The National Science Foundation and Advancement in Artificial Intelligence

https://mindmatters.ai/podcast/ep184/

Announcer:

Welcome back to Mind Matters News. This week, we're joined by IEEE fellow and retired National Science Foundation program director, Paul Werbos. Early in his career, Paul developed the neural network training algorithm known as error backpropagation, which has been foundational to the vast majority of today's advances in artificial intelligence. Listen in, as we revisit his work in this area and other topics, including his tenure with the National Science Foundation, which he described as the greatest temple of truth in the history of humanity. Enjoy!

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 trained 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.

Robert J. Marks:

The applications are legion ranging from finance, power load forecasting, detecting disease from medical images and even predicting what crops a farmer should plant next year.

Robert J. Marks:

Neural networks are ubiquitous as a search for neural networks on Google scholar returns over two million, two 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.

Robert J. Marks:

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. 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 network 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 10th of 1% of its members can be admitted to the fellow status each year. Dr. Werbos is also a retired program director from the National Science Foundation where he oversaw the NSF's program in neural networks in machine learning. He has served as a congressional aid in many aspects, including to the late U.S. Senator Arlen Specter. Paul, welcome.

Paul Werbos:

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

Robert J. Marks:

Okay. You know, 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, easily.

Robert J. Marks:

Okay.

Paul Werbos:

So the problem people have out there to try to understand what's going on in the world today, they're 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 in 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 a hundred 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. Okay. Could we start, could you give kind of 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." And then later I meant 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 sort of like glorified hackers. They were looking at themselves in the mirror at 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 spend a lot of time reading John von Neumann and van 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, 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.

Paul Werbos:

But that backpropagation, which I developed was actually a part of a larger design for intelligence systems, and in 1972, I presented that to my Harvard thesis PhD committee, and I said, "Okay, this is what I want to do with 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 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 kind of 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, how you solve the problem that you described in your book." That was a great conversation, but the bottom line was Marvin Minsky kind of 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:

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 this system, yes.

Paul Werbos:

Yeah. Well actually there are many kinds of feedback in the brain and in any really powerful, intelligent 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 is another level of recurrence, we're constantly changing your view of the world. Like 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 kind of feedback when we adjust our image of the world. It's not like learning, it's just adapting to where we are.

Paul Werbos:

So that kind of recurrence is important to how we see things in reality. So yeah, I offered Minsky, I even said, "Hey, I'm at 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 feed forward 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 kind of 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 Erdos 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. 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 kind of know what motivated you. Do you remember having like 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 hangups before that.

Robert J. Marks:

Well, now that's a good point, and 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 sort of obnoxious friend who really believed in Sigmund Freud and was telling all of us how crazy we were.

Robert J. Marks:

Well, I'll tell you, Paul, that sounds like an oxymoron, 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, "You know, it sounds to me like there's something here."

Paul Werbos:

And I thought about it. And at some point I wanted to train neural nets to do things like recognize characters. And I kind of figured out how to do that. And that was in what 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." 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 with 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. And there was a next generation, in fact, where the first generation you can 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.

Paul Werbos:

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, but Ho was not part of that thesis committee, he had a close friend named Mera 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:

You know, 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, and Lagendre. And if you're a mathematician, these names, you go, "Wow. Wow. Wow."

Paul Werbos:

Well, I recognize those names.

Robert J. Marks:

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

Paul Werbos:

That's neat.

Robert J. Marks:

Yeah, it is.

Paul Werbos:

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 sinusoids? 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, while Neumann translated Fourier into math.

Robert J. Marks:

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

Paul Werbos:

I used the term dynamic feedback.

Robert J. Marks:

Dynamic feedback. Okay.

Paul Werbos:

That's what I called 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 feedforward term which is called the layered perceptron.

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:

In the paper that he did did he talked 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. 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 Hunt and I think they called them the CDC books. And I even forget what the initial 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 independently or 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 rem...

Robert J. Marks:

I'm familiar with it. It was interviews with many of the pioneers and 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 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're 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:

I learned a lot about the funding of science. When I was working on that project at MIT and Harvard, and I really want 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. It's kind a new question. Do you think that a version of error backpropagation occurs in the human brain? You've 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 will 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...

Robert J. Marks:

All right.

Paul Werbos:

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, dammit. I'm going to do what I wanted other people to do that they never did." 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.

Paul Werbos:

And that includes... And backpropagation is part of these algorithms. In fact, let me say, I got a hint of this a day 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 can't, 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:

Sounds like error backpropagation, right?

Paul Werbos:

You could imagine how easily I could imagine something like that.

Paul Werbos:

You could imagine how easily I could imagine something like that and so 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...

Paul Werbos:

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 neurosciences is all over the place. But the thing that clearly is applicable in a very fundamental sense is Hebbs 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:

And I find that just incredibly powerful in error backpropagation and I've seen it used in psychology. They talk about Hebbs law. What is it, neurons that fire together or wired together, I think is the little phrase but, that's the reason that you get habits.

Robert J. Marks:

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 fired together or wired 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 on the global performance. That is really astonishing to me and still remains astonishing.

Paul Werbos:

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

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... I have never, have you ever made honest mistake? I certainly have so.

Paul Werbos:

So there was a time I was still in NSF. There was a time maybe around 2005. I even sent some money to computer scientists and cross-disciplinary projects. I was amazed. One of them became coauthor of the number one textbook in computer science and people cited it as a Bible. And in this Bible it said, and 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 problem and we computer scientists know these problems and those idiots who want to use neural nets in general learning machines, my God, don't you know you've got to have expert systems.

Paul Werbos:

It's got to be hard wired and all that stuff. And I looked at that stuff and most of the big computer science companies were informed by those kind of experts. However, we changed the game. And the way we changed the game out of NSF, I funded a project with Andrew Ung and Yann LeCun and this was the birth of the deep learning revolution.

Paul Werbos:

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 Ung 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 and they said it's not-

Robert J. Marks:

Are you serious?

Paul Werbos:

They said this is not sufficiently innovative.

Paul Werbos:

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 Ung went to Google to Sergey Brin and said we use these neural net algorithms and here's what they did, which was impossible.

Paul Werbos:

And they did it. We broke the world's record on A, B, C, D and E and when Andrew Ung 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 webpage. If people have patience, my webpage has a link to Sergey Brin's speech where he said, and this guy basically Andrew Ung 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:

Isn't that the truth with any innovation.

Robert J. Marks:

The National Science Foundation or NSF is a powerful force in guiding research in academia, in the United States. A grant from the NSF is very prestigious, if a new professor was awarded an early career award from NSF, they got tenure almost certainly, so what's going on at NSF behind the scenes. Hey, what year did you retire from NSF? You said you retired.

Paul Werbos:

Yes, so it's a long story. I started there in 1988 and my retirement, I came home to work for a new boss, my wife on Valentine's day, 2015.

Robert J. Marks:

2015. So you spent before that over 30 years as a program at NSF that largely steered NFS's interest and research into artificial neural networks, during your tenure at NSF, what did you see, the major turning points in machine intelligence? You mentioned last podcast, the genesis of deep learning as one of them.

Paul Werbos:

It became obvious to me on day one, my understanding of how a brain works and what real intelligence is requires a lot of steps forward. And I wrote down these steps and the question is, how long will it take for our science culture to a catch up to even half of it. And I do have papers out there with roadmaps. One of them goes a hundred years into the future and I know how to get there, it's just, people have to do the work there are just a lot of steps. And so I would say my whole tenure, my 30 years at NSF, I went through one step after another, after another. It's like every four years, it was a different world and the steps are not all done yet. In the very beginning people did not believe in neural networks almost anywhere.

Robert J. Marks:

And why was that? I think that was because of the terrible fall of interest in neural networks and I kind of time it to the publication of the book Perceptrons by Minsky and Papert that dried up the research. And so people were disillusioned. And so neural networks had to be reproved using the algorithm that you created in order to show that many of the objections raised by Minsky and Papert were wrong and so that was what you were up against, right?

Paul Werbos:

That is pretty much the story, but there were a whole lot of other little stories too. When I had that little talk with Minsky, I mentioned, I was talking about why it was that none of those neural networks they came up with were working. And I basically said, there are a couple things you got to change but number one is, it's a bad model of the neuron. You're assuming the neuron is a square wave generator. It's like you think it's a digital thing. Everybody believed you're scientific only if you're digital, you output one's in zeros you're scientific, anything else is not scientific. And our brain being intelligent must be scientific so it must be based on one's and zero.

