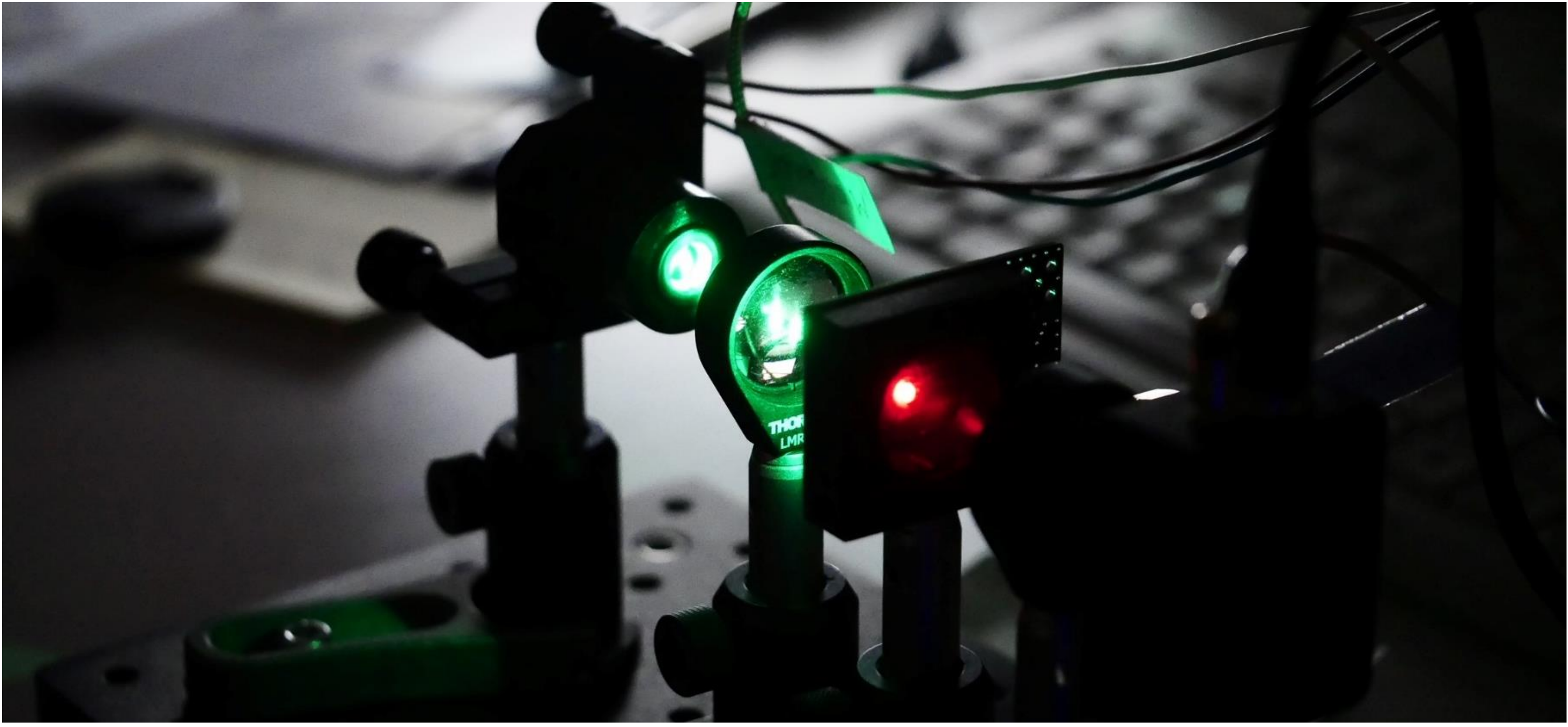

Quantum Computing Lecture V2.0

Introduction and Conceptualization Qubit

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Preamble

Hello everybody.

I am delighted to have the opportunity to introduce you to this very special Quantum Computing Lecture.

First of all, thanks to the dedicated Prof. Dr. Carmen Winter from the DHBW Stuttgart with her amazing networking qualities – I'm proud to be a part of her team.

