Quantum Computing: The Quantum Advantage

Featuring Dr. Jason Larkin as Interviewed by Suzanne Miller

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Suzanne Miller: My name is Suzanne Miller. I am a principal researcher here at the SEI. And today, I would like to welcome my colleague Dr. Jason Larkin, who is a researcher in the Emerging Technology Center here at the SEI.

Today, we are here to talk about quantum computing, specifically, the quantum advantage work that we are doing here and why this is important to the SEI and the federal government. Welcome, Jason.

Jason Larkin: Thank you. It is good to be here.

Suzanne: Glad to have you, and we are, as we have been the last couple of times, here remotely. So, I hope that you will have some patience for us as we work through this. But before we get started in the quantum computing itself, I would like to ask Jason a little bit about how did you get into this? This is not the typical, you know, *Oh, I am going to be a quantum-computing guy when I grow up*. How did you get into quantum computing?

Jason: I talked about this a little bit on the cyber minute or podcast that we did with our intern Matias [Jonsson] because the same question got brought up. I went into it a little bit. But basically, I got into quantum physics back when I was in school, which is kind of strange because I was a mechanical engineer. But basically, when I went to grad school, I took a bunch of physics courses, and quantum physics was one of them. In fact, I took several quantum physics courses. Then, I got to use that stuff in my PhD work, my thesis work, but this was like using quantum physics to model materials and other things. Then, I put that stuff down for a while, for a couple of years, until I started working at SEI. By the time I started working at SEI, now quantum computing was starting to become a thing.

I have done quantum physics on and off for a long time, but then I had a dormant period, but then it kicked back in because of this interest in funding that is in quantum computing. I think I said in the podcast, part of my code got reactivated in my own brain.

Suzanne: It is in your genes. So, quantum computing is a subject that is coming up in the literature and in the news. First, give our listeners sort of a, *What is it*? What is the foundational concept of quantum computing? And why is it difficult?

Jason: Oh, yes. So fundamentally, it is about using new devices as the fundamental unit of computation, and these things are called qubits, instead of classical bits, or C bits as they are sometimes called. There are operations and behaviors of these qubits which are clearly different than classical bits, and these different behaviors potentially allow you to do things that are not able to be done in classical computers or sometimes called classically intractable. That just basically means that some computational tasks that you would like to accomplish that have some use, we would like to do them on quantum computers, and we would like to do them a lot faster than on classical.

So, I think there is a duality. It is difficult for a few reasons. One is because it is still quite new as compared to classical computing and classical algorithms, and it has been the better part of a century we have been working on that problem. Whereas for quantum computing, the idea for it was really solidified in the late 70s, early 80s, and then algorithm development has only taken place over a few decades' time frame. I think there is great potential for the technology, and I think that is also what makes it hard. In some sense, it is two things. It is hard because it is new, and it is by and large unfamiliar to computer scientists and people like that. Then second, I think it is hard because the potential power that is there is tremendous.

Suzanne: One of the things that, in my reading about this, the classical bits are deterministic. You are a one or you are a zero, and that one-or-zero state is what determines what happens next. But the qubits are probabilistic in some ways, and so that seems to be one of the things that makes my mind jump around a little bit and go, *How can that be?* So, you want to say a little bit about that?

Jason: I think maybe one thing to remember is we can do probabilistic classical computing as well. There are lots of ways of throwing stochasticity into a classical computation. But you are right, the thing that seems most different is this probabilistic nature of quantum computing. What is more specific is the particular probabilistic nature of it in that it is even different than what you can achieve probabilistically with classical computers.

So, it is like a particular flavor of probability theory. That is really, in some sense, like, Scott Aaronson has a very nice quote on this where he basically reduces quantum physics down to a particular kind of generalization of probability theory. Maybe that is the most weird thing, is that really down at the subatomic, atomic level, and sometimes larger levels, that reality behaves probabilistically. I can say that like from physics, like this idea about the interpretation of quantum mechanics which relies on us having to treat all this probabilistically. Even that is not agreed upon, or I should say that it is a major point of contention in physics. If we assume that that stuff is true, and quantum computers behave probabilistically, or at least when you do the entire computation, you execute something on a quantum computer and make measurements, that process is probabilistic. So, this means that whenever we are designing quantum algorithms, they have to rely on this probabilistic nature. Or not relying on it, but they have to confront...

