

EPISODE 444**[INTRODUCTION]**

[0:00:01.3] JM: Computer chips have physical limitations. When transistors get too small, electrons start to behave in ways that make the hardware modules less reliable. Our reliable technological progress has been enabled by Moore's law, the idea that the number of components that we can fit on a chip doubles roughly every 12 to 18 months. We can't keep shrinking the size of these components because physics is no longer complying.

Quantum computing allows us to operate on qubits rather than bits, which gives us better data parallelism and continued reliable progress. Quantum computing is still mostly an area of research rather than production systems, but it's rapidly approaching usability and Zlatko Minev joins the show today to explain how quantum computing works and why software engineers should care.

Zlatko is a PhD candidate at the Yale quantum information lab and today he describes how qubits work, which algorithms quantum computing impacts, and which parts of modern computer architecture will work on a quantum computer. We may have to throw out the Von Neumann architecture when it comes to quantum computing.

This episode is a great compliment to the episode we did with Vijay Pande from Andreessen Horowitz about quantum computing. So check out that episode if you're looking for more in the quantum realm and I'll certainly continue to cover it.

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[INTERVIEW]

[0:02:53.1] JM: Zlatko Minev is a PHD candidate at the Yale Quantum Information Lab, also known as the Qlab. He is the founder and chair of Open Labs and he is the recipient of the Yale-Jefferson Award for Public Service and today, we are talking about quantum computing.

Zlatko, welcome to Software Engineering Daily.

[0:03:11.8] ZM: Hello Jeff, I'm glad to be on.

[0:03:14.0] JM: We did a show previously about quantum computing. It was from the standpoint of a venture capitalist who invested a lot of money into a quantum computing company called Rigetti Computing. That's the name of the company, the quantum computing company.

Today's show is going to be a little bit lower level, we're going to talk about how quantum computing actually works. If people want to know about motivations for this show or the higher-level atmosphere, the business atmosphere around quantum computing, that previous episode might be a good place to start or to listen to after this episode.

But in order to ease us into a conversation about quantum computing at this lower level. I think we should start with the physical limitations of our modern consumer computers. I've got a laptop on my desk right now, I've got a smart phone in my pocket, what are the physical limitations in the processors of our modern consumer computers?

[0:04:16.7] ZM: All right, thank you for starting with this question. I guess I'll start from the beginning. The typical way and the way that you'll read the news that computers are made faster and cheaper and better and so forth is by taking the beating heart of the computer, the transistor, its building block and scaling it down making it smaller and smaller, and smaller. Now, the question is, how small can you go? Well, you would say very small, sure. You know, we have invested on this for 60 years.

If you take your iPhone and you zoom in to the processing unit, the chip, its heart, and you go down to the level of that building block and you look at it and you could sort of zoom in, you could actually count the size of its features in number of atoms. It's about a hundred atoms across at the current stage, the 12 nanometer lithography stage that folks are doing.

We've really gone very far away at the moment from wires or, you know, vacuum tubes. If you love guitars, you probably know about vacuum tubes. We've gone down to the atomic scale in terms of what chip manufacturers like Intel and AMD and so forth are doing. When you get to that level of the constituent matter, these are the atoms, the building blocks of nature, you can no longer talk about current running down the wire because the current is now just 10 electrons or some number of electrons jumping across atoms. So a lot of the usual laws and the way things are done breaks down.

One of the main limitations for instance and current modern technology and the transistor wipe is power dissipation. There is a large heat load and one of the ways that this arises is the fact that the channel which blocks the current is so thin, it's just atoms, it's just some number of atoms across that current electrons can actually tunnel. In a quantum mechanical sense they can almost teleport, if you want. They can tunnel across the barrier because the barrier is so thin. So they're never physically, if you want, inside the barrier. They can just pop up on one side without ever being in the middle. This is just one of the richer ways in which nature behaves at this more fundamental level.

[0:06:35.2] JM: Are you saying you start to lose power or you start to lose signal? When you start to hit these physical limitations, you just – what exactly is breaking down? What becomes less effective? What is the functionality or the power level that's restricted because of these low-level physical limitations?

[0:06:56.6] ZM: Right, for this case it would be the leakage current. The way that we've encode typically ones and zeros, you can crudely think of it as having zero current or a lot of current or some voltage. But when this transistor is supposed to be blocking the current when it's supposed to be off, you're still – you can't actually turn it off completely because of this quantum tunneling, so you're getting this energy dissipated through anyhow.

More generally than that, if the control of the system becomes harder and harder and more challenging, the smaller you get. In addition to just the difficulty of constructing that device. Again, crudely, if you have two wires nearby each other and you're sending some information down one of them, some electrons, in principle they can actually just teleport to a nearby wire without ever sort of being in the middle and that's clearly an issue.

