combine, decode information, and integrate it and boom, you can make a decision just in a little branch of a dendritic tree, which involves multimodal information and memory and all that.

So, this is really much more powerful and so we are beginning to understand that this is what dendrites are doing and it turns out that-- so this is what I call the dendorcentric view. So, if you incorporate these concepts of how the brain works, there are several implications that are just mind blowing. It takes it to a whole new level.

Fairbairn: So, has that latest understanding, the dendrite-centric view, been reflected in current research, or are you just starting to think about it or what's going on?

Boahen: Yeah, so this is something I'm beginning to understand. You know what I'm saying? We are unblocking this part of what we don't see. But the biologists, over the last 10 to 20 years, the discovery that dendrites can make these dendritic spikes goes back to 2000. It's called an NMD apike, and the discovery that they are sensitive to the sequence in which the inputs come in, in other words, the weight could be the same, the same set of inputs, the same set of weights. Depending on the order in which you activate them, you get a different response. That was discovered in 2010, 10 years ago, and then recently there's all kind of-- Part of the reason why we can see this now is that people can basically observe in an animal-- we can basically thin the skull or we can put a little surgical window, a glass window there and we can put the animal on a little ball and it's like a treadmill that so can it be running while we are plugged into this microscope and we can use two-photon scanning with these lasers to see activity. We put in a sort of dye which binds to calcium, and when these inputs get into the dendrite, it opens calcium channels when they activate it.

So we can see the activity playing out along a dendrite and you see this stuff happening, so you we're able to see at the scale. Now we can really see what's going on, and so this changed the view, but it's not yet been translated into this new generation of neuromorphic chips. This is something that I'm advocating, and I'm just beginning to appreciate how important this is. And it's related to real problems and constraints that we are running into and basically Moore's law. So this is what I call the LA-versus-Manhattan model, so the way we build chips in 2D is basically like LA sprawl. We just make these, pack more and more and more devices and circuits and wires on the chip, but it's 2D. So, it's like LA but except that we don't make the city bigger. We make the people, the roads, the houses, everything smaller, and we pack more stuff. That doesn't change the fact that now the distances that things move, like you get to your office, you're doing work, but then to get back home and get to the office, that distance is way longer relative to the amount of distances you move to do the work. So you spend all this time commuting, and you have very little time left to do your work. This is what's happening in a chip. For us to move the data around, it's not really even-- we no longer have this von Neumann architecture. We run tons of processors on a chip, and we've got memory distributed all around the chip. This is what these GPU and TPUs are doing and so we've broken that von Neumann bottleneck, but still, these processors and these memories have to work together to solve a problem. So they have to exchange information, and as these processors and memories get smaller and smaller and we pack more of them, we have to exchange information over longer and longer distances.

So we spend more time, so right now the energy that we're using to communicate on a chip is like 1000 times more than the energy we are using just to compute. Computation is free. Once you get the thing in there, that little logic circuit multiplics. Boom, boom, boom, it happens. You don't even see it. So that's kind of where we are at, and now the electrons are complaining. They're like, "This transistor's too small. I'm bumping into all these"-- you can't make it any smaller. So that's why people are saying it's the end of Moore's law, but actually it's not true. Moore's law says you're going to double the number of transistors on the chip. And that's still happening. And the way that it's happening now is that you can't shrink the transistors anymore and so you go to the Manhattan model. You used up all the real estate, so you want more people, more cache, more stuff, you build these skyscrapers.

So, the memory guys are doing this. Like, in your phone you've got a terabyte of memory and that terabyte of memory is a little package with eight memory chips stack together and each of those chips has 1050 layers of transistors and wires and all that stuff, 3D NAND NAND-flash. So it's already a skyscraper, and then you stack eight of these together. That's 1000 layers of memory cells, and so you can pack all this memory right next to the processor and just go boom, boom, boom, boom, boom, boom, boom. Part of why you're able to do all this stuff with your phone and it's on your battery.

The memory guys actually went this route in 2013 and they stopped shrinking transistors. They said, "Look, memory has to be abundant. It has to be cheap. You're going to go 3D. It's too expensive to shrink these things. They're complaining too much." So there we have it, and so that's the path forward which people are beginning to realize. You got to go 3D, and the memory guys have already done that. Now they're 150 stories high on the chip but the challenge is that, in memory, you only activate one layer at a time but if you're trying to process in 3D and activate all these layers simultaneously, you're going to melt the chip. Even just one layer, one 2D chip, you need this huge heat sink. Right?

