Dr. Paul Werbos: Artificial Neural Networks

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Robert J. Marks:

Artificial neural networks are a huge part of artificial intelligence. Today on Mind Matters News, we talk to the man who invented the method used for over four decades to train artificial neural networks. Dr. Paul Werbos is our guest today on Mind Matters News.

Robert J. Marks:

Greetings. I'm your guiding host, Robert J. Marks. Artificial neural networks are everywhere. Given a big gob of data, neural networks can be trained to understand the data. For example, you train on a neural network on a bunch of pictures of Sumo wrestlers and basketball players, then given a picture never seen before, the neural network will identify it as a Sumo wrestler or a basketball player. The applications are legion, ranging from finance, power load forecasting, detecting disease from medical images and even predicting what crops farmers should plant next year.

Robert J. Marks:

Neural networks are ubiquitous as a search for neural networks on Google Scholar returns over 2 million, 2 million scholarly papers on the topic. Now these are just not posts or news articles about neural networks, these are scholarly papers, collectively known as the literature. And most of these papers use something called error backpropagation, an algorithm invented by our guests today. And our guest is Dr. Paul Werbos. He's an American mathematician and machine learning pioneer, and maybe is best known for his PhD dissertation, which first described the process of training artificial neural networks through backpropagation of errors.

Robert J. Marks:

Paul has served as the president of the International Neural Network Society, and is a recipient of the IEEE Neural Network Pioneer award. In 2011, he received the Hebb award of the International Neural Networks Society, and he's a fellow with the IEEE. That's pretty prestigious. IEEE is the largest professional organization in the world, but only one-tenth of 1% of its members can be admitted to the fellow status each year. Dr. Werbos is also retired program director from the National Science Foundation where he oversaw the NSF's program in neural networks and machine learning. He has served as a congressional aid in many aspects, including to the late U.S. Senator, Arlen Specter.

Robert J. Marks:

Paul, welcome.

Paul Werbos:

It's great to talk to you again, Robert, and thank you for that kind introduction.

Robert J. Marks:

Paul, I was thinking, I'm an electrical engineer and we are taught algorithms as undergraduates and graduate students. And I would think of those algorithms that we are taught that your algorithm, currently called error backpropagation, probably is in the top 10 algorithms used currently in computers. So if we look across the world and look at the algorithms being executed, I think that yours would be in the top 10. And I'm thinking of things such as compression, like doing zip files. I think that's a pretty common algorithm. I'm thinking of Fourier transforms like the FFT. There's something in JPEG images using the co-sign transform that uses the Fourier transform. And I think error backpropagation is probably up there. So I think yesterday around the world of the algorithms I'm thinking of that yours is in the top 10. What do you think?

Paul Werbos:

Easily. The problem people have out there to try to understand what's going on in the world today, there are just a whole lot of pieces, and you don't really know what's happening until you can put them together and know what they are. And it's really scary to be one of the few people in the world, even now who really knows what these algorithms are. I see people talking about artificial intelligence and neural nets and their future, and it's amazing what kind of theories you can hear on TV, a lot of it from people who have political motivations. And the connection between those theories and the real technology and the real math, it's like 100 years difference.

Robert J. Marks:

Yeah. So do you think that there's a lot of fake news about artificial intelligence? I certainly do.

Paul Werbos:

Oh yeah. Oh, absolutely. It's overwhelming.

Robert J. Marks:

Yeah. Could we start, could you give a high level nutshell overview of your algorithm, error backpropagation, which is the dominant 99.9% of the time used as the algorithm for training artificial neural networks?

Paul Werbos:

So backpropagation really came from me trying to understand how brains work and how you could build a brain like a brain. And when I was growing up, I read a lot of books I was excited by. There's a book called Computers and Thought, which was the start of the whole artificial intelligence world. And believe it or not, I was inspired by a chapter by Marvin Minsky who said we could build human-like intelligence by using something he called reinforcement learning. And I said, "Wow. It would be nice to build something that can do it."

Paul Werbos:

And then later I met Minsky, and he said, "Nah, that idea never worked. I couldn't figure out how to do it." Nobody could figure out how to do it. And I said, "I can figure out how to do it," because I knew the math, and a lot of these people were glorified hackers, they were looking at themselves in the mirror and how proud they were, how clever they were. And they didn't go to the math.

Robert J. Marks:

Well, I call these people keyboard engineers. They just sit down and they go to the keyboard and that's where they try to get all their answers, as opposed to understanding the underlying, deeper mathematics.