Robert J. Marks:

And that's right, your error backpropagation algorithm, although highly digital is based on continuous partial derivatives and calculus.

Paul Werbos:

So in front of Marvin Minsky, when he repeated, but everybody knows the brain is one, zero. I said you know what? I took this course in neuroscience at Harvard, let me show you the textbook. Let me show you the time series of the outputs of these neurons. Do these things look like square waves to you? Look at these things. Let's build a model that fits the data and the data show that it's basically frequency coding, above a certain level there's a limit to how much output you have. There's a lower limit and upper limit and you can pretend it's linear in the intermediate range but the point is it's continuous, it's not one zero. You have continuous variables and if you do it that way, then I said, I have new way to calculate derivatives. And I can prove that it'll work so we have a provable way to do the derivatives, we have provable way to train it and it fits the empirical data.

Robert J. Marks:

But Minsky didn't like your argument.

Paul Werbos:

And Minsky said, but all the computational neuroscientists know the brain is a square wave generator and they all know it's one's and zero's. That's what McCullough told us and if I disagreed with a neuroscientist, they would laugh at me because I'm not from the right field. I'm not from their field, you've got to be a neuroscientist to get away with stuff like that and I said, but what if there's data, even data won't change them. If you're not one of the right people, they won't listen to you. That's what he said.

Robert J. Marks:

Oh my goodness. Okay. So what were some of the other turning points you saw? Could you elaborate on the deep learning? I think the deep learning is largely credited to Geoffrey Hinton who came up with convolutional neural networks.

Paul Werbos:

Oy vey.

Robert J. Marks:

What's that?

Paul Werbos:

Oy vey I'm not Jewish, but there are times when you got to say Oy vey. So there is so much false history out there. It's just pathetic.

Robert J. Marks:

Well, I've seen even an article where Geoffrey Hinton was credited because of his involvement with the PDB book as being the originator of error backpropagation.

Paul Werbos:

There's a whole lot of stuff.

Robert J. Marks:

Which is not true, you are the one that did that.

Paul Werbos:

No. And not only that, it wasn't independently rediscovered either. That's also false. I don't want to get into the whole history of who did what, with what motive, it's not very constructive.

Robert J. Marks:

Well we talk about the book, Talking Nets, where you get into that.

Paul Werbos:

Some of that, right. There's a lot more, they thought that was racey they didn't even see the half of what's happened, but let me come back. The PDP books do have a role in history. There's no question that the history of the field was strongly influenced by the PDP books and I think that old boss of mine was involved in funding them somehow. I was talking about that too but bottom line is these books were influential. No question about it and the cognitive science part was really very insightful in cognitive science, but the main machine that Hinton was pushing was something called a Boltzman machine. And the quick summary is it basically didn't work, it was based on not understanding the math.

Robert J. Marks:

I remember Boltzman machines so we're going to talk about annealing later on, which I think he used in the Boltzman machine, but let's not go there now.

Paul Werbos:

But the bottom line is you got into Hinton because of something else.

Robert J. Marks:

I got into Hinton because, convolutional neural networks, which I think, by the way convolutional neural networks, I don't know who came up with the idea, but they're brilliant.

Paul Werbos:

Okay. Convolutional neural nets became popular when I was at NSF. And I have to admit the first that I heard of the standard convolutional neural network. I thought of it as occluse so see it works and it was something I wasn't backing. Where did it come from? It came from AT&T bell labs.

Robert J. Marks:

Really?

Paul Werbos:

And if I had to guess, I would say, I think it came from a French woman, to be honest, either that or an Israeli woman, they had a whole group. The bell labs group was really amazing and certainly Yann LeCun was a key part of that group. There's no doubt. Yann LeCun was a lot of the success of that group, but there were a lot of other really important creative people there whose names should come to my head but the bottom line is they were the ones who took this idea I believe it started in France.

Paul Werbos:

I think it was the group that was working together in a small company in Paris and then they moved to bell labs where they became rutin eyes. And I think Yann LeCun has some personal affection for Geoff Hinton who was kind of bringing him to the world of cognitive science, which is an important world, connecting him to a community. But to be honest, I really don't think the convolution network came from Hinton.

Paul Werbos:

I'm pretty sure it came from this group in France. And then with LeCun and for many, many years, I certainly cited this group. In fact, I remember there were 15 authors of the seminal paper on the convolutional network and there were early tests by the post office on who can recognize zip code characters. There were two groups that just beat the world in the competition that the post office set up.

Robert J. Marks:

That would be a perfect application for convolutional neural networks. Wouldn't it?

Paul Werbos:

And that's sort of where it started. This huge zip code recognition competition funded by the post office and I later worked with a guy, I believe he was Chinese American who moved to UTC, who led that competition. There were so many false papers about that competition.

Paul Werbos:

So many people said, I won this competition with X, I won it with Y. And so I went to the guy who actually ran the competition I said, hey, you've got the scores who won it. He said, two groups won it. And they both had convolutional neural nets from independent sources, one German, one French originally.

Paul Werbos:

And I believe that LeCun's group was one of the two that really won the competition. It was a huge breakthrough. They did much better than anybody ever did on that problem before. But it was just the zip code recognizer because the original convolutional network had certain limitations. And we had ways to go beyond that. In fact, we have networks today that are much more powerful than the convolutional networks and in the test, the new networks are much more powerful, but most of the people graduating computer science don't know about them.

Robert J. Marks:

You mentioned deep learning as one of the things that took off during your tenure at NSF, could you differentiate convolution neural networks, which were a specific case of deep learning from the field in general?

Paul Werbos:

Okay. One be bad thing that happens when you make it to Oprah and everybody reinvents you. They come up with 20 definitions of the same word. You used to think you had a word and then all of a sudden there are 20 different definitions.

Robert J. Marks:

The one that I remember on that, Paul is artificial intelligence. When I was a boy in artificial intelligence, artificial intelligence meant the stuff that Minsky did, which was a rule based sort of thing. If this, then this, if this, then this, and we didn't like this in connectionist, I think you would probably agree. That's the reason that IEEE started the word computational intelligence to differentiate from artificial intelligence.

Paul Werbos:

You're the guy who came up with the computational intelligence.

Robert J. Marks:

Well, yeah. I was on a team of three people. I think Jim Bastek and Pat Simpson and I came up with it in an email exchange but the point is that, to your point, the definitions change. Today artificial intelligence subsumes all of this, it subsumes neural networks that subsumes expert systems and everything else so there is, there's an evolution.

Paul Werbos:

It assumes a hundred cultures that use different definitions, the same thing with the word consciousness. And even the word love means different things to different people.

Robert J. Marks:

Yes.

Paul Werbos:

And certainly the word God means different things to different people.

Robert J. Marks:

Well, yes. Okay.

Paul Werbos:

Yes, indeed. And then the question is, which of these things are the real ones and which are the made up definitions and believe it or not, we have that problem even in the world of neural nets. So to me, convolutional neural nets and deep learning, I think they're well defined words, but most people are hearing different things these days.

Paul Werbos:

To me, what the deep learning originally meant is just, you have many, many layers, typically with a feed forward network. And we were doing many, many layers long before these people were using the term deep learning. I was funding supporting and actually I wrote the original mathematics for... Because if, with one or two layers, everybody could see just by eyeball. If you wanted to do it with many layers, you got to know the math. So I funded a guy named Krishen Kumar, working with NASA who applied many, many layers and he was doing this long before any computer scientist had even heard of the term deep learning and he didn't even call it that I didn't call it that.

Paul Werbos:

I think my paper in ICNN in 1988 was the first reasonably open publication of what you can do with many, many, many layers and how to do it. But there's a problem with that. Okay. Yes, we can use many, many layers. The mathematics of many, many layers is good, but the way the brain does it is different. The brain has a more powerful way to do the same thing using the same math, but more general, the kind of recurrence that we have in the brain can do anything a deep network can do and basically better so understanding how to really use recurrence is much more powerful than what they're doing with a deep learning. But having many layers can be useful and there's good mathematics and it's the same mathematics. So that's deep learning.