Fairbairn: Right. Yeah. Exactly.

Boahen: So that's the challenge. We know we have to go 3D, and if you go back to the analogy, you take all these guys in LA, you shrink them, you put them in Manhattan, you're going to take all that smog, even though the smog is going to be less because they have to drive shorter distances, the area over which it's concentrated is even smaller. So it's going to get worse, and so this is why they don't let you drive or make it very expensive if you drive your car. They put in you public transport in the trolley or down on the subway because a subway car can move like 50 people for the same amount of smog that one car makes. So then you've solved the problem.

So the analogy in a chip, again like I said, communication is using all the energy. You have to send fewer signals around and the way you do that is by packing more bits of information in each signal. That's like the subway versus the individual car, and so that's where now, in the insight from the brain, it turns out that, yes, the brain has figured out how to pack more bits into each of these spikes and it doesn't use a binary code. It uses what's called unary code, and then it's figured out how to decode. So these spikes-- I can explain this in more detail but then these codes end up using sequences of spikes, so that's the encoding and this is why the dendrite is sensitive to the order in which the spikes come because it has to decode a sequence. So let me stop here. You direct me.

Fairbairn: Well actually, yeah. This isn't sort of meant to be a technical lecture, but I would like to go back and put this in perspective and see where the impact is starting to be felt in terms of real-world kinds of things. So you're pursuing this. I guess the fundamental reason is, the thing you're relating to, is the fact that the brain is thousands, millions of times more efficient in terms of both space and power and, in fact, the thing that we're struggling with in our datacenters and our computers and our chips is we can't get rid of the heat. It's taking too much power. We can do these wonderful computations, but it's sucking in too much and giving out too much heat. So this is an exciting path in terms of being able to make radical improvements in terms of the power efficiency as well as perhaps physical efficiency.

So as I see it, and correct me if I'm wrong, there's been these two parallel paths. You've been following a path where you have continued to understand better how the brain works and how computation is done in the brain and building analog realizations of that in the physical world and new chips and so forth that you're developing. In parallel with that, there's this group of people who have just discovered that this basic deep-learning model and layers of neural networks, sucks up an incredible amount of energy and everything, but it works. And so, so far, they've been willing to pour in whatever it takes in terms of power and cost because of this great revelation of what happened in 2012 or whatever in terms of all of the sudden machine learning and neural networks has shot to the fore from being a backwater technology for all the years. Right? So there are these two parallel paths where this one is making great-- I'm sorry. One path, the neural network, the digital neural networks are making great progress in terms of results, but they're in the process of, or about to hit the wall, in terms of how much power can you get. In fact, the latest issue of Business Week about all the startups that are focusing on how do you cool these datacenters, do you immerse them in water? All these different technologies for keeping them cool. You're trying to keep them cool by not consuming all of this power, so meanwhile in parallel, you're pushing forward on the analog computation model. So where have there been bridges so far in terms of spinouts from your technology that have impacted what's happening in the commercial world, and what do you see in the future? When does-- when is there a substantial impact from the kind of work that you and your colleagues are doing on this incredible problem that the deep-learning people are having?

Boahen: Yeah. Since we're at the Computer History Museum, the...

Fairbairn: And correct me if my characterization of history is incorrect here.

Boahen: No, it's good, but it's important to recognize that there's something called the hardware lottery.

Fairbairn: Hardware...?

Boahen: Lottery. You can win the lottery, and you win the lottery now because you're the best technology but by some accident. So this part that you describe where this deep-learning thing kicked in in 2013… When I arrived in Stanford in 2006 and we started working on Neurogrid, which is the first system with a million neurons, and had gotten funding to do this and I was talking to my colleagues in CS, I remember talking to Sebastian Thrun. We went to Peet's and we got coffee and also Andrew Ng, and in those days, those guys were trying to get these deep-learning things running on GPUs. Andrew was telling me-- so this is 2008 or something-- that every time they get a new GPU chip and they put more of them together, they get 10 times more power, they train a 3-times-bigger model with 3 times more data, they get better performance, and they don't see this stopping. So yeah, so long as everybody is cranking out GPUs, they're going to do this. It's just a matter of time, and so he was telling me like, "Yeah, so if I look at that, and honestly, you can build a system. That can get us so something like"-- I said I was going to build this million-neuron system. He's like, "No. If you can get to 100 million maybe it's interesting because we don't see"-- and kind of similar thing from Sebastian Thrun. It's true.

