[Scientific Innovation Series 7]
양자컴퓨팅 시대 녹취록

행사일: 2021 년 5 월 17 일 (녹화) / 6 월 11 일 (송출)
기록자: 김지수, 박유원

Introduction

Taeghwan Hyeon:

Welcome to the Chey Institute's Scientific Innovation Series. Today is the seventh iteration of the series, we will focus on quantum computing. I am Taeghwan Hyeon at Seoul National University. I'm really excited to serve as moderator for today's webinar with the world's leading scientists in quantum computing area. Before we get started, please welcome President Park to deliver a welcoming address.

In kook Park:

Good afternoon, ladies and gentlemen, it is my great pleasure to welcome all of you to today's webinars titled The Quantum Computing Era. Today's webinar is seventh iteration of Chey Institute's Scientific Innovation Series. The success of our scientific innovation series was only possible with the wholehearted support and enthusiasm of dedicated supporters of our program. While most people doze off within 10 minutes of scientific lectures, we have captured the attention of almost 9000 people in our previous special lecture on the future of battery technologies and almost 5000 people on the future of semiconductors, respectively. I truly commend those who are there to sift through almost four hours of highly technical presentations.

We will continuously pursue high level discussion with Nobel Prize worthy speakers on key pillars of emerging scientific innovation or the Fourth Industrial Revolution. Today's webinar will take on the exciting yet daunting issue of quantum computing. The past few years in the world of computing have witnessed revolutionary changes that is ushering in an unprecedented era. That is, we are beginning to evolve beyond the classical, binary computing. The quantum computing is expected to be millions of times faster than any classical computer. But it also raises significant apprehension as quantum computing may compromise our vulnerable cybersecurity framework and render existing password system obsolete.

Currently, the quantum computing is still in nascent stages, coined by John Preskill as NISQ era, or noisy intermediate scale quantum technology era. The NISQ computers are kept in ridiculously low temperatures, that is equivalent to about a -273 degrees Celsius, in order to shield it from noise. And the issue of scaling up both in size and reliability is a huge challenge for the commercialization of quantum computing. To address these issues, academia, tech giants and governments are all now investing with heightened intensity in research and development, which entails far more time, capital and effort.

Today, we are very lucky to have world leading scholars that are working relentlessly to get us into the next era. We have specially invited Professor David Awschalom and Kim Jungsang joining us from the United States. And we have Professor Chong Yonuk from the Korean side. In addition, we have Professor Hyeon Taeghwan, who was named as a possible candidate for the Nobel Prize by Clarivate Analytics, who will moderate this afternoon. I hope today's session will clarify many of the questions we have about the quantum computing and share insights on the exhilarating opportunities of this new computing paradigm. I thank you.

Keynote Session

Taeghwan Hyeon:

Today, we have excellent three scholars in quantum computing area. Professor David Awschalom from the University of Chicago and Professor Jungsang Kim from Duke University will joining us by Zoom and Professor Yonuk Chong from Sungkyunkwan University joining on site with us. First, let me introduce the first speaker of today's webinar, Professor David Awschalom. Professor Awschalom is the Liew Family Professor and Deputy Director of the Pritzker School of Molecular Engineering at the University of Chicago. He is a senior scientist at Argonne National Laboratory and a director of the Chicago Quantum Exchange. And also he's the inaugural director of the Q-Next, one of the US Department of the Quantum Information Science Research Centers. His research includes implementation of Quantum Information Processing, with potential application in computing, imaging and communications. Today, his lecture title will be The Quantum Revolution Opportunities for New Technology. Professor Awschalom, please.

David Awschalom:

Thank you very much and thank you for giving me an opportunity to speak with you today. While I wish I could be there in person to share this special event with you, this is the next best thing. So, again, I'm very grateful to all of you for giving us a chance to chat about what really is a very exciting moment in time. Now, one of the things I hope that that Professor Jungsang and I will be able to present to you this morning is this field is filled with surprises and we have to become used to thinking about the unexpected. Trying to exploit a world that isn't directly observable to us every day, but trying to mimic the way electrons and atoms work in their world at the atomic scale and bring that to our world for a new technology. And to put this in perspective, it's quite sobering to think where we were 50 or 60 years ago, where on the left I'm showing you from the Smithsonian, a picture of ENIAC, which was arguably the first general purpose computer. It weighed 30 tons, was the size of a house, and took 150 kilowatts of power. And you compare that to our chips today, where companies like Intel shipping 800 quadrillion transistors every year and each of these technologies on the scale of a millimeter or so, a few millimeters taking 150 watts, a 1000-fold less power. It's an extraordinary time, an extraordinary voyage. But now we're thinking about building a technology based on not small devices, but atomic scale systems. Technologies at the level of individual electrons, individual atoms, individual quanta of nature.

It's an extraordinary thing. And as we just heard in the introduction, classical computers, as I'm using to speak with you today, is based on transistors and binary logic. Zeros and ones. Electrons being present or absent from the gates of devices like transistors. Quantum machines don't work that way. Quantum machines extract exotic properties of quantum mechanics where these quantum bits are not just zero or one. They are zero and one and superposition of this. Infinite combinations of the two at any moment. So, what does that mean? At the end of the day, quantum information science is based on two fundamental properties of quantum mechanics. The first, superposition. Superposition is the ability of any individual object, an atom, an electron, to exist in multiple states at the same time. And the ultimate state they're in depends on how and when you look at them. And while that seems counterintuitive as the way to base the technology, it offers, as you'll see this morning, some extraordinary opportunities. And when all of us in science and engineering are trying to do is exploit these peculiarities, to manipulate objects at the atomic scale for this technology. So, superposition is one of these two critical aspects of quantum computing. What is the other? Well, the other is entanglement. As I mentioned, at the very small scale of individual and it was electron's nature behaves in ways that simply cannot be explained by classical physics. And quantum information science provides new methods of creating and controlling information based on these unique properties, superposition and entanglement. And entanglement is perhaps one of the most peculiar aspects of this technology that has absolutely no classical analogue in our world. In entanglement, particles or quantum bits, can become and remain connected even if they're spatially separated over extraordinarily long distances. You create information in pairs or triplets or large ensembles of particles, separate them and they maintain connection. This is what Einstein referred to as "spooky action at a distance." The act of looking at one impacts all the others because they're entangled. And this entanglement, as you'll see from the series of talks this morning, really is the critical key to scale and build extraordinary machines. Now, where will this have an impact? Well, as we heard in the introduction this morning, we're thinking a lot about quantum computing in the science world, in the industrial world. But the field of quantum information sciences, more than computing. It's sensing and communication in addition to computing. You can think about these as three legs of the stool all forming this field. Computing, as we've heard, offer the opportunity to solve problems not possible, even on extrapolations of future supercomputers. And it's clear there'll be impacts in optimization, encryption and security. It's also worth looking at the left-hand side here, communication. This entanglement I spoke of not only is the core of computing, but it offers a unique pathway to build a new type of communication network, to create a hackable communications and even teleport information over extraordinary distances. And finally, each of these quantum bits, as you heard earlier, we work very hard to protect from the environment so they can do their job and compute. We can turn them inside out and expose them to the environment, at which point they make outstanding sensors. Atomic scale quantum sensors capable of measuring individual quanta of heat, electric fields, magnetic fields, vibrations even to be placed in intracellular systems for sensing and control. We offer extraordinary opportunities and all these will work together to wire sensors into quantum computers, all quantum mechanically to build quantum networks. It's an extraordinary challenge and an extraordinary opportunity that will clearly impact all aspects of life as we think about it today, from finance to security, to developing new materials, to secure elections, to be able to map structure and function of individual proteins, efficient distribution and monitoring of energy. It's hard to know exactly where this will go, but we're beginning to see applications and all of these areas not just in the world of science, but as industry begins to pick up the space and think about where this might go.

Now, how do you build these quantum machines? So, I'm an experimentalist and we think pretty hard about how we can begin to harness these properties and the field of quantum information science has been working with photons, with semiconductors, with individual atoms, with superconductors and being incredibly ingenious and trying to harness these individual properties to build extraordinary technologies. And then in the talk after mine, you'll hear about some remarkable accomplishment with cold atoms to build and scale up amazing quantum machines at the chip scale level. I wanted to share with you the fact that people are working on many platforms, some more successful than others, some in its infancy, some more mature. And I'm going to talk about just one of these today and you'll hear in the following presentation another. But I wanted to give you the sense of the community working with different materials, different techniques. But at the end of the day, they're all trying to do the same thing, create and control quantum state of matter very precisely and very, very cleanly.

So, why are people doing this? I have just this one very simple example, and for those of you who are experts in the field, please forgive me for this rough approximation (that means you, Jungsang). But when we think about our classical technology today, again, using the laptop I'm speaking with you right now. I'm using an Intel i7 core processor. It has 700 million transistors, which is quite amazing, and it's a quad core machine. And if I want to double the computational power of this laptop I'm using, roughly speaking, I would buy a second processor. A second Intel core processor, another 700 million transistors. I'd add those two together. And very roughly speaking, by doubling the number of transistors, I doubled the computational power of my computer. And I could do that again and again, and maybe I could put 4 or 5 of these in here and have 5 times the computational power of this machine. It'll start to get a little warm but it would work. Now, what about a quantum machine? Well, let's say we've built a really simple quantum computer, which today is still not so simple. But let's say we had 10,000 quantum bits or 10,000 transistors, if you like. Now, let's say I add just one quantum bit to that 10,000. Because of entanglement, because of one quantum bit interacts with all of them in quantum mechanical way, adding one bit doubles the power of this machine. Not 10,000 bits, but one. So now many of you can see where I'm going with this analogy. If I have a 10,000 quantum bed machine, pretty small on today's standards, and I added 10,000 quantum bits just like I would you classically I would end up with a computer, 2 to the 10,000 times as powerful. And for those of you who have a few seconds on your hands, you could add that into your phone and see what 2 to the 10,000 is. It's a very, very, very big number. It's this scaling, this entanglement driven scale that is driving much of the excitement of quantum information science with computing. It's an extraordinary thing. It's the power of quantum scaling.

Now, what does that mean? Do I need 10,000 quantum bits? I don't. And again, you'll hear more about this, I'm quite sure, in the next presentation. But just to give you a sense, if I only had 50 quantum bits, just 50, I would need a classical machine that could handle 2 to the 50th memory elements just to record all of the of states of that quantum machine. OK, so I would need a classical memory system with 10 to the 15 sites just to store all the information that machine can hold. And you can see where this is going with a handful of qubits on the order of few hundred, you can begin to store more information than the number of atoms in the observable universe. So it's a really sobering to think about what can happen with quantum technologies and what we might do with technologies like this with extraordinary power of computation. But with that, extraordinary challenges.

So, what are companies doing? Well, in the United States, IBM has had a very aggressive roadmap. If you look at this, they've just published this about a month ago. And if you look at where we are in 2021, which is roughly the middle of this PowerPoint image on the left side of the screen, you can see that there have been 127 quantum bits now, made available commercially. And when you think about that on the scale of what I just talked about, it's already an impressive technology with a roadmap and a few years to go over 1,000 quantum bits. And to get a sense of the scale of this from an experimentalist perspective, there's a sort of an interesting photograph on the right hand side here where you can see on the left the CEO of IBM sitting on what will be an ultra-low temperature cryostat, the director of quantum research at IBM and research in general, Darío Gil, in which this will set a custom dilution refrigerator, as you heard in the introduction to cool a superconducting based quantum machine to millikelvin temperature, fractions of a degree, above absolute zero. And you can see the room filled with electronics for systems that control these quantum bits and deal with some of the problems we'll be hearing about later this morning. So, the point of this is that people are beginning to think very aggressively about how we might move forward.

But I want to go back to what I spoke about before when we talked about the ENIAC and the laptop in front of me. The world has an incredible infrastructure right now with building transistors, some data here from the left shows that Intel alone is making five billion transistors every second. Twenty million transistors per person on the planet every year. And globally, when you think about these numbers, they are extraordinary. The number of transistors shipped all over history will be roughly equivalent to a number of human cells on the planet by the year 2025. It's amazing. And one of the things many of us are thinking about is that, can we harness this amazing capability of making a near atomic scale devices with silicon, using today's transistor technology to create and to control individual electrons, individual nuclei at the quantum mechanical level start to build quantum sensors, quantum computers, quantum communication networks? And I'm going to show you this morning some paths. We're beginning to make some progress here, and oddly enough, one of the way these paths began to form was to embrace something in technology that the world had been disposing of, which are defects. In materials like silicon and other solid-state systems, we've worked very hard as a community to remove defects to make extremely pure materials, to make high-performance electronics. But oddly enough, for quantum technology, it turns out putting the defects back in and missing atoms, if you like, in a lattice offers a way to trap individual electrons, access individual nuclei to perform very clean operations. Oddly enough, it's a defect-based quantum technology. And in materials like diamond, which are semiconductors, the different colors you see from diamond come from different defects in the material. And those of you have purchased a diamond know its value is based on the color, the clarity, the carat, and the cut. In a quantum world, we think very differently. We have another type of 4 C's, if you like.