Paul Werbos:

The term deep learning became popular when a bunch of computer scientists learned 20 years later, stuff we were doing before, but they applied it and it was useful. They have every reason to be proud that they brought it to application, but convolutional networks are totally different. Convolutional networks are something I don't think I really understood until the late 1990s.

Robert J. Marks:

Well, you beat me. I think I only understood about five years ago, so, okay.

Paul Werbos:

So I think I got something like seven patents at about just the late 1990s and those patents already address many of the technologies of the future that they still haven't fully caught up to. Because they're just a whole lot of pieces.

Robert J. Marks:

Oh, how many patents do you have?

Paul Werbos:

They're probably expired by now, but probably about I don't know, seven, eight, something like that.

Robert J. Marks:

Did you get these when you worked for NSF or these after?

Paul Werbos:

Yes.

Robert J. Marks:

So it's assigned to the government, I suppose.

Paul Werbos:

You asked about how NSF is doing.

Robert J. Marks:

Okay. Yes.

Paul Werbos:

And I'm glad I won't have to get into every gory detail because they got ups and downs like the whole world. But for many, many years, the office of general counsel, the number one lawyer for NSF, there was a guy named Charles Brown.

Paul Werbos:

And when I think of the greatest glories of NSF in its absolute peak period, Charles Brown, the general counsel had a lot to do with it. He went to the Harvard law school, he learned about freedom. He learned about free speech, intellectual truth a whole lot of very basic principles.

Paul Werbos:

He understood the spirit of the constitution and his way of dealing with regulations and rules. He respected the rights and the privacy of everybody and the integrity of the system. So at some point the idea came up, I've got a few ideas. What should I do about patenting? And I talked to him and he said, we now have a clear policy.

Paul Werbos:

And in the those days we did, he said, the clear policy is if you come up with a patentable idea, we want you to get it patent. And it won't be an NSF patent. We will have to make a decision. Whether the idea came from your work as an NSF employee or did it come from outside of your job? And if it came from your work, the government has an interest, which is a no free use of the thing. But even then you're allowed to patent and we encourage you to patent because if you don't, the Chinese will patent it two years after you invent it and we won't be allowed to use it, he said.

Robert J. Marks:

Is that right? Do we have a patent treaty with China?

Paul Werbos:

Well times have changed, patent law has changed.

Robert J. Marks:

Okay.

Paul Werbos:

Patent law has changed, I probably have 10 more patents if they hadn't changed the patent law.

Robert J. Marks:

Okay.

Paul Werbos:

But, they have substantially changed the patent law in ways that are not so good for small inventors in all fairness.

Robert J. Marks:

Yes, I did as an expert witness in a number of cases involving kind of computational intelligence, artificial intelligence and things have changed. It's almost impossible for the little guy anymore.

Paul Werbos:

Right? So the only thing the little guy can do is talk to the people in China who are willing to pay for that kind of stuff and a lot of that is going on.

Robert J. Marks:

I have a friend who has a bunch of patents and he says all the patent is good for is it gives you the right to Sue people. And that's basically what it is and it costs big bucks to Sue people.

Paul Werbos:

So anyway, basically I had a misunderstanding when I was in early graduate school, some of my first papers on reinforcement learning, brain-like intelligence. I believed that the kind of design I did for my PhD thesis with a few tweaks parameters, basically could replicate what a mammal brain does and then I learned a lot about mammal brains. I learned step, by step, by step mammal brains, do this, do that, there's some fundamental mathematical principles and you can build a universal intelligence doing what I did in my thesis, but it's not a fast universal intelligence.

Paul Werbos:

You can build a faster, more powerful one by using some very fundamental principles. And I even did a paper in World Congress of Computational Intelligence, 2014 in Wiki, I said, here is a four step procedure, math one, math two, math three, that'll bring you up to at least the mouse level of universal general learning ability.

Paul Werbos:

And one of them, one of the key levels, I call, full spatial intelligence and it's like a convolutional network, except it exploits more general spatial symmetries and the more general spatial symmetries give you a power that a normal network doesn't have, a convolutional network doesn't have, you have to have this additional power in the spatial intelligence algorithm. And I was so proud giving that talk at Wiki and everybody seemed to listen, except the Chinese government really listened and started a new program and there was a U.S. intelligence agency guy there who said, no, no we can't do this, we have to stop this work in the U.S.

Robert J. Marks:

Oh boy.

Paul Werbos:

So they stopped that line of research in the U.S. and they expanded it in China.

Robert J. Marks:

Why, for what reason would they want to stop the U.S. research? Were they going to take it under the umbrella like NSA or something? Probably you can only speculate.

Paul Werbos:

No, no. Well, I spoke to the guy, but he didn't tell me his total game plan and I have circumstantial evidence about what happened. I Have discussed it with other people at NSF. There were a lot of people in NSF who were concerned about changes that occurred in many areas and we debated whose fault are they and what's the reason.

Paul Werbos:

People once told me, when I worked for the department of energy 10 years before NSF, people used to tell a joke, the department of energy has already been privatized, It's a joint corporation owned 60% by the oil industry and 40% by the nukes.

Paul Werbos:

And it was like that my last few years there, when I went to NSF, I said, now I'm in a place where the powers that be are the American Physical Society and the deans and the American Physical Society and the deans, respect scientific values a lot more than those other guys did.

Paul Werbos:

And that's why that was a big part of why I moved to NSF because the culture was totally... The deans and the APS and they're not perfect, but they have high values, but then came this Washington corruption business. My theory is that Washington corruption is what really hit more than anything else. But that's my speculation. I had friends who had other theories.

Robert J. Marks:

I wanted to ask you since your retirement, I'm sure you've kept your fingers on the pulse of what's happening in our neural networks artificial intelligence. What do you see some of the major advances in machine intelligence since your retirement.

Paul Werbos:

I have to confess. One of the joys in retirement is I have a few other retired friends and one is a woman named Frederica Darema. Who used to be head of the air force office of scientific research and every time people ask me, what's a quick summary of what is going on today with all of these algorithms and all of these different forms of AI, the best source I recommend to them, Frederica Darema organized a conference a few months ago, global zoom type conference on something she calls DDDAS.

Paul Werbos:

And if you want to know the answer to your question, the starting point would be, do a search on DDDAS, video, 2020 or 2021. And from her conference, I learned just how diverse the world is.

Paul Werbos:

There are so many different things they call AI and there are so many experts who think they know things that are mutually contradictory. But I would say out of a hundred groups, there's a major percentage where they think the best way to solve the problems of AI is to get rid of it and go back to what we did 40 years ago in mathematics, before they even had AI, let alone neural networks, there are people getting funded to do that and they persuade people, this is the greatest clever thing you haven't heard of it in the last 20 years, that's because it's a hundred years old.

Robert J. Marks:

Wait a minute, Paul, they want to have abandoned AI. I think that is especially stupid in terms of only national security.

Paul Werbos:

If you go to the DDDAS website, you'll see that there are groups who are trying to sell that approach. Out of maybe a hundred groups, the biggest number or sort of your routine cut and dried baby MLP, 20 years old at least there were two groups that were just way the hell ahead of them and in this particular conference, one of them was PWC and one was RTX. RTX is the new merger of Raytheon and UTC where my old-

Paul Werbos:

RTX is the new merger of Raytheon and UTC where my old post office friend went. PwC is, well, Pricewaterhouse, what's left over after they killed Arthur Anderson and they got a new competitor. Both of those organizations have people who are not doing the more advanced stuff we talked about but they at least caught up with the most advanced stuff that we were doing. People will tell you, "Oh, you'll never build a Terminator robot. Don't worry about things like slaughter bots and Terminator weapons and autonomous weapons. That's all science fiction." These groups would say that science fiction, maybe in a hundred years will learn how to do it and then another group is doing it and they're building it and nobody is stopping them from doing it. There are people stopping them from advertising it for obvious reasons. But the bottom line is that, there are very advanced projects going on in the world that are decades ahead of almost all of their competition. There is mathematics which is decades beyond them so it's just incredible what the diversity is.