[0:07:54.2] JM: Is that happening today on the chips that we're building today for consumer computers?

[0:07:59.7] ZM: Yeah. So the question you might ask is, "Do chip makers like Intel and AMD need to go and learn atomic physics?" And in a way, they have. They've had to and they really have to think about and model a lot of these things at the very quantum level at almost the atomic level. That's not to mention the maybe more obvious problem, which is to say that, "Well, we've been making the transistors smaller and smaller and we've gone down to about a hundred atoms across, right? Now, how small can you go? I mean, eventually you're going to get down to an atom and you certainly can't go further than that. So then the question is, "What's next?"

[0:08:37.2] JM: What is next? We could answer with quantum computing. Let's talk a little bit about quantum computing, and we'll come back to modern computer systems and slowly bridge the gap between modern computer systems and quantum computing.

What is quantum computing? Give the high-level 10,000 foot view.

[0:09:00.2] ZM: All right, let me give a shot at this. Quantum computing; well, it's not just a better version of classical computers, okay? It's not just making a classical computer a little bit

faster or a lot faster. It really takes and it also encompasses — So basically in principle, everything we have already done in terms of computers is a subset of what is possible with a quantum computer, okay?

Quantum computation is maybe the scientist way to answer some of these challenges with the scaling down and coming down into the regime of the nuisance's presented by quantum mechanics for chip makers, okay? Now, what are seen as nuisances and problems to chip makers like Intel and AMD in terms of this quantum effects, to scientists they're an opportunity. They're extra richness of nature that we have never tapped into previously. It's new potential, if you want, that hasn't been capitalized and quantum mechanics originated about in the 1910's and so forth. So it's been about a hundred years since we understood that quantum mechanics, quantum physics describes what these atoms do.

It's only really in the last 20 - 30 years or so that we have started to be able to not just look at the effects of quantum mechanics but start to tame some of them and start to think of how to use them for useful technologies. To be able to actually control them. Quantum technologies are very precarious things — quantum systems are very precarious things. They are quite susceptible to a number of noise processes and this extra richness, well, it's more to deal with and so you have to figure out how to deal with it.

[0:10:52.7] JM: Okay, so you've given us an overview of what quantum computing is. Where are we today? Because this idea has been talked about for such a long time and just a few companies are starting to do work around it with actually I guess companies have been doing work around it for several years. There's the Rigetti funding was more recent but I know Google has been putting money in doing it, Microsoft's been putting money into it for a while. There's that company D-Wave.

Are we at the lab stage? Are we at the emerging technology stage? Where is quantum computing?

[0:11:26.0] ZM: Well, thank you, yeah. I can be happy to also give you a history perspective right after this. But in a very typical quantum fashion, and remember one of the strange things about quantum mechanics is that an electron, a thing can be here and there at the same time.

In this very same way, I think my personal answer to the question of, “Is quantum computing at the lab stage or the emerging tech stage?” I think the answer is that quantum computing has arrived and simultaneously it hasn’t arrived. Let me clarify what I mean by that.

You’re right, the idea of quantum computation that you can take this extra behavior of nature at its most fundamental level, that initial idea of maybe precipitated in the late 80’s. But it wasn’t really until 1996 when Peter Shor came up with an algorithm that would break essentially the RSA, the standard encryption model, cryptography model in terms of how we encode our information and protect it from bad people. It was until then that it gained a lot of attention. Because suddenly, it was realized that it could provide an exponential speedup over what’s classically possible. That was one of the very first applications.

But there was a lot of skepticism in the following years, knowing that quantum computers are – the quantum machines are very susceptible to noise. As people progressed, there was this big revelation all of a sudden that, “Well, we can do error connections even on quantum systems and get around this issue of noise in addition to just building and controlling them better.” Fast forward to today or actually, let’s say two weeks ago, even one week ago at the Microsoft Ignite Conference, you know, Microsoft CEO announced, he said, “There are three key technologies that will drive us forward.” It was augmented reality, machine learning and quantum computing.

For the software developers on the podcast, I think you’ll be excited to know that by the end of the year, you should be able to download Microsoft Visual Studio and do quantum coding in a new quantum programming language as well as simulations. Now, this is just one out of a few possibilities in terms of where you can actually start to get applications and really either work for startup or an established company or develop code for quantum software.

Quantum software I would say is arriving at this very moment, there seems to be a lot of attention on that. There’s also the IBM Python module package, there is the Rigetti one, there is the D-Wave one, just to name a few. At the same time, have we built a quantum computer yet? No. We haven’t yet built the full machine, we’ve built very small prototypes of it and I guess in the later part of this talk we’ll probably get into what are some of the architectures and so forth. But I would say that – yeah, go on.