The quantum coherence, how long can the quantum state survive? How can we control it? How well can we communicate with it? How do the quantum states couple to each other? And I want to focus a little bit at these defects with a small, small film, just a small animation to give you a sense of what do I mean by defect. Well, in a material like diamond, which in a sense is one of the simplest semiconductors, is a lattice of carbon atoms. And we look deep into the lattice, you can see the blue carbon atoms. And if you look carefully, you can see some impurities which are nitrogen atoms in red, which gives some of the diamond its yellow color, if it's not absolutely clear. But there could be a defect, a missing carbon atom. And the missing atom and this defect offer an unusual electronic structure to effectively create one electron that can be trapped and studied with pulses of light, microwave fields. And ultimately, this data shows you on the right, even at room temperature, on the desktop with a microscope objective, you can create, manipulate and control that quantum state quite beautifully. One electron, one quantum state at room temperature. And if you want to, you can add defects. You can take beautiful diamond, start to systematically destroy it, which is something my own students are quite good at, and making arrays of these defects. And the image in the bottom right shows you thousands of these defects, some fraction of which are working as quantum states. And we can grow these materials as other groups can now in the laboratory. Beautiful single crystal, synthetic diamond made from carbon. So, this is one direction to think about building quantum states, using semiconductors and putting the defects back in.

That was from a number of years ago. Where are we today? Well, I just wanted to share with you some recent work they're showing now in commercial wafers, not a diamond, but another semiconductor called silicon carbide, a very common, high powered electronic material that's used in aircraft, solid-state lighting, electric vehicles. It's a very powerful, very common semiconductor system. You could see a wafer on the left-hand side here using the same idea of by putting defects in there, one can create and control individual quantum states. And that data in the middle that looks very much like one atom is a single electron on a commercial wafer whose quantum properties are being controlled with a 99% fidelity. And this is an example to show you how fast this science is moving, how the knowledge of one material can be moved to another, and really pushing this physics towards technology. And the curves on the bottom on the left, for example, show you some theoretical methods applied to these experimental systems to extend their quantum coherence time 20,000 times longer than they exist naturally. Now in the many tens of milliseconds hitting one hundred milliseconds. And that may seem pretty short, but given that it takes picoseconds to flip a spin, this is a very long ratio of operations you can perform to the lifetime of the state. And the curve in the bottom right shows example of single nucleus in that same commercial wafer. It is the nucleus of silicon-29. Putting the information into that nuclear spin, using it as a single atom nuclear memory and coming back later to investigate it. And all this is to show you how quickly and how powerfully the experimental techniques are moving to build atomic and subatomic technologies in a handful of years.

Now, what's the industry doing with this? I thought I would share with you one very recent result from Intel, where they pose an interesting question. Could you use today's commercial fab lights? Just what I was saying in the very beginning of my discussion. Could we harness today's fabrication techniques to build a quantum technology? And they had an idea using a 300 millimeter wafer facility and relatively inexpensive optical lithography to start a path to build a billion quantum bits on a wafer. And this is an experiment. They have not done this, but it's an experiment. And they even came up with a theoretical idea of how you could connect and control these quantum bits with transistor type gates. I won't go into that now, but let me just show you what they did, which was just announced about a month ago. They took this idea and they developed the entire chip on their fabrication line. And the data in the middle of the screen in orange is these quantum states in silicon of individual electrons through a commercial process. So, the reason I wanted to share this with you isn't because this is a working quantum machine, it's not. But it shows that the industry is trying to harness today's fabrication techniques, being pushed to the nanometer scale for transistor technology, to build quantum technologies. So, we're not there yet, but it's an exciting development.

Now, this is computing, what about communication? So, entanglement offers an unprecedented way to develop connections between remote states by using entanglement as an unhackable platform, but also as a way to teleport information. So what do I mean by that? Well, many of you are probably familiar with the fact that looking at a quantum object changes it. The act of looking at it perturbs it. Ad you might think, well, that's that's not very good for a technology, which I might need to look at. But it's exactly what you want for a secure communication technology. If I send you a message and you want to be sure no one has used it or looked at it or tampered with it, wouldn't it be nice to have a quantum secure link where anybody looking at my message would destroy it and you would not receive my message? So this is an exciting direction to think about. But once you've established entanglement between the two of us to send information, you can do something else which is unique in the quantum world called teleport. I can bring a third object to this entanglement link and instantly send information from one place to another. Information (in blue) brought to the entanglement, you see, gets transferred instantly to the destination. And people are thinking in the world of theory and experiment, how one can use teleporting has a new means to do secure communication. And while you can actually teleport now at the level of individual photons and information from individual atoms, there's a lot of work to do to build a meaningful communication technology based on this platform. Now, that's not stopping people working on it. How are quantum networks being developed around the world? Well, much like we do today and the way that I'm communicating to you right now. Through satellites and optical fibres. Using satellites as ways to create entangled pairs and distribute them to earth bound stations. Many of you know the beautiful experiment in China, building quantum satellites to do this entanglement distribution over 1,200 kilometers. It has an advantage, obviously, of using very long-distance paths for the satellite. But there are experimental challenges. There's limited bandwidth. There are concerns about weather. They can be relatively expensive to launch. In parallel, people want to use today's optical fibers. We have fibers all over the world for communication. Can we use the same fibers for quantum communication? Well, the advantage is we could build quantum technologies that are compatible with these networks. They're reliable. They have high bandwidth. But there are other challenges. Much like today's technology, we need memories. We need ways to swap the entanglement from node to know to node to reach long distances. Are people working on this? Who's working on this? Many people are working on this. Six or seven years ago, there were a handful of groups and now, satellite and ground based programs span China, Japan, Canada and Singapore, Switzerland and the U.K., the Netherlands. The Netherlands had a very nice, recent, beautiful announcement about protocols to develop their plans to reach in next year quantum links between all four major cities in the Netherlands for quantum entangled networks. It's extraordinary to see how rapidly this field is moving. And how the world of science and engineering are coming together to take information from one and apply it to other and use scientific discoveries to develop new technologies. New technologies probe new scientific issues. And working together, there's been remarkable progress in this direction. Now, I'm in Chicago right now. And we have our own prototype network here. It's a 52-mile quantum communication testbed in the suburbs of the city. And I wanted to share with you, why would we do this?

What do you learn by trying to send quantum states in the real world versus a laboratory? And one of the things you learn in the real world, which to date on the right shows, is that in the real world, particularly here in Chicago, we have weather. So Jungsang is smiling because he happens to live in a part of the United States where it might have less weather that we have here in Chicago, but there could be big temperature changes during the day, even with optical fibres underground. And this is some data taken by one of our students in the course of one day, roughly 24 hours, looking at the arrival times of entangled pulses as the fiber changes its length due to changes in the ambient temperature. And over these 52 miles, these fiber lengths can change on the order of half a meter. They can change a lot, which means there are other issues with quantum communication to think about. Synchronization, timing of entanglement, how the changing of the length of the fiber (stretching it, if you like) changes the polarization of light going through it. So as you move from the laboratory into the real world with quantum technologies, it's important to think about and be prepared for unexpected developments, which you might not anticipate in the very beginning. And that's what we're learning here by doing exactly these measurements.

Now, I've talked about quantum sensing and a little bit about motivated quantum computing, but I haven't talked about quantum sensors. And quantum sensing metrology is arguably one of the most rapid growing aspects of this field right now. And already quantum sensors are being deployed. So if we take these quantum states and expose them to the environment, as I mentioned, every quantum bit is a sensor. And these sensors can measure very small fluctuations in magnetic fields, electric fields, temperatures, phonons or vibrations. And in many of these materials, like diamonds I mentioned earlier, these quantum states are inert, meaning they can go comfortably in living cells. And the middle image here are diamond nanoparticles in the human umbilical vein, endothelial cell they use to measure the temperature of the cell as it grows. Now, you might wonder, why do you want a nanometer scale sensor in a living cell? What's the question? Well, in these experiments, not in this umbilical cell, but in other cells, the question is, oddly enough, a pretty simple one. How does temperature affect cell division? And is the temperature uniform in a cell? And recent experiments of quantum sensors have showed an extraordinary result that in fact the temperature of the cell is based on where you look. And where the temperatures are changing affect the cell division. There are extraordinary discoveries being made now with quantum sensors that will impact how we live. Another example was an effort that started many years ago, actually at IBM, joined with universities, which is can you take magnetic resonance imaging or NMR and push it to the level of single molecules? Today's commercial NMR instruments, or magnetic resonance imaging, use roughly 10^{20} to 10^{22} nuclear spins for their images. Imagine you could build a technology that could resolve a single nuclear spin. And imagine you could do nuclear images of individual molecules in real time. So, that's hard to do and that has not been done, but it is possible to start taking nuclear detection of individual molecules at room temperature. And this early data on the right, which doesn't contain any structural information, but just very nice room temperature detection of nuclei of a molecule on the desktop. Again, improving the sensitivity at least tens of orders of magnitude. Imagine how the world would be different if we could look at the structure function relationship of any arbitrary protein in us. Imagine how this would impact pharmaceutical design, disease detection. Quantum sensors have extraordinary promise. And while they have incredible sensitivity, there are challenges. How do you do these measurements quickly? How could you do them at the time you continue to in a solution with real vibrations and noise, anticipation in the system?

There are many challenges in front of us, but the goals are incredible and the impacts of quantum technology and life sciences could be extraordinary. And we learn a lot. As you heard earlier, cooling the systems down to low temperatures is to protect the quantum state. We also need to be able to handle the noise and protect the quantum state of the sensor. So many of these challenges will be threading all of these disciplines: communication, sensing and computing.

Now, what's fascinating to many of us is a decade ago, these were emerging opportunities. And now we stand back, we can begin to think about where are these efforts happening around the world. And it's amazing. There are quantum efforts at the national level: Canada, the United Kingdom, Germany, China, the Netherlands, France, Russia, Korea, of course, Japan, Australia, Singapore, Europe and of course, the United States. There's a global effort of now over 25 billion dollars focusing on national programs for science and technology. It's an incredibly exciting time to be a student. It's incredibly exciting time to be a scientist and engineer. And one of the challenges that all of us face is how we build a worldwide workforce of quantum engineers. Many of the people that we're speaking with in this webinar will be the users of this quantum technology. I'm not sure how many of the speakers will be the users of this quantum technology at a serious level. So I hope that's OK to say. We will be playing with it, but I think the next generation of scientists and engineers will really be deploying it. And for that and I think all of us need to think very carefully about how we're going to build a global workforce. Are people comfortable with these exotic properties of entanglement, superposition teleportation and how will deploy these things that are genuinely new?

So, I think I'm approaching a good place to stop this morning. I hope they give you a flavor of how the world is working quickly to approach single atom technologies. Something that I think 10 years ago was somewhat unthinkable as we hear about companies see the 10-nanometer scale and 8 nanometer scale of electronics. We're doing this in the other direction from the bottom up, building a single atom and single electron technologies whose quantum properties can be controlled exquisitely with extraordinary precision. And I would argue that quantum engineering is now a reality. It's a genuine discipline. It's a discipline that where we need to build a new workforce, think about teaching science, engineering in a different way and attracting a far more diverse and inclusive group into this field. I hope to give you a sense of quantum sensing. That there's amazing opportunity of pharmaceuticals and materials discovery by quantum design. We can turn these problems around in so many directions. Using quantum computers and quantum machines to help discover new chemical molecular systems that help develop new pharmaceuticals and new materials through exact and predictive calculation. It's a promise that really is worth driving the science and technology in this area. We've talked a little bit about developing security through quantum communication. Quantum states, at first blush, seem so delicate. The act of looking at them impacts them. But in fact, looking at them and impacting them is also the basis for building secure communication to ensure that we can extract, copy and replace information during transit to be sure that information sent is ultra secure. And in the shorter term, perhaps as a physicist, if I'm allowed to wear my physics hat for just the last 30 seconds or so, being able to develop quantum sensors to explore the basic fundamental scientific processes in physics and chemistry and biology, using these quantum sensors in a way to explore things which have been difficult, if not impossible, to look at in the past, is something that many of us find incredibly exciting. So, thank you very much for letting me share this with you this morning. I appreciate being here.