Paul Werbos:

That's exactly the key thing. We need to understand the math to get it right. And so I spent a lot of time reading John von Neumann, and von Neumann had a lot of really good thoughts about how to do it. And I was amazed people didn't follow up on some of these thoughts. So I decided, well, okay, I'll take the mathematical approach. I'll solve these mathematical problems. Here's how to do it. And believe it or not, reinforcement learning was the first thing, how to come up with a system that could learn to act and achieve goals.

Paul Werbos:

And then I realized, okay, to make this work, I need to have a subsystem that learns how the world works and that's what they now call backpropagation. But that backpropagation, which I developed was actually a part of a larger design for intelligence systems.

Paul Werbos:

And in 1972, I presented that to my Harvard thesis PhD committee, and I said, "Okay, this is what I want to do my PhD thesis on." I actually posted that thesis proposal in a weird place called ViXra, and there it is 1972. Here's how to use backpropagation to learn how the world works dynamically over time, and how to use that as part of an optimal decision system, and here's how it fits the brain. And when I presented that to the Harvard faculty, their response was, "There's enough material here for a thesis. In fact, maybe there's too much. How about you take a little piece of it, the piece we can understand and write your thesis on that piece." So I said, "Okay." So they didn't believe backpropagation at first.

Robert J. Marks:

Well, in fact, you talked about Marvin Minsky and I think he was one of the people that did not like neural networks.

Paul Werbos:

That's true.

Robert J. Marks:

He wrote a classic book with Papert called Perceptrons, which kind of killed the funding of neural networks and one of the waves of neural networks. So it's interesting that your inspiration came from Marvin Minsky, who didn't like that. He liked the rule-based way of looking at artificial intelligence.

Paul Werbos:

Well, he started out believing in reinforcement learning and maybe he even believed in neural nets, but he couldn't make it work. He couldn't find anyone who could make it work. And then he said, "Okay, we'll play with something else. If I can't do it, it must be impossible." That was his basic problem.

Robert J. Marks:

Well, one of the things that you did with error backpropagation, is you overcame the objections, or at least the main objection, which was raised by Minsky and Papert in their book Perceptrons that dethroned neural networks. You came around with a method to get around that.

Paul Werbos:

In fact, it's more entertaining than that. The real history has never been written. It's like a soap opera you wouldn't believe. So one episode of the soap opera, I needed support to do a thesis. And I had taken independent studies with Marvin Minsky. I knew his way of thinking, and I walked in and said, "Marvin, you've got this great book, but the thing is, the problem can be solved. Here's how to solve it. Why don't we become co-authors so that you don't be embarrassed when it comes out? I'm willing to share, I'm not trying to own all this. Here's how you solve the problem that you described in your book."

Paul Werbos:

That was a great conversation, but the bottom line was Marvin Minsky said at the end, "This may be true, but if I do this, the modelers will all kill me, and I have to deal with my reputation. And bottom line is all those people who think they know how brains work, who don't know how brains work, they'll kill me if I start getting associated with a different way of doing how brains work."

Robert J. Marks:

Oh my goodness. And he never really changed, did he? He never came over to what he called the connectionist model, the neural network model.

Paul Werbos:

In a way, I think what he did was he decided to avoid the subject.

Robert J. Marks:

Was that it? Okay.

Paul Werbos:

Yeah. He wrote some books about Society of Mind, and he said some things about language. So he basically wrote about some other subjects, that's basically what happened. And to be honest, I even once decided, "Hey, let's try to make peace." I never wanted to make war. So when I was at NSF, I said, "Tell you what, Marvin, there's a part of your book they never really paid attention to. The part about what you can do with recurrent networks that you can't do with feed forward networks."

Robert J. Marks:

And you had a lot to do with the pioneering of recurrent neural networks too, where you had feedback in the system. Yes.

Paul Werbos:

Yeah. Well actually there are many kinds of feedback in the brain and in any really powerful intelligence system. There are many kinds of feedback. And there is the short term training feedback, which I think of is a lot like what they pay you to do an odd job around the house. It's very similar. In fact, there's a mathematical parallel. This is just a casual observation. There is mathematical economics, which matches exactly to what we do with backpropagation. It's very precise. We can learn a lot about economics from knowing this math.

