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INTERVIEW

Quantum Technologies and AI Interview with Tommaso Calarco

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Prof. Dr. Tommaso Calarco has been a full professor at the University of Cologne since 2018 and at the University of Bologna since 2023. He received his PhD at the University of Ferrara and then to worked as a postdoc in the group of Peter Zoller at the University of Innsbruck. He was appointed as a Senior Researcher at the BEC (Bose-Einstein Condensation) Centre in Trento in 2004 and as a Professor for Physics at the University of Ulm in 2007, where he then became Director of the Institute for Complex Quantum Systems and of the Centre for Integrated Quantum Science and Technology. He has authored in 2016 the Quantum Manifesto, which initiated the European Commission's Quantum Flagship initiative, and is currently the chairman of one of the Flagship's governing bodies: The Quantum Community Network (QCN). In 2020, together with the QCN, he has launched an initiative towards the creation of a consortium of European quantum industries, which has been legally established in 2021 under the name of European Quantum Industry Consortium (QuIC).

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1 Introduction

KI: Tommaso, thank you very much for being available for this interview! Let us first briefly introduce you to the readers of this AI journal: How did you enter the field of quantum technologies? What were and are your main personal motivations to work in the field?

Rather than me entering the field of quantum technologies, the field entered into my life when it was not even called that way but foundations of quantum mechanics. I first became interested in this field when doing my diploma thesis, and then for several years I kept a position as a elementary school teacher and then a high school teacher as a sort of fallback option. Because at that time, I was pretty sure that I would never have a career working in such a fascinating but utterly useless field as quantum mechanics; in fact, everybody was telling me that if I will do then I would ruin my career. But soon after that quantum technology started entering the world and our lives with the discovery of the first quantum algorithms, the Shor algorithm and the Grover algorithm, together with the first gate-based implementations of quantum computers. From that point on, it became clear to me that quantum mechanics was not only fun but also useful, such that perhaps a career could eventually come out of it, which then indeed happened to me.

KI: How would you define useful in this context?

I would say that useful in the trivial sense is something where I can build a device which can be used for some purpose but rather outside the science it is originated in. For

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instance, my diploma work was about the Bell inequalities, something of great use to reflect in depth on whether the world exists locally or not. Which is as philosophical as it gets for any question and brought Alan Aspect, Anton Zeilinger and John Clauser the Nobel Prize in physics (in 2022 for showing that the quantum world is not local in real through his experiments in the early 1980s, which validated the principle of quantum entanglement by violation of Bell's inequalities). But the usefulness of that was sort of, say, purely scientific in terms of advancing knowledge only without any broad application of it.

KI: What are your current main activities in quantum technologies, both scientifically and as a community leader?

Well, I have started several years ago with my research to leverage ideas from machine learning and AI, especially reinforcement learning to improve the performance of quantum devices. I have founded a department of the Research Center Julich that focuses on this subject, called automated optimization and quantum optimal control. On a broader level, I am trying to connect the dots and keeping together the community, for example, by chairing the quantum community network, which is one of the three governance bodies of the European quantum flagship. And at the same time, I am doing my best to connect what the community is thinking, conceiving and seeing as the future vision towards decision makers, especially at the European, but also at the national level with different kinds of strategies, documents, events and initiatives.

2 Quantum Technologies

KI: You are well-known for your work in quantum technologies, which indeed made quite some headlines particularly over the last years. But are quantum technologies really a new thing - or what is now different compared to a few decades ago?

Let me give some sort of quantum answer, yes and no. There is nothing conceptually new, because all of these concepts used in quantum technology, such as superposition and entanglement, are actually something which was already present and very much at the core of the theory of quantum mechanics since its inception. But then what is new? We only started to realize in the 1980's at the earliest that quantum mechanical systems can be used for the purpose of processing information. Richard Feynman and David Deutsch started asking whether we can use quantum mechanical objects to process information. This was the birth of quantum information, which is not new physics, maybe not even really a new theory. But it is indeed very much a new way to look at those known quantum phenomena and combining them, which ultimately leads to interdisciplinary links with information theory and computer science. In addition, we can do way more with quantum computing resources available to us nowadays than the founding fathers of quantum mechanics thought would ever be possible. For example, Erwin Schrödinger said that it is ridiculous to even imagine to experiment with a single atom in thought experiments, though we often do that, as this always entails ridiculous consequences; it would be like the idea of raising a pterodactyl in a zoo. Since then, huge progress was made in the refinement of capabilities to manipulate individual quantum objects, which allows you to also use them for processing information. This is what really led to this development of quantum technologies.