Taeghwan Heyon:

Thank you very much Professor Awschalom for the wonderful and comprehensive lecture on quantum computing. Now, let's move onto our second speaker. Jungsang Kim is a Professor of Electrical and Computer Engineering and Physics at Duke University. He is also the co-founder and Chief Technology Officer (CTO) at IonQ, Inc. Jungsang received his Ph.D. in Physics from Stanford University working on quantum optics, and worked at Bell Labs on optical and wireless communication technologies. Since moving to Duke in 2004, his work has focused on engineering quantum computers based on trapped ion qubits. He co-founded IonQ in 2015 to commercialize quantum computing technology. Today's lecture title will be "Practical Quantum Computing with Trapped Atomic Ions."

Jungsang Kim:

Thank you very much. I hope everybody can hear me. I would like to actually start by acknowledging my deep gratitude to the late Chairman Chey who founded Korea Foudation for Advanced Studies. I've actually been supported by his initiative since I was an undergraduate student. And I still remember the day when he invited us to his office in downtown Seoul in the summer of 1992, just as I was leaving for my graduate studies. And I really would like to thank Chairman Chey and his initiatives for seating outstanding science and technology research for for the Korean community.

Now I'd like to start my talk and it's always a big challenge to follow David Awschalom because he gives us such an outstanding talk. But he has also given us a very broad perspective on the quantum technologies. I'd like to really thank him for that. What I would like to do is zoom in just a little bit more into a little bit more narrow area of quantum computing and maybe give you an example of where that technology is. And this is an area where a tremendous amount of activity, very exciting activities are happening in both academia, national labs around the world and also in industry. And I would like to actually start by sharing some of the examples of technological progress that the community is making. But very lately, as some of these quantum computers start to become available commercially, meaning you don't actually have to know how to build a quantum computer to actually use one. And that's actually a big step in the process. I'll give you some examples of some very exciting applications. These are still very early applications, but some very practical applications that are coming about that we have learned in the process. So, Professor Awschalom gave us an introduction of what a quantum computer is. These are making computers out of atomic scale devices. And one of our colleagues, Professor Bill Phillips, who's a Nobel laureate in 1997, indicated that a quantum computer differs more from a classical computer than a classical computer differs from an abacus in the sense that we actually treat information with fundamentally different rules of basic science. And also, this also means that (Professor Awschalom showed us the picture of the very early days of computers) the way that quantum computers may look, maybe very different from how we think about classical computers today. So with that, I'd like to really give you an example of the power of quantum computing in a little bit more concrete form. So Professor Awschalom also mentioned that if you add an atom, add a single qubit, the power of quantum computer doubles.

So, the first enlightening example of this is the factoring problem. This is actually a mathematical problem where if you have two prime numbers and if I tell you how to multiply to give me an answer, we know how to do that. Actually, it's a very simple algorithm. We learned the multiplication in grade school and it's just a bigger version of it, but the algorithm is actually extremely well known. But if somebody gives me a product of two prime numbers and asks what are the factors of those two multiples, that turns out to be a pretty daunting problem. At least classically, the mathematicians and number theorists have not figured out how to do this in an effective way. And this is an example of a one way problem, where multiplying a number is easy, but to factor is really difficult. And these types of one way problems are extremely important practically because that's how we build encryption systems (cryptosystems). For example, if you try to purchase something through your online typical online network today, you encrypt your credit card information and send it over the network and all of that is secured. Or you make a banking transaction, all of those are secured through this public key encryption techniques. So this actually underlies a lot of our e-commerce today, not only national security and things like that, which was an important application 30 years ago. Today, this is everywhere in enabling our online economies. So it's very important to make sure that factoring numbers, that problem remains difficult. Because if somebody can factor these numbers, two trillion dollars a day of commercial transactions in banks can actually be completely compromised and then our banking system basically will collapse. All right. So fortunately, that turns out to be a hard problem. And (actually, let me go back a little bit) this NFS or Number Field Sieve algorithm, which is the very well-known algorithm for factoring numbers. And if you look at the technology at 2003, which is almost 20 years ago, it turns out that with that technology, if you have a 1000-bit number that you have to factor, that will take on the order of a billion years. And that is a long time. And people feel that a 1000-bit encryption is actually pretty safe. And that underlies a very large part of our e-commerce today because it will still take millions and millions of years, even with today's computational technology, to factor this number. Now, in 1994, Peter Shor discovered a quantum algorithm. And basically, if you had an access to a quantum mechanical computer, as outlined by Professor Awschalom, taking advantage of the superposition entanglement principles, you can actually build a quantum computer that runs at one hertz. This means, like a clock cycle, is very slow. You do one logical gate per second. And this exponential problem actually turns into a polynomial problem. Now, this may sound a little bit exotic, but this basically means a problem that's considered really hard all of a sudden because something that is very, very manageable to solve using the technology today. And this huge gain between the exponential and polynomial advances is called quantum enhancement.

Now, it turns out that once you have that, which people have done. My colleague R. Van Meter Have done some studies in the early 2000s to show that just by improving the architectures with without necessarily improving the clock speed, you can actually improve the performance quite a bit. So, with a thousand bit number with a very traditional machine, a hypothetical quantum machine, still takes a thousand years to solve. Just by improving the architecture of these devices, you can actually make sure that these problems can be solved within days. And a billion years or billion years in a day is a very different scale. At this point, you will seriously have a problem with the security of the encryption systems. And of course, if we can actually build quantum computers that can run a lot faster with the clock speed of a megahertz, then this billion year problem can potentially be solved in just a few seconds. And it turns out that this purple line and the blue line down here, these two straight lines, they span over about 12 orders of magnitude in performance. But indeed, the last 50 or 60 years history of classical computers have accomplished performances of computers that are about 12 hours of magnitude more powerful. So, we believe that these are within the realm of engineering and technology. So if we figure out how to build a quantum computer, then you can actually really change the landscape of what's known as hard and easy problems. And of course, we can talk about the implications in cryptography in the future, in later discussions. But this just highlights the potential power of what quantum computers can do. Now, this is just the first example that inspired people to think about quantum computers. And, of course, you can say but Moore's Law says your classical computer's power doubles every 18 months. And that is actually true. And you can actually say that that's why Moore's Law for another 30 years, so that these classical computers become a million times more powerful. Then it is true that this classical curve moves down by six orders of magnitude, an effect of a million, and billion year problem can become a thousand year problem. But by the time you increase the size of your key from 1000 bits to 2000 bits, you're right back where you are because the scaling is actually exponential. And therefore, the power of quantum computers truly differ dramatically in terms of power compared to advanced classical computers. But there are many other examples. People are starting to find out the materials and chemistry optimization and quantum machine learning or different types of algorithms that may actually render comparable or superior power to classical computation. And many applications, as David mentioned earlier, finance and logistics and research and energy and climate research, automotive and manufacturing. There are many, many areas where quantum computers can potentially have an impact. That is very similar to the in the 60s and 70s when people started to build digital computers. You asked the question, what are computers useful for? And people have thought about, yeah, maybe you can make better handheld calculators. That's exactly what Intel was doing. And today, of course, 40, 50 years later, we can have a meeting like this online because with computers and communication technologies have made a tremendous amount of progress. So, it's very hard to foresee what new enabling technologies at this scale can do, but it will be probably an understatement if this technology becomes successful, that it will transform the way we do business or research in pretty much every aspect of our society.

All right. So, let's dive in a little bit more and think about elements of quantum computers. The quantum computers have built out of quantum bits or qubits. Classical bits represent zero one, but quantum bit can be in a superposition state and then it can also be entangled state as discussed earlier today. So, we focus on bits and then we, of course, have to be able to manipulate these bits using logic gates. And very similar to how classical information, classical bits are manipulated using this logic gates to create a general-purpose classical computer, there are this class of quantum logic gates that work on quantum bits that also generalizes and allows us to build a generalized quantum computer. There are some single bit gates, or single qubit gates, and there also what's called entangled gates, which creates entanglement between different qubits. And CNOT for example, is an example of such a gate. But these are what we think about. But what we actually often don't think about or miss is the importance of connections. If you take a classical computer, this is a picture from IBM, and look at what is in the classical chipset. It turns out that we build a single layer of transistors on the surface of the silicon wafer, but we stack on top of that typically a dozen layers of wires. And if you go talk to a circuit designer who actually builds these computer chips, they spend all of their time thinking about how to connect this. And it's really the complexity in the connections that you make between the transistors that actually give you the functionality of the chip. And therefore, our transporting qubits between logic gates inside a computer chip or a quantum computer is just going to be just as useful or important in creating a functional quantum computer that can actually solve practical problems. So, I'd like to highlight the importance of quantum wires, quantum communication within the computer chip.

All right. So at this point, I'd like to start jump in a little bit and think about how we actually build these things using single atoms. Professor Awschalom mentioned about these individual defects in diamond or silicon carbide as potential qubits. But (here on the ion trap side) we actually a little bit more lazy than that. So, we actually just start with single atoms. And this type of technology has been available and being looked at from atomic clocks for many decades now. And here we take an atom in this example, I show you Ytterbium atom, what we do is we strip one electron out, so the atom gets charged and that's what we call an atomic ion. But at the end of the day, this still is a single atom. And if you look at the ground state of this Ytterbium atom, because the electron has a spin of one half and this atom happens to have a nuclear spin of one half, they actually interact with each other and the most stable ground state actually splits into four different levels. And if you pick these two levels in the middle, they actually serve as a very good frequency reference, which can also be used as a qubit. So in some sense, we actually in the ion trap case, we store the information roughly in the nuclear spin of a single atom, and then we actually manipulate that using the electron spin that we can couple with a laser, which is a very similar spirit to the systems using diamond defects and things like that. It turns out that in order to make sure that the qubit (sorry, I'm getting into a little bit of math here). But if you think about a qubit, you can think of a qubit state as living on the surface of a sphere where the North Pole is a state zero and the South Pole is a state one. I'm sorry, this label is somehow messed up a little bit. And then anywhere in between is a superposition of the states and the actual weight of the superposition is defined by two numbers. One is, if you will, if you think about your position on the surface of the Earth, there is a longitude and latitude that actually identifies exactly where you are in the space. It turns out that the latitude that you think about is basically the weight between the zero and the one state and in a hyperfine qubit like this, that natural decay takes thousands of years. So it's actually not measurable. It's practically limited by the collision of these atoms go through inside the vacuum chamber. So the more better vacuum you make, the so-called the T1 time of this qubit state can be made as long as you practically need it. And then the longitude, which is called the phase, shows the relative phase between the zero and the one state. And that is actually defined by the accuracy of the frequency between those two levels. And this physics called the hyperfine interaction, which is the interaction between the electron spin and the nuclear spin of the atom is actually one where the frequency is actually the most stable. This is the most stable frequency system that we know today. In fact, if you think about a similar hyperfine state of a cesium atom, the actual frequency splitting between these two levels is actually 9.192631770 hertz. And it turns out that this frequency separation is exact. Exact so that in the sense that we actually refer to this as the absolute reference of frequencies that mankind measures for any application you want. This is the most stable thing. And that's why we define this. Our second is today defined by the hyperfine state of cesium. Turns out that the hyperfine splitting of the Ytterbium is just as stable. You might as well choose the Ytterbium as your hyperfine absolute reference if you choose to. And therefore, the actual coherence time of the system can be made actually arbitrarily long. We're actually limited by how well we can lock a classical clock to this atom rather than the property of the physical system itself. And therefore, people have demonstrated coherent times of hours in this physical system. And therefore, if you think about a qubit that actually maintains this property for an arbitrarily long time, when it's not perturbed, this would be your choice. And that's why we think this is a very compelling system to build quantum computers on.

Now, although when you if you don't touch this qubit at all, it's nearly perfect. When you start to work with it, then, of course, other physical interactions come in. And then, of course, your system becomes a little bit error prone. So, some of the things we have to do is if you want to initialize quantum state to a well-known zero state, we can do that using a process called optical pumping. And you can do it with very high fidelity, probably error rates of maybe 10^{-6} is actually quite available. Qubit measurement is done by what's called the resonance fluorescence, meaning if you shine one laser beam, if your qubit in one state, it will actually scatter photons and it will glow. If it's in the other state, it will not. And you can do state detection with a much better than 10^{-3} to 10^{-4} levels. A single qubit gates are carried out by what's called Raman transitions. This is shining some laser beams in a particular way, and people can routinely achieve very high fidelity gates using this, where the errors are in the 10^{-4} to 10^{-5} range. And then the entangling gates, which creates the entanglement, uses again Raman transitions but applies what's called a state dependent force and very high fidelity. Two entangling gates has been demonstrated. In fact, just in the past week, there was an experiment that demonstrated 99.94% entangling gate in trapped ion systems. Again, these are all limited by our manipulation technologies to some of the numbers that are shown here. So, you can actually build a pretty stable quantum computers using this technology.