Suzanne: Accommodate.

Jason: ... take advantage of it, accommodate it. Yes, exactly.

Suzanne: OK. So, let us lead that into, what is the SEI doing? We have an initiative called Quantum Advantage. So, would you explain that to our viewers and tell us why is that important that we have this initiative and what is its importance to us as well as to the federal government?

Jason: Yes. So, I would say that I think the way that we pitch our initiative in totality is like the search for quantum advantage, which I would say is also what is driving most companies and researchers in general. What people think is an example of quantum advantage was the Google quantum supremacy demonstration that happened last fall. The definition is, there are some well-defined computational tasks that we can execute on a quantum computer and a classical computer, and the question is, *For that computational task, does the quantum computer outperform the classical computer?* And there are a few different ways you can measure *outperform* or *performance*, but this is really the bottom line. So, like, we are spending all this money on quantum computing and spending all this time researching and developing them, *What are they really good for?* And maybe one step further, *What are they game-changing for?*

That is definitely like our initiative. And our goal is to try and find…and to find this quantum advantage the soonest. So, there are a lot of things that we can look out on a 10- to 20-year time frame and say, *Ah, if we have a big enough quantum computer with high enough fidelity qubits and operations, then we know we can do these classically intractable problems.* But the harder problem is in the next five years or less, what is the answer to that question? So what applications will we find quantum advantage for?

Suzanne: Are there things you are looking forward to that you think might be promising from that viewpoint? Is there something promising in that five-year time frame that you can talk about?

Jason: Yes, so I would say that there are initiatives across the board looking to answer this question. There is an entire DARPA [Defense Advanced Research Projects Agency] project dedicated to answering this question, like every one of the companies that are designing the hardware and building it and funding and all that. I would say that there are probably…two or three, maybe more primary focuses in what they call this NISQ era, the noisy intermediate-scale quantum computing era. Perhaps maybe the first one, and maybe the one that has the most computational complexity or algorithmic complexity evidence that we would see quantum advantage, this is in material science. So, this is looking at problems like trying to solve for the ground state of molecules or excited state of molecules, these types of systems. I think one could say that the computational complexity evidence is strongest for advantage in that domain. After that, people are looking at trying to do optimization. So what kinds of optimization you might find in machine learning, or in problems for like routing, scheduling, logistics. So, these are like the...

Suzanne: Audiostatic management?

Jason: Yes, sure. Then maybe another one which has a lot of focus is in machine learning. There are some things I mentioned, like an optimization that has applications of machine learning and other domains. But, there is really a big focus on looking at quantum computing for machine learning, I think probably because the business model or value proposition, if one found advantage in that space, is pretty obvious because of how much machine learning is pervasive now, and every organization is looking at it. But I think maybe from what I can tell from the field, there is less, I would not say hope, but there is less theoretical evidence specifically for machine learning that we will see quantum advantage of the type that we would like to see it, like intractable advantage, like transformative advantage.

Suzanne: So those are research areas that we still have to work through and figure out? Is this a viable area for us to put our research thinking on?

Jason: Yes. Those are three good, broad application areas. There are other applications. So, this is all within quantum computing, which I think is mostly the scope of what we are talking about. But we are also beginning to look at other aspects of quantum information science. So not just computing, but sensing, communications, because you can imagine in, like, they call this the quantum IoT or this, like, the quantum Internet of Things.

Suzanne: Internet of Things.