I am not an economist, and I am also not a quantum physicist, but as an engineer, I am extremely inspired by this new field that is emerging in technology.

My education began by studying communications technology at the Esslingen University of Applied Sciences, a well-known engineering school in Baden-Württemberg, in the late eighties. At that time, communication technology developed more and more into optical concepts, so these became part of my professional work. Later, I studied philosophy for a few semesters where I focused on the philosophy of science.

Today, I am primary responsible for infrastructure at the SWR, a well-known German broadcasting institution. I am part-time lecturer at the DHBW Stuttgart since more than 15 years.

1 Introduction

Let me start with a question and two distinct answers.

Question: Why quantum computing now? Or, more broadly:
Why is everybody so interested in quantum technology these days?

First answer: Once we know how to use quantum technology properly, we expect a huge performance enhancement – that will bring a remarkable R.o.I (return of invest).

That is the business perspective. I will give you some numbers and statistics later.

Before that, we watch the following clip and learn the reason for this groundbreaking difference in the dimension of principle possibilities.

Clip: "Quantum Information's"

Second answer: Let us pursue a thought of Werner Heisenberg, one of the fathers of quantum theory.

Quantum technology opens a path to a new and larger perspective, that could connect science and its origin, namely the metaphysical questions of people all over the world. Being aware that Heisenberg stated the following in the context of World War II makes it even more radical.

In Heisenberg's opinion the physicists social responsibility concerning the high risk of quantum physics being used for a new generation of weapons – or today perhaps we can add: the problems of nuclear waste – that was a deep, but not the deepest impact on society. The most important impact of quantum physics is its philosophical aspect: [1]

Our reality is not only a big deterministic machine – it follows even deeper rules.

That our reality does not always work in a predictable way can be experienced in relatively small experiments, for example in the new Quantum Lab at the DHBW-Stuttgart. You can see it when a beam of single photons is shot to a beam-splitter, and you realize that every discrete photon makes an individual, but clear probabilistic decision. At this moment, a real miracle can be measured: the sequence of photons at a beam-splitter will result in a well-ordered superordinate image.

This observation has the power to deeply change your thoughts.

With today's extension of quantum physics ideas into quantum technology, we address a broader community, so: you could be part of this change today – that's the great mission.

Now, I will elaborate the structure of my lecture:

Table of Content

2 Financial Expectations

Let us investigate selected economic aspects and the financial expectations of quantum technologies – from the perspective of well-known sources.

2.1 Bundesregierung Deutschland

The “Handlungskonzept Quantentechnologien der Bundesregierung [Deutschlands]” calls “great challenges and extraordinary potential“ [2], and references to studies with estimation of an annual market volume of several hundred billion euros in quantum computing! [3]

The authors describe that in 2021, almost two thirds of all investments in ‘quantum technology start-ups’ were hardware-based, which amounted to more than USD 1.4 billion. That’s more than twice as much as in 2020.

2.2 Gartner

Gartner published a list of „cool vendors with quantum computing software and services“ that support various technologies for implementing qubits. Gartner regards the following three approaches as innovative to devise larger, more scalable systems augmented with software and services:

- gate-based superconducting,
- trapped ion and
- photonic techniques.

But the current landscape of quantum computing vendors and service providers is highly fragmented, which leads Gartner to predict a potential risk for investments in infrastructure and operations. [4]

They also predict the overwinding of the plateau in their “Hype Cycle for Deep Technology 2023” for quantum computing in a time span of more than 10 years, for quantum sensing in 5 to 10 years and for quantum key distribution also postquantum cryptography in 2 to 5 years. [5]

2.3 Center for Strategic & International Studies

The Center for Strategic & International Studies (CSIS), in 2023, released a report about the applications and implications of quantum technology, in which they listed the projected global investment in 2022.

In total, they came to the following estimate:

- China with $10 billion, followed by EU with $8.7 billion,
- the US with $7.4 billion, UK with $5 billion,
- Canada and Japan with each $1.7 billion,
- Australia with $1 billion,
- Russia with $790 million and India with $730 million

– in sum around $40 billion in 2022 worldwide [6].