They won the hardware lottery. Nobody designed GPUs to do this. They're designed as graphics chips, and you just hand out that. The gamers were buying so many of these chips, NVIDIA could continue cranking them out at the latest technology node that TSMC was providing and gamers would pay for them. They are the first customer. They get on the first, most advanced process, and yeah, the game is about paying, footing the bill. So, you win the hardware lottery. It's there. It was quite tricky and all that stuff to do reverse engineering, get it to do the stuff, but hey, once you did it, you're good. So this is the kind of accident that happens. Something is developed with some purpose and it gets repurposed and so forth and that's the hardware lottery.

So bring this back historically, that's what happened and so the question we should be asking ourselves is that now that we know this thing is awesome, it's really great. It's like these guys weren't talking shit the whole time. They can do something. Then, we should go back to a clean sheet of paper and see if this is the sort of computation we're trying to do, and instead of winning the hardware lottery, getting lucky, we should really purposefully design a system to do this. So there are companies thinking about it, who are trying to do this because we know that it's going to be impactful. It's really going to be useful, but of course, NVIDIA's not going to give up winning the lottery so easily. That's where we are at. We just luckily got this to work. It wasn't forethought. It wasn't planned out, and now we really need to think it through and plan it out. This is where the insights we're getting on the brain can help us really think this through and plan it out.

The other example I'll give, I'm going to tie in sort of more detail, the other example that I give, that like you said, it's very true. The resources we're using in energy, time, money, is just incredible. Since 2013 when these things showed that they can really work, we've been doubling the amount of compute we use to train these things every three and a half months. That's 10 times more compute in a year. That's like 7 times faster than Moore's law, which is double the transistors on a chip and therefore how many processor you can have every two years. All right.

So that means that what we are doing in unsustainable. It's just costing you more money so these latest models, like GPT-3 from OpenAI, it's like $5 million to train this language model and the amount of energy you use in these datacenters is like using 50 cars for a full year. That's how much carbon footprint we're generating, and this is going to be 10 times more next year and then 10 times more and this is just totally unsustainable. So it's very clear that we can't continue to do this, and so this is also why you're seeing all this activity. What I'm advocating is that you shouldn't be looking for a-- the terrific thing about Moore's law is that it ran for 50 years or 60 years and that you have a thing that's scalable. You know what you have to do and you're not just going to get the payoff this year and next year's you'll get it, you get this kind of thing.

We have to come up with a similar kind of scaling law, principle, that can run us 50 years by doing more of that thing, not that every year we do some special thing in there and we get this and we do this trick. We can't rely on a different trick every two years. It's just too expensive. You don't leverage. You don't build them out, then you go and do all of that kind of stuff. This is what we should be thinking about, so that's what I've been thinking about. It goes back to what I said earlier, and this is really where I started. I was really inspired by these quantum computing guys because I said, "Wow. That's really what the lesson that that's teaching is that we've been focusing on the wrong things." You should really, if you think it through clearly, which details do you keep, which details do you throw out. You should keep the details, in other words, pick a computing primitive and a signaling code, like for the quantum computer it's these Qubits and entanglement and superposition, and if you pick the right ones you should be able to show that you are on a better scaling.

In other words, let's say, you increase the size of the task, the amount of volume, the amount of energy and so forth will increase more slowly than the competition. In a quantum computing case, computation is using exponentially more hardware to do something, and this thing's using polynomial hardware. That comes back to what you get when you replace bits with qubits and disjunction and conjunction with superposition and entanglement, so it was in there. You didn't have to write any algorithms to show this. You could just argue from first principles that it's going to kick ass. Then it was 12 years later that Shaw or up with this algorithm for factoring prime numbers and so this is what I've been thinking about the last two years is following this program. So what are the right codes and primitives? Well, if you look at, again going back again to the hardware lottery, back in the '40s, during the war and after the war when ENIAC was built, ENIAC was using decimals. It didn't use binary stuff because we are all familiar with base 10, but the problem they quickly ran into, it was built with 18,000 vacuum tubes and these things would die out all the time so half the day it would be not functioning. It would be down, so the engineers realized that they need to find a way to build these systems with fewer-- if they could reduce the number of vacuum tubes, they could run longer. So that's why they switched to binary because if you replace base 10 with base 2, which means that instead of 10 symbols you have only 2 symbols, then the logic gets much simpler because the number of cases that you have to handle in your logic corresponds to the different pairings of digits that can happen. There's only 0-1, 0-1, and 1-1 that could happen, and so you have to handle those three cases. You can build them up and it is much simpler than trying to do it in base 10 where you have 100 different pairings that can happen, and you have to handle all those cases.