[0:14:36.6] JM: Yeah, okay. So great, you've given us a picture for how things stand today industry wise. Let's talk fundamentals. In computer systems, information is represented as bits. We have a hard drive where these bits are represented as different regions of magnetization, we have other parts of the computer where bits are represented as high or low voltages, this is when information is moving around.

We seem to have settled on the binary system where a given bit can be in one of two states. Yes, why do we represent things in terms of bits? You know, just ones and zeros and two states when we could represent them in so many different way and why is it relevant to quantum computing?

[0:15:25.1] ZM: Perfect. We don't have to use bits. That's maybe the simplest answer. We could use three states or more states of the system to encode the information. It has just been that in fact, there's also analog computing and neuromorphic computing now, which are coming back and that's a different way to represent information, which is actually potentially quite viable. But anyway, we came down to the idea of bits I believe because it's the most irreducible building block. Also theoretically, this is an easy way or a good way to study scaling.

Now, the idea was that if you can build just one building block and then you could just scale it up and make billions of them, if you could make one good one and then make a billion good ones, it didn't matter so much if it's three or two and two seemed like an easy way to do it with, that was scalable. So maybe that's the big picture view.

How it's relevant to quantum computing? In a way you can say quantum computing is different because you don't just encode the information in two bits, you know? Is the coin on the table facing up or facing down? That's one possible representation of the information or a seesaw if you want, it is the seesaw on the left side or the right side? That could encode as zero and one.

Now, in quantum computing, if we take the coin analogy a little bit further, I could say, "Well, okay, the direction in which the heads of the coin points, that's one and the other way is zero." But I can take that coin and pick it up off the table and all of a sudden, I have a different way to encode the information. The information is still one or zero, right? It's still – there's still just

heads or tails, the coin doesn't change. But the direction in which the head faces can now point anywhere in 3D space. Think of a little arrow that you hold in your hand.

That's very much like a qubit, a quantum bit. It can only be one or zero, it can only be heads or tails. However, the encoding direction of the information is more complicated and it can live anywhere on the sphere.

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[INTERVIEW CONTINUED]

[0:19:03.3] JM: That's great, disambiguation for you know, we can represent information in different ways. We don't necessarily need to do this binary format. This is kind of a, you know, it came to a consensus on this convention about binary information but in the quantum world, we are not necessarily representing things in the binary terms. So that's the information theory point of view.

Let's talk about the hardware point of view. We've got conventional circuits, we've got conventional hardware. What are the components in a circuit chip today and how might those change or how might those map to a quantum computer?

[0:19:42.3] ZM: Okay, great. So maybe on the higher level, there is different modules which do different operations, there is a central processing unit, there is memory unit and there is wiring and connections. You would think making one bit or one qubit is the hard part and then you know, you just build a thousand of them and put wires between them. It should work great, right? Well, putting things together is actually one of the main challenges of systems and especially how do you interconnect and, you know, putting two things together doesn't mean they'll both work just as well.

So there is a lot of work that goes into the interconnects and also the isolation of each of the modules so that they really work as independent modules and they're not interlinked.

[0:20:30.8] JM: By the way, when you say modules, you are referring to and gates or, or gates or NAND gates, right?

[0:20:37.6] ZM: Yes. And/or NAND. Even on a higher level in terms of circuits buildup of those which it's really like a Matryoshka doll, like one of those Russian nested dolls because it's modules and modules and it just, you know, it goes crazy from there.

[0:20:54.2] JM: Right. So, one level of modules might refer to and gates and or gates, you know? If you take a Boolean algebra class or an electrical engineering class, you have ones and zeros, low voltage and high voltage, and you use and gates and or gates to create more complex logic like an arithmetic logic unit, which might also, you could refer to as a modules. These different modules fit together to be constructed into robust operations.

[0:21:26.1] ZM: Precisely. All of this is actually quite analogous to the quantum computing world but each of those steps just gets a thousand times harder.

[0:21:38.2] JM: Yeah. So we've got these traditional chips, these circuit chips that are built up of modules, this and, and or gates and then those and, and or gates build up into higher level modules like arithmetic logic units and eventually we get to actual computing at computer architecture fits together like that.

But at the lowest level, these and, and or gates are built out of transistors. These transistors consist of electrons that are flowing through or being blocked in the sense of one or zero and the transistors as they get smaller and smaller, the pathways are becoming as narrow as an atom and traditional computing starts to get less reliable when these transistors get narrow, when the channel gets this narrow as an atom. We've been forced into this place where we have to build at the quantum level and this creates a difficulty but it also creates an opportunity.

Explain what's going on. You know, you touched on it a little bit earlier. Maybe you could refresh us, what is going on when these transistors, these channels get narrower than an atom? But what are the opportunities also at this quantum level?