KI: In the early 2000s, quantum computing was one prominent research topic to work on even in funded projects. Is the situation today really so much different from back then?

Well, again, yes and no. It is different in the sense that 15 or even 30 years ago, we thought it was a dream. When I started teaching my course on quantum information more than 15 years ago in Ulm, I said to students: nice ideas but they are more or less science fiction. But today, from the physics point of view, the situation became substantially different in that we now have quantum computers with dozens of quantum bits such that it might become really possible to do these things from the technology or applications point of view. Though we do not yet have a quantum computer which can really do something qualitatively different in the sense that no classical supercomputer can perform, I think, we are well on our way there. In this respect, a cautious but strong optimism is justified.

KI: From your perspective, how are Europe and Germany positioned in this field today, technology-wise and regarding research funding and investments? Does Europe lag behind in this respect compared to the current major players in the field, USA and China?

Short answer: In terms of private investment yes, but public funding no, in the sense that Europe is the highest public net investor with around 9 billion Euros in quantum. The US is not investing so much, at least not in the open. Private capital is just the reverse: Way more venture capital and private investment are in the US. I think, that is also a major risk we have at the moment, in terms of sort of limited ability from our startups to really scale up. In addition, there is the risk that foreign capital is acquiring our startups and essentially doing what happened with the Internet having been invented in Geneva by physicists but the whole money being elsewhere. I did ask the head of Google quantum AI lab what he thinks we can do to stimulate a comparable level of investment in Europe as we see in the US from the private companies? The straight answer was that we cannot because we do not sit on a pile of cash.

Now, consider, for example, the Samsung Galaxy Quantum smartphone which has the simplest possible quantum device inside, that is a quantum random number generator, designed to secure sensitive transactions. The generator gets a qubit in a superposition zero plus one, and measures it, and then you get a result with 50% probability. This is the first consumer electronic device that contains quantum technologies of the second quantum revolution, though, without a quantum computer inside and no quantum communication. This quantum device has been developed by the Swiss company ID Quantique (IDQ) in Europe but South Korea Telecom now owns the majority of shares for IDQ, the company producing it. So, I think, we should avoid that foreign capital can come in and acquire our companies, thereby depriving our ecosystem of the not only technological, but also value chain creation sovereignty, which is necessary to fuel the whole system and generate more venture capital and be able to invert the tendency. That is one main challenge that we have now.

3 Quantum AI

KI: Let us talk about quantum AI which combines quantum technologies with AI. From your perspective, what are the general relations between both disciplines, and how would you assess the current status of quantum AI, regarding quantum computing for AI, and AI for quantum computing?

Exactly, quantum AI goes into two directions: One refers to the the use of classical AI for different tasks which help in building and operating quantum computers. For instance, one could leverage reinforcement learning for optimizing the control, performance, calibration and characterization of quantum devices in order to suppress errors and drive our systems in the best possible, coherent and quantum way.

There are other applications of AI in the field of quantum technologies which also go on a higher level in the stack in terms of, for instance, synthesizing and compiling algorithms for quantum computers. For a certain algorithm one could synthesize a gate sequence which sort of breaks it down into assembler language, in such a way that you get it in the most efficient possible way. One thing that we might envision is using AI in order to develop a search for new algorithms, potentially because we do not have a systematic theory of how you can synthesize or find algorithms. The limited number of quantum algorithms that we have are more or less anecdotal, and even the people who proposed them cannot explain in a systematic way how they came to the idea. So we do not have a general understanding of that, such as we have in classical programming.