So they made a conscious choice to reduce the amount of hardware or logic at the expense of, well, increasing the number of digits because in a binary number it takes much more digits to represent the same decimal number. So it means that they were using more wires. They were sending more signals around, but they were saving vacuum tubes. We are now in the opposite condition. Transistors, cheap. Computing something, trivial. For how many rows, we don't care. The thing that is burning all the power is how many signals are we sending around. Yeah, and so we should be switching over to the other side, which is using a very high-radix number system, and this is exactly what the brain is doing. So if you have a layer of neurons in the brain, they are not using a binary signal. A spike is not a 0, 1. It's really a choice out of, let's say, a thousand neurons I have in this layer, I'm going to pick one of them to fire. One out of a thousand choices is ten bits. Two to the ten is one thousand twenty-four. So that choice, that one spike is encoding ten bits. So you can think of it as a thousandary number system where we've got a thousand symbols and each neuron spike is a different symbol, and if we have, you may say ten places in that thousandary number, we're going to send ten digits, then we make ten spikes and the sequence in which the spikes happen tell you which place you are in that number system. This is using much fewer signals because it's packing a lot more bits in each signal, and it's very sparse. It's one out of a thousand guys.

Fairbairn: So there's clearly a path forward, including an opportunity to get there, but in fact, the work that you've done or the work that you and your colleagues have done has had an impact in terms of there are commercial or other work being done in making use of some of this analog technology. You have an example, I think, with the-- tell me a little bit about that and how that...

Boahen: Yeah. So in terms of how things have-- what would I say-- percolated out, of course this is what we do as professors. We train students and they go out and they do much more practical stuff than we do. So when I came, like I said, we had built all these different pieces of brain. We had developed these ways in which we could stitch chips together into a bigger system and so forth, and so when I moved to Stanford I decided-- I had already gotten tenured at Pennsylvania and I came with tenure, and I was like, "We are going to the next level." So we proposed, at that time, by stitching together these little chips we had built and all this infrastructure.

The biggest system we had built had something like 30,000 neurons, which we were using to model a little piece of the visual cortex, like detect orientations and things like that from the silicon retina feeding into these chips, from the image feeding in. So I put together a proposal and I said, "We're going to build a million-neuron system," so that's 30x bigger than anything I'd built before and I got one of these NIH Pioneer Awards which were for high-risk, high-reward research, which is a nice chunk of money for five years. So we, starting in 2006, by 2010, we had a system up and running. We did all the whole software stack, so there was a nice GUI. You could write Python to describe your model and map it down onto this board right here, and you had a million neurons running in real time and so forth. So, then that, being partly responsible for DARPA's synapse program, so back in 2008, a guy called Todd Hylton, who was the new program manager DARPA, heard about what we were working on and came by and we showed him all the stuff. One of the problems he identified and others identified was that, yes, we don't have any learning on this board so in your program, you say which neurons connect to which ones and those connections are static while the thing is computing. So it was really designed as a way, kind of like a circuit designer, you could design, build circuits that up to a million neurons, and you could explore different ideas of how they could do some interesting computation or perform some interesting behavior or something like that. The problem with having learning on the chip was that each neuron is a thousand synapses and if you're going to implement those synapses in CMOS with the same transistors that you're trying to build the neurons, these synapses take about a thousand times more room than the neurons. So enter the 65,000 neurons on each of these chips. Well, we have only 65, and 65, it would be less than 200 neurons on the whole board.

We always recognized that scale was important in terms of building infrastructure and being able to, so we were working on that side of the problem and we were hoping that, okay, we'll have some better way of making these synapses smaller so we can then have that, as well. And so, the goal of the synapse project was to use nanotechnology with these. We thought nanotechnology was going to be something different from silicon. It'd be some fancy stuff that you'd put on top of the chip and you could make it really small, really tiny and those would be your synapses on top of your neurons and all that and the connection would be all in CMOS. So that was the synapse project, and so I was part of the team led by IBM and involved in writing that grant and so forth and we were going to help develop this special nanosynapse stuff.