[0:22:54.9] ZM: Great. You're right, the transistor is essentially a three port device, there is an in which is the emitter, an out which is the collector and then there's a base which regulates the flow of current through the device, through the in to the out. As all of these features get a lot closer, a lot smaller, usually that has been – we've been able to increase the clock cycle or the frequency at which these things work. All of this quantum effects become more and more pronounced. As you go to higher energies and as you get to smaller and smaller scales, this is the world of quantum mechanics, the world of small things.

In quantum mechanics, there are a couple of things that are essential to the idea of quantum. One is that things are discreet too as that they're random and three that they can tunnel through barriers for instance. When you establish an electrical barrier between the input and the output then as the frequency or the energy and it gets larger and as you make the barrier smaller, it's more and more likely for the electrons from one side to tunnel to the other side. So that causes a lot of limitations in terms of power consumption and so forth.

Now, you would say that okay, we might have to go — to do quantum computation, we might have to actually go down to the single atom and take that atom and now try to control it in some manner. But what we have realized in the last 20 years is that while that's one approach and we can actually do that more or less, this is bionic computing, another very viable approach, which looks very much like classical computers is to take circuits built of billions of atoms and billions of electrons and cool them to an incredibly low temperature. To negative 273.14 Celsius. A lot of people will say that's colder than outer space, but it's a little funny of a saying.

Now, when you go to such low temperatures, what happens is a freezing out of a lot of the noise, of a lot of the individual agitation of the electrons. These electrons will essentially condense into one fluid, a super conducting fluid, if you want. One body. Even though there's billions of electrons, they can actually act as if they were a single electron and from that wire you can now take – you can take that wire and essentially design an artificial atom. An artificial atom in the sense that it's made from many atoms and many electrons, but is printed on a circuit board and you can design its electrical properties. But in many ways, it acts just as if it was a single atom in space. What's great about that is you can really engineer its electrical properties, its coupling strengths and so forth.

Yeah, and I can actually build on with a little analogy if you want in terms of...

[0:26:06.7] JM: Please do, yes. Continue.

[0:26:07.9] ZM: Yeah, to give you a little bit of a perspective. Okay, you might say, "Okay, this is kind of crazy, why are these things just coalescing into this electrical fluid?" I think of it a little bit like this: think of each electron as a penguin, all right? When it's hot, each of those electrons, each of those penguins is going to be very, very agitated. They don't like it. They're going to be running around, hitting into each other and that's a lot of noise, that's a lot of deep clearance, that's kind of what electrons do when it's room temperature.

But as you make it very cold, as you take energy out of the system, these electrons, these penguins, they start to freeze, they start to get cold. Now, they can never completely freeze but what they're going to do is start to get close to other penguins and it will become energetically favorable for them to be close to each other and kind of, you know, snuggle up close to each other and walk in unison. That's the way they can keep warm if you want. It's the energetically favorable thing to do.

[0:27:04.4] JM: So these atoms that are operating together in a way that we can control to some degree. How does this relate to the concept of a qubit? Because I know a qubit is this thing that we can implement in super conductors or atoms or other devices. But don't quite know what a qubit is.

[0:27:27.0] ZM: Great. One of the issues we talked about in a classical computer is well, there is this extra flow of electrons and that causes dissipation, it causes heat load and modern supercomputing centers are really limited for instance by the heat load. There's even – by the heat load and also by the power consumption that they require due to the heating. You know, there's even plans to build nuclear reactors next to super computer centers. That's how much power these things take.

Now, a super conductor doesn't really dissipate energy in principle. It's a super-conductor and that's what we mean is that the electrons coalesce individually and they move in unison coherently. The individual excitations of all the bumping around, that's sort of bad, that causes dissipation. One way to design a qubit is to take this flow of electrical current of super current and for instance, you might put it in a ring and now the current can circulate clockwise or it can circulate counter clockwise in that ring and that could represent a zero or a one. That would be the simple equivalent.

Now, what's special about this state is because there is not dissipation, just like the coin, it doesn't have to be on the table, okay? Dissipation is a bit – is going to very much constrain the coin which is heads or tails to be stuck on the table. But once you remove dissipation, I can pick the coin off the table and now I can orient it in an intermediate direction. In an analogous manner, the current can be going clockwise and counterclockwise, if you want, at the same time or some of the – You know, you can build this extra encoding of how the qubit, where the qubit is.

[0:29:24.2] JM: Okay, so I think I'm understanding. So first of all, is the qubit this condensation of electrons that you were talking about earlier? This self-made condensation of electrons?

[0:29:37.0] ZM: Great, well that's one embodiment, that's one physical embodiment of a qubit, one way you could make it. The qubit is more of a concept, a notion, just like a bit in the classical sense. A bit just means one of two states, you have a choice, it's the minimal unit of information. So a bit can be made out of current on or current off. It can also be made from a seesaw being on the left or the right. It can be made from a wooden machine, which is sort of what the original computers were like.