All right. So given that scientific background, what are some of the practical quantum computers can we build today? And I'll give you an example of the systems that we built in IonQ. Again, this type of system has been researched in universities for a very long time, but we actually took that university research and see if we can actually turn it into a practical product. So, this actually is an example of what a typical ion trap lab looks like. This is actually a picture from my colleague and my co-founder, Professor Chris Monroe. This is what an atomic physics lab typically looks like. And this shows an example of an ion trap experiment with a few optical tables full of equipment and packed with control instrumentation and so on. And you can see that, OK, this looks like an experiment, that this really doesn't look like a computer that you think you can you can deploy somewhere. So about five years ago, we decided to take on the challenge of taking the system and turning it into something that is a little bit more manageable. So we went through a system design process. This work was funded by IARPA starting 2016. So we took the very complicated experiment and see if we can compartmentalize them into different components, subsystems. And then we actually figured out a way to pull it together and then see if we can actually deploy a software controller. So, you can actually operate this by entirely by software control and remove all the students and postdocs who are turning knobs and take them away. So that actually gave us a blueprint for which we can actually start to build commercial systems. So, we launched IonQ in 2015 and started building commercial quantum computers in the beginning of 2017, which is about four years ago.

All right. So, the qubit technology here is that we start with a chip and this actually shows an ion trap chip that was micro fabricated using standard silicon fabrication process at Sandia National Labs. The middle of this chip is about a centimeter and a half, maybe 1.2 centimeters in size. And then in the middle of this, blown up is shown a chain of individual atoms. Each of these blue dots correspond to a single Ytterbium atom. And in this picture, we certainly show 80 individual atoms or 80 individual qubits. And the separation of these atoms is just a few microns. So, for example, these 80 individual atoms fit on the length of less than half a millimeter of space. And these are based on individual atoms. And then we actually design our control architecture so we have a full flexible control over this thing. And we really don't have to worry about manufacturing errors because all of these atoms, it's the same isotope of the same species of an atom. They're exactly identical. So one of the things that we do is we learn how to manipulate these things.

So here in this video, you see atoms, these individual dots, that's showing up. What we're doing is we're loading individual atoms from one corner of this trapped chip and then we're applying voltages through these electrodes and move it into the middle. And then we're building up a long chain of ions that we use as a quantum register. In this example, it shows you how to load exactly 23 ions. And that's how we actually build this system. In this example. this is all done at room temperature. The way we control them is we start with a laser that we split in this example 32 ways. And then we focus each of these 32 laser beams onto individual atoms. And then when you have a quantum circuit that you have to run, what you do is you start by initializing. This is called an optical pumping so all of the quantum state initialize to zero. And depending on the actual circuit you have to run, each of these laser beams that you're seeing actually shows the action of entangling gate or single qubit gate. This is how you actually run the gates, similar to how you run gates in classical computers to carry out your computation. And these are completely programmable by turning these lasers on and off with certain processes. When you're all done, you shine a laser beam and some of the atoms will glow, others will not. All the glowing atoms will give you a result of one, and the non-glowing atoms will give you a result of zero. And that's how you read out the computation at the end.

Now, the nice thing about this architecture is that for example, here we show an example of an 11 qubit fully connected quantum computer that we built maybe two and a half years ago. And here, all of these 11 qubits are in a single chain. But it turns out that we can actually pick arbitrary pairs of ions in this chain and apply an entangling gate. Although they are in a linear geometry, you're not limited to nearest neighbor interactions. You can actually do arbitrary connections. And therefore, in an 11 qubits, there are 11 choose 2, which is 55 entangling gates you can do. And that is somewhat different from other solid-state technology where you actually have to print the wire between the qubits to actually exert that gate. Now there are people are really starting to appreciate the value of this all-to-all or higher levels of connectivity. And this actually inspired a lot of research in various communities on various physical platforms to improve the entangling connectivity of the system. But you can see that in this experiment, we have demonstrated all 55 pairs of entangling gates with a relatively uniform performance that we're able to accomplish. And in order to actually start to compare how well quantum computers work, just like in a classical computer, when we buy a computer today, we don't necessarily ask how many transistors on the chip or what is the clock speed anymore. We used to ask that question. We don't do that very much anymore. But we think about how fast can it actually solve our problems? What is the speed by which you can solve a mathematical problem or how fast it can communicate to some other person? So the actual benchmark of the performance should actually be performed using algorithms. And this is an example of some work done by Professor Margaret Martonosi's group out of Princeton University a couple of years ago, and they actually compared commercially available quantum computers from IBM and Regetti with an experimental system they had access to at the University of Maryland that had 5 physical qubits. So if you look at this bar, all of these correspond to various types of quantum algorithms you can run. These are all relatively small algorithms you have because the quantum computers today are not very large. And if you look at the black bar is the ion trap machine they had access to. The light brown colored ones are IBM and the grey colored ones are Rigetti. You can see that in some of these things that requires 6 and 8 qubits, you could not get any results from ions because they only had a system with 5 qubits. The next thing you see is this HS2 and QFT. These are some simple algorithms that have relatively simple connectivity. You can see that all of these computers work pretty well. So this success probably means how well does a computer actually return the expected results? You can see that the bars are pretty high on these algorithms. The ion trap is a little bit higher because their fidelity is a little better. But these algorithms actually have simple enough conductivity that most of the systems work really well. But if you start to look at other algorithms where the connectivity starts to matter, you actually have to sometimes translate one logic gate into multiple logic gates and those actually start to cost your performance. And here is where the all-to-all connectivity really shines. You can see that the ion trap performance is uniformly high and that really tells you that depending on the structure of your problem or the architecture of your hardware, sometimes there is a match and the performance is good. But if there is a bad match, then the performance actually will suffer. So this actually shows you the importance of that connections and wires and how you architect your processor once you have a good components to build them with. So this should be something that the community should really think about in building more and more powerful computers.

All right. So, I'd like to spend the last 10 or so minutes just talking about some useful near-term quantum algorithms. And this really has been growing very, very rapidly just in the last year or so as people who have ideas and algorithms actually start to have real access to quantum computers. Now, these quantum computers are not very powerful yet, but they are available through IBM and IonQ and places like AWS, Amazon Web Services, and Microsoft Azure. So as people actually start to get access to computers, it's very similar to when I first learned how to program in the 80s. I could actually buy a small computer that allows me the basic interface so I can start to program. Then I think these kids who don't really know how to build a computer can actually start to learn how to use it. And it's very, very fascinating that that we are actually approaching that stage. So one of the things that are really starting to show up is quantum machine learning. There are some really fascinating theoretical progress in all of these papers, all in the last six months or so. There have been some fundamental quantum advantages that have proven for learning complex patterns, exponential gain in predicting certain errors and utilizing quantum correlations in generative modeling. Now, these are some of the fascinating and very practical advantages that people have proven. But now we can actually take some of these ideas and start to see if we can implement them in real quantum computers. And then the other is quantum chemistry and material studies. There are variational quantum eigensolvers and the simulations of dynamics of excitation. These turned out to be very, very complicated problems in classical computers that blows up on you and the computational chemistry or materials community have been struggling with this problem for the last 40 years. And there is a true opportunity for future generation quantum computers to really change the landscape on which the complexity of these problem stand. And then the optimization problems. There have been a lot of progress on this as well. These are very important problems that have a practical impact on logistics. And logistics meaning if UPS or FedEx or Coupang wants to deliver thousands and thousands of packages to thousands and thousands of people, what is the optimal way of doing that? If you're building automobiles with very complicated manufacturing floor, what are some of the ways to optimize how to utilize the resources? So these are tremendously difficult problems that classical computers have a very hard time solving, and if you can actually come up with a solution that just gives you a few percent improvement over existing solutions, there is a tremendous amount of commercial value there.

So today, I want to give you some example of learning complex patterns, which was run on a real quantum computer. So here we think about what's called a nearest centroid classifier. And it's a classic example of machine learning. And here you're given a data set. In this example, there is what's called an IRIS dataset. And this is thousands of pictures of these flowers, iris flowers. And there are three different types of them. And what your goal is to look at the pattern of the shape of the flower and tell which one of these three that your iris belongs. So, a typical machine learning problem will be given thousands of pictures. You actually look at them and then you train your machine and then you give it the next data point and see if it can tell which one of these three categories that the iris belongs.

Same thing, an example here is a handwritten database. This is an MNIST database of handwritten digits. And the question is, can you actually give it a digit that it recognize? Can it recognize what number it actually corresponds to? So what you do is you take this training data and then create a model and then you find the centroid of these of these things and then you actually do a classification. And here what we call, you define a measure of a distance and if you're given a new data point, what is the closest centroid can you find? And that's called a nearest centroid classifier. Then once you have this model, then when somebody gives you a new set of data, can you predict the labels of these new data using a quantum mechanical method? And that is actually the problem, very useful in in character recognition, image recognition and things like that, which has a very large number of potential applications. So in collaboration with QC Ware, we have come up with a logarithmic depth circuit, which is extremely efficient in taking advantage of the fact that we can provide all-to-all connectivity, which means that an entanglement gate like this crossing multiple qubits across can actually be executed very effectively. And then you actually also have a distance estimated circuit, which is very similar when you run this in reverse order. And then you actually do the data analysis. And then we also figured out some error mitigation techniques. So there are certain patterns of data that's expected and certain patterns of data that are not expected. And if you see the unexpected data show up, then you conclude that some error happened in your computational process. So you can actually use that information to actually exclude that from your data, because you know that error has happened. It is a kind of an error detection technique. So we ran this over imaged data sets of viruses. And the classical classifier has an error of about 8 or 9%. The quantum error models, we started with something like 30% errors, but we've actually done this post-processing and then was able to reduce the error down to about 15% or so. So this is still not super competitive with classical classifiers quite yet, but we think we can do very well. And we can also show that in some of these areas, once you do the error mitigation, you can see that some of these confusing points can actually be rejected. It turns out that in these three irises, one of the irises is very well separated from the other two. Meaning that it is so different that it's really easy to tell one from the other two. But the other two are very confusing from each other. So you can see that naturally the data actually has some overlap. And that's why even for classical classifiers, they actually suffer from some additional errors. We've actually done this over MNIST database using handwritten characterization from 8 qubits. So here we look at 40 samples, just trying to differentiate between zero and one. And the classical accuracy of classical threshold is here in diamond. When you do an error mitigation technique, we actually see no errors in quantum computer. So this zeros and ones are very easy to distinguish. 2 and 7 a little bit more confusing, but we can actually perform just as well as the classical classifiers. And by the time you get to differentiate the 4 characters and 10 characters, we were doing as competitively as well as the classical algorithms can. So these are literally run on our quantum computers. And you can actually today run some of these examples by using commercial systems. This is another example where instead of characterizing or identifying the characters, we can actually start to generate these arbitrary handwritten digits using quantum computers. And this is so-called generative adversarial networks. These are machine learning techniques to generate patterns from component patterns that you have. In this example, the handwritten digits on the right. These were actually generated by our quantum computer. It's given a database and if you look at some of these performance metrics of blown up here, we actually compute extremely well and sometimes outperform classical generator patterns. So some of these machine learning techniques, very practical ones are starting to become quite useful. And then this shows an example of a binary paint shop problem. This is an example where we did not know that they did it, but Volkswagen and some researchers there have used IonQ quantum computers through the cloud to run through some of these optimization problems that actually pertains to an abstraction of an issue they see on manufacturing floors at the factories.

So, what I like to jump over to is see if we can just think a little bit of the future where we can go. So Professor Awschalom mentioned that by the time we get to hundreds or thousands of qubits, we can start to do some truly challenging problems that are intractable in classical computers. So we can actually think about scaling these quantum computer design, trapped ion quantum computers. First by having a finite number of beams that control this but by moving the ions back and forth, we can actually address a larger qubits. Or there are some technologies to shuttle atomic ions from one location on the chip to another. And this allows you to build multiple chains of quantum processor nodes that can actually communicate with each other by physically shuttling ions from one location to another. And then the final opportunity is using the basic foundations of quantum communication technology. This is called an entanglement distribution. By entangling the memory qubits into photons and letting the photons interfere with each other. You can use that as a mechanism to allow the photons to interact and create entanglement between atoms in two different locations. And while that actually forms the foundational technology for quantum networking, it can also be used to build what we call the modular, scalable quantum computers. And in this example, we think about having 16 different quantum computing nodes, but they actually have this fiber optic through which they can send single photons. And by adjusting this optical cross connect switch, you can allow entanglement to be generate arbitrary pairs of these units. And what you can do is you can now, just like how we build our most powerful computers by building racks of computers and connecting them through Ethernet and communication infrastructure to build data centers, we can actually build scalable quantum computers by generating large numbers of individual computers and connecting them through a photonic quantum network. So that's kind of a very exciting prospect. Of course, none of these are easy. We have a long way of technological evolution to go. But in trapped ion quantum computers, you know, we started from this kind of lab scale experiment in 2016. By 2018, we built commercial quantum computers that are the size of a couple of meters. And these are the quantum computers that you can actually access today on the cloud 24/7. In more recent experiments at Duke University, we actually have taken some of these optics and started to contract them down to a level where we actually now have an overall quantum computer that fits on a roughly a cubic foot of space. And this actually has a small room temperature vacuum chamber that has a volume of about one cubic centimeter. And then all of the lasers and imaging systems are now integrated into this little box. And then more recently, people have started to build in some of these optical beams, which we typically run through optical fibers and focus them onto the ions. They actually have started to pipe all of these photonic routers underneath the trap. And this is an experiment done at MIT Lincoln Labs just last year, where all of the optical ions traps are now actually integrated into the chip. So we can actually see that by introducing more and more aggressive integration technologies, we can one day put an ion trap quantum computer something very close to a chip. Although we started from the laboratory experiment like this, very similar to the ENIAC classical computer that they showed earlier in the talks, we can actually now move to a much more integrated photonics devices in the future.