Jason: Now, we can think about, *Well, in the future, if we are going to have quantum computers, and we are also going to have quantum sensors, and we are going to start connecting these things by a quantum network, now we really have a distributed quantum Internet of Things*. So, we are looking at computing and in particular, those applications I mentioned before, but we are also trying to broaden, because at the SEI, this mission is in terms of technology readiness level [TRL]. So, we know quantum computers, if people keep going, and they keep funding it, and we eventually get a quantum computer with a million qubits with fault tolerance. We know that there are classically hard problems we can do on that machine. We know there are going to be good things that will come from it. But the best estimate right now is that is going to be 10 or 20 years away. Now, the question is, within this domain, *What is going to be available in five years or less?* I think we have begun to broaden our scope beyond just computing and looking at these other aspects of quantum information science as well, because I think that seems like what the SEI should be doing, given the mission statement and everything.

Suzanne: Well, just from what you have said, I can think about some notional things that are in, what we call the last mile where we have tactically disadvantaged computing. If we have networks that are more probabilistic that have this ability to really find the optimal path through something much more quickly than a deterministic kind of classical computing, that is an example I can think of that would be attractive to emergency responders and others that are in that last mile and technologically disadvantaged.

Jason: Yes. So, or you can think of a situation where we are going to have, instead of just having one really big quantum computer, it may be what we already have with classical computers, we have lots of smaller intermediate-scale computers, but we want them to share the information that they have processed. We do not want to just have a bunch of processors where we make measurements and collapse the state and so forth. We would like them to share their distributed computing in much the same way we do now with classical. That would open the door for, *Now we need a way of communicating the quantum information which is on these processors without destroying their state.* Then there is also the advantage that comes up with being able to send information, which is encrypted or is protected rather by the nature that the information is contained in a quantum state.

I think moving forward for the SEI, I think it is important to open up the portfolio, so to speak, because this allows one to select from it and figure out, *Oh, what's the stuff that is going to transition sooner?* For example, quantum sensing; quantum sensors are already available now, and they are being utilized in the field. Again, the same idea moving forward. So now if we have this world with lots of quantum sensors, perhaps we would like to have these quantum sensors communicate the output of their sensing to each other before the state is reduced to a classical state. So again, this notion that going forward, maybe in the decades to come, we will really be thinking about the quantum Internet of Things, and about moving data around in a quantum way and all that. So, quantum information processing…The question I think with all this becomes like, given the TRL definition, *What is the best candidate of all this technology? What is the stuff that is going to transition the soonest?* And all that.

Suzanne: So, there is an aspect of that that is…one way to think about technology readiness levels is we move from pure research into engineering. In your judgment, where are we? Are we moving it? It sounds like in sensing, we are moving into the engineering realm already. But there may be some other areas where we are still very much in the research, *What can it do?* Is that a good characterization the mixed bag of where quantum is at right now?

Jason: Yes. I would say that for computing, for example, that we just recently submitted some work on looking at a quantum algorithm for doing optimization. I think that given what you just said, where is the status of this thing at? What is the nature of the work? Is it looking at technology or an algorithm that you can execute next year and it is going to provide advantage in some mission context? Or, is it really looking at something that is further down the road? I think that you can characterize the paper, the results in it are of a general nature, which I think in terms of let us say a protocol, it is broadly useful for a lot of different optimization problems. It generally looks at increasing performance.

But the results of the paper make some assumptions, or you have to make some assumptions for the paper to interpret the performance results. These assumptions are basically that for the paper to be true, we would need quantum computers available that have much higher fidelity than we have available now. So, then you can ask the question, *So, when would a quantum device exist that could demonstrate the proof of concept essentially that we have in the paper?* I think this is really difficult to predict because of how quickly progress is happening. So, there are a couple different dimensions in quantum computing along which we seem to have a kind of Moore's Law type behavior, an exponential improvement in performance, not across the board, but there are a couple of different measures. But if you take this extrapolation and project it out, then it is more like what we demonstrated in the paper: if it is going to provide advantage, it is probably not going to do so until, like, five years from now let's say. With a big arrow bar on that projection because it is, like, five years, plus or minus five years. Not quite that bad but....

Suzanne: Well, and this is the world we are living in today, we are seeing breakthroughs that that were not anticipated, certainly in many areas of technology, and this could be the next one. So, for those that want to create the breakthroughs, if a viewer has an interest in quantum computing but really is not that involved in it yet, what kinds of things would they be able to access from the SEI or other sources that you want to mention that would help them to understand whether this is a fruitful area for them to put their own research thinking, or even if they are thinking about transition, say that the quantum sensing is a little bit farther ahead, you know, how would they get information about how to make use of that?