[0:30:09.9] JM: So, a qubit is not a physical concept? It's an abstract concept?

[0:30:14.7] ZM: Yes, it's the minimal quantum system, it's the minimal information. You can't really have one state because, you know, two states is the minimal you can really have.

[0:30:26.0] JM: Okay. How big are we talking here in terms of the physical implementations like how much space does a qubit occupy?

[0:30:36.2] ZM: That's great. There are two things to that. The first was that there are atomic qubits made out of individual atoms, which are exactly one atom large. Now, working with those qubits is a bit more challenging in the sense that you can just have this atom like floating in space. You have to entrap it, you have to isolate it from the environment and so forth. There is some complexities associated with that. It's really just one atom large.

A super conducting qubit on the other hand can be billions of atoms and you can make its size more or less whatever you want. It can be a millimeter or we can even build them down to the nanometer size. Though the current superconducting qubits are physically going to be a little bit larger than the transistors. But that is not so important because the physical size is not as important because what really matters is the potential for computation that they offer. You know, one bit does not equal one qubit. The state space that you can explore with n bits is 2^n whereas the states based that you can explore with n qubits is 2 to the 2^n .

[0:31:53.4] JM: Why is that states base so important? Because I took a class in college and maybe I was misinformed by the professor, but I thought the professor talked about this thing where there was a period of time in the 80's or early 90's or something where people were experimenting with ternary systems where you could have zero, one or two, and how that was represented on the hardware level is like transistors today is low or high voltage.

But those voltages are just ranges so you could also have a third range. You could have low, medium or high voltage and we decided not to do that as the entire computing industry is just like, "No let's just stick to binary." How is this discussion of qubits representing a more rich information possibility space? How does that differ from the whole ternary question?

[0:32:45.8] ZM: Yeah, great question. It's a bit like if you want that's really the footprint that you care about is your configuration space relative to the physical size. So in that sense that's how you win. It's because for less physical elements here you have a lot more possibilities to explore. I mean it's more subtle than that. There are special rules in quantum mechanics but to a first order.

Consider this: you go to a dinner party and you and your nine other friends there's 10 friends, you guys want to sit down around the table and you try to figure out, "Well, how do I – John wants to sit next to Jen," and so forth and you might think, "Okay how do I figure this out? I can think about all the combinations. Well, there are 10 factorial combinations for 10 people sitting around the table that turns into three and a half million possibilities already. So you can see that this problem actually grows very quickly and to explore those possibilities, you want to be able to in call them somehow and that's one challenge.

[0:33:48.4] JM: Okay, well we have the logical abstraction of a qubit and then we have the physical manifestation of the qubit or we have some different ways that we were implementing it. You mentioned a nuclear qubit and I think some other – and super inducing qubit, okay. In these cases, what are we doing? How are we taking advantage of those physical properties and what can we do with a qubit?

[0:34:18.0] ZM: Great. So, some of the things that people have been doing – Well with a single qubit it's like a single bit. You know there are some fun things that you can do but it's fairly limited. The power of computation really comes from many of these being put together, interconnected and so forth. The atomic qubits for instance are controlled with lasers. So you shine light, you shine a laser light and that is how you can control it.

The super connecting qubits on the other hand use microwaves or microwave light sort of similar to what you would use for cellphone communication range, but very high precision. Now when you put many of these qubits together some other things that you can do even at the current smaller stage of I think currently we're generally at about 20 qubits in terms of what people are doing at the moment. There was a really cool paper recently from the IBM group on simulating the chemically stable ground state of certain molecules.

So one of the things you can already start to – some of the questions you can already start to answer are about physical problems like simulating chemistry simulating nature at this level. Now those problems tend to be quite difficult again because chemistry and these physical atoms, physical systems are often quantum and so they have this large state space that a classic computer needs to simulate. But that's very expensive because the scaling between the two is exponential.

A quantum system is very apt and able to simulate another quantum system. So it's quite efficient and quite good at that. Some of the applications of that are a lot of the physics or chemistry, some of the larger perspective, one of the things that I am actually I think is really cool is once you can get more of this qubits together and you can really start to represent more and more complicated states there are speedups, exponential speedups. There's an exponential speedup for all of the blast routines, the basic linear algebra sub-routines such as finding eigenvectors, finding eigenvalues, solving linear equations, free transforms and right now, we have they exhibit quantum — Quantum basically linear algebra sub-routines exhibit exponential quantum speedups over their best known classical counterparts.

There are caveats, which are important in terms of the encoding, the time it takes to encode the information, the sparsity and rank of the matrices and so forth but I think the progress has been really, really amazing.