So with that, let me try to conclude. It's very exciting that fully connected, programmable quantum computers are actually available today for anybody who's willing to use it. And actually, that changes the landscape of how quantum computing research is done. I do believe that we have to continue to invest in various qubit technologies. But I do also believe that people with ideas of how to apply these quantum algorithms onto a various range of problems can actually start to work and not wait anymore for quantum computers to become available.

Progress in quantum machine learning, quantum chemistry and quantum optimization algorithms are starting to really compound. And some new approaches and proves are suitable for this near term. These intermediate scale quantum computers are starting to make be available. And all the implementation of some really practical, useful applications, such as image recognition and such and optimization problems are really starting to take hold today. And I think we're on track to reach the commercially useful applications in this decade for sure. Hopefully a lot sooner. And I'd like conclude by following David's comments that workforce development, the scientists, physicists and engineers who can actually build the next generation of quantum computers is extremely important. But also we're ready to actually train those programmers, like myself in the 80's. I don't know how to build a computer, but I know how to program and I can start to figure out how to use these machines to our advantage. I think we are similar to where we were in the 70's and 80's, where we can start to train the next generation of scientists and engineers to actually learn how to use quantum computers to their advantage. And as the power of quantum computers continue to compound, the real applicability and opportunities for that application space, I think will open up very quickly. And with that, I'd like to conclude and thank you for your attention.

Taeghwan Hyeon:

Thank you very much, Professor Kim, for the wonderful presentation. Now let's move to the final speaker, Professor Yonuk Chong, at the Sungkyunkwan University Nano Engineering Department. He's also serves as the director of the Quantum Information Resource Support Center (QCenter) funded by NRF of Korea since August 2020. His work has always been focused on the quantum application of superconducting devices, especially with the Josephson junctions. He's now leading a project team on the superconducting universal quantum computing system development. Today's lecture today will be "Superconducting devices in quantum technology: quantum computing made it easy." Professor Chong, please.

Yonuk Chong:

Thank you for inviting me to this nice workshop conference, and I really appreciate the previous speakers, David Awschalom and Jungsang Kim, giving a great introduction about quantum computing technology and the ecosystem—how it's evolving rapidly these days. So today, I will introduce the superconducting technology, which is one of the major platforms in quantum technology these days. I will try not to dive too deep into the technology, but I really want to deliver to you how we can approach the quantum technology in terms of the device that's made out of the semiconducting technology that's existing in the present days. And also, I will shortly address the Korean government's strategy on how to follow the leading countries or leading technology platforms in terms of the nationwide projects.

So, as you heard already, quantum technology is used in various fields, including quantum computation, quantum communication, quantum simulation, and quantum sensing. To make these things possible, there are many platforms—we call them platforms—the physical systems that enable quantum mechanics in the real world. That includes superconductors, ions, quantum dots, defects in diamonds, and also photons, or the laser light. I will mostly focus on the computation and the technology here.

So as the previous speakers mentioned, quantum computing was kind of initiated, everyone says, in the early '80s following Feynman’s mention, “Hey, the world is quantum. So, why not simulate the world in terms of a machine that's perfectly working in quantum mechanical principles?” Yes, but that was physicists’ dream until mid-'90s, maybe, where Peter Shor suggested Shor's algorithm that may have cracked the crypto system of these days after the efficient factorization algorithm.

But if you look at the first conference that's in '81 in MIT, there were really great scientists gathering there, about 50 scientists together, talking about how the quantum computer can be something, but none of them thought that that was a real serious job. But they had some really great ideas. And another amazing thing is I'm pretty sure none of them was thinking about superconductors as one of the major platforms to make a quantum computer in those days. They were thinking of naturally quantum objects like atoms and photons, etc. So, this year is the 40th anniversary, and IBM and MIT have some online conferences about the 40th anniversary, so you can look up on YouTube about Charles Bennett and the early pioneers talking about the early days of quantum computation. What I really want to say is that this is only a 40-year-old idea and the initiation of the real technology development was about two decades ago. But now we see that quantum machines, quantum computers working perfectly quantum mechanically on the cloud 24/7, so you can access them anywhere in the world through the Internet.

The superconductors came late. I mean, in the initial stage, they were mainly thinking about atoms and ions. After the suggestion of the Shor algorithm in '94, right after that, the quantum operation of quantum objects, qubits, was demonstrated in ions. So, superconductors came a little late, but about the same time when they thought about the quantum computer idea in the early '80s, Tony Leggett, the famous Nobel laureate suggested, "Hey, can we think of a macroscopic object—macroscopic means a big object. It's not the atom, it's not the electron, it's kind of material or stuff that may be visible under the microscope or even with naked eyes. Can we think of that as a quantum object?" And the question was answered by the pioneering scientists, John Clarke, John Martinis, Michele Devoret in mid- '80s. When you make a superconducting device, then we can think of it as a quantum object. That means a superconductor is, as you may know, a metal that flows current without any voltage, without any dissipation, so zero resistance. But at the same time, a superconductor or a metal piece can be thought as a big chunk of quantum object which resembles atoms and electrons in a microscopic world. Yes, in order to make a quantum computer, we need qubits, as previous speakers explained in detail. So, when you have some objects that have two quantum states, you can make a superposition of the two states—it's like Schrodinger's cat. You have a cat that may be alive or dead or you can make a superposition of a live and dead cat, which we can call a zombie cat. And when you observe this zombie cat, it can be either alive or dead. So, it's not really proper to say that live and dead states co-exist, but we can say that the cat is alive or dead. But before we observe, before we see it, we don't know whether it's really alive or dead, but it's kind of in the middle of a live and dead state. That's the superposition, roughly speaking.

If you have two of these qubits, then you have you can make entanglement between them, meaning you have two qubits far apart, but somehow, they are connected by some magical word entanglement, that if you measure one qubit, if you see one qubit, one cat, live or dead, and the other qubit's state is kind of determined by the measurement of that qubit. So yes, you have a qubit that has two states at the same time, kind of, and you have entanglement that remote two qubits can be connected quantum mechanically. And actually, we have some more scientific definition of qubits that's called the DiVincenzo criteria.

If you have qubits, then you can make a quantum computer. Yes, so this is already well explained. If you have ten qubits, then you can have 2^{10} combinations, so a thousand twenty-four combinations, out of the ten qubits. And then all these combinations, coefficients, the colored clovers here, are actually your encoded information and you can do the operation on these qubits that make all the combinations rotate together. That’s kind of parallelism, so you can have a big computation space, you can operate on them in parallel, so you have some computing power.

In the end, only you can measure 10 qubits. So, you have to make some smart algorithm that you can solve your problem in this big computation space. But in the end, you can read out only 10 qubits, but still you can get the answer. But the size of this computing space is huge. So, when you have 50, then that's already bigger than the memory of the best supercomputer on the earth. And if you have 300 or 400 atoms, that's more than the atoms in the whole universe.

So naturally, you may think that a quantum state system is made of ions and atoms. Of course, this is the ion trap used in the IonQ system. And after two decades, maybe a quarter of centuries of scientific development, we have many platforms that can perform quantum operation on it. And today, I will mostly focus on superconducting devices. Actually, there are already quantum computers, quantum machines on the web you can access. All the big companies are actually building or actually providing quantum computer service around the world. And if you look at those companies landscape, IonQ is providing an ion-trap quantum computer together with Honeywell. And there are companies that are trying the ion-trap like AQT, and PsiQ is providing photonic service, but most of the companies are actually providing superconductor-based based machines, especially the big size machines are superconductors. Size matters, but the size is not everything, I will tell you about it later. The superconducting qubit was demonstrated in ‘99 by the pioneering scientist Yasunobu Nakamura at NEC at the time. 20 years after the demonstration of a single superconducting qubit in ‘99, we now see that we have a system that's running autonomously. So that means you have this system, it's running 24/7 without any person in there. It's calibrating itself and it's running all the time.

In 2019, eventually the Google team demonstrated quantum supremacy. Quantum supremacy means you make up some mathematical problem that's pretty hard for conventional computers, currently classical digital computers, but may be easier for a quantum machine that can solve that. So, they built a 53-qubit Sycamore processor and the whole system and let it solve the sampling program they created, and then they predicted the classical super computer Summit could not solve it in a million years. Of course, classical computers can make a better algorithm to shorten that. But as David Awschalom said in the previous talk, if a classical computer wants to double its computing power, you have to build another supercomputer next to your current supercomputer. In a quantum device, if you want to double your process, you just need to add one more qubit, assuming that you have a full entanglement scheme in your process. Of course, that's not everything, you need a device, but also you need all the stacks of computer, meaning the control circuits and software stacks, etc. But in the end, superconducting technology enabled that. Starting from the device, you need a big and cryogenic system, a cooler I mean, to bring the superconducting device down to 10 milli-Kelvin, which is one hundredth degree above the absolute zero, which is cool. And you need to have all the microcontrollers to have quantum gates on your devices, and you need all the software stacks to control and run the algorithm on top of that. The whole system engineering has been developed for the last 20 years and now it's pretty mature so that you can use it as a kind of cloud-based system. The real system looks like that. it is the one with my lab picture. Don't panic, the cryogenics is hard, but it's not that hard because you can buy it. So, you just buy a cryogenic system, push the button, it cools down. You don't need to care. And especially on the user side, as Jungsang said in the previous talk, you don't need to take care of how the system looks like, you can just access it, run your program on it, and you can get the answer. But as a hardware developer, then you need to know that the inside of cryogenic system looks like that. You have a warm stage, then you have a little bit colder stage, and you have a little bit colder stage. And at the end, at the bottom, you have the coldest stage, which is about 10 milli-Kelvin all the time. And you attach the device here and run the device here through all the micro-connections from the room temperature to the cold storage. And all the microcontroller is coming from the outside usually. And here we have this and all the microcontroller circuits here. Of course, we need to miniaturize them and actual quantum computers have custom-made miniature version of this.

So how can we make a superconducting device as a quantum device? So, in the atom, you may remember from your high school year physics class that you have an atom, then you have a nucleus, and your electrons are circulating around your nucleus and you have a small orbit that's your low energy state, and a bigger orbit that is a higher energy state that encodes your information zero and one in your quantum state. Actually, this is kind of the oscillating of electrons. So, we can model it as a kind of oscillator roughly. In electrical circuits, you can make an LC oscillator, which is an inductor and a capacitor that make your electrons oscillate back and forth. And this oscillator can be treated as a quantum mechanical object when you just think of it as in the cold stage. That means you have an oscillating electron that has a zero state and a one state. A zero state means your electron stays still and a one state means the electron is oscillating.

To make your qubit meaningful, you need a non-linear device called Josephson junction, which is a device that two superconductors are sandwiched in non-superconducting materials in the in the middle so that you can make superconducting electrons tunnel between these two electrodes. And the current-voltage relation has this Sine term in it, which is the famous Josephson relation. And this Sine term gives your non-linearity. Why do we need the non-linearity? When you have an LC oscillator, you have all the quantized energy levels, but these quantized energy levels are equidistant. So, you cannot select two of them to make your qubit as your data encoding system. But when you have a non-linearity, you can distort your Hamiltonian. So, you can make specific two systems in your specific frequencies and all other systems are separated in your frequency domain. Another advantage of the superconducting device is that when you make a device, after running your system, you can tune your frequency. That's kind of an advantage and also a disadvantage of the superconducting system because you have freedom to change your frequency so that you can make your system tunable so you can tune your system afterward. The disadvantage is that also it's sensitive to the outside fluctuations. So, unlike atoms—for atoms, the frequency is fixed, so it's ultra-stable—the superconducting device can suffer from the outside fluctuations. But this is again an advantage that we can tune the system after we fabricate. And this is actually used in entangling two qubits in the end.

This is just an equation of how to explain your system as an oscillator and a qubit. What I would like to say is that your system, your qubit, is actually an oscillating electron. It's not some special, magical, mythical quantum mechanical effect. But you have a device. The zero state means your electron stays still if you ignore the zero point fluctuation of quantum mechanics, and your electron is just oscillating back and forth and when you encode the one state in your qubit.