Jason: Oh, OK. So, with respect to quantum computing…With quantum computing, making an impact there is, I think, a combination of things. So let me say first and foremost, we would like hardware to be a lot better. Maybe that seems obvious, but I think a lot of this depends on hardware getting a lot better. I think a lot of, let us say, breakthroughs or algorithmic development, it really is going to require access to this better hardware, because the whole point about quantum computers is their ability to do things which are classically intractable. Now we are still figuring out what exactly those things are and how much practical use they have, right? But that is sort of the point, and so that means that there is a huge premium now and also moving forward with having access to these real bare-metal devices, bare metal meaning like the actual physical thing. Because there is no way to substitute for it. You can play games in classical computers and simulations, but you can only do that up to some point. So, getting access to those is going to be very critical I think for all parties involved, anyone who wants to make a dent, so to speak.

Beyond that, I would say that right now there is actually kind of an explosion of content of ways, of different approaches to understand quantum computing depending on what level you are coming in at, whether you are coming in just as a computer scientist or a software engineer or something, you have no prior knowledge of quantum physics versus maybe somebody who has quantum physics as a background and across the board, right? But I think what we are seeing, and also participating in this process ourselves at SEI, one of my colleagues who helped to teach a CMU course last semester, and we can provide all these references and stuff in the transcript.

Suzanne: In the transcript, absolutely, definitely.

Jason: We can provide a lot of different resources, and I think resources that span the spectrum of prior knowledge because that is a real difficulty with this field is that, depending on your background, you come in with different expectations, with a different agenda. Like, *Why am I looking at this technology? What do I care about it? Should I care about it now? Should I care about it two years or five years from now*? I think we can provide a list of different references which I think are useful for this spectrum of person who is coming in. I think that is very important, because how do you determine the fundamental questions we were asking, like how much should you care about this technology and when should you care about it? It can be very difficult to determine that coming in, especially given the variation in background, and also given I think…yes.

Editor's Note: Dr. Larkin provided the following urls to reference:

Blog Post:

- Achieving the Quantum Advantage in Software

Shorter videos:

- Quantum Supremacy: What is it and what does it mean?
  Sabine Hossenfelder
- What Quantum Computing Isn't
  Scott Aaronson

Longer videos:

- Quantum Computing for Computer Scientists
  Microsoft Research
- Quantum Supremacy Using a Programmable Superconducting Processor
  John Martinis
- Perspectives on Quantum Computing: Education, Applications, and the Future of the Field
  Jason Larkin
- Quantum Computing Intern Update
  Jason Larkin and Daniel Justice

Suzanne: OK. So, if you were to advise a computer scientist who is just getting into that, we [have] some resources, are there particular areas where you would say, *You know what if you are new to this, this is the place to start? Like, sensors is the place to start*. Where is the place to start that gives people an idea of what this is like to work in but isn't necessarily the really deep, deep, deep research kinds of focus?

Jason: Yes. So, let us say in the references, I think we can do it like this. We will figure out a set of references that is, let us say 5 to 10 minutes in length, but really is worth the bang for the buck. I can think of a number of different references. Like entry level would be, *In 5 to 10 minutes, tell me why I should bother with quantum computing, or why should I bother with quantum information science, or why should I bother with quantum sensing? Like what is the fundamental thing which makes it attractive as a technology? Quantum communications, quantum key distribution, and so forth?* So that is a good like 5 or 10 minutes, and what is the entry level, you know? What is the entry-level value proposition, let us say?

Then there is another tier, I would say, which starts to bridge into, like, the hour-long. For quantum computing, we can put a link to what I think is the best use of an hour or an hour and a half, for, let us say, a data scientist or a software engineer. *If you watch this for an hour or an hour and a half, this is going to give you a tremendous bang for your buck in terms of understanding, let us say, for quantum computing, what is the fundamental program that a quantum computer runs? What are the fundamental operations of a quantum computer?* So, we have a good reference for that that lasts about an hour. So, we can go from like 10 minutes to an hour, and then...