Robert J. Marks:

Wow. Very interesting. You mentioned, if somebody has the money, you have to dance to their tune and that's frustrating sometimes and we have that, to a degree, at NSF. I think that steering it is important. Research agendas are often dictated by the National Science Foundation where you spent 30 years as a program director. To what degree does NSF consider innovative proposals off their radar and don't fit into a predefined program and is there any thought of tuning this trade off to get the biggest impact for our federal bucks?

Paul Werbos:

Since I'm usually criticizing people, let me change my pattern and stress the positive because sometimes that's the right thing. I am so grateful that I had those 30 years to work at NSF in part of the period of peak creativity in that building. I even remember a day in 2014 when I knew I was going to go in the next year. I remember looking around me in that building in Boston saying, "This is the greatest..." Gee, I'm breaking up as I say it, "This is the greatest true temple of truth in the history of humanity."

Robert J. Marks:

Wow. That's quite a statement

Paul Werbos:

That was how I felt and I believe it was true. I hope we can do better. There are special areas where they're better but NSF certainly focused on its mission, I believe was, the greatest temple of truth in the history of humanity and I'm so grateful that I was able to learn all I could in those surroundings and it has a lot to do with innovation. The way the NSF became so great was because of a guy named Bush.

Robert J. Marks:

Okay. The junior or senior?

Paul Werbos:

Vannevar Bush, he was in MIT. I forget whether it was only a professor or also a dean, he was high up in MIT in the old days.

Robert J. Marks:

So this was not a president, this was somebody else.

Paul Werbos:

Yeah. It was not a president. It was before me, would be a great president. But shortly after World War II, there were people who really said, "The United States really needs to develop real science. We shouldn't depend only on Germany for God's sake." And so Vannevar Bush, apparently he was closer to our neural network world than I knew until a couple years ago, he was not so far from our community. Vannevar Bush put together a document, a manifesto, The Endless Frontier and if you go to the NSF webpage today, nsf.gov, and search on The Endless Frontier Vannevar Bush, you can still find it. I'm really glad it's there because that corporate culture, that Bible of NSF was really crucial to being an honest pursuer of truth which is not what you always get.

Robert J. Marks:

Could you spell his first name? Vademir?

Paul Werbos:

Vannevar, V-A-N-N-E-V-A-R, Vannevar Bush. In recent years, I've been talking to UN people saying, "You got to read it. You've got to reinvent this. We need this corporate culture. What you got at the UN is not working. We need a culture that works. Vannevar Bush had a really good manifesto on how to do it." We had have learned a little bit. A lot of people at NSF when I was there, we're working very hard on how to do better because a big part of the corporate culture was you are not following. It's not the Tom Wood. It's not a book of rules from ancient times. It's a living guideline. Every year, NSF would really think hard on, "How can we do the job better?" That was true for my whole tenure there and there were different approaches, different philosophies, again, from 1988 to 2015, I saw a lot of different things. But until about 2014, maybe 2013, we were following one Vannevar Bush's corporate culture and it was the greatest temple of truth there ever was.

Robert J. Marks:

Now, what was the official role or office of Bush at this time?

Paul Werbos:

I think he was the first director.

Robert J. Marks:

First director. Okay. I believe it started... Didn't John F. Kennedy start the NSF in response to Russia's Sputnik?

Paul Werbos:

No.

Robert J. Marks:

No?

Paul Werbos:

No, no, no. That was later. Kennedy was later. This was after World War II.

Robert J. Marks:

I see. Okay. Go ahead please.

Paul Werbos:

At least I hope I'm not that mixed up. I went to work there in 1988 so I can't say I really know the history so personally before 1988.

Robert J. Marks:

Okay.

Paul Werbos:

Okay. A major part of his role was innovation. When I was there, I was allowed to follow Vannevar Bush's approach and part of the approach was... I had... I did know some economics. Economics, I do have a couple degrees in that. A major part of economics is, "What do you do with high risk research which cannot be totally funded by just one player? It has value because it cuts across, it has value across many people," and high risk research is especially suitable for government funding. I remember people used to ask, "What is the role of the government? Shouldn't the private sector do everything?" and the best answer that said it should be doing something was an answer that said, "Well, there are externalities. There is high risk research that you can only do on a kind of a pooled basis."

Paul Werbos:

NSF was the source of money of last resource for high risk projects and that was really critical. Now the problem is, there's some way out ideas that are so way out, it's difficult to do justice to them. For a long time, we had many debates on, "How do you do justice to really out of the box innovation? How do you do justice to fundamental new directions?" I would say from the day they hired me to a year before I left, that was sort of my personal responsibility, was to be especially vigilant that we not lose these more aggressive opportunities. Golly, I could talk about that because we were very specific. They hired me to run two programs in 1988, 1989. One of them was the neural network program and the other one was Emerging Technologies Initiation, a special crosscutting program designed to fund new emerging areas that wouldn't be funded under the conventional framework.

Robert J. Marks:

So that's the response to my question. That was the program that allowed people with innovative ideas to propose for funding to the National Science Foundation.

Paul Werbos:

Yeah.

Robert J. Marks:

Great.

Paul Werbos:

By the way, the guy who set it up in the first place was a double E, double degree law and electrical engineering, my first boss. He ran a whole division and I was brought in to run the program but it changed through time. They've changed somewhat how they do that but innovation has always been a major issue. I will never forget the day when the Deputy Director of Engineering said, "Paul, when the really weird, hard to understand things, come in, like the guy really... It sounds like perpetual motion and it looks like there's math but we can't believe it. The really crazy stuff, we want you to handle the really crazy stuff." And so, that was a side job I had for a few years. If it was really, really strange, they would let me try to figure it out and that was very entertaining.

Robert J. Marks:

Oh, you mentioned your tenure at NSF. NSF was, in your own words, the temple of truth. What's happened since your retirement? Do you have any forecast? Well no, do you have any thoughts about the way the NSF has been operating since then or do you know? I mean, you've been out of the loop.

Paul Werbos:

No, no. I know... I don't want to get too far into all of the details. I can say, when I decided to retire I remember speaking to a couple of administrative personnel about it and I still remember one woman who looked like a character in the Beetlejuice movie. I don't know if you ever saw that movie.

Robert J. Marks:

I've seen pieces of it. I couldn't sit through the whole thing but was she one of these zombie ghost sort of people?

Paul Werbos:

Oh, yeah. Yeah. There's a scene in Beetlejuice where the guy has just died and now he's in the other world and what are they going to do with him? They put him before a desk and there's this weird clerk with orange hair who is, "Ugh, next." He's like, "My god, I just died. The guy next to me is a pygmy with a shrunken head." Just, "Yeah, yeah. Next," and it was a lot like that. It was really weird what was happening that year. I think... I'm pretty sure it started in 2013.

Robert J. Marks:

Okay.

Paul Werbos:

I was sort of halfway through the wave of stuff that happened and I talked to a lot of people about what was happening... I'm tempted to name names but I can say that there was a debate I had with a close friend who was high up in the management. I said, "We both agree something very bad has happened. We both agree there is this following stuff going on but we don't know who's responsible. They're not telling us who they are." There was one theory that it was Obama and there was another theory that it was a guy in the Republican party. What can we say? There were different theories. I went to a university where one of the deans had heard about weird things, he said, "The people we work with think it was the Gestapo are you Jewish?" I said, "No, I'm not Jewish." "Are you sure you're not Jewish? He told us the Gestapo came." I said, "No, no. It wasn't that."

Robert J. Marks:

Boy, talk about fake news, huh? Yeah.

Paul Werbos:

Yeah. But my theory, and it gets to be a theory, is that until about 2013 the deans in the American Physical Society were very much had us under their protection.

Robert J. Marks:

Now, what do you mean by the deans? Do you mean the deans of the major universities or what?

Paul Werbos:

Yeah. Yeah. Yeah. The universities had tremendous power at NSF and I'm sure they still are listened to, but it was basically the APS and the deans between them, they could protect us from the worst evils of the world. Where are the worst evils of the world? My theory is that money in politics in Washington, DC twisted to serve special interests and special stakeholder friends. I have seen that work in many government agencies. After all, I was in DOE too, I interacted with a lot of agencies. My feeling is it was a shift to the stakeholders and in 2014, in fact, I was invited to two meetings with stakeholders with very large financial commitments. There are things they wanted from us, very different from what NSF was giving them in the past and when I looked at what they wanted me to give them I said, "Okay. Better I should retire than do what these guys want me to do."