2.4 Pricewaterhouse Coopers

To put this into perspective: according to a study by Pricewaterhouse Coopers (PwC) from 2022, the estimated total investment in digital transformation by the industry will amount to around 1,000 billion USD per year [7].

Please bear in mind that there are more participants in the field of digital transformation than in quantum technology. In Germany, for example, there are three times more computer science students than physics students. If only half of computer science students worked in digital transformation and probably only a small percentage of physics students work in quantum technology, then the per capita funding ratio would look very different.

By the way: For Germany, the CSIS Report shows an investment of $3,2 billion with a part of only 100 million USD from private investors.

Switzerland seems to act in a more conservative manner and secured their government support in 2023 and 2024 in the amount of SFR 10 million. [8]

To give you a positive aspect: 40 billion dollars in quantum technology are not enough to be the direct target of corruption – but it is still a lot of money.

So much for the financial aspect, seen from the perspective of a non-economist 😊. Your takeaways:

- There is an extraordinary potential.
- The corridor for the early birds is the next 5 – 10 years.
- There is a large amount of funding and venture capital on the market.

3 Technical Overview

In this chapter, we first look at:

- the Bra-Ket Dirac-Notation as a special notation for mathematical expressions from the field of linear algebra
- the idea of a qubit as a superposition quantum state
- the ubiquitous wave function Ψ.

We then look at the last 30 years of quantum computing and follow the idea from basics to application.

3.1 Qubit, Superposition and Hilbert-space – a placement

The available time is too short for elaborating the complete quantum theory; however, it is sufficient to cover some basics that you will also find in the standard literature. So, let me introduce you to a few technical terms and mathematical symbols along with one possible physical representation of a qubit – the photon, the quantum particle of light.

First – the quantum state:
You can map a quantum state on a single photon through its polarization. You can polarize a photon in a horizontal or a vertical direction – in this case you have a state-space of two possible states.

In general, we talk about a state-space as a Hilbert-space, that's the generic concept with more than two states and typically complex variables. You can write down that kind of a quantum state using the so called "Dirac-Notation"[1] with an "Bra" as a not relevant symbol for the moment on the left side of the Bra-c-ket $\langle \ldots \rangle$ and a "Ket" as the right side of a Bra-c-ket $\langle \ldots \rangle$ which is a symbol for a normal vector representation.

In quantum literature you will always see this Bra-Ket-Notation.

$$|\mathrm{A}\rangle = \begin{pmatrix} \mathrm{a} \\ \mathrm{b} \end{pmatrix}$$

You can interpret the basic states in a two-based system as the classical logical 0 and 1:

$$|0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \text{ repr. e.g.: H} - |1\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \text{repr. e.g.: V}$$

[1] According to Paul Dirac

Whenever you measure such a quantum state you will measure one of these both basic states and nothing other than that.

We often use a symbol for the quantum wavefunction of our photon, called Psi. And we write:

$$|\Psi\rangle = a \cdot |H\rangle + b \cdot |V\rangle$$

That is the mathematical concept for a superposition, a linear combination[2] of the above two basic states.

In practice you can realize the qubit as a quantum state for a photon that represents an arbitrary polarization, something between the two states horizontal and vertical. The qubit represents both parts of the wavefunction as a single entity.

A qubit, in comparison to the classical interpretation, is a more generic concept for information with a new kind of parallelism. Both digital states are part of the calculation in this specific state $|\Psi\rangle$.

But, through the peculiarity of the quantum measurement process you never can get this information of a quantum state $|\Psi\rangle$ through a single measurement. You can only measure one of the two basic-states. We will talk a little bit more about the possibilities of a quantum particle to transport information in our next session.

For now, it is important to know, that you need a probabilistic interpretation of several measurements. This interpretation of such a quantum measurement process is the result of the computation process from a quantum computer.

You must realize that the result of a quantum computing calculation is not a specific value it is a probabilistic distribution. That is a fundamentally new kind of interpreting results of a computing process.