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[0:37:04.1] JM: At Software Engineering Daily, we need to keep our metrics reliable. If a botnet started listening to all of our episodes and we had nothing to stop it, our statistics would be corrupted. We would have no way to know whether a listen came from a bot or a real user and that's why we use Incapsula to stop attackers and improve performance. When a listener makes a request to play an episode of Software Engineering Daily, Incapsula checks that request before it reaches our servers and it filters the bot traffic preventing it from ever reaching us.

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Thanks again, Incapsula.

[INTERVIEW CONTINUED]

[0:38:53.5] JM: Okay, you are giving a tangible example for why using these qubits is going to be really helpful. We've got all these matrix operation, these mathematical operations that computers are doing all the time, whether we are talking about scientific applications or signal transfer, I think, is what you see a lot in Fourier transform stuff and of course, machine learning is all about matrix multiplication at the lower level. That's why you see people like Intel and Nvidia rebuilding their chips to do and like the tensor board or the tensor processing unit at Google, they're rebuilding these systems to do matrix calculations faster.

Maybe you could help up with – Okay, Google just heard me. I don't know if you heard that, which my Google just prompted.

[0:39:54.6] ZM: I did.

[0:39:55.2] JM: Oh my gosh, shut up Google. I don't need you right now. Okay, tell us how we do some of these advanced operations? How are we going to take advantage of qubits to do machine learning faster?

[0:40:08.6] ZM: All right, let me give you one of the possible examples. Suppose you have a maze and take a particular concrete example, maybe as a kid you played with one of those little boxes. It's a maze and there's a little metal ball and you have to kind of take the box and twist and turn that left and right and space until the ball goes from point A to point B on the maze. Now how would one solve this problem classically?

One way you could do is — take in an algorithm makes sense, one thing you could do is take this box and the ball and basically try every single possible combination. That will take you the time to do all of those combinations, right? Which is one of this exponentially scaling problems. On the other hand what would be the kind of analogy to a quantum computer? Like we said, a quantum system can essentially explore multiple possibilities at the same time. So solving the same problem with the quantum computer would be like taking water and flushing it through the maze.

Some of that water is definitely going to make it from point A to point B very fast and you have simultaneously explored all the possibilities. So you can see that there's clear advantage here. Now this advantage comes also with some subtleties. On the output you also get a bunch of water. So you have to figure out how to engineer the output of the algorithms so that this water coalesces on the output in a meaningful way so that it tells you exactly which is the right path to take.

This is where a lot of the subtlety and trickery of the actual designing of quantum algorithms comes from. You know they offer so much more richness but that richness also means more complex to work with. So we have to learn the rules of quantum software.

[0:42:10.3] JM: So maybe how would that be like a — so your analogy how would that be analogous to a machine learning problem is I think in machine learning you want to test different weights, different hyper parameters in each iteration of your training and you want to do all of this training and you could typically, you have to do it iteratively. But maybe in a quantum world you could test a bunch of different iterations all at once and then just check the outputs against each other.

[0:42:41.3] ZM: To build on that, there's quantum annealers are a very popular approach pursued by a number of people. You have to now imagine that you have some cost function and this cost function is over some state variables. Anyway, it represents a landscape. There's some hills and valleys, peaks and troughs. You start the system and the goal is to find the state of the system, so the configuration. Are my bits one and zero here? How should the ones and zeroes be distributed so that the energy or the cost – so the energy is minimized or the cost function of this system is minimized? This is the variation — this can be done with the variation approach.

But what you can do with the quantum system is start the system anywhere in any configuration. So it might be in a maximum or a minimum and there could be many minima's which it could get trapped in. But you're guaranteed pretty much the quantum system will eventually always tunnel down to the ground state as time goes on and so you will in principle never get trapped in one of the local minima's because you can always just tunnel out of it and find your way down to the ground state. There are subtleties in terms of how long it will take you to tunnel out of the system but that would be one idea.

[0:44:01.3] JM: I've got to tell you, I'm still very confused about how we are using this qubits. I understand we can use them to explore multiple things at once. They can be in multiple states at once but I am still having trouble kind of thinking, how are we reading a qubit? How are we writing a qubit? How do we coordinate these qubits to represent something? Or are those even not the right questions to be asking?

[0:44:30.1] ZM: Yeah, well I can try to answer that one. To take the analogy with the coin again, we said you can take the coin and basically encode it to be up or down by taking your hand and applying some force on it and you can flip the coin. So that's applying some force. It's basically the same thing with the qubit. It's just that the force now is going to be some light pulse, let say a microwave pulse and you can in that pulse encode a certain amplitude of the rotation of the coin and space and you can encode a certain phase. So you can choose the axis around in which you rotate the qubit encoding and that's how we can write the information to the qubit and control it and do gates, the single qubit gates on it.

[0:45:15.5] JM: Gate; what is a quantum gate?

[0:45:18.4] ZM: Well a quantum gate would be similar to a classical gate. Let me give you maybe the simplest example of a gate.