And there are more fields in which you can use AI in the context of quantum computing such as for simulation, classification, and investigation of many-body quantum states, which is relevant for quantum simulation. For example, in my institute, we have a young investigator group which is oriented towards using so called neural quantum states. In other words, AI-inspired classification to calculate computer dynamics of many-body states. There is really a host of different applications of AI within quantum. And, of course, one idea that we are also considering is, would it make sense to have a large language model (LLM) which is dedicated to quantum? The European Commission is considering those options, and research is sort of very diverse in this one direction of quantum AI: AI for quantum computing.

The other direction of QAI refers to the use of quantum computing for AI. Now, is there really such a link? Well, from my perspective, there is one which is conceptually very clear and refers to a computational speedup of quantum search algorithms of which Grover's algorithm for search in a structured database is a popular example. Another link is adiabatic quantum computing, or quantum annealing for complex optimization problems in AI. There is a hope that quantum annealers can help now to reach production capability. This would require the capacity of writing and reading in quantum memory, like having a huge number of qubits which can be kept coherent with error correction in a recursive way to achieve fault tolerance. We need coherent qubit operations, even in the presence of errors over a very large number of qubits combined and error corrected, with a lower error rate, and that needs to be scaled in a recursive way. So, the optimization aspect is one clear direction and bridge between quantum and AI.

KI: In the past couple of years, a tremendous progress has been made in showing quantum utility of direct quantum or hybrid quantum-classical algorithms for solving certain computationally hard problems over their classical counterparts in AI. In this regard, quantum AI is not an academic moon shot anymore. But, from your perspective, what level of maturity has QAI reached? Do you envision sufficient commercial potential of what kind of real-world QAI applications that, in turn, may drive research and software development in this field even further?

I agree with you that there has been a lot of progress on the software side and on the theory side in this field. Whether and when this can be commercialized and used in practice at large is literally the multi-billion dollar question, in the sense that it completely hinges on the progress of quantum hardware development. The quantum computing resources needed to implement those QAI algorithms are really beyond NISQ (noisy intermediate scale quantum computers), and NISQ is the stage in which we are mostly finding ourselves with a few dozens of physical qubits today.

Some people argue that the recent result by Harvard with 48 logical qubits [1] takes us one step beyond NISQ towards the real age of quantum computing. But we need full scalability in the hardware for those ideas to become practically relevant, in the sense that you can not only think that there is an advantage, but you can actually deploy it. In a sense, it is reminiscent of classical AI in that a lot of ideas for, for example, deep learning were already present before the required sheer computational power and data became available.

So, there are a lot of amazing developments nowadays, but conceptually, a lot of what we see today is building on a foundation which was already laid some time ago. But, you know, then the first and also the second AI winter came just because the hardware could not keep up with these wonderful ideas; so, in this sense, I do see an analogy here. But yes, the potential is there, and, yes, the conceptual maturity of quantum AI is there. But we need, you know, those engineers in quantum computing and AI which will make these things real.

KI: One might argue for not lagging behind in or even giving up on research and development of quantum AI algorithms just because quantum computers are not yet ready enough for their deployment at large scale. What is your opinion in this regard?

Yes, I think, that is a very, very valid and important statement! As a matter of fact, it has always been the case that the amazing developments on the algorithm side have been really a strong pull for the hardware to come along. Without even those few early quantum algorithms like Shor's factoring algorithm, we would not be where we are now with quantum computing. Because what it promises or threatens is to break conventional encryption schemes was certainly a big driver for funding research and pushing for the development of the hardware. So, absolutely it makes sense and we should develop further those ideas of quantum AI even though the actual deployment on quantum computers at large scale may be a few years down the line.

KI: Apart from showing the feasibility of quantum AI algorithms for solving selected hard AI problems, investigating their potential of quantum utility, rather than quantum advantage, is of particular interest. This activity is complemented with the development of appropriate (non-NISQ) quantum computing devices which would become available when, in 10 or 20 years from now?