3.2 Quantum Computing – Why Now

Quantum computing is one of the most spectacular parts of the whole quantum technology. In the clip we have seen the explanation: Quantum computing will be a game changer! Not in computing as we know it – this will exist parallelly. Quantum computing will be a game changer for a special class of problems that a classic computer never will be

[2] Normalized to: $|a|^2 + |b|^2 = 1$.

able to solve in adequate time. This kind of tasks we call NP-complete problems[3]. By the way: this was one of the motivating factors for Richard Feynman 1982, when he first proposed the quantum computer. [9]

That is relevant because all our ongoing cryptographically technics are based on the asymmetry of building big numbers from factors instead of finding these factors in a reverse prime number decomposition process.

Let’s have a closer look to: What were the relevant development steps to make quantum computing usable? [10]

3.3 Shor-Algorithm

The momentum of quantum computing started in 1994, when Peter Shor found a new solution for factorizing a large number [11]. His quantum computing-based solution was exponentially faster compared to the classic algorithm. Since then, it is clear: with an “up and running” quantum computer, classical cryptography is dead.

Now, you probably can assume why post quantum cryptography is such a hot topic in modern information science. This Shor algorithm is hitting asymmetric cryptography. This means: "All asymmetric cryptography is dead."

After the discovery of the Shor-Algorithm, a run to find new kinds of algorithms for other kinds of problems began. The collection of algorithms discovered by now you will find on this website: www.quantumalgorithmzoo.org. Actual we know round about 65 quantum algorithms which are for sure or assumed to be faster than classic approaches.

3.4 Groover-Algorithm and Others

Another famous and practical relevant algorithm is the Grover-Algorithm to get findings in unsorted databases. The Groover-Algorithm brings results in a quadratic improvement.

Also known are quantum-based algorithms like: “Matrix Rank[4]” – for simulation approaches and modeling tasks.

[3] For Example, the Traveling Salesman Problem (TSP) belongs to the so-called NP-complete problems. NP stands for "non-deterministic polynomial" and refers to a class of problems for which solutions can be checked in polynomial time. NP-complete problems are special problems within the NP class for which there is probably no polynomial algorithm for the solution, but it is easy to check the solution when it is proposed. For Instance: Solutions for 5 towns: 12 possible routes; 10 towns: 181 440 routes; 15 towns: 43.5 billion routes, at round about 200 towns it is not possible to find a direct solution.

[4] An example out of the class of singular value decomposition of matrices.

Great hopes exist also in the field of Machine Learning.

3.5 Quantum Advantage

Today, we all wait for the first practical use case demonstrating quantum advantage, an advantage in a real task compared to a classical computer, following up the demonstration of quantum supremacy in recent years in the context of boson sampling problems [12] [13] [14].

Boson sampling problems are very special designed problems to find solutions for a bulk of identical bosons – like photons – witch scatter in an interferometric arrangement.

This helped proving quantum supremacy, but practically, you can summarize: “solutions for boson sampling problems are not really relevant”.

3.6 NISQ

In the current implementations for real quantum computers, we have a great problem.

The number of available qubits is not fully usable because of a high noise exposure. Here, we talk about NISQ-Computers. NISQ is an abbreviation for Noisy Intermediate-Scale Quantum Computers.

The problem is more serious than expected: We only can use a very small amount of the physical qubits. Out of one thousand physical qubits only a few are usable as logical qubits.

But knowing that more and more people with fresh ideas, like error estimates or prediction instead of error correction [15] [16], or the improved version of the approximation equation for tunnel junctions in the Josephson-Contacts[5] of superconductive Qubits [17] [18] become involved in this new field, or brand new, a paper in Science from March 2024, which brings the photonic quantum computing back to the stage with a demonstration of logical states for a fault-tolerant light based approach [19]. All these new developments give us hope that solutions for all these sorts of problems will be found. By the way, these outstanding examples alone are from the last few months![6]

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[5] **Josephson effect** is a phenomenon between two superconductors. Brian Josephson, a British physicist predicted in 1962 the relationships between the current and voltage across such a weak link.