Paul Werbos:

But leaving that aside, there's another level of recurrence, we're constantly changing your view of the world. When we see things, the image we see in our mind is not what comes to our eyes. It's an image we make up in our cerebral cortex, the outer surface of our brain. We make up an image of the world. And every time we see something, we adjust our inner image of the world, but our image of the world is something different. And so there's a feedback when we adjust our image of the world. It's not like learning, it's just adapting to where we are. So that kind of recurrence is important to how we see things in reality.

Paul Werbos:

So yeah, I offered Minsky a... I even said, "Hey, I'm an NSF now. I can give out EAGER awards. The kind of network you described in your book, the good part of the book, that is a powerful network. It'll do things that the simple feedforward nets can't do. So I'd be willing to send a grant to you at MIT if you guys are willing to work out more of the mathematics of this kind of recurrent network and what kind of power it has." But he never followed up.

Robert J. Marks:

Just to elaborate, you got your PhD from Harvard, and I believe you did a lot of interface with MIT faculty. Is MIT just down the road from Harvard?

Paul Werbos:

Oh, well, they had an arrangement where you could cross register and I took a few courses at MIT. And at some point I needed money. There comes a point in this story of a graduate student, when you have to figure out where's your income going to come from.

Robert J. Marks:

Absolutely.

Paul Werbos:

And there was a joint Harvard, MIT software project called the Cambridge Project, and they offered me a job to implement backpropagation in the MIT Time Series Processor system. This is for econometric models. So the very first application of backpropagation in the world was not actually the neural nets. I took the general theorem out of my thesis and applied it to econometric models and it worked, and that's how I got a job. And it turns out it was a joint Harvard, MIT project, but the paycheck said MIT.

Robert J. Marks:

Okay, that's fascinating. I want to take you back to your time in the 1970s, when you came up with this idea. As you mentioned, it was a much larger idea when you were thinking about it. But if you look at the mathematics, if those that are interested in looking at the mathematics behind error backpropagation, it's really beautiful. I think it was Paul Erdős said that there's certain mathematics that can be written in God's book. This is just beautiful mathematics that is as simple as possible and no simpler, and there's just kind of a beauty of it.

Robert J. Marks:

I think mathematicians look at this like a connoisseur of fine art would look at a great painting and say, "Oh, I see such beauty there." And I see this beauty in error backpropagation. Can you remember back when this first entered your mind? I'm interested in the process of creativity. We know what motivated you. Do you remember having a flash of genius when you did this? Do you remember the time when it came to your mind?

Paul Werbos:

Yes, I do. But first, I guess I owe people a warning that we are entering a period when there is no problem so simple that one flash does the whole thing. And usually when people say, "One flash does the whole thing," what that meant was they were hung up and one flash got them out of that hangup, but usually there were half a dozen hang ups before that.

Robert J. Marks:

Well, no, that's a good point. I think a lot of people have talked about a flash of genius as a sequence of flashes of genius. So that's consistent with what you're talking about. Yes.

Paul Werbos:

So there has to be motivation. So let me come to the moment I think that's closest to what you're saying. Actually, maybe there are two moments now that I think of it, but when I was not even in high school yet, I had a obnoxious friend who really believed in Sigmund Freud and was telling all of us how crazy we were.

Robert J. Marks:

I'd tell you, Paul, that sounds like an oxymoron and I'm not an obnoxious friend. Okay.

Paul Werbos:

So he explained to me how Freud thinks about how the human mind works, and I listened. Half the mathematicians I know would never listen to a guy like that. And then other people would worship Freud and they never understood the math. But I said, "It sounds to me like there's something here." And I thought about it. And at some point I wanted to train neural nets to do things like recognize characters. I figured out how to do that. And that was in what I proposed. I remember going to Professor Ho at Harvard, like 1970 or 71 saying, "I think I can demonstrate a new algorithm that will recognize patterns."

Paul Werbos:

I thought it would be a nice little demo. It was a small part of my bigger theory. I said, "We can recognize things like characters with this kind of an algorithm. And here's how it works." And Ho said he wouldn't believe it would work. I showed the exact algorithm of backpropagation. He said, "Not in a million years would this ever work." And so the Harvard faculty, the first thing was I had to prove it. And then I thought back and said, "Okay, well, I took a course in mathematical logic many years ago from a guy named Alonzo Church at Princeton. I know what a theorem is. I can prove this. I can turn this-"

Robert J. Marks:

You took a course from Alonzo Church? That was the guy that consulted with Turing.