But it ended up being that approach didn't pan out. It turned out that they could build very small systems, examples of these memristors and things like that, but they couldn't scale them and you couldn't build a large system. So to meet DARPA's goals, the IBM team eventually went with an all-digital approach. They just basically used the most advanced technology, which was 28 nanometer at that time, and they were able to take a million neurons, each with about 256 synapses, and fit them on a single chip. As were the lead, my former students, who worked on this Neurogrid system designing that chip. They were the lead designers, John Arthur and Paul Merolla, and so that got IBM in the game and then that generated interest from Intel. Then, Intel started a neuromorphic project and so on and so forth, so that's how this stuff has percolated out into the valley.

Fairbairn: So I mentioned there are a couple of companies, one in particular, Mythic, that is doing some analog work. Are you familiar at all with what they're doing?

Boahen: I don't really keep track of it. I know they are out there and BrainChip and all this kind of stuff, but I don't really have any connection with those guys.

Fairbairn: So what do you-- you're in two areas, that is sort of the biology side and the artificial intelligence and machine learning side, that are both are sort of, there's a lot of debate going on in terms of what's good, what's bad, what comes of it, what's the impact on society and so forth. Are these topics that are discussed within your lab? Do you run up against that, or are you pretty much at such a basic research level that...?

Boahen: No. I mean it's funny. I mean we'd been talking, Carver had been talking about energy efficiency and low power in the '90s. Nobody was talking about it. You just have to go faster. You just have to pack more transistors. He was talking about that. He had extrapolated, even by taking Moore's law, you'd still be using a million times more energy than the brain. That's where your problem is because to do something that takes 20 watts you need 20 megawatts. That's a whole datacenter and that's a million times more resources, carbon footprint and all this stuff. We've been talking about this for three decades. That's what they're just doing, what we said is going to happen. Why should we be talking about this? it's not news. This is why efficiency is what matters. You look at the brain, and I told you there is all this complexity, but it's not alien technology. It's following the laws of physics. The cost of computation with the brain are the same as the cost of our chips. It's using electricity. It's generating heat. It's using space, so you can compare it. It's ridiculous, what they are talking about it. I mean it's kind of like we told you. What are you talking about?

Fairbairn: Clearly...

Boahen: That's why we were working on what we were working on at that time.

Fairbairn: ...coming up with the technology would be a huge positive impact...

Boahen: Yeah. That's why we are not taking a digital approach.

Fairbairn: ... in terms of the energy savings and so forth.

Boahen: That's why we're doing what we are doing because this is going to destroy the planet. It doesn't make any sense.

Fairbairn: Right, right. So how do you-- how do people view it at Stanford now? What's their-- or you feel like you got momentum building? Are you still pushing against the thing? You know, what's the...?

Boahen: I describe it as the transition from-- and Carver tells stories like this. When Carver developed VLSI and he was showing people democratized chip design, he went and talked to-- you mentioned Ivan Sutherland. One of them, Sutherland and something, they made graphics processors.

Fairbairn: Evans and Sutherland.

Boahen: Evans and Sutherland. Right. Yeah. They were building these things out of discrete chips, whole cabinets and everything like that, and Carver went and told them that, hey, you guys are dinosaurs.

They are like, "What are you talking about?" He's like, "Look, somebody's going to build a chip. It's going to reduce this whole thing to one chip, and they're going to take over your market." They go, "Come on, those chips?" "Yeah, those little baby things." This is what Silicon Graphics did, Jim Clark, so by way of saying that—

But the example that I personally like is, again, if you go back to the ENIAC, they were the ones. ENIAC is a digital computer, and there were computers at that time. They were analog computers. They started out with these mechanical things and then they started building them electronically and all this stuff, so you had autopilot and controls for planes and fighter planes and all those. So analog electronics, you have integrate and differentiate and you do all these controls. And there was analog computers in there that did that.