[6] Shortly after publication, a paper appeared in which the improvement of the error correction codes by IBM by a factor of 10 was presented: https://www.ibm.com/quantum/blog/nature-qldpc-error-correction; https://doi.org/10.1038/s41586-024-07107-7

Today we can build physical qubits in many ways. It is not clear which technology will win the race. The most promising platforms are based on

- superconducting qubits;
- trapped ions - Rydberg-Atoms[7];
- NV-Diamond techniques;
- photonic qubits.

More or less large PoCs (proof of concepts) exist for all of these platforms, the challenge today is not to build such a system. The challenge is to scale it to the necessary number of qubits. And this will become an engineering challenge.

3.7 Fundamental Research

The first 20 years since 1994 can be seen as fundamental research conducted by a very small group. With Peter Shor's invitation, the community immediately started with first hardware realizations on the level of logical gates.

1994, Ignacio Cirac and Peter Zoller proposed a solution for a two-qubit CNOT-Gate based on trapped-ions [20]. This was a breakthrough for the foundation of a fully generic quantum computer.

Already in 1995 Dave Wineland conducted the physical realization at the National Institute of Standards and Technology [21].

3.8 A New Era

In 2016, IBM entered a new era with their web-based portal for the use of its quantum computing system for a broader community. This era brings more and more people to the community, and it is driven by efforts to develop concrete applications and products. Google and other companies, for example Xanadu follow with other relevant frameworks.

In the last 10 years, with the foreseeable realization of possibility, more and more governments all over the world have launched major funding programs, as shown before.

So much for the possible concepts for practical use of quantum technologies.

[7] High exited Atoms with electrons far away of the nucleus and approximately classical properties.

Your takeaways:

- You get in first contact with the Dirac-Notation and the concept of a qubit.
- You see that a result of a quantum computing calculation is not a specific value but a probabilistic distribution.
- You realize some main steps on the way to the actual situation.

And you see that there are a lot of challenges but also the idea, that the greater community will help.

4 Philosophical Remarks

Since the last 25 years, quantum technology got a new form of acceptance. Not in the form, that the theory itself evolved, it was more a revolution in the field of experiments: We can now realize the famous Gedankenexperiments in a graspable reality.

4.1 The First Part

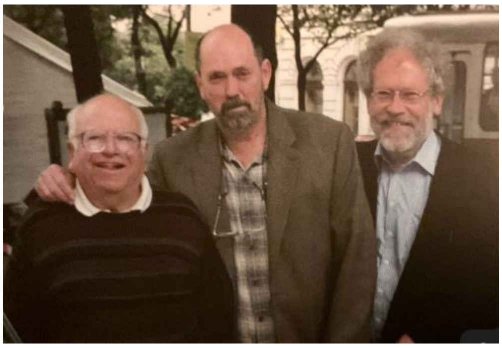
These Gedankenexperiments are originally designed to demonstrate all the peculiarity of quantum theory. And now we use them in a completely different way.

We use it for example to measure interesting things or to realize quantum networks based on teleportation with entanglement photons. Today “We just do it!“.

People like Greenberger, Horne and Zeilinger, founders of teleportation, were young and unexperienced enough to say: “we will just do it!”.

Grangier, Roger and Aspect, who demonstrate the particle character of photons, build the anticorrelation-experiment and experiments to demonstrate Bell’s inequality, which is no longer a Gedankenexperiment.

And by the way: Zeilinger and Granier were awarded the Nobel Prize for physics together with Clausen in 2021.They all were fed up with all the philosophical discussions of Quantum theory and were now bold enough to do things practically.



left side: from left to right: Dirk Bouwmeester, Harald Weinfurter, Anton Zeilinger, Jian-Wei Pan, Manfred Eibl, Klaus Mattle. Das Team, das 1997 die erste Teleportation in Insbruck durchführte.,
right side: from left to right: David M. Greenberger, Michael A. Horne u. A. Zeilinger. Die Autoren der GHZ-Arbeit.