I would indeed say between 10 and 20 years from now, as that is also the expectation in the quantum community today. And I would like to come back to one expression that you used, which is very, very important in this context, which is the concept of quantum utility. Very correctly, you contrasted it with quantum advantage, because quantum advantage has long been, with good reasons, of course, the holy grail of the scientific community in terms of asymptotic advantage. Like, I build a quantum machine for something a classical supercomputer will never be able to reproduce. That is, of course, fantastic, fascinating, a wonderful dream, and we know it is nowadays realizable for some very specific, not practically relevant problems. But industry might be very well interested in something which, from the theoretical computer science perspective might be completely boring, like 'only' a factor of ten improvement in your computing power already bringing a lot of value, then a hundred fold improvement is enormous. So this aspect of quantum utility, which is the practical, the pragmatic aspect, is really what we should be focusing on now, because that should be not like the holy grail, but really the carrot hanging from the stick, in a sense.

KI: Regarding the various subfields of AI the field of quantum AI is not just restricted to quantum machine learning as it is still widely assumed by many. But: How to address what kind of potential problems the strong interdisciplinarity of QAI might impose on scientists from the originally separate fields of quantum physics and computer science?

In this regard, at the moment, there is the, may I say, kind of a little bit old fashioned physicists way of looking at things: There are those engineers, those computer scientists to be evangelized about the holy world of the quantum, and then they will be enlightened. No, what we need is really a two-way education. This is in my little corner what I am trying to achieve for myself and for my institute. We need a lot more interdisciplinarity. We need, as a scientist, a lot more conferences, projects, more activities on that subject QAI. As a matter of fact, I am aware that the European Commission is discussing about starting a seed activity on quantum and AI in both directions, to start laying the ground for this.

KI: So, it appears that interested scientists from related disciplines such as computer science, AI and quantum physics still would need to somehow develop a common culture, mentality and standard of working together in quantum AI. But what are the currently most promising directions and challenges of research and development in QAI?

Well, first of all, certainly developing a common language, like a glossary of terms which are known to both computer scientists and quantum physicists. Second, developing a reciprocal understanding of, really, the potential. Third, I would say, identifying cases of application, developing a systematic and deep understanding of all the possible implications of the acceleration, which can come from the few problems that we know how to solve with algorithms on a quantum computer. Where is it that they can provide utility, not necessarily advantage, as you said before, a systematic investigation of that. I am not aware that this exists, though there are a lot of points of evidence.

The other challenge is really a thorough understanding of the resources associated, not to fall back to the often used argument "Oh no, this is not realistic, so let us forget it". Rather we need to be able to prioritize, to understand what are the low hanging fruits in this respect, what are the AI applications which cost the least quantum resources per utility. That is, we need a systematic investigation accompanied with the hardware challenge of making sufficiently stable quantum memory and so on.

KI: And finally, is there anything on the potential benefits and risks associated with development of quantum technologies and AI that we do not have on our radar both as a community and we as interviewers that you would like to emphasize?

Well, yes, there are two risks: Again, one practical risk is a foreign direct investment and acquisition of quantum AI technologies taking over our own quantum technology ecosystem, and the other one is the dual use of it. We know that some countries such as Spain, France and UK have started listings of export control regulations for quantum computers with certain number of qubits and error rates and so on, to counteract the fear that the capabilities of quantum computers can be potentially abused by non-likeminded countries.

KI: What advice would you give young researchers who want to enter the field of quantum AI: How to start, where to start?

Oh, well, if they want to enter, there is just a plenty of opportunities. First, they should know that they are very much welcomed in the sense that there is a strong need for such people, not just but in particular in the context of funded quantum AI research projects. They should just look, for example, for opportunities on the community website of the European Quantum Technology flagship [2]. They should not be intimidated by the purported difficulty of quantum computing. Actually, within a few weeks, with reading, for example, just a few chapters of the book of Nielsen and Chuang [3], you can get to know enough about quantum mechanics to start working with the basic building blocks of quantum computing here. So they should just engage and not be afraid!

KI: Tommaso, thank you very much for your time and this very enlightening interview!

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