Paul Werbos:

When I was in high school, I took a graduate course of Alonzo Church. I took the bus from my high school to Princeton to take Church's course, and I got graduate course credit before I graduated from high school. So I knew a bit of logic, to put it mildly.

Robert J. Marks:

So cool.

Paul Werbos:

And they said, "We don't believe it works. You have to prove it." I said, "Hey, I know how to do a proof." So the most important part of my PhD thesis, some people say, is I translated backpropagation. First, it was Freud, then it was an algorithm, and then it was mathematics. So I translated it into something I called the chain rule for order derivatives and proved it very concisely and very rigorously and very directly from first principles as a universal way to get the kind of derivatives you need for many applications, neural nets, econometric models, sensitivity analysis. And I had all those applications lined up, and I pretty much implemented all of them by the time I was done.

Paul Werbos:

And there was a next generation, in fact, where the first generation, you could only do it for feed forward systems. And then I figured out how to do it for really true simultaneous recurrence, which is what a lot of econometric models are. And you can do a lot of stuff with it.

Robert J. Marks:

That is interesting. I think you had a little bit of pushback from your PhD committee. You mentioned Dr. Ho, for example. What was going on? What was their pushback? Was it similar to what Minsky was saying, or what was going on?

Paul Werbos:

As I say, it's like a soap opera. Every person is a different story. There's a key step in getting a PhD from Harvard then. The rule was we had to have an oral exam where we would defend two possible thesis topics. I was thinking about a topic in quantum physics, but I decided I wouldn't solve it in time, so I got to do something easier. What are the two easier topics I would defend? One is a mathematical model of intelligence, which would do pattern recognition and decision-making just like a brain. That was the easier topic. And then there was something about the mathematics underlying the dynamics of history.

Paul Werbos:

And when I was defending these topics, they wanted to talk about history. They were so surprised at the things I could tell them about how history works and biology and Spangler and all of that. I didn't even have time to talk about the theory of intelligence. So after they passed me on that, I think they were a little surprised that I decided I was going to pursue the theory of intelligence. And it took a long time to get acceptance and it went through a lot of steps, but eventually they accepted, but I had to change things. I guess it's the way it is with a lot of theses. If you have a new idea, you have to go through a few iterations. And I did, and it worked out in the end.

Paul Werbos:

But Ho was not part of that thesis committee. He had a close friend named Mara, who was in similar areas who was on the committee. And we had Mosteller, who was a crucial statistician. Mosteller played a critical role. And my thesis advisor was Karl Deutsch, a political scientist. And the way he saved me was he said, "You guys don't know whether this thing will work. Well, I have a very hard problem. I have eaten dozens of graduate students trying to translate my theory into mathematics that works and they always failed. If this works, that should be enough for a PhD, right?" And they said, "Okay, if he can do it." And they doubted I could do it. But I did it.

Robert J. Marks:

This reminds me, I don't know if you know the history of Jean-Baptiste Fourier. He was the father of the Fourier transform. His examining committee included incredible mathematicians like Lagrange, Laplace, Legendre. And if you're a mathematician, these names, you go, "Wow, wow, wow."

Paul Werbos:

No, I recognize those names.

Robert J. Marks:

Yeah, you recognize them, and they did not like Fourier's dissertation. They said, "We don't think that this is going to work." So all this is characteristic of great ideas, I believe.

Paul Werbos:

That's neat. That is neat because I can relate that to stuff like in control theory, people use Fourier analysis in ways that would make Lagrange cringe.

Robert J. Marks:

Oh, exactly, exactly. What they didn't like about it, Paul was that, how could you fit a function which had quick discontinuities with smooth sinus wipes? They didn't like that. That was against their experience. But again, Fourier dominated and probably has one of the algorithms implemented as the Fast Fourier transform, which is up there with your algorithm and error backpropagation, which is the most commonly used algorithm in the world right now.

Paul Werbos:

So I translated Freud into math, von Neumann translated Fourier into math.

Robert J. Marks:

That's fascinating. Now in your thesis, you didn't call it error backpropagation. What did you call it?

Paul Werbos:

I use the term dynamic feedback.

Robert J. Marks:

Dynamic feedback. Okay.

Paul Werbos:

That's what I call it. Later on someone told me the term backpropagation was used by Rosenblatt to describe a totally different algorithm, but there are a lot of people out there who will take a word that sounds good and use it for something else. So that's what they did.