Robert J. Marks:

My goodness. I do remember reading a lot, that a lot of the policies of NSF were painted by political issues which is kind of sad.

Paul Werbos:

It was a big shift. It was a massive shift. It's not that NSF ignored politics. NSF, broader impact is about serving society in general, Joe Bordogna was a pioneer of making people pay attention to broader impact, and that's good.

Robert J. Marks:

Okay. Who is Joe Bordogna?

Paul Werbos:

Oh, he's another double E.

Robert J. Marks:

I should know him then, I'm a double E so... I don't though.

Paul Werbos:

Well, you should have known him.

Robert J. Marks:

Okay.

Paul Werbos:

He was a critical force in the history of NSF and I had a lot of contact with him but what stories do I not tell about Joe Bordogna? But Joe Bordogna defended the concept of broader benefit. He had a vision of, "We should fund work which pushes the frontier but it's also serving the larger needs of society in ways that others can't," and there's also the human development, I guess those were the three real priorities.

Robert J. Marks:

It sounds like you're saying, that the status of NSF as the temple of truth during when you were there has developed to the point where that's no longer true. Have you seen any development since then?

Paul Werbos:

Joe Bordogna was consistent with the temple of truth. It was later people and as I said, we argued over who it is. They were very stealthy and I got a lot of clues but the question is, "Will we build back better if you forgive the expression?" and-

Robert J. Marks:

I forgive you, Paul.

Paul Werbos:

Okay. I have a foot on both sides and when I was in NSF I did my damnest to have a foot on both sides.

Robert J. Marks:

You have to. I mean, that's part of being a part of that organization. You try to remain apolitical as much as possible.

Paul Werbos:

Yeah. Yeah. It was... I think, probably, part of the Bible according to Vannevar Bush, that we want to be trustworthy and reliable for leaders in both parties and whenever they try to do good for the country, we should always try to help them do good for the country. And then they try to do good for the country in different ways, but if they're trying to do good for the country we should try to make sure it works out best and that they're happy and we're happy and everybody's happy. We don't want to take sides in political wars. I took that to heart very, very deeply. I really tried to follow that.

Robert J. Marks:

Well, I think you're mandated to do that by your job description, right? I mean, it probably says in there you can't be political. Probably just like people in the military, they can't take sides, political sides.

Paul Werbos:

Yeah. However, in the era of stakeholder politics it gets to be a little dicey because if a big stakeholder tends to be associated with one party and not the other... I'm glad I don't have to deal with that as much but I'm hoping they will build back better and I see happy signs and I see bad signs. But what worries me the most is, it took so damn much work to make it the temple of truth that it was. It's not enough to have an ordinary level of competence. And so, there's some good intentions but there are also some big stakeholders with money still in operation in both political parties and the role of these big stakeholder money things and the difficulty of reconstructing what we used to have, I'm hopeful I do what I can to help if I can but it's a hell of a challenge.

Robert J. Marks:

One of the interesting things, historically, is the involvement of big tech in technical development. I think of the heydays of Bell Labs. Now, Bell Labs who had incredible advances. One of the things I'm really interested in and I teach a course in it is information theory that came from Bell Labs. The laser, many inventions came from Bell Labs but Bell Labs folded because somebody said, "In order for a country to have a poet, the country has to be rich," and I think that Bell Labs began to lose that after divestiture.

Robert J. Marks:

But now we're seeing more involvement, especially in artificial intelligence with people like Amazon and Google. Now Bell Labs, in my knowledge, was always apolitical. We see a lot of political things happening with Amazon and Google and they're making great progress in places like deep learning. In fact, they're even making their AI software available to anybody who wants it. Google, for example, has made something called tensor flow neural network training available to all. I use it with my graduate students. I've heard, I have heard, I don't know if this is true, but I've heard that Google's research budget, it's currently larger than NSF. If that's true, that's really interesting.

Paul Werbos:

Yeah. I have been following those things. In fact, my younger daughter just recently retired from Google and I have been in touch with some of those kind of people. After all, Sergey Brin was the guy who really brought us back to neural networks, right? But on the other hand, Sergey Brin kind of has other roles in the government now and world politics is tricky.

Robert J. Marks:

We're going to talk about Turing machines. Now, there are so called specific task Turing machines, to give you a little background, and there's also general purpose Turing machines. One of the most famous specific task Turing machines cracked the Nazi enigma code that helped win World War II. Alan Turing was on the team that cracked it at Bletchley Park in England and this is depicted in the movie, I think the name was Imitation Game with Benedict Cumberbatch as Alan Turing.

Robert J. Marks:

The enigma code breaking machine was designed to solve one problem, specifically crack the enigma code. So the question was, Alan Turing asked, the father of modern computer science, "Could there be a general Turing machine that could be programmed to simulate all specific task Turing machines? In other words, a Turing machine that could do anything, any algorithm that you wanted. Alan Turing introduced this machine in 1936 and the Church–Turing thesis says, "Any problem that can be performed on a super duper modern computer could also be performed on a general Turing machine." It could take though, a billion times as long but we're still constrained by that. Quantum computers promised to incredibly increase computing speed and do Turing machine sort of operations. I want to ask you about David Deutsch.

Paul Werbos:

Sure.

Robert J. Marks:

Because he was the guy... Was he your PhD advisor?

Paul Werbos:

No. Carl Deutsch was my thesis-

Robert J. Marks:

Carl Deutsch. Okay.

Paul Werbos:

Carl Deutsch.

Robert J. Marks:

Lots of Deutsch's in the world, I guess.

Paul Werbos:

Yeah. They keep coming up.

Robert J. Marks:

They do. No relation, I suppose, but David Deutsch, he first proposed the quantum Turing machine. Did you know Deutsch at all? I think I have them confused, the Deutsch's.

Paul Werbos:

Two Deutsch's.

Robert J. Marks:

I'm confused.

Paul Werbos:

And I run across other Deutsch's sometimes but, yeah. I mentioned werbos.com. I have a new link on what is the soul and a new link on sustainable, intelligent internet. We need a new type of internet, sustainable, intelligent internet. On that website, I have links. One of them is to the quantum view of reality. Actually, the mind brain and soul link. I talk a little bit about reality too, souls are a reality and in... Come to think of it, in that link, I talk about reality and I talk about David Deutsch. I say that David Deutsch, by all rights, should be a face that everybody on the earth knows as much as they recognize Einstein. I began that YouTube talk on reality with four phases. First is Albert Einstein and I believe in Einstein's view of reality. I didn't used to believe it but I've learned a lot about how the math works.

Paul Werbos:

I believe that Einstein was basically right even though it didn't seem like it. About his basic principles, he did make mistakes like everybody. Right next to him is David Deutsch, I put Einstein and David Deutsch on top. David Deutsch has two great things. So great everybody should know his name and his face. One of the things is the modern version of the multiverse theory of physics, how the universe really works according to David Deutsch. I believe that David Deutsch's theory of quantum physics is the best solid mainstream description anybody has of how the universe works.

Robert J. Marks:

Well, let's talk about that for a minute. I think that there's a bunch of different models of quantum mechanics. One is the Copenhagen model and another one is the multi-universe sort of idea which means that every time there's a quantum collapse, that two reality split off and you have these different realities. I think you're referring to David Deutsch as one who believed in the multi-universe is that right?

Paul Werbos:

Yes. Multiverse.

Robert J. Marks:

Multiverse. Thank you.

Paul Werbos:

In fact, if you go to YouTube today you can search on Deutsch multiverse and you get some really neat YouTube videos. I have to be careful... Everything in science, there are always these caveats, okay? Deutsch has a version of how the universe works. Some of it actually started with a guy I met named Hugh Everett and John Wheeler and I have some corrections to fix up Deutsch's model to make it a little more reliable.

Robert J. Marks:

Now Wheeler, Wheeler is the one that came up with the It From Bit sort of thing, is that the same Wheeler?

Paul Werbos:

Yeah. Yeah. He's a creative guy.

Robert J. Marks:

Boy, I guess so.

Paul Werbos:

Creative guys sometimes do more than one thing in their life. John Wheeler of Princeton certainly did a lot of different things in his life.

Robert J. Marks:

Yeah. That's him. Okay, go ahead. I'm sorry.