[0:45:24.8] JM: Like an and or or.

[0:45:26.2] ZM: Exactly, and or or, or not. Let's say the simplest gate is probably not. If I have one not, one is zero. If I have zero nots, zero is one. You can do a similar thing with the quantum bit. You can do a pipe pulse, which takes a one to zero and a zero to one. The thing about quantum gates is that they are more possible gates than just classical gates. Things that don't make sense classically. For instance we set a not but in quantum mechanics, you can do a thing which is a square root of a not.

And that really only has meaning because of the different possible encodings but classically square root of not doesn't really mean anything.

[0:46:08.5] JM: How do we build a quantum gate?

[0:46:12.5] ZM: Right. Well at the moment, the way that they are often done is by having a classical computer and an external control manipulate some electronics and feed those down for the superconducting qubits into a dilution refrigerator and apply these microwave pulses that rotate the qubits. That's how you do single qubits to actually do and or xor. Those are rather complicated gates or can be or let's say more primitive gates like CNOT controlled not gate.

So one qubit controls the other qubit. We often take the two systems that represent each qubit of two physical systems and interact them, turn on an interaction between them for some amount of time. So it is really harnessing their physics and physical dynamics in order to come up with what is the right physical action that would map into realizing this concept of a controlled gate or some other quantum gate.

[0:47:18.0] JM: Let's go back to the example of today's physical computing where we have ones and zeros being represented by magnetism in the case of a disk or in electricity. We are representing ones and zeros in the case of transistors being high or low voltage. How does that

physical representation of ones and zeros, how does that map to the state representation in quantum computing?

[0:47:49.7] ZM: Yeah, so how are classical bits of ones and zeros similar to and different from the quantum bits? Well they can be totally different and for instance in the case of an – because also there are multiple implementations of qubits, we are still exploring many possibilities. Microsoft is pursuing Majorana's. A lot of the other communities pursuing super conducting qubits. Other folks are pursuing ions and so forth. Some people are doing NV centers and diamond.

There are quite a few implementations and most of those are totally different than what we do in classical computers. Maybe the closest one is the super conducting one where we actually build circuits in the exact same way that Intel and AMD and so forth build circuits. In fact some folks, TU Delft is building quantum computing chips at the Intel fab facilities and we build circuits but they are different circuits. They are super conducting circuits and they are the actual structure is really quite different.

We really build these, they are all essentially based on the Josephson device. Josephson was awarded the Nobel Prize some time ago and that is one of the effects again that uses the tunneling of electrons or [kuper pairs] through a barrier.

[0:49:17.3] JM: Okay, so this is really helpful because I am starting to understand this idea that a qubit is again this — it's a logical construct. This is not a physical construct. Just like a bit is a logical construct. People represent bits in different ways, you mentioned the seesaw or the coin. A bit can be a seesaw, it could be up or left or right is down and you could have a network of bajillion seesaws and that would make up a computer and you could build up computing systems out of that.

Similarly, a qubit can be represented by these different physical manifestations that we are experimenting with and in any of these cases, the qubit algorithms, the algorithms that you are building off of qubits tend to be things where you're representing — you can represent a wider range of states because instead of just a one or zero binary, I believe you have more of a matrix

of different ways that a single qubit could – a single qubit could represent and it could represent multiple kind of things at once. I am starting to understand that lower level concern.

What else changes at the higher level? So like, we have things like the Von Neumann architecture. I don't remember exactly what that is but it has something to do with like the story of storage and computing. These different higher level regions of computing. Does that stuff stay the same in the world of quantum computing or does our entire higher level architecture change as well?

[0:50:54.6] ZM: Oh yeah, this is a very exciting question. It changes, yep. The touring machine is like if we take it to a very high conceptual level, you have to expand that notion to now a quantum touring machine. You know again, everything we have done so far is really just a subset. The analogy I would use here is to say that classical computation is like painting on a canvass but is painting on that canvass in black and white.

So if you try to paint the sunset for instance, you're limited in the ability of what you can achieve. But if you now enable yourself next to richness and dimensionalities, for instance you can explore more possible states to take crude analogy, if you can pain on that same canvass in full color you could do whatever you did before. You can paint the same paintings, but you can now also achieve more even though you are still working on the same landscape. So yes, we have to rethink basically the last 60 years.

[0:51:48.0] JM: Okay, all right. Well let's talk more practically. So we understand qubits, we understand that because we're in the qubit world now we've got to rebuild a bunch of architectural concepts, but what else do we need to actually build a physical – what does a quantum computer look like today? Or I think it's kind of we are doing a lot of virtualization of a quantum computer sort of, or I guess take me through what – let's look at it this way; Take me through your favorite labs and your favorite industrial examples and what they're doing. Like what are they doing at Rigetti? What are they doing in Intel? What are they simulating, what are they experimenting on? Give me a whirlwind tour.