4.2 The Second Part

The second part is, that we learn more and more that Schrödinger's Cat was a black and white model. Schrödinger's Cat is a famous Gedankenexperiment from the early days of quantum physics. It describes the curiosity of a superposition.

Instead, we realized that the interaction of isolated quantum systems with their environment, is a continuous process. Also here, we have done things in a bold way. We did not only pump native quantum objects through the double split, we also did this with bigger and bigger objects. And what we learned is, there is no crazy imaginary boarder between the old classic world and the new quantum world.

Looking closer – that means, when our measurements and control mechanism become more and more precise – we see quantum behavior also in very small, microscopic – "near cat-like objects", and someday later we will see it like even "bigger cats".

Both worlds are of the same nature.

All these experiences have a reverse impact to the theoretical understanding. In the context above, the concept of decoherence was added to quantum theory to explain how these crossing between the classical and the quantum world came about.

Still, future developments in quantum technology will have a fundamental impact on our understanding, even on our instinct.

Following Susskind, one of the founders of string theory, we can say: we have no instinct for quantum physics, because it would not have given us any advantage in the evolution. When faced with the decision between attack a wild animal or run away, these tiny quantum things are definitively uninteresting.

But quanta were there before we developed quantum theory and maybe we do have a use for them.

In contrast, Roger Penrose, winner of the 2020 Nobell Prize in physics, for example, suspects that quanta play a role in the formation of consciousness. He hypothesizes that the brain performs functions, that no finite-algorithm can perform, and that some thought-processes have to be fundamentally non-algorithmic [22] [23].

4.3 Closure

Paul Hoyningen-Huene formed in his theory of systematicity [24] the term of “epistemic connectedness” as one important component of science knowledge.

Epistemic connectedness is what we discover these days.
Epistemic connectedness is what you will experience in your great future in quantum technology.

Your takeaways:

- You can see that we have entered a new part of the story.
- New players have new ideas, and more new players have more new ideas
- What we do in quantum technology in these days will have an impact to the theory, it will enhance our view on quantum physics.
- Although quantum physics is our best tested theory, you can guess that we are not at the end yet, and we have to say today: “things are not fully consistent”.

Further Reading

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PART II

Preamble

Table of Content

1 Repetition of introductory concepts

Looking back on part 1 of our quantum computing lecture, we considered it preferable to focus on the philosophical ideas and their impact on this particular area of science.

Let’s have a look at the lessons learned in March.

We found that in financial terms …

… there is an extraordinary potential in the field of quantum technology.
… the next 5 to 10 years are ideal for investing in quantum technology.
… and finally, that there are lots of offers for funding and venture capital.

Concerning technical facts …

… you got to know the Dirac-Notation and the concept of a qubit.
… you saw that a result of a quantum computing calculation is typically not a specific value but a probabilistic distribution.
… and you got to know essential milestones in quantum technology since the mid 90s until now.

Finally, we started our philosophical journey with the following thoughts…

… we have entered a new era in realization of Gedankenexperimenten.
… the more (new) players, the more (new) ideas.
… actions using quantum technology will have an impact on theory and will enhance our view on quantum physics.
… and although quantum physics is excellently proved, it is still not fully explained.

2 Philosophical Remarks

Now, let’s have a look at this exciting moment in the history of quantum physics.

First, let me introduce you to the idea of Thomas Kuhn’s Scientific Revolutions, and then get to know a thesis about the current state of quantum physics. We will close with the idea of an evolution caused by new diversity throughout the quantum technology community.

Thomas Kuhn’s book ”The structure of scientific revolutions“ [1] was published 1962. He introduced the term ”paradigm shift“, describing the dynamic developments of science theories over time. His work followed theories of Karl Popper[8], who was a high-influential Austrian-British philosopher of science of the 20th century.

2.1 The Idea of Thomas Kuhn

Kuhn establishes the following descriptions:

Science is always based on background assumptions, traditional knowledge, rules and examples.

These assumptions determine the action.

And: These assumptions are subject to change and can be replaced by new ones.