Paul Werbos:

Okay. So, Everett, Wheeler, Deutsch and my fixes to Deutsch, there's a version of the multiverse theory of physics which I believe is by far the best mainstream version of how the universe works in existence but I still believe Einstein was right it anyway. I believe that I can believe both of those things because Einstein himself once said, "Quantum mechanics probably works because it's a good statistical description, a good statistical approximation of things that are actually more like my kind of theory down underneath."

Robert J. Marks:

Okay. That's the so-called Hidden-variable model, I believe.

Paul Werbos:

Some people phrase it that way. Yeah.

Robert J. Marks:

Okay. The Hidden-variable, wasn't that addressed negatively by, I think it was, Bell's Inequality.

Paul Werbos:

I can tell you the name. I know these guys. I knew some of these guys. Okay. So we live in this horrible world of fake history. By coincidence, I had strange luck always to see the real history. When we talk about Bell's Theorem and were Hidden-variables disproven, the story is worth a few minutes. It started with Einstein. Einstein, Podolsky, and Rosen said, "If you guys, if your Heisenberg theory is true, I predict the following kind of thing with correlated photons and I don't believe that we should do the experiment," and that's a very rational thing but then nobody did the experiment. I think Bell had some papers of ideas and there were various theorems and finally, one of my classmates at Harvard was part of a group of four people who really changed the world. Their names were Richard Holt, Clauser, Holt, Shimony, and Horne.

Paul Werbos:

CHSH is their paper. If you look up CHSH, you'll probably get to one of their papers. Now, as it happens, they had four important papers that year and I could got to see all of them. When I look, today on the web, I only see one paper that's cited a lot. I think the other papers were really important too. But basically, the paper that really impressed me when I talked to my classmate over tea was the paper he showed me they had just done where they proved a theorem. They said, "If you have two entangled photons, if Einstein's kind of theory is true, the results will be in one region but quantum mechanics predicts a different result, we can discriminate which is true by doing this experiment."

Robert J. Marks:

Yeah. Just a little bit of background, the Hidden-variable model, see if I get this right, Paul, the Hidden-variable model says that, "Yes, we have this model of quantum mechanics and we treat things as probabilities but there's something happening deeper underneath that is going to explain it," and this was the theory which was adopted by Einstein and Rosen and them. Is that, pretty well, the idea between behind the Hidden-variable?

Paul Werbos:

Okay. This is where words get screwed up in science.

Robert J. Marks:

Okay.

Paul Werbos:

And discussions of reality and consciousness and God, my god, do people do weird things with words. My first language was mathematics not English and if I relied totally in English, I would be totally confused.

Robert J. Marks:

Paul, you're bilingual. That's good.

Paul Werbos:

Yeah. Yeah. I had a friend from Nigeria. I was saying, "Yeah, I speak English as a second language."

Robert J. Marks:

Okay.

Paul Werbos:

And that made a big difference. But yeah, Hidden-variable, I don't use the term very often because people have really played games with those kind of words. But I do know what Einstein's point of view really was and I do know that Einstein changed his views from one year to the next. But the core vision of Albert Einstein, which I've slightly altered, I call hardcore Einstein realism. And in my old age, I have come to the conclusion, "Yeah. I believe in hardcore Einstein realism." But somebody would say, "Well, what the hell is it that you believe? I don't believe every word Einstein ever said. He said some pretty funny words."

Robert J. Marks:

What is Einstein realism?

Paul Werbos:

Okay. So in that webpage, Mind, Souls, Brains, I have a link to a YouTube talk on reality. Actually, you could probably search Werbos Reality on YouTube, probably would get there. I don't know. In that talk, talking about reality, I start with a question you might appreciate, Bob.

Robert J. Marks:

Okay.

Paul Werbos:

How can you believe in hardcore...

Robert J. Marks:

Okay.

Paul Werbos:

How can you believe in hardcore objective reality like Einstein, or Ayn Rand or Lennon, and also believe we have a soul and a spirit and a spiritual destiny and they are real?

Robert J. Marks:

Well, I think that boils down to your philosophy whether you are... There's lots of theories which divide that question and which give you different answers. One of the things that we're looking at right now, at the Bradley Center, is a so-called mind brain problem and whether the mind is the same as the brain. And there's lots of emerging evidence through something called Libet's experiment and near death experiences, et cetera, which kind of illustrate that there're parts of the mind which are not resident in the brain.

Paul Werbos:

Yeah. I agree with that theoretical bottom line that you just stated.

Robert J. Marks:

Okay. Well, that's good. Okay.

Paul Werbos:

It took me a long time to face up to reality and to face up to the fact that reality is not as simple as it seems.

Robert J. Marks:

Well, also, the thing is in mathematics, as you know, Paul, there's lots of things which are unknowable. You can prove things that exist, and you can also prove that they're unknowable and you wonder if this applies to things such as consciousness, in terms of a global understanding of what is going on.

Paul Werbos:

Boy, would I love to talk about that a little further. But bottom line is the talk starts simple with Albert Einstein and goes from there to David Deutsch and hardcore Einstein realism. I don't even know if Einstein uses the term hidden variables. I know he used terms like the Lagrange equations and Minkowski space. So there's that view of reality, but David Deutsch's theory is much more a mainstream theory and one of the pieces of work I am proud of, frankly. I am the one who developed the mathematics, which best connects Einstein's assumptions with what we see in the David Deutsch statistics. At one point, Einstein said, I think you could deduce the shorter equation from the statistics of my fields and Norbert Weiner tried to do it and he failed. I read his papers, he just didn't do it. He tried hard.

Robert J. Marks:

Really Norbert Wiener, for our listening audience is the founder, in fact he coined the word cybernetics, right?

Paul Werbos:

Yes, that's right. He's a very respectable guy. He couldn't solve this problem. That's why I decided maybe I won't do this for my PhD thesis. Maybe it's a little too hard. It doesn't guarantee I'll graduate. I'll work on it after I graduate. So I did and I finally figured out how to solve it. It took a long time. The papers are very heavy mathematics. They're not very well known, some of them are new, but the bottom line is I think that David Deutsch's approximation is the best that we have in mainstream science.

Paul Werbos:

It has been tested in quantum computing applications, much more than all of these philosophical interpretations you read about. There are a million philosophical interpretations what quantum mechanics should be, but David Deutsch's version of quantum multiverse technology, that's the one that has been used in the experiments, billions of dollars all over the world, trying to make quantum technology.

Robert J. Marks:

Oh, everybody's in a race to do quantum computing.

Paul Werbos:

So the quantum computing is based on David Deutsch's theory of quantum Turing machines. And that theory has been tested empirically at a level that these philosophers would not even dream of. The empirical work that's gone into quantum information science, huge. It's by far the best empirical theory we have today of how quantum mechanics really works.

Robert J. Marks:

Here's a question that I have for you, Paul. I don't know the answer to this. Turing's enigma machine did one operation, right? It was designed to crack the enigma code. In quantum computing. If you take a graduate class or an undergraduate class in quantum computing, you're introduced to things like Shor's algorithm, which does cryptology and Grover's algorithm, which do search. These remind me of special purpose Turing machines that are designed to do one operation. The thing I don't understand is Deutsch's. Is his proposal to simulate a general purpose quantum computing machine, Turing machine?

Paul Werbos:

Yes. There are two pieces of work that I cite. Deutsch has done many things in his life, but whenever I got to be brief, there are always two things I cite from David Deutsch that everybody should know about. One of them is the multiverse stuff. He has a book and videos and the other one is the quantum Turing machine. He has one well cited in many other papers proving the universal quantum Turing machine. The concept of a universal quantum Turing machine, that's more universal than the old Turing machine, his theorem, his mathematics, his concept and his design, his vision. David Deutsch is a truly great person, but I need to be careful.

Robert J. Marks:

Okay. Why do you need to be careful?

Paul Werbos:

Okay. Because David Deutsch's vision of what is a universal quantum Turing machine. There's an analogy to Turing's vision of the universal Turing machine, yes? And you and I both know that Turing's vision of a universal Turing machine is not really the most universal thing you can do because it assumes binary type variables. We know there's a thing called neural networks.