Suzanne: Then you can decide if you want to get deep.

Jason: Exactly. This stuff is very important, right? One thing that has been really great to see with quantum computing is just how much content is being pushed out for a few different reasons. Like a few of these institutions, which are creating the technology, they also have a vested interest in training as fast as possible as many people about the technology. So, there are a lot of open-source efforts, and there is a lot of content out there.

Suzanne: I think it is very true. I am going to look at some of those resources because I am fascinated by this area. I have been in this business for 40 years, and this is the most different aspect of computing since I have been involved, since the early 80s. This is very cool stuff, much stuff to learn.

Jason: It is cool, and I think that the resources and all that stuff are great because you could rank the order for the technology, what are the most important things for it? A lot of people with number one, would say the hardware, at least for computing, and you would be hard to argue against it. But number two after that has got to be algorithm design and the fundamental understanding of the technology, and people who have to understand. So, it's like, one, two, and then, you know….

Suzanne: So, if you are bored with your classical computing tasks, we have something new for you, right?

Jason: Yes, and by the way, learning quantum computing, it actually helps to bear fruit going back into classical land. Like right now, if you had to sum up, if the field stopped, like everything just ceased, all progress ceased, at least specifically, with quantum money, the major advancement so far has been in a deeper understanding of computer science of computational complexity, and of improvement in classical algorithms.

Suzanne: Yes.

Jason: That is the major benefit thus far. It is not a trivial benefit. There has been a ridiculous amount of new understanding just by considering what a quantum computer is, and what are the computational complexity classes of a quantum computer, and what implications does that have for the rest of the complexity classes and all that? So, this would be the stance of like Scott Aaronson and other theoretical computer scientists working in quantum computing. They do not really care if there is ever a use case commercially for the technology, they are just happy that someone built one. Perhaps Google violated the extended Church-Turing thesis, they built a device that no one has built before.

Suzanne: I think that is important to say that sometimes research like this does not necessarily take you where you think you are going to go, but it helps you to understand another area more deeply. So, I know there is a resource called Q Hub related to quantum. Could you tell our viewers a little bit about how that works and how they would want to look at it in terms of its…as a resource for quantum computing.

Jason: Yes. So, we made this QHub, and it is basically just the JupyterHub server that we run and we keep it up to date with all the different content that we as a group, and also, by that I mean also as an extended group. So, the people who use the resource are myself, and Daniel Justice, and Catherine Bernaciak, and other people in SEI, and we use it to do the work that we do, research and try to publish and all that. And then we also have an extended group network which connects to campus. So, we have a few campus faculty and some of their students. It is basically a place where we can bring these people together, and we can configure the system with the necessary software-development kits, and potentially connect them to backends to real quantum processors that are available from like IBM and Rigetti and D-Wave and all this. Then we use that to do the research that we do. Some of the references and stuff I mentioned bfore about like, oh, 5 to 10 minutes, and then like an hour long, we use that resource primarily for people who have gotten through that level of content and are ready to try and actually publish something or do some research at that level.

Suzanne: An experiment.

Jason: Yes.

Suzanne: Well, I want to thank you very much for joining us today remotely. And in addition to published works from your team, which we are going to link to, there is also a blog post that is recent on quantum computing. So, we will ask our viewers to go to insights.sei.cmu.edu and search under Larkin, L-A-R-K-I-N, in the author's name field. That is the easiest way to find your blog post.

I want to thank you, Jason, for being here, and sharing your experiences and helping people to get an idea of why this might be important to them. To our listeners, I want to thank you for joining us today. We are going to include links in our transcript to all resources that we mentioned and some that we haven't really specified. There will be some lists for you there. As always, you can get these podcasts anywhere that you get your other podcasts, SoundCloud, and other places as well. So I want to thank you all for joining us today, and have a good afternoon. Thanks. Bye.

Jason: Thank you.

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