He found out that science does not evolve linearly, but in recurring cycles, triggered by the changing of assumptions. These ”periodic revolutions“ he called ”paradigm shifts“.

2.1.1 The Model

Kuhn described 5 stages of a **periodic revolution[9]:**

1. the **pre-paradigm stage** where there is a lack of a paradigm to explain a phenomenon or observation;
2. the **normal science stage** describes the stadium where there is an enforced paradigm in place;
3. the **stage of anomalies and crisis** is the stadium when a paradigm is no longer sufficient to explain phenomenon or observations.
4. In the **stage of paradigm shift** the community no longer has a common sense about the following paradigm.

[8] Popper stands above all for the idea that theories cannot be validated but only falsified.
His ideas play a major role in the design of experiments to test the empirical level of theories.
The standard example is that it is not easy to test whether there are only white swans, in particular you have to test ALL swans, but it is clear that if you have found a single black swan, then the theory that all swans are white can be discarded.

[9] One of Kuhn’s examples was the Copernican Revolution in Planetary Astronomy. He described the dynamics of the transition from a geocentric to a heliocentric view of the world.

And last:

5. Revolution and incommensurability[10] – **the stage of resolution** designates the replacement of the former paradigm with a new one.

2.1.2 Consequences

One of the consequences of the periodic revolution – as described in 2.1.1 - is, that in the **normal science stage**, instead of exploring issues all anew, they will be adapted to the paradigm until the community accepts their explanation. Anomalies will be ignored or are used for modifications and enlargements of theories – just as long as possible and until the paradigm shift becomes unavoidable.

2.2 Quantum Physics in the Model of Thomas Kuhn

Let's take a look at the stage we are currently at, as we begin to expand quantum physics to include quantum technology:

Following the fact that there are several issues that lack a proper explanation, like the famous *measurement problem*[11], it is likely that quantum physics left the **normal science stage** already. At least in philosophic terms it has already entered the **stage of anomalies and crisis**.

Quantum technology even creates new issues, like teleportation with entanglement photons, that urge paradigms towards the **stage of paradigm shift**.

Currently, scientists search for approaches and methods to solve basic problems and to get a deeper understanding of the nature of quantum physics or at least to find enhanced interpretation of established theories.

From my point of view this development indicates the rise of the **stage of revolution**.

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[10] Incomparability of substances with measured values due to lack of suitable properties for comparison

[11] The measurement problem describes the phenomenon that the wave function collapses at the moment of observation. You can only measure the base states that we have talked about. The idea is that if you don't observe the quantum state, the wave function doesn't collapse - so there is a special and inexplicable role of the observer.

That would mean that quantum technology could act like a catalyst on the way to a new paradigm.[12]

2.3 The Counterattack from Paul Feyerabend

Nevertheless, in addition to the schemes described by Karl Popper and Thomas Kuhn, there have been groundbreaking advances outside of their frameworks. That is why Paul Feyerabend, a companion and discussion partner of Kuhn, spoke out in favor for an anarchy of methods, pointing out that science benefits of a variety of approaches and ideas. His book “Against methods” [2], published 1975, culminated in the well-known term “Anything goes”.

2.4 Summary

Let me summarize my thoughts and theories in one sentence:
Adding quantum technology to scientific work on quantum physics opens the door to a huge diversity of new ideas – and every one of us could be part of this paradigm shift.

Thank you for listening and for your interest in this year’s Quantum Computing Circle.

[12] I'm not really drawing any normative conclusions - that would of course not be permissible in the sense of Hume's law (is-ought problem, i.e. the problem that arises when one makes assertions about what is supposed to be based exclusively on statements about what is.) - but it's intended as a suggestion to get you thinking and assess the potential.

References

[1] T. S. Kuhn, Die Struktur wissenschaftlicher Revolutionen, Bd. 24. Auflage, Frankfurt am Main: suhrkamp taschenbuch wissenschaft, 2014.

[2] P. Feyerabend, Wider den Methodenzwang, Bd. 13. Auflage, Frankfurt am Main: suhrkamp taschenbuch wissenschaft, 2013.