Paul Werbos:

In fact, there's a paper I cite a lot by Siegelmann and Sontag. There are other papers and people debate, which is the best paper I don't want to get into that kind of fight, but I often cite the paper by Siegelmann and Sontag and the basic idea just in the classical world, forgetting the quantum world, in the classical world, the full power of analog neural network type architecture is like a whole level beyond what a Turing machine can do. I think of the Turing machine as aleph zero, the simple infinity, the countable infinity, and I think of the theorems of Sontag and Siegelmann and other people as aleph one computing. A continuum, which is a much bigger infinity than aleph zero.

Robert J. Marks:

Yeah. The aleph zero, Aleph is for example, the counting numbers and it is a smaller infinity than the number of points on the interval from zero and one. This was pioneered by Georg Cantor if I remember.

Paul Werbos:

Oh yeah. It's the Cantor sequence. So now bottom line, there is a paper in the journal, Quantum Information Processing by Werbos and Dolmatova.

Robert J. Marks:

Could you spell that last name please?

Paul Werbos:

D-O-L-M-A-T-O-V-A. In that paper, which has a very interesting history and has an updated version, I say, look Deutsch showed, add quantum entanglements, add the big cats, the Schrodinger cats. And you go from one way of aleph zero to aleph one. That's basically what David Deutsch did with the Turing machine.

Robert J. Marks:

I see.

Paul Werbos:

Do it another way you go from aleph zero to aleph one. Do both of them you can get to aleph two or aleph three.

Robert J. Marks:

Well, aleph two, by the way, I've heard described as all of the scribbles and shapes that you can draw on a sheet of paper. And I believe that aleph three are higher is something which is beyond our comprehension. It's like forth spatial dimension or a fifth spatial dimension.

Paul Werbos:

But believe it or not, I hate to say it. It's not beyond my comprehension.

Robert J. Marks:

Okay, good.

Paul Werbos:

Because there is this paper... In fact, maybe I should even be more precise. The updated version of the paper I posted at werbos.com/triphoton.pdf T-R-I-P-H-O-T-O-N.pdf.

Robert J. Marks:

Okay.

Paul Werbos:

And basically that includes a roadmap for how to get past the quantum Turing machine to basically four more levels beyond that.

Robert J. Marks:

And what do you think you can do with these higher level Turing machines that you can't do with Turing's original machine?

Paul Werbos:

Yeah. Well, I might call these post-Turing, but what can we do? To begin with, a lot also, it's the hardest math I've ever worked on in my life and that is saying something.

Robert J. Marks:

Well, one of the things classically a Turing machine can't do is things like the halting problem. If you could come up with an aleph one or aleph two sort of machine to solve the halting problem, that would be an incredibly big deal.

Paul Werbos:

So just two months ago, I put out a plan for how you could build what I call a quantum annealing of things and what you can do with it. And I view that as an example of a third generation, quantum technology. Everything the US government is funding today is pretty much the first generation. It's all the quantum Turing machine. It's all the first generation.

Paul Werbos:

We had a leader for the quantum information sciences coordinating group who was looking beyond the first generation and he invited me to a big meeting in Baltimore in 2015. He was going to announce these new directions, but he died mysteriously. And there were only four people who were left of the plan he had to talk. One Indian, one, Chinese, me and a contractor.

Robert J. Marks:

Okay. Now, Paul, you need to hire some personal protection here, don't you?

Paul Werbos:

No joke. So at any rate, so at least since then, so far as I know, the US government has pretty much focused on the quantum Turing machine. The more advanced generations there is stuff in other countries, but not in the US.

Robert J. Marks:

You know, Austin Egbert, who's our director, pointed out that you talked about quantum annealing. This is something being, I think, pursued by a company called D-Wave. Are you up on that?

Paul Werbos:

Absolutely.

Robert J. Marks:

Okay. Are you impressed with what they're doing?

Paul Werbos:

Well, it turns out that I have I think a whole YouTube talk on quantum annealing and it's certainly in the website that I sent you where I just this year came up with a plan. Now in my original vision, in the triphoton paper, I described five generations of quantum computing. Some of which are pretty hard to understand, frankly.

Paul Werbos:

And then what I did this year was I said, okay, why don't we try to do something simple. A friend of mine had an application in mind that had to do with astronomy. He said, can't you do better in this application? I said, maybe I could use D-Wave. That's the only third generation, but that third generation could be used to solve your problem in looking at the sky. And I got very excited by it. In fact, I even was talking to a friend of ours, Don Wunsch.

Robert J. Marks:

Oh yeah.

Paul Werbos:

In Missouri. I was even trying to talk to his people. Hey, maybe we should try to get some IP, because I have an idea how to use a D-Wave to solve this astronomy problem.

Robert J. Marks:

I get a brush of greatness claim here, Don Wunsch was my PhD student.

Paul Werbos:

Ah, okay. The future of NSF may depend a lot on him, actually.

Robert J. Marks:

He does great, incredible things. I'm proud of them like a father,

Paul Werbos:

Great. Okay. Well, he is facing some pretty heavy challenges, but he also has some exciting opportunities. When I think about whether we will build back better. A lot of my hopes do involve Don, but God is he facing a lot of heavy stuff.

Robert J. Marks:

Well, again, I think as we talked in previous podcasts, when you come up with in innovation, there's always an inertia resistance to that.

Paul Werbos:

That's an understatement.

Robert J. Marks:

Yeah.

Paul Werbos:

Yeah. Have I learned about that, but let me come back. So I was really excited and then I studied D-Wave more. I studied the other stuff more than D-Wave. D-Wave was, it's just third generation. I was more interested in the fifth. But I decided, okay if we have a quick and dirty application, that's really exciting. Let's get the IP on how to use D-Wave.

Paul Werbos:

And then I got a friend from Canada and he spoke to the D-Wave people and I got a literature survey on D-Wave like you wouldn't believe. It's a gigantic literature from all directions. But basically what I found out is that D-Wave annealing is not true quantum anneal. D-Wave has real markets, it has real clients, it has useful tools that will forever be useful, it's got a big market, it's an important player, but at the center of its box, it does not have what I call a true quantum annealing box. So what I have posted this year are directions for how do you build a true quantum annealing box and how can you use it for applications D-Wave hasn't even thought of yet.

Robert J. Marks:

Let's go down a little rabbit trail here and explain what annealing is.

Paul Werbos:

Good.

Robert J. Marks:

As I understand it, the term comes from metallurgy and the idea is how you cool down a molten metal to get optimal properties.

Paul Werbos:

Yeah.

Robert J. Marks:

And if you cool it down just right, slow enough, you get a really good metal. If you do it too quickly, it's bad. The great example I've heard of is ice cubes. If you start with water and you freeze ice cubes real quickly, you get cracks in your ice cube. Whereas if you slowly lower the temperature, you get nice clear ice cubes.

Paul Werbos:

Beautiful.

Robert J. Marks:

Isn't that a nice explanation.

Paul Werbos:

It is beautiful. And in my explanation for why D-Wave is great, but they don't have what they need for the greatest power. They have a real in a real product, but you can do a hell of a lot better. And the reason why they're not doing the best you could do is the people who design their system don't really understand what you just said.

Robert J. Marks:

Okay. Okay.

Paul Werbos:

Okay. They don't understand what you just said with true annealing and one reason I was able to figure this out is I knew about annealing, right? You're not the only one who's learned about it. I knew what real annealing is.

Robert J. Marks:

We should say in machine learning annealing corresponds to adding a lot of noise in the beginning and then slowing down the noise. The more noise, the greater the temperature, the greater the shaking noise. So that's the translation. Go ahead, Paul.

Paul Werbos:

Okay. The truth is I have learned about annealing from three sources. One of them is the stuff I just learned about D-Wave in the past year. The other one was the metallurgy and solid state physics stuff that I knew about from other engineering applications. It's not only metallurgy. It's also solar cells, to be honest, I learned about it from solar cells. And in addition, there is what you just mentioned. There's something called the metropolis algorithm. So in people who do numerical algorithms know about a kind of a annealing algorithm used for this metropolis kind of stochastic search. And that's the one I know the least about ironically.

Robert J. Marks:

Okay. Let's back up. Let's back up a second. What's the big deal about quantum annealing? Which in my cursory understanding involve things like quantum tunneling and stuff, but what is the effect of quantum annealing and why is it such a big deal? And why is D-Wave interested in annealing? We all know about quantum computers and the fact you do all of these operations in parallel, but what about the quantum annealing and why are we interested in that?