So when they developed ENIAC and doing this digital stuff, the analog designers were like, "What's that?" "That's a digital computer." It's like, "How fast does it go? What? Ones and zeros? What?" They could never differentiate or integrate. They couldn't even dream of doing that. It's too slow, and it didn't have floating point and so the analog guys were like, "Okay, fine. That's good for databases and tables and things like that, but you're not going to use this to control a plane." So you see a period from '45 to '50 where-- and you guys have a fantastic display of analog computing downstairs. You see there was a period with this huge innovation. They were coming up with all these bells and whistles and [ph?][4]-- because they were dying. They were dinosaurs. They were just trying to survive because eventually digital was going to just take over, and that's what you see right now. All these companies, they have some little secret sauce they add to it and some twists. They do this. They do that. This is what you're seeing. It's dying.

Fairbairn: So do you believe-- you've mentioned quantum computing several times and perhaps, I mean, do you think that will be the technology that-- is that...?

Fairbairn: No, no. What I think is that we have to go to 3D. We have to go to the Manhattan model, and when we go to the Manhattan model, this digital approach doesn't work because it generates too much heat. So then, but in terms of the brain is 3D, and so its style of computation that it's doing really is compatible with a 3D chip. The amount of energy and heat dissipates scales, not like the volume of the brain but just like the surface area. And it scales linearly with the number of neurons instead of quadratically which is what happens when you spread it out in 2D. Then, you can arrange things. The data activity is sparse. Then you can arrange things and scale it linearly and this fewer, smaller and smaller fraction of the neurons in that volume signal. Then, the energy it dissipates scales like the surface area, so everything is cool. It doesn't overheat, and so yeah, this is why I'm excited about this. The more that I look at 3D, we have to go 3D, and then the more that I take into account the constraints of 3D, the more it makes sense that we have to do what the brain is doing. So neuromorphic really comes to fruition or becomes really a uniquely advantageous approach.

[4] Interviewer was not able to resolve this inaudible.

Fairbairn: Okay. So I think that's actually a good place to stop with the exception of another sort of thing that we ask our oral history candidates to do is offer some advice to a young Buster, a young Kwabena, somebody high school, early college, whatever. What advice would you give them in terms of directions to go, things to pursue? What do you tell your young students?

Boahen: Follow the two-year-old program.

Fairbairn: Follow the...?

Boahen: Two-year-old program. Go back to the way you were when you were two years old. I learned a lot of stuff from Carver. He's a great teacher, but my favorite professor is Professor Boahen. Everything he teaches me, I understand perfectly. I never forget. It makes so much sense. It's just fabulous. I can go back and come out with completely different ways of looking at it, and it makes so much more sense. So this is what it is. You follow the two-year-old program. We really destroy this in the educational system. We put the kids back in. Sit down and keep quiet. Two-year-olds don't do that. We explain something to them. What did I say? They have to parrot it back. Two years old don't do that. Then, you put them somewhere. It's like, they come in. "What should I do?" Then, you have to tell them. Two-year-olds don't do that, so you just go back to that program. You're going to be fine. <laughs>

Fairbairn: All right. Well, that's...

Jon Plutte: I have one. What do you think of the value of a computer history museum is?

Boahen: Yeah. I mean, I've given that example several times the greatest influence of my dad. It's important for people to see this hardware lottery. They think we're doing things a certain way because we thought it through and because that really makes sense. But it's usually some accident of history we are doing things the way we're doing them. You need to understand that and then you also need to train yourself to think from first principles so you can look at the thing at face value, whether that decision really makes sense or not.

Too many people think by analogy, so that's that contrast. So if you take them through the history and they see how many accidents happen and these things were just accidental. Then they realize that they shouldn't be taking things at face value. They should be figuring out for themselves why it makes sense or it doesn't make sense. So this is Neurogrid. It's a board. In fact, there's a date on here someplace. This is a 2009 version of the board with a million neurons on 16 chips. It's a mixed analog-digital system. All the computation is happening with these analog circuits that are operating with picoamps, carrying picojules and then the communication is happening with digital circuits that don't have any clock. They just send a signal when it happens. It's generated by these analog circuits and that way we can communicate among all these chips and all this happens is this routing circuitry for them to talk to each other and to talk to the computer and all that is built into the chips themselves. So you don't need anything else but hook it up over USB to your computer. And we have a software stack that allows you to configure it and to visualize what's going on when it runs your model.

Fairbairn: Okay. Okay. Thank you very much, Kwabena.

Boahen: Okay, Doug.

Fairbairn: We really appreciate your spending the time and a fascinating story. So thanks very much.

Boahen: Yeah. Well, thanks. Thanks for the invitation. Yeah. Yeah.

END OF THE INTERVIEW