Robert J. Marks:

Rosenblatt, by the way, was one of the early pioneers in neural networks and laid the foundation for the Perceptron. And your error backpropagation is applied to a neural network, at least in the feed forward term, which is called the Layered Perceptron. So he was-

Paul Werbos:

He came up with the word.

Robert J. Marks:

He did.

Paul Werbos:

He came up with the word. He just didn't come up with the algorithm. Didn't have the math, that's the problem.

Robert J. Marks:

So, yeah. And the paper that he did, did he talk about error backpropagation at all, or why he called it that?

Paul Werbos:

Other people have told me that's where they got the word, but I read a little bit of Rosenblatt, but not so much.

Robert J. Marks:

Okay. Now I got to admit, Paul, historically I was introduced to your algorithm through the books of Rumelhart and Hinton. I think they call them the CDC books. And I even forget what the initials stand for.

Paul Werbos:

PDP, Parallel Distributed Processing.

Robert J. Marks:

PDP, that's right. Thank you. I've long since lost my copies of that. Did they reference you or did they come on this independent layer? What's the deal?

Paul Werbos:

There are happy and sad aspects of the history. And in fact, there's a book called Talking Nets by Anderson and golly, I really should remember...

Robert J. Marks:

I'm familiar with it. It was interviews with many of the pioneers in neural networks.

Paul Werbos:

So part of the history, I spent a whole chapter talking about it. It's probably not helpful to the community, but let's just say I learned a lot of sobering lessons about what it takes to survive in this world and what you have to assume. I was very excited when my boss at the Department of Energy in 1980 suddenly got funding to study something that sounded like it wanted neural nets. And I said, "Hey, I can do this for you." And I was told that it was a policy by real high up Department of Energy people. Find the right idea and then give it to the right people. And he said, "This is the right idea, but you are not the right person." And he funded the Rumelhart Group.

Robert J. Marks:

Really? That goes to the point that I make is I think MIT could burn to the ground and in 10 years it would still be ranked number one in terms of prestige in the nation. There's kind of a brand that funding often follows. And that sounds like it was the case with you.

Paul Werbos:

Yeah. So I learned a lot about the funding of science. When I was working on that project at MIT and Harvard, and I really wanted to do dramatic new things, I discovered the main barrier to my doing dramatic things there was that, well, the funding agents want X, Y, and Z, and we have to give them this. So I said, "Okay, if I want to change the world, if I want to change the culture, I got to become one of the funding agents." And that was a successful strategy for changing the world.

Robert J. Marks:

And that's what you did. You went to work for the National Science Foundation as a program director. That's kind of cool. Let me ask you this. This is a new question. Do you think that a version of error backpropagation occurs in the human brain? You have alluded to the fact you think it does. Could you elaborate on that a little bit?

Paul Werbos:

Oh God, could I elaborate on that. I think I sent you some links.

Robert J. Marks:

We will make sure that all the links you've provided are available in the podcast notes, and we'll also provide a link to Talking Nets.

Paul Werbos:

Okay. So let me start with an easier one. Let me start with an easy one. My website might be a little too big, but it's easy to remember: www.werbos.com.

Robert J. Marks:

Oh, that's a rough one, werbos.com. Okay.

Paul Werbos:

Yeah. And near the top, it starts with very general stuff, but I have a wild and wooly and crazy link. And only now that I'm older, I'm living off of a pension, I don't have to worry about offending people so much, there is a link called Mind, Brain and Soul From the Viewpoint of Mathematical Realism. And if you click on that, it gives a link to a one hour talk on new discoveries about how the brain works. When I retired from NSF, I said, "I'm not constrained by the government anymore. Damn it. I'm going to do what I wanted other people to do that they never did."

Paul Werbos:

So I went to the very best, real-time brain data available in the entire world. It came from the lab of a guy named Buzsaki, who's number one in that field right now. And I went to his data. I analyzed it, and the data is very clear that the higher centers of the brain follow my model, follow this kind of algorithm much more than they follow any of the kinds of models people were talking about in the past. And backpropagation is part of these algorithms.

Paul Werbos:

In fact, let me say, I got a hint of this data earlier. I was speaking to a guy from NIH, the guy famous for the work on neural coding, Barry Richmond. And Richmond once told me after he'd had a little bit to drink, he said, "The data we see is so weird. You wouldn't believe it. I don't want to publish it because it's so damn weird." I asked him, "What do you see?" "When we look at the real time data from the cerebral cortex, we see a forward pass followed by a backward pass in the opposite direction. Could you imagine something like that?" he asked.