How to make entanglement? So, this is a typical to 2-qubit device, for example. You have one qubit here. This is a qubit called transmon. You have another qubit here. When you shine several frequency microwaves here and there, in the end, you make this qubit and this qubit entangled with each other, which means if you measure this qubit and see whether it is one or zero, that determines this qubit’s state automatically because they are entangled. So, this is called the cross-resonance scheme used by the IBM group. And this makes the so-called C-Not gate that makes entanglement between these two qubits.

How to make them? It's also very classical, so you make a bridge, so you just evaporate one metal from one side, oxidize the surface of the metal and you evaporate the metal on the other side. And then you make a small overlap point in the middle. That's here about 100 nanometer size overlap area between two electrodes. That gives you Josephson junction. So, it's not some magical device, but it's just 100 nanometer sized overlap with two metals which can be made in currently existing semiconductor technology pretty easily. I would say easily, but not that easy because you have to make it really uniformly and you have to make a really good parameter you are targeting. Usually you can make several percent of spread when you make a wafer scale device. And in that sense, it's pretty mature. I mean, the Josephson technology is pretty mature. It's already about half a century, I think, people have pursued this technology to make a real useful device and even you have some foundries you can use to make superconducting electronic devices and you have more fabs that can make large-scale, I think thousands or tens of thousands, even millions of junction scale circuits can be made. Qubits again, we really need to make it uniform. That's the challenge. Another thing is the connectivity. Jungsang explained pretty well about the importance of the connectivity. So, to make this superconducting circuits useful, we have to make it connected pretty well. So, in the two-dimensional plane, the connectivity is anyway limited. So, you have to make it connected to the three-dimensional space and stacking chips in three dimensions is not again new technology, but we can use existing semiconductor technology for stacking chips. What we really need to do is to make the stacking interposers superconducting, so this technology is processed already by many groups. And if you see the devices, something like IBM devices, you already see that the chips are stacked together. So, this is one of the devices presented by IBM with a big bridge. The message I would like to say here is that the chip technology is borrowed from the semiconductor industry. So, it's pretty mature. Chip-stacking is there. You can do that. So in principle, we can say that we have scalability, which is not really limited for now and for the cryogenics you can make this big bridge on the bottom right side that you can you can host many chips or qubits there. We don't know whether this works or not. But anyway, it's pretty reasonable to predict that we can make bigger chips in the end. Depending on the types of the driving force—driving means control—if you control your chip with electric fields, you call it a charge qubit. If you control your chip with magnetic fields, you call it a flux qubit, etc. The message here is that superconducting qubits are a circuit. So, a circuit is something you design. That means you design your atom or you design your Hamiltonian as physicists or XXX, and that means you have a Josephson junction and you attach some LC components, which gives you some kind of control over the quantum system that you designed.

In fact, you have an open-source design toolkit already, so this looks like a conventional student's version of the elementary level CAD tool from the semiconductor industry. But in fact, you can design your qubits with buses, connecting qubits and read-out circuits and then you can also make paths and then you can just tune the parameters and you can run the simulation. So, it’s a pretty mature technology borrowed from the semiconductor device. You can design your chip. And as long as you design your chip, you design your Hamiltonian, now you design your quantum system operating in quantum mechanical principles.

The most widely used qubit is called transmon, which is one Josephson junction with a big capacitor in parallel. Again, it's a circuit that stabilizes your qubit against the charge noise from outside. If you put your qubit in the microwave resonator, it's not something special. A microwave resonator is a big metal box that confines your microwave at a single frequency. And you couple your microwave photon with your atom, which is a Josephson junction transmon, now. And depending on the state of your qubit, your transmission of a microwave frequency changes, meaning you just read out the microwave transmission between these two input and output ports. Then you will see that, "Hey, my qubit it is in state one or two." And also, you can control your qubit with the microprocessor so that your state can be zero or one, which is that your qubit state can be a dead cat or a live cat.

And another point is that when you see the envelope of this control, this is a so-called rabi oscillation and envelope decays, which is kind of a lifetime of your quantum state. And this is called the Schoelkopf Plot. Robert Schoelkopf made this plot, I think maybe seven years ago, and this plot shows that at least the coherence time of the onducting qubit evolves pretty rapidly much faster than the Moore's Law. And also, if you look at the scale of scalability of the quantum system from '99 to 2009, about 20 years of development, you can see how fast the technology is developing these days. And just saying that this is a 53-qubit system in terms of the number of transistor count, it's about a 150-transistor chip, which is a really primitive level in terms of integration. But again, I would say that making more qubits is not everything because as Jungsang mentioned, the error and connectivity and all the other factors are coming in. And these days, if you buy your computer, you don't count your number of transistors in your computer, but you need some performance benchmarking.

In terms of the number of qubits, yes, superconductor is the winner so we can make a bigger system. But actually, the IBM group suggested a good benchmarking index called quantum volume, which considers the number of qubits and also the error rates. And also IonQ suggested something called algorithmic qubits, which means how many qubits are really useful in your big system. But anyway, if you consider all these indexes, superconducting qubits are providing something like 50- to 200-qubit systems these days, and you can access those machines through the cloud service, IBM's and IonQ's, Righetti's, and Google's, etc. You see the most of the big systems are superconducting technology.

The more important thing is what algorithm you run. So, there was a pretty decent BCG (Boston Consulting Group) report a couple of years ago that you have many algorithms that can approach your problem through some mathematical tools and you can visit the site called Quantum Algorithms that collects the available or possibly available quantum algorithms. A recent demonstration about the chemical simulation is that you can just get calculate really, really small molecules' binding energy, etc., using quantum computers in hybrid with classical computers.

About 2-3 years ago, you see that quantum computing results deviates a little bit from the ideal or exact solutions. Right now, they have tricks for error mitigation, etc., and they have a far better machine right now, so they have a little bit bigger results by now. And this is the one of the IonQ machines' results about water molecules. They have a pretty good chemical accuracy. The point I would deliver here is that, yes, again, most of the simulations are done on the cloud without knowing the hardware details. And the second thing is most of the simulations are done on the superconductor-based machines, just because they are kind of stable to operate, they provide good access, and they are bigger in terms of the size.

The U.S. is leading the business, of course, but many countries are now starting to build their own system on their own. And you can see France, Germany, Israel, and Finland, and they are all trying to make a sizable quantum computer system on their own. They are all based on superconducting technology, not because it's just too easy, but because if you want to make a kind of tens or twenties of hundreds of qubit system, you have to borrow some technology from conventional wisdom, which uses semiconductor technology, etc., and also the micro-technology from the communication technologies too.

We know that Korea is far behind in terms of this technology, so I would like to deliver to you what the Korean government’s strategy is to close the gap between the leading countries and Korea. I would say the gap is not small, but I would say that it is not invincible. The Korean government has launched at least four programs in 2019 and 2020 about the quantum programs. They have pretty much 30-50 million dollars for 4-5-year program for quantum computing, quantum sensing, quantum communication, and quantum ecosystem. For the quantum computer program, which is about 45 million dollar 4-5-year program, now it's running about 30 projects, including small projects for individual researchers and kind of 5 big group projects. One of the big projects is superconducting technology development, and it's not a single device or single technology development, but it's a kind of system development technology, but kind of the demonstration of the system integration, not really a full system development. So most of the universities are involved in these projects, and also the government level KRISS and our Sungkyunkwan University, too.

This is a kind of primitive result. I'm showing this just to tell you what the current status, what the level of Korean technology right now is and what the future is. In terms of fabrication, we are pretty good. We are making chips within the about one percent spread across the chip and two percent spread across the wafer. So, in terms of making devices, we can make right now hundreds of qubits or maybe several hundreds of qubits on a chip pretty nicely. The goal of the project in 5 years is to demonstrate a 5-qubit process. Yes, this is a 5-qubit processor we are just running these days and as you see, the qubits are there. You can make the entanglements between them and you can make the all the microwave control. Why 5? Making chips is not a big deal, but controlling five qubits in a coherent way is a challenge. So, it's not just a chip-making project, it's a system development.

The problem is that when you are running these four big programs in government, we ran out of people, so we don't have more people to run this program within the Korean Peninsula. That was a problem. So last year, the government launched this Quantum Eco-System project, and they launched a center that should educate and train people and make infrastructure within the Korean Peninsula, doing education and quantum fab for device fabrication and quantum computing cloud service.

There are tens of items we are providing these days, but I just introduce one of them. If you want to make a quantum device, a device that works in a quantum mechanical way, yes, we can adopt the technology from the conventional semiconductor technologies because Korea is in a pretty good status in the semiconductor industry. So, we have many infrastructures doing all the semiconductor materials. Number one, quantum devices are using little bit different materials. So, some of the materials are not welcomed in conventional semiconductor, perhaps. Number two. If we want to make a quantum device, the wafer sizes are small. We don't use eight-inch wafers in quantum device fabrication except for the silicon cases. So, somehow the semiconductor industry is too advanced. So, we don't have high-end fabrication facilities in Korea dealing with two inches and three inches anymore. So, we are building small wafer, but high-end technology perhaps these days. So, Quantum Fab is collaborating with KANC, one of the major nano-fabrication facilities in Korea. All the common processes are done at KANC, but some specific material processes or the small wafer scale fabs are done at Sungkyunkwan University. And these two institutions are about 15 minutes of driving distance, so it's a pretty good cluster of quantum fab. And the government plan is that by next year, 2022, if you have some GDS file out of your CAD program designed by some students or some research scientists in superconducting devices, within a month you will get a chip that works as designed.

Another thing we are doing is that we just have a partnership with several of the quantum cloud providers. We have pretty good partnership with IonQ starting this year. And we just started the IonQ Hub this month. So, we are gathering proposals from the research scientists and students. Even individual students can apply and we just provide them access to the quantum cloud system through their laptops. It's not just providing times, but we really need to provide education, how to use it. So, every Tuesday, for example, we have a workshop about all the quantum cloud programming and also the quantum computer hardware, and so we need time to educate and train people. But after doing this about half a year, we are amazed at how fast students are learning how to a program quantum computer. I have to spend five to ten minutes with some PowerPoint slides to explain what the superposition is, what the entanglement is, etc. But if you teach your students with this programming and they just run the codes about control nodes and the hot thermals and etc., after, let's say, less than one month, they learn by heart what superposition is and what entanglement is without thinking too deep about Schrodinger's live or dead cat. And that may be a little superficial, but when you are accustomed to say that entanglement and superposition and you have the kind of picture what it is in your code space, it's a really good thing, I think, to expand the quantum community and quantum research landscape in the end.

OK, this is just the goal of the Quantum Center, and you can visit our Quantum Center if you want some more information.

So, the message I would like to deliver today is, I didn't go into too much into the technical details, but superconducting devices are working perfectly in a quantum mechanical way. It's visible and you can see the device with your naked eyes. It's big, but it's quantum mechanical. And again, you can design your chip and as you wish, meaning you design your quantum systems' Hamiltonian, quantum system's governing rule by your hand. And if you may design your chip, you can make a chip in the conventional semiconductor cleanroom and you have to put it into the cryogenic fridge, a cold fridge. But the cold fridge is pretty automated. You can buy it and push a button and it cools down. On top of that, you need all the microcontrollers, which are complicated, but all the microcontrollers are already mostly available. The challenge is now how we can make all the systems coherently and all the systems are kind of efficiently controlling your quantum system, but at the same time, preserving your quantum system long enough to make your calculation possible. Again, the cloud quantum computers are really accessible these days, so I really suggest you to connect to one of the cloud systems. There are some free machines, too. And also, you can get access from the government program and get the idea of how the quantum system is working. And that makes you kind of quantum smart people in the end. Thank you.

Discussion Session

Taeghwan Hyeon:

Thank you very much for all three speakers for the wonderful presentations. Now let's move on to the discussion session with our three speakers. The audiences that register for this webinar has left many thought-provoking questions for the panelist. Based on these questions, I have a few questions for the panelists. OK, let's move on to the first questions. Actually, as you might have heard, you know that there is broadly speaking, several different kind of hardware, like the structure is for the quantum computing. You know, such as the trapped ion as presented by Professor Kim and also like defect diamond structures by Professor Awschalom and also as presented by Professor Chong, the superconducting qubit systems. So, for the real commercial application of this quantum computing, what kind of advantages of each of these kind of like hardware systems for the quantum computers, what is the current limitation, and what shall we do to overcome this kind of limitation to the fully commercialized kind of quantum computing technology? Professor Kim, could you start?