Paul Werbos:

Okay. So again, we have to be really careful with words in this business because D-Wave sells a box, which is useful and it does something. And in my recent paper, when I had to be really precise, I called it DQUA D-Wave type quantum annealing. And what I'm proposing is a different technology, which I'm calling true quantum annealing, TQUA. And there are three generations that you can build. The basic concept of true quantum annealing, my kind of quantum kneeling, is basically following the vision that David Deutsche applied to digital computing. And so maybe I should explain a little bit about what David Deutsche's vision is.

Robert J. Marks:

Okay.

Paul Werbos:

It starts with a cat. Everything really important may start with a cat.

Robert J. Marks:

Like Schrodinger's cat, right?

Paul Werbos:

Exactly that cat. And I've spent a lot of years learning about that cat. It's a very important cat.

Robert J. Marks:

But we're not sure whether it's alive or dead.

Paul Werbos:

Yeah. Yeah. There's some politicians like that, but...

Robert J. Marks:

Zing. Okay.

Paul Werbos:

But I'll resist. It's a big and real subject. It's not a joke really. It's real. But coming back to this cat, most people probably need a refresher on what the real story is with Schrodinger's cat. Schrodinger, De Broglie, and Einstein all believed the beauty of their new quantum field way of thinking over the old particle based Lorentz physics. Lorentz believed in particles and matter. And all there is force fields in Einstein's space. De Broglie, Schrodinger, and Einstein were pretty much of this same school. And then came this Heisenberg guy and Schrodinger, Einstein, De Broglie couldn't believe half the things that Heisenberg said. And at some point they realized a Geiger counter is sort of a quantum mechanical phenomenon. It's stochastic quantum mixed-state thing.

Paul Werbos:

And so Schrodinger proposed this experiment. He said, okay, put a cat in a closet point a gun at its head, have a Geiger counter control it with a timer so that it runs for three hours and set the numbers so that quantum mechanics predicts precisely a 50% probability that the cat's brand gets shot out and a 50% probability nothing happens. That's the basic experiment. Oh, and the experimenter leaves the room locks the door. Schrodinger said, the reason why you're crazy Heisenberg is because your crazy theory predicts the following. It that as soon as you turn on this machine, the cat gets put into a mixed-state so that half the cat is alive, half the cat is dead and it still doesn't make up its mind even after the timer stops. It's sitting there half dead, half alive. And it doesn't change until the human opens the door and looks at it. And by the act of looking at the cat, you make it be alive or dead. Isn't that dumb, said Schrodinger. And that was also where Einstein's EPR experiment came from was this sort of idea. However...

Robert J. Marks:

EPR is?

Paul Werbos:

Sorry. Einstein, Poldosky, Rosen.

Robert J. Marks:

Oh, okay. That was their thesis about hidden variables. Okay.

Paul Werbos:

People call it Bell's theorem because it was done by CH and SH about Einstein. They liked Bell, he was their friend.

Robert J. Marks:

Yes.

Paul Werbos:

He wrote a nice popular book and it was a good book. But the actual theorem is different from any theorem that Bell ever published. It's a totally different theorem and the implications are very different and very important. But they did the experiment and the cat, is it alive or is it dead?

Paul Werbos:

The bottom line is Einstein lost his debate on the EPR experiment. The experiment disagreed with his intuition, but that doesn't mean he was wrong in his whole theory. That's why you have to get rid of part of his ideas, but not all of them. The key thing in that experiment, David Deutsch has a different explanation for what happens. He said, okay, you shoot the Geiger counter, you can put a cat in a mixed state. You can generate a Schrodinger cat. You can generate a macroscopic object in a mixed state. You can split the universe into two parts and it's alive in one and dead in the other. And when you open the door, you connect yourself to the cat. So there are two of you and the universe has split bigger. So there's one of you that sees a dead cat. And there's another one of you that sees the live cat. And that's the multiverse.

Robert J. Marks:

Man, if that's true, Paul, there's a lot of parallel universes, man.

Paul Werbos:

Absolutely. I didn't believe that for many years. I was an ultraconservative. I read the work of a famous guy named Tony Leggett who argued that somehow there must be a way out of this. Maybe quantum entanglement breaks down with distance and there have been thousands of experiments on this.

Robert J. Marks:

Oh yeah. Yeah.

Paul Werbos:

And they all prove there are macroscopic Schrodinger cats. And that was David Deutsche's idea. He said, if you can put a cat in a mixed state, you can put a computer chip in a mixed state. And if you have enough leverage, instead of making two copies of the same chip in different states, you can make a million copies.

Robert J. Marks:

Well, that's the foundation of quantum computing, right?

Paul Werbos:

Exactly. That's what it is. It's quantum entanglement. It's herding cats. You've got a million Schrodinger cats, if not a trillion Schrodinger cats all at once, all doing different jobs. And then you put it together at the end and it's parallel process.

Robert J. Marks:

Yeah. But the trick I understand is making it collapse to the correct solution. Or in the multiverse case, making sure you're in the right multiverse. How do you assure that?

Paul Werbos:

It feels like defalsification. But let me come back though to the point. Forgive me if I go back to where I was heading. What Deutsch did was he showed that our old ideas of Turing computing can be generalized by making a programmable computer, which runs a million programs on a million copies of the same chip in parallel. That the core idea. And I just want to go that far right now.

Robert J. Marks:

Sure.

Paul Werbos:

The thing is though it still is like a computer. It's like our concept of a classic Turing machine. You write a program, you hire programmers. The US government has hired so many programmers to try to come up with good programs to make quantum computers do something. And that's where Shor comes into it because he came up with the first program that you could run to factor large numbers that just happened to be the critical thing you use for old style polynomial, key coding with cryptography. There's a lot these guys don't know because they live in their little ivory towers. There's a lot of stuff they don't know about this stuff and where to begin.

Paul Werbos:

Well, we started with D-Wave and the idea was instead of what if we are not trying to run a computer program, what if we define our task differently? What if we're trying to solve an optimization problem? That's the obvious thing you would want to do with annealing. So what if you want to build a box where you have a million Schrodinger cats running around at the same time, and you want to do the quantum mechanics such that the cat which survives is the one you want, and that gets to your final ending decoherence kind of stuff.

Robert J. Marks:

Yes.

Paul Werbos:

Right? You want the cat you want to survive. You want the others to lose. If you know the physics, this is an obvious answer how you do that. You're using energy to represent what you want. You're mapping into a minimization problem. If you want lower energy, if you want to do annealing in physics, what you do is you shed heat to your environment and you equilibrate to a state of low energy. That's how the physics works. These guys were not physicists. And so they didn't even consider the possibility of doing it that way. So instead of shedding energy to the environment, which is what my specification calls for, they just circle around in the environment they're in. And they adjust coupling coefficients, but they don't dissipate energy. It's entirely within the box. And they're entirely right. That the minute you connect outside the box, you make life more complicated. But sometimes that's what you absolutely have to do. If you want to get results.

Paul Werbos:

If you want a quantum computer that works, sometimes you need a cold environment. Same damn thing with a true quantum annealing. And you got to worry about is the environment cold enough? Can you shed energy to it? But the bottom line is if you design the box to do true annealing where you're shedding energy to your environment, it's obvious to the right kind of physicist. But I read that literature and it wasn't obvious to any of them because they were all busy doing other stuff.

Robert J. Marks:

Wow.

Paul Werbos:

I was kind of amazed when I discovered my God, this is like the guy who lives a $20 bill on the floor. I'll pick it up if I can.

Robert J. Marks:

So Paul, you're going to supply us a lot of links to some of this literature so that we can put them on the podcast notes, right?

Paul Werbos:

Yeah. True quantum annealing.

Robert J. Marks:

Okay, excellent. Excellent. We're out of time but I wanted to thank you Paul, for your time you've spent with us. We've been talking to Paul Werbos, he's the inventor of the most commonly used technique to train our artificial neural networks in the world, AI backpropagation. And he's also doing some pioneering work in quantum computing, which is going to be the future of the world if we can ever get coherence, I guess. So thanks for listening until next time. Be of good cheer.

Announcer:

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