Robert J. Marks:

Well, sounds like error backpropagation, right?

Paul Werbos:

You could imagine how easily I could imagine something like that. And he said, "You don't think I'm crazy?" I said, "No, actually I don't." And so I went to look at the data myself, and it's true. You go to the cerebral cortex, you see a forward pass and a backward pass. And a backward pass is in the opposite direction from the forward pass. And it's there in the data. And from that data, we can reconstruct a lot of how the mammal brain works. And it's all there up on the web. And the key papers have been published. But I'm retired. So I don't know if anyone reads these papers anymore, but at least it's out there. It is out there.

Robert J. Marks:

I got to tell you, the thing that most impresses me about error backpropagation, as it relates to the human brain. I'm not an expert in the human brain, but I've talked to a bunch of people that do know the human brain, including Michael Egnor, who's a brain surgeon who doesn't have a high opinion of neuroscience. He says neuroscience is all over the place. But the thing that clearly is applicable in a very fundamental sense is Hebb's law. And one of the beauties about error backpropagation is as follows. If you look at a deep convolutional neural network, you have thousands, maybe millions of knobs to turn and turning those knobs in a global way is certainly not possible. But error backpropagation allows you to update all of the weights each knob only by two numbers, the two numbers that are connecting the knobs, if you will.

Robert J. Marks:

I find that just incredibly powerful in error backpropagation, and I've seen it used in psychology. They talk about Hebb's law. What is it? Neurons that fire together are wired together, I think is the little phrase. But that's the reason that you get habits. You develop habits. I used to be a smoker and I would develop a big habit and those would be my neurons linking together in my brain, neurons that fire together or wire together. And in order to quit smoking, I had to dissolve those interconnections. And I see this sort of thing happening in error backpropagation where just local events have an impact of the global performance. That is really astonishing to me and still remains astonishing.

Paul Werbos:

Yeah. There was a time when people in computer science said it's impossible that this could work.

Robert J. Marks:

Really?

Paul Werbos:

Oh, golly. In fact, I know the names of people and I shouldn't repeat them because they made honest mistakes in some cases.

Robert J. Marks:

Well, have you ever made an honest mistake? I certainly have.

Paul Werbos:

Yeah. So there was a time I was still at NSF. There was a time maybe around 2005, I even sent some money to computer scientists in cross disciplinary projects. I was amazed. One of them became co-author of the number one textbook in computer science and people cited it as a Bible. And in this Bible it said, of course, neural networks will never be able to solve these kinds of problems. We all know that, this is the inherent limit. We have these problems and we computer scientists know these problems, and those idiots who want to use neural nets, general learning machines, my God, don't you know you've got to have expert systems, it's got to be hard wired and all that stuff?

Paul Werbos:

I looked at that stuff and most of the big computer science companies were informed by those kinds of experts. However, we changed the game. And the way we changed the game out of NSF, I funded a project with Andrew Ng and Yann LeCun and this was the birth of the deep learning revolution. If you think something happened in this century, if you think the game changed, I believe it all goes back to this grant that I gave to LeCun and to Andrew Ng. And we all talked about the substance before it went out. People didn't want me to fund that grant. People threatened me with a lawsuit if I funded it.

Robert J. Marks:

Are you serious?

Paul Werbos:

Yeah. They said, "This is not sufficiently innovative. He's using old algorithms that you used before on problems people have studied before. It's not innovative enough." But under the rules, I was able to make an argument. They made an exception. They let me fund it. And then Andrew Ng went to Google, to Sergey Brin and said, "We used these neural net algorithms. And here's what they did, which was impossible. And they did it. We broke the world's record on A, B, C, D and E." And when Andrew Ng went to Sergey Brin with that, Sergey Brin has a video talk up to the World Economic Forum. I posted a link to it on my web page, if people have patience, my webpage has a link to Sergey Brin's speech where he said, "Yeah, and this guy..." Basically Andrew Ng came around and showed him that they work after all. And his feeling was, "My God. My teacher didn't tell me the truth. This stuff works. Okay."

Robert J. Marks:

Yeah. Isn't that the truth with any innovation? Paul, I want to dig deeper with you and the history and especially what happened at NSF during your tenure there in a subsequent podcast, but we're running out of time. So let me go ahead and wrap this one up. We've been talking to Paul Werbos, Dr. Paul Werbos, inventor of the most commonly used technique to train artificial neural networks in the world. Thanks for listening. Until next time, be of good cheer.

Announcer:

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