Jungsang Kim:

Sure, I think it's actually a fascinating field where we have outstanding researchers and engineers who are working on various technology platforms. I think it is very true that everybody believes their technology will win. I think it'll just have to be that way. And there are many advantages each approach takes and then there are challenges. I do believe that in macroscopic if you categorize them, they really go into two camps. In one camp, they leverage the existing semiconductor fabrication technologies because it's one of the most advanced ways that we can make anything today and see if we can leverage that as a technology to fabricate good qubits. And I think that's one camp. On the other camp is where we start with qubits that are given by nature. Atoms and photons and just fundamentally quantum objects. Now, of course, the advantage there is that the qubits actually can can have a lot of interesting advantages because they're naturally quantum. But the challenge is the technology scale is not there. We have not built very complicated things with atoms and photons in the past. And then, of course, on the manmade qubit side, the technology to back something is there but the device that you make tend to be not very quantum mechanical, and therefore you have to make a lot of effort to make those qubits more uniform. They behave better with low temperatures. So I do believe that these are somewhat complementary approaches. And it's fascinating that there are many people who are pushing the envelope, these technologies together.

And I think at the end of the day, there is a lot you can learn from each other. For example, we've worked with atoms. Our integration technology does not exist, but we try everything we can to borrow technologies from other industries to make it work. For example, the core of the laser systems that we use to control the qubits, we actually pull them out of the lithography system directly. Both the laser and the modulators that are used are actually the technologies that are use to make the optical lithography best today. We take advantage of them. So I think there a lot of things we can learn of those who are working with the qubits that Mother Nature gave us. But there I think our challenge of innovation is to see if we can develop the technology, leveraging as much of existing technologies we can. You've seen that our ion traps are using the silicon fabrication technique today.

Now on the other side of people who are trying to leverage the existing technological advances? I think a lot of these manipulation techniques, if you think about the cross-resonance gates, a lot of these techniques are actually developed in atomic and molecular physics laboratories. So I think there's a lot we can learn from each other. And eventually I think it will come down to performance. Performance, not at the device level, but performance in terms of what kind of problems can it actually solve, what kind of computational capability delivers. Because at the end, we're actually trying to build quantum computers here.

Taeghwan Hyeon:

Thank you, Professor Kim. Professor Chong, could you add on some, especially on the superconducting system?

Yonuk Chong:

Yes, so superconductors are relic devices, I told you. So, the advantage, like Jungsang Kim said, it's based on all the fabrication technology, which is mature, developed in the semiconductor industry. Another thing is that it's based on microwave control and microwave is kind of easier to handle compared to the laser technique. That's the advantage. The disadvantage can be that ions and atoms are proven to be quantum. They are quantum just from the beginning. Superconductors are pretty much quantum, but it's suffers from the outside fluctuations that kills your quantum properties. So in the end, the precision or the lifetime maybe catching up ion trap or maybe not catching up. So bigger systems better in superconductors; precision, ion traps; and connectivity, maybe ion traps; designing your system, maybe superconductors. They all have good points and bad points. So I think the best way is hybrid. Everyone is talking about a hybrid of taking good things out of each systems. But (maybe David knows much better) the system doesn't talk too friendly. So they are talking to each other until now. So maybe the best way would be you have ion trap system, a superconductor system, etc together, but take advantage of each system by making some hybrid network between them in the end. Another thing is that the Google, IBM, they are dealing with a superconducting system and partly because it's pretty much a conventional system to scale up. So I think in the end, superconductor will make even bigger system, much better system after the development of decades of research. But in the end, we don't know which system will win in the end. So that's my point.

Taeghwan Hyeon:

All right. Thank you, Professor Chong. David, could you actually elaborate more on the emerging quantum computing technology, especially what you have been working on for the last several years. What is the limitation and advantages over the superconducting system or the trapped ion system. Please.

David Awschalom:

Sure, I'm thinking about all of these remarks and thinking how bad we are at predicting the future. So historically, when you look at earlier conversations like this with other technology, most of us had it wrong. So I'm quite confident we'll be wrong here. But, you know, I don't think it's one or the other. You know, I think it's more of an end function. In the sense that I think that in the end, quantum technology would be a hybrid combination of these things, much like our technology today. But I mean, we communicate using photons. We do logic with electrons. Until recently, we stored information with magnetic materials. Things were much more of a hybrid environment that I think at the end of the day, quantum technologies will be nothing without communication. I think even building quantum supercomputers will mean there have to be quantum connections. Those will be photonic systems, almost certainly. So I find it hard to believe that photonic interfaces will not be vital for all of these technologies, whatever we end up using. I also think that based on the application, there likely to be different systems configured with different materials. So maybe superconducting machines will be used for certain things. Trap atoms for other things. Solid-state maybe for a smaller class systems. Or maybe, if the scaling does work well, it's an enormous barrier right now, but having a billion qubits is not inconceivable if one can correct materials challenges and it may take decades to do that. It's hard to know. So, I think solid-state has enormous potential. In some ways, it's the furthest behind right now because it has real environments and those are complex environments for qubits. Superconductors are clean and beautifully engineered and really impressively accelerated. I think the trapped atoms systems, it's hard to think of a better, cleaner quantum object than an isolated atom in a near vacuum. It's a spectacularly successful quantum bet. But I think one thing we've learned is semiconductors, at a first blush, they seem a little dirty because they have a complicated environment that also leads to a very rich set of controls which will take longer to unravel. So that's a very long-winded way of saying, I don't really know. But I want to echo what Jungsang said in the beginning. All these technologies share common techniques so they all use microwave control. They all require error correction. They all require clean interfaces. They all require programming languages. They all require transduction, trying to move one modality into another no matter what system we're looking at. So I think, you know, the common language of all of these platforms will push the field forward. But I would hesitate to say which will win, because I think that answer has to be qualified based on what the destination is. And I am guessing they'll be very different.

Taeghwan Hyeon:

Thank you very much, David. Let's move on. And what I'm really curious is, what the quantum computing can do, which binary/conventional computer technology cannot do. What kind of really wonderful applications of a quantum computing which conventional computing technologies cannot do? Could you just elaborate using some example? I'm sure you already gave some examples during your three presentations, but could you more elaborate on details on the future application of quantum computing? OK, David, do you want to start?

David Awschalom:

Sure. So there are so many problems that are intractable with today's computing. But I think the one thing this community can agree on completely is that thinking about using quantum machines for molecular calculations offers extraordinary promise. So I often say that, even simple molecules like the caffeine molecule are molecules that are beyond the reach of any supercomputer and even an extrapolation of today's supercomputers. They're not that many atoms in the caffeine molecule, but they're an extraordinary number of electronic states. And to capture that with a pure quantum mechanical model through quantum simulation, I think Jungsang you should correct me, but I think that's beyond the reach of today's computers. But being able to use this technology to create new molecular systems and new materials to think about addressing problems like photovoltaics and photosynthesis and energy conversion. These are things that I think are well within the reach of quantum machines.

Taeghwan Hyeon:

Thank you. Jungsang, could you add on some of the realistic future application of quantum computing technology?

Jungsang Kim:

Sure, I think the topic of cryptography really sparked the advances in this field. But in a very fortunate way, I really think that the complexity of that problem is very, very large. So you will need probably many years of development before quantum computers can effectively tackle that. And that's good news. That means we have some time to react to that. And then the next one, as as David mentioned, are materials and chemistry. And those are problems. Computational chemistry, even

40 years after Richard Feynman mentioned this complexity still remains extremely challenging. And there are energy industry and pharmaceutical industry and materials that can really benefit from a much better and improved simulation of chemistry. So I think still many of the chemistry problems that we have done some analysis on, the big molecules seem very challenging. So the real question is, in the next few years, can we find some interesting molecules that we will be able to assimilate with the advancing quantum computers in the future? I think the real surprising thing, at least for for me in the last six months, maybe a year, is all these new ideas are coming out that we didn't even envision five years ago or three years ago when we started the company. These quantum machine learning ideas, some of the early ideas were esoteric, interesting, but not very practical. But it's it's really impressive to see how the people who really dig into these algorithms and figure out how to make that more practically usable can actually make them extremely useful. So I do feel like the early technology applications of quantum computers that make an impact in the real world is yet to come. It actually is interesting because it's not 20 years into the future. It's probably two or three years into the future and we still don't know what it is today. So I do feel like as we reach out as quantum computers become accessible to a much larger group of people, and these people start to understand how it works and continue to innovate, I think surprises will come. There is a big difference between having even the smartest 100 researchers in the world working on something versus allowing millions of people to think about the problem and then something interesting or unexpected comes about. It's very exciting to think about those possibilities. So I think if we make the quantum computers available to larger groups of people more quickly, I do believe that that application that we don't know about today, the discovery of that will accelerate. So I think in that sense, we're sitting at an extremely interesting place today.

Taeghwan Hyeon:

All right, sure. It seems like there is a huge opportunity for the quantum computing, which we cannot imagine now. So when we talk about quantum computing, people are talking about the cryptography. A couple of weeks ago, actually, I saw the news saying that in the United States, there's a gasoline distributing company / energy company was hacked by hackers. And there is a long queue in the every gas station in Texas. That was really shocking. In terms of that, when quantum computing technology becomes really feasible in the ordinary life, people worry that's going to be a big problem. Right. In the beginning, Jungsang, you mentioned about the cryptography. Why don't you just elaborate more on this kind of quantum computing for the cryptography applications and also some threats and some opportunities and that kind of stuff. Why don't you elaborate more on that.

Jungsang Kim:

Sure, I could start. You know, I started my career in graduate school working on full time single photon devices and semiconductors. And those indeed in the 90s, there was a lot of interest in utilizing that for quantum cryptography. And as soon enough, the Shor algorithm really put a fundamental threat to the way we communicate securely. And I've also since spoken with a lot of people who are in the industry. Some of the people who worry about security, the big banks and so on. And they do feel like this is a real threat and the cost of this threat, when it becomes real, is catastrophically large. So the good news is it does look like quantum computers that can crack these codes probably will take a while to build, but transforming or transitioning existing cryptography infrastructure to something that is robust against quantum attacks, that transition and deployment can take a couple of decades. It can take 20 years. So the good news is at least in the United States, people have started the official process of identifying the next generation cryptography techniques that are robust against quantum attacks. And then they also have to be extremely practical in the sense that the nice thing about quantum cryptography is that the channel becomes secure. But the downside is you actually have to upgrade all of your Internet infrastructure to have quantum sources and detectors, and that becomes almost cost prohibitive. So people do believe that implementable approaches that does not require an uphaul of your entire Internet infrastructure will be a requirement before you can transition to that. So somehow, I think this cryptography, it's always a fight between a spear and the shield. If there is an attack and you think about how to defend it and it's going to evolve with each other. I do believe that this cryptosystem that will be robust against quantum attacks will be an algorithmic innovation. At least that's how people are thinking about it.

Taeghwan Hyeon:

So good to hear that, at least for the next couple of years, I don't have to change all my password for my banking systems and the credit card and that kind of stuff. Good to hear that. So, I mean, Professor Chong, could you add on some on this issue of cryptography?

Yonuk Chong:

Yes, all the Shor algorithm predicts that you can break the RSA-based public key communication by doing the factorization really in a fast way. But I would say you don't need to worry too much for now because it's only hacking the factorization-based cryptography systems. There are other cryptography systems like elliptic curve, etc. So, you can still keep your secret even though you have some quantum computer running somewhere outside there. But the problem is that those cryptosystems are pretty heavy. So as long as you know what your enemy is, like Jungsang said, then you can prepare the system for the hacking. And also the time to prepare and the time for the real massive heavy quantum computer to come to break the currently used RSA 2048 code is maybe 10 years, 20 years or more. So we still have time. On other catch is that you can download all the data into the Internet in your data system. So, you can keep the secret for 20 years until the quantum computer is really realized in the end. And you can hack your saved data in 20 years. Some secrets should be kept for half a century or more. So if you think your secrets are really important, you have to change your cryptosystem in a year or two. Also, I think NIST already suggested to change your cryptography system based on quantum safety. But if you are doing just your ordinary job, unless you are worrying about your data is hacked in real-time, I think for the coming decades, you don't need to worry too much about the quantum computer to come and hack all your secrets. But in the end, I do believe that quantum computer will proceed and we will make a big system to break Shor algorithm in the end that may come out of IonQ or IBM or Google. I really hope to see that.

Taeghwan Hyeon:

David, you have something to add for this kind of issue?

David Awschalom:

Well, I'm not sure I have anything more to add to the encryption part, which was covered so eloquently by the other two speakers. But I do think it's worth maybe taking a slightly different perspective, which is what this level of encryption could do in terms of impacting society. So beyond finance and national security, I do think it's likely to have interesting impacts on things like a 100% secure elections where people can vote remotely and on society. I imagine how the voting rates in many countries would change if people knew for a fact that it would be impossible to know how they voted and all you can know is that they did. The second thing is, I think it's also interesting to think about with a new technology being born, how important it is to think about policy at the birth of the technology, not after the technology is being deployed. One thing I think we learned is society with nanotechnology and even things like genetically modified foods is how important it is to think about policy as the technology is being created. Like blind computing, right? A quantum computer can be built and owned by someone and run in a way that the owner of the machine has no idea what it's doing. Is that good or is that bad? And what does privacy mean and something like that? So I think when you think about encryption and you think about privacy, it's more than just sending a message or a financial transaction, although that's important to all of us. I think there are bigger implications here which we'll be thinking about.