[0:52:31.0] ZM: All right, let me try to tackle that one. The field is big and there's a lot going on. Let's see, so virtualization I think is here. You can work with simple quantum computers. Like I

said there is the Microsoft thing, there's Rigetti, IBM, etcetera. You can download Qtip. Qtip is an amazing package, by the way. You should use it. But can you anybody actually take a quantum computer right now and work with it? The answer is again quantum mechanic yes and no.

There are, yes you can. There was the IBM quantum experience where anybody could go on and program their quantum computer and they would actually run on this at negative 275 Celsius and execute your program. That's the yes part then you are now get into a little more of that. The no part is that well it's a computer but you know it's only still a handful of qubits. So I wouldn't say that we have yet built a quantum computer, depending on what you mean by quantum computer. You know is the Antioch the first classical computer or is there something before that?

So there are quantum machines, primitives of quantum computers which really exists today, which you can start using programming and playing with. What do some of these look like? Well I mentioned the ionic ones. The ones that I work with and the ones that I am familiar with are the super conducting quantum computers, which look a lot like printed circuits. But those circuits sit at the base of what's called a dilution refrigerators, this thing that takes temperature down from room temperature to 15,000 civic Kelvin above absolute zero and so where would you like me sort of to go from here?

[0:54:12.0] JM: So let's focus on set of some of the top companies and research labs that are doing experiments and research in quantum computing today. Maybe you could tell me what is Microsoft doing, what is Rigetti Computing doing, and what are you doing?

[0:54:32.8] ZM: Oh okay, great. I can talk about that. Right so the quantum computer doesn't just have one embodiment at the moment. We are really I think also really exciting to me and to anybody in the field is that we can really choose and have an impact in terms of how the quantum computation, quantum technologies of the future look like. We are exploring various possibilities. Again, there is a lot of richness here to play with.

For instance, one of the things that Google and IBM and Rigetti, all of these players are using gate based quantum computation versus doing a annealing. But all of these groups including

my group at Yale, we're all doing super conductors, these low temperature printed circuits. Now, within that space, we're really broken up into different approaches.

For instance at Yale, we're really pursuing a different way to encode the information, to encode a qubit, quantum bit, in terms of hardware-efficient manner, built from super conducting cavities, which are not a two-state system. They're not actually bits or qubits themselves. They have many more states but the idea is to use those many more states to redundantly in an area correctable way encode information. Folks at Rigetti and IBM, Dell, et cetera — There's too many names to name them, sorry if I'm missing anyone — are pursuing the idea of building really good individual bits as good as they can get them.

But, the way that they'll actually protect their information down the line is to take those bits and make many of them. Usually in a thing that's called a surface code, it's a way to redundantly encode the information in a clever manner so that if an error happens, and those errors do happen, you can recover the information.

So it's really building many, many, many qubits to encode one logical bit of information. You know, you can think of the simplest classical encoding mechanism, which is to say, "Well, if I have three coins and I want to give them to my friend if I want to really just tell him I want it up or down, I might send him three coins that are all heads so that in case one of them gets flipped in the transmission, he can still figure out that by majority voting two of them are heads so I must have meant heads." Because there's always noise in the communication channel and classical computers likewise have error correction built into them at the lower level.

[0:57:20.2] JM: Let's begin to close off and talk about where we're at today? When quantum computing is going to start to be used? How long do you think it is before somebody can put a quantum computer in the cloud and start to accept requests?

[0:57:40.1] ZM: There are people that will say that they have that ability at the moment and I think even, you know, even companies like Alibaba I believe, I think I just read an announcement yesterday that they are planning to do a quantum computing in the cloud. There's also Microsoft and Google and IBM and D-wave and Intel, probably and so forth. But again, when we say quantum computer at the moment, we really mean, a handful of qubits.

Now, even though it's a handful of qubits, because of this 2^n idea, some of the computations you can do are already getting to that stage where we can do problems that no classical computer can hope to do at the moment. It's questionable whether we've reached that at the moment but a lot of the projections are that by the end of this year, we'll really break through some of the first examples of algorithms and solutions to problems.

A lot of them in the simulation of physical systems or chemistry that we'll be able to do problems at classical computers shouldn't be able to do anytime in the near future. This is the sole notion you might read about in the news about quantum supremacy. Quantum supremacy, it doesn't mean that quantum computers have broken all classical computers but it will mean that this is really one of the tipping points of when quantum computations starts to get ahead of potentially what's possible with classical computers.

[0:59:13.1] JM: All right, well, this has been a great explanation for how quantum computing exists today, where it's going and some of the big questions that remain.

So Zlatko, I want to thank you for coming on software engineering daily, it's been great talking to you.

[0:59:29.2] ZM: Yeah, it's been great being here, Jeff.

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