Taeghwan Hyeon:

That's right. That's right. Thank you. Now, let's move on to the relation with the conventional binary computers. Although quantum computing technologies is evolved and developed to the certain stage, I still think we still need the binary conventional computers. So what do you three think about the relationship with the binary conventional computer and quantum computing systems? Going to the future, are they going to go together or are they going to competing each other or what? David, why don't you start?

David Awschalom:

I think that they'll be together. I don't think that quantum computers will replace today's machines personally. And I think a good analogy is even with the Internet. Many people wonder, will a quantum Internet replace a classical Internet? And I think people are appreciating it's just the opposite. One will need a much more robust classical Internet and more powerful classical Internet to run a successful quantum Internet. And I see the same thing happening in computing. Quantum computers are extraordinarily powerful for certain classes of problems. And I believe there'll be greater class of problems, as Jungsang said, as millions of people begin to play with these machines, I am sure there'll be more discoveries, more algorithms, more opportunities. But they're still likely to be many scenarios where today's classical machines will do better. So I think we'll need both.

Taeghwan Hyeon:

Yeah, Yonuk do you want to add some issues of dealing with a binary computer.

Yonuk Chong:

Oh, I would say that the quantum computer will never replace the classical computer. My vision of quantum computer is that quantum computers is actually the supplementary for the classical computers. The old boys will remember the core processors in the first IBM personal computer. They had a main process and math coprocessor that has some subroutine that have some special calculations. And then quantum computer will work as a math coprocessor in a way that they do a specific subroutines that's fit for the quantum calculation. But otherwise all the computational work which the current classical computer is doing will remain in the classical computers domain in the end. I think partly because it is technologically advanced and partly because it's much cheaper. And I cannot envision quantum computer can be cheaper in several decades than a classical computer in usual digital calculations. So I would say they coexist and quantum computer is pretty much helping classical computer job which classical computer can never do it.

Taeghwan Hyeon:

Thank you. Jungsang, could you add on this issue on the relation with binary conventional computer and quantum computing?

Jungsang Kim:

Absolutely. I think there are already examples. If you look at today's modern data centers, if you actually want to go to AWS and run some computational test, they actually have lots of different resources. There are the CPUs, what we call the central processing unit, which is conventional kind of processor chips. But they also provide GPUs. These are graphics processing units. And they give you a TPUs, these tensor processing units. And, you know, depending on your applications, these are highly optimized for the types of applications you do anyways. And there are jobs that CPUs can do better than GPUs. There are other jobs that GPUs can do a lot better than CPUs. And there are TPUs invented for a reason because when you go through massive data crunching and machine learning, CPUs and GPUs both fail. So I think that is kind of the ultimate of hybrid computing. And in the modern world, and I think probably much more so in the future, when you are a developer or programming something and there happens to be some big matrix falsification you have to do, all you do is you call a subroutine and then the machine will figure out that this kind of a routine was much better on the GPU than CPU and will run a thousand times faster. And it will just deploy there, get the results and then make it kind of seamless for the end user. I think that type of an infrastructure is already there. This type of hybrid computing, even with or without quantum computing. So I think the most natural way things will evolve is QPUs, quantum processing units, will become an available resource that is really specialized at certain tasks. I think that integration can actually happen a lot sonner than you think just because this kind of hybrid computing architecture in a cloud system is already there today. So we are actually engaged in a lot of very interesting discussions with HPC developers, and that's the way they see QPUs coming into the picture. So nothing to add other than the fact that these kinds of hybrid computing is going to be a lot closer than you think.

Taeghwan Hyeon:

All right, thank you. We mostly talk about the hardware systems so far. What do you think about the software, such like operating systems and algorithms, that kind of stuff? Do we need any new kind of like software for these quantum computing systems compared to the conventional binary computing systems? What do you think about that? David, could you start on this issue?

David Awschalom:

Well, I think I should let Jungsang have you start on this one, because it's an incredibly hard question to me. I mean, I think companies like IonQ and IBM and Google and Microsoft have been developing software platforms as an interface. I think that's already happening. But I actually think there's a deeper problem here, which is how you integrate fields like computer science into quantum engineering. So most areas of science and engineering have a common link, which is people entering this discipline of quantum computing have some experience with quantum physics. Computer scientists are often an area where they don't need to and typically don't have that exposure. And there is a bigger knowledge gap here. So when I think in the world of experts for programming and designing interfaces for computing, it's often the computer science domain. And I think somehow we have to develop a mechanism to bring those experts in computer science into the world of quantum computing. So I think there's been great progress by companies in developing interfaces right now and different toolkits for doing this, I personally think the biggest acceleration will be when we bring that community in.

Taeghwan Hyeon:

All right. Thank you. Yeah, because you have your own company, Jungsang, why don't you add on that. You've probably faced this kind of problem every day.

Jungsang Kim:

Oh, absolutely. Yeah. So, I mean, this is an interesting question because I think this is one area where the industry is definitely leading the academic communities. Because if you look at what academic researchers do, they usually have to get research funding to do things and they tend to stay very close to their disciplinary tracks because that that's where the community is and so on. And when it comes to new areas like quantum computing software, there is really not an academic community. But we have a need. So if you look at IonQ employees, half of our engineers are software engineers and they typically don't come with quantum experience because you don't find quantum trained software engineers with experience because that industry did not exist. So we have a lot of opportunities and challenges in software realm. At the lowest level, how do you actually control your quantum computer? How do you write the software to do that? What kind of operating system? Real time control and operating system. But then there are lots of tools. If somebody writes a program, how do you actually compile that? How do you optimize the circuit so that it runs better on on your limited hardware? How do you optimize for the architecture? And these are compilers and schedulers and tools like that, circuit optimizers. These are things that are today completely open field. And if you look at the existing tool sets, it's very similar to programming your old computer in assembly language. And we've come a long way from assembly language to compile languages and semantics and all of those. All of those are yet to come. And I think it's very important for us to actually take some of the highly, widely used core, let's say if we build a quantum computer that can do some optimization of machine learning extremely effectively, we want to build optimized software tools and then libraries so that high level users can call it without necessarily understanding what it is. That's how machine learning is done today. If you look at machine learning engineers working at whatever company you can think of, they don't really go and develop their software tools, right? They actually just call libraries and software tools because the classes of problems are highly optimized all the way down to the hardware. So there's tremendous amount of opportunities in all of these areas and challenges. We need to train more people who are trained very well in software engineers and architectures to come into the quantum world, learn a little bit about quantum so they can actually start diving into these tools. I think all of that exciting thing is actually happening in industry today. And that's one area where I think industry actually leads the academic community.

Taeghwan Hyeon:

Thank you. Thank you. That's great. Like any other technologies like quantum computing, like communications and interfacing between the hardware and software is really critical. And it seems at least computer programmers, they have to learn some quantum mechanics now if they want to survive at a quantum computing era.

Jungsang Kim:

Yeah, absolutely.

Taeghwan Hyeon:

So related to that, there should be huge business opportunities for the quantum computing in the next several decades ahead. The three of you already elaborate on this business opportunity for the quantum computing. Could you add some more on that and discuss about this kind of business side of that? Because a lot of the audience of this webinar are actually venture capitalist and a lot are business oriented or software companies or Samsung, LG Electronics. There are a lot of company people watching this webinar. Could you tell us about the business opportunities, please?

Jungsang Kim:

To me?

Taeghwan Hyeon:

Yes, because you're running your business, right?

Jungsang Kim:

Yes, absolutely. Now, I think at the end of the day, I think there is an inflection point, like the critical point, where the quantum computing technology which today I don't think we can do things that classical computers can't, but we actually have to get to that point very quickly. Meaning build hardware that can actually surpass the capabilities of classical computers in more general terms. So, the Google milestone of reaching quantum supremacy is a very important one. But then we have to go very deep into crossing that boundary to make room for useful applications to run on very powerful computers. But that's not enough. We actually have to have people who are thinking about real world applications. And even if you can hand somebody an outstanding quantum computer today, because quantum computers did not exist to this point, there really is not a business model. People don't know how to use it to take advantage of it to build their business. But I think that's that's actually the opportunity for industry. If you're in the financial industry or chemical industry or automotive industry, just think about like not foreseeing where computers will come into your industry and you can see how much leg up you can get, even if the computer's power is not available quite yet. So I think this is time to really think about what are some of the hardest problem you have and explore whether there are ways you could tackle it with quantum. And those are some of the most exciting conversations that we're having with various industry partners. They typically come in without a quantum background. They come in with a lot of problems that are very hard to solve. And then they are starting to kind of dig into what quantum can do. And we come up with very ingenious ideas. And some of them machine learning examples I showed you are some examples of those and I'm sure more will come. So in some sense, this is what we call the blue ocean. This is like wide open opportunities. You just have to dive in and look in a focused way. Just look for how you can leverage this capability to your business and then roughly get a sense of what do you want the quantum computer hardware vendors to do for you to actually bring that timeline closer together? And those inputs that we get interacting with the customer is extremely valuable. That actually helps us define our roadmap and then understand what we need to deliver to actually create a real impact to the world. Just like classical computers, I think the first real world impact may be small in a niche area. But once that happens, I think it's going to snowball from there. So the question is that point two years from now, five years from now, or 10 years from now? And I think it's somewhere there. It's is definitely in that decade. The sooner we can bring that inflection point, I think it will very quickly expand to a very large number of industries quickly.

Yonuk Chong:

Yeah, so in terms of industry, I'm not in the industry part. But there are worries and also hopes. The worry is that we know that it will take a long, long time, not really long, long but a little bit long time to have really great big machine to be useful and also for the company/people pay for it. But we need to keep investment and development until that time where real quantum machines are coming. So the business part, they should have some business model to have a little bit of revenue or investment to keep on going. What I find interesting these days is related with algorithm issues we mentioned before. There is some area called quantum inspired area. People are learning new things from quantum machines and use it in non-quantum classical machines inspired by the quantum mechanically working machines. That's called quantum inspired. That part can be a kind of short term business model in a sense that because when you see the students, they really don't care about what really quantum computer programming or what classical computer programming is. When they know the rules and they follow the rules and the codes are running and the program is optimized in a sense, I think this kind of inspired by the quantum programming is one thing we can just pursue. And another thing is in terms of business, like IonQ and they are actually the quantum computer hardware company, but behind those hardware companies, there are many components companies, like cryogenics and optical components like optical modulators. And all those companies are actually earning money by the investment of the governments that wants to build quantum computers these days. And I think those kind of high end, really specific purpose, quantum-grade quantum-guaranteed component companies can also drive the industry in a sense that they can support hardware companies until real hardware can make money with the quantum computers. So I think those business models can sustain our ecosystem until we get real quantum machine dominating the world.

Taeghwan Hyeon:

David, could you add on the some of the business models or some of these real commercial applications of quantum computing?

David Awschalom:

Yeah, I actually think this is an incredibly exciting moment. I think Jungsang summarized nicely. I think in a sense, my analogy would be you can't boil the entire ocean. You have to decide what parts of it you might heat up. And, I'm fortunate enough to help run an organization called the Chicago Quantum Exchange. We have several dozen companies thinking about applications of quantum technologies. And what's interesting to us is that they're across the spectrum. So it's a very broad set of companies thinking about impact and optimization. For example, where quantum machines might be able to have very big impacts to clocks. Trying to improve navigation and what the impact of navigation will be if you could improve that significantly. So you know, at least from my perspective, I'm seeing some camps forming where people do see some high impact targets. Not enormous numbers, but very clear ones now. And I think Jungsang said very nicely, I think we're going to hit an inflection point where one of these will hit gold, whether it's optimization for assembly or energy distribution or whether it might be improving GPS a few orders of magnitude, where you imagine how that would have enormous impacts. Whether it's in self-driving cars. Whether it's in aircrafts. So I'm very optimistic. As systems become open sourced a bit, we use types of crowd sourcing for larger companies to think about poking at this problem to look for unique openings. I think I also agree in the next five years or so, we'll begin to see something.

Taeghwan Hyeon:

All right. I think it's time to conclude. Thank you very much, all three of you, for the wonderful presentation and also exciting discussions on quantum computing. And I also would like to thank all of you watching this webinar. And I hope that today's webinar clarified a lot of questions about the quantum computing and I hope you learn something useful about the quantum computing. And then, I hope to see you again in our next webinar of the Chey Institute for Advanced Studies. Thank you very much. Again, goodbye.

All:

Thank you. Thank you very much.