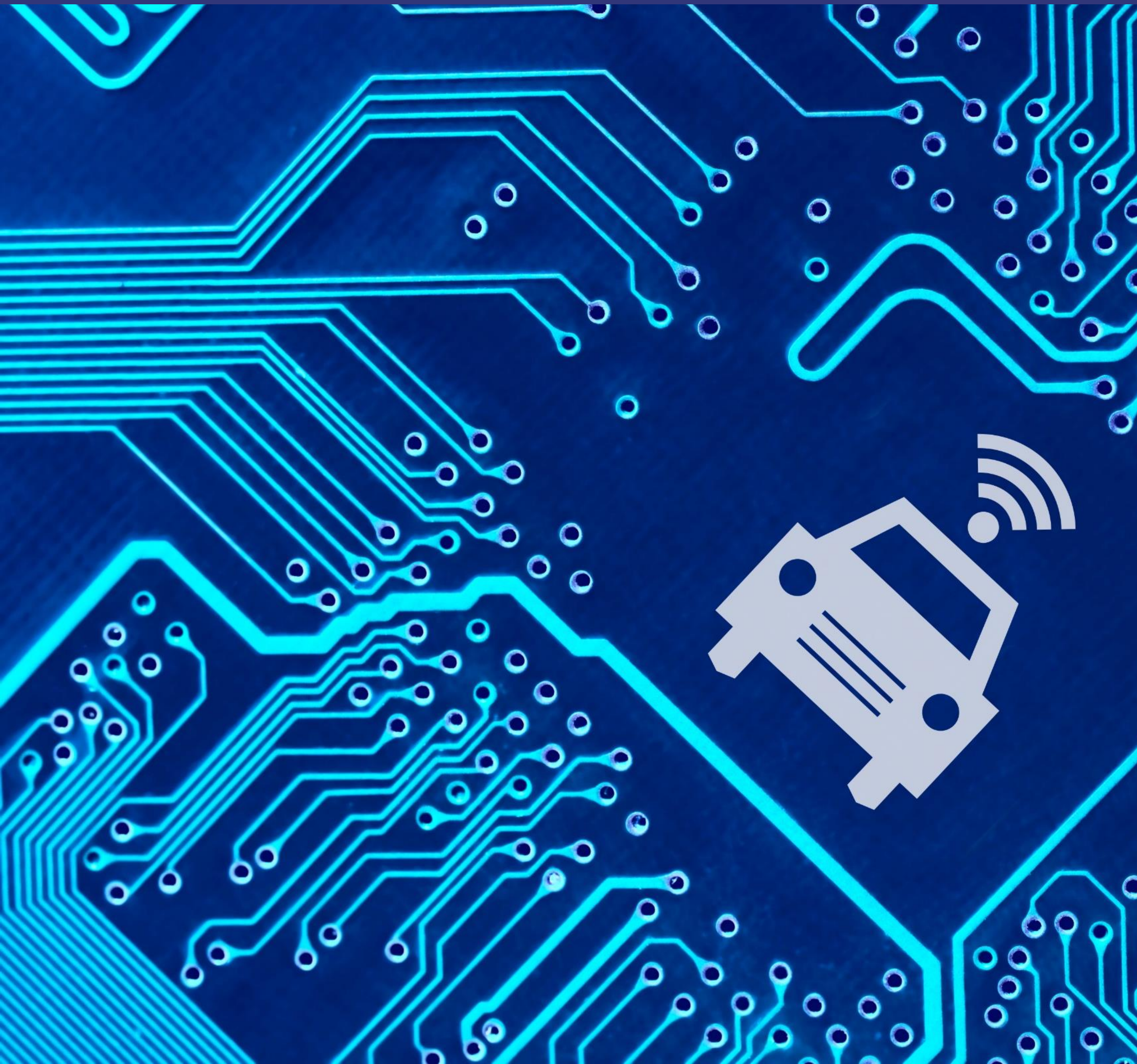
Bird & Bird & Quantum Computing in the Automotive Industry

Applications, Opportunities, Challenges and Legal Risks



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Introduction

Quantum Computing is a new buzzword[1] – generally in the IT and high-tech industries and also already in the automotive industry[2]. In fact, according to McKinsey, 10% of all potential use cases for quantum computing could benefit the automotive industry, with a high impact to be expected by 2025[3].

Quantum computing will have real implications, benefits and risks for the automotive industry. More generally, it is a disruptive technology as regards high performance computers and super-computing processes.

A key advantage of quantum computing is that its computing processes are much faster as they are no longer based on algorithms and mathematics, but on quantum physics (see below III. and IV.); quantum computers are able to do several calculations at the same time (in contrast to traditional computers) which make them exponentially faster.

This is possible because quantum computing builds on the advantages of the laws of quantum physics, where subatomic particles can exist in more than one state at any one time; their behaviour causes quantum computers to be more powerful, efficient and faster than the conventional digital supercomputers.

[1] From quantum advantage (Digitale Welt 2/2021, p. 86) https://digitaleweltmagazin.de/d/magazin/DW_21_02.pdf and Google's alleged Quantum Supremacy via the EU Commission's Quantum Technologies Flagship https://digital-strategy.ec.europa.eu/en/policies/quantum-technologies-flagship and "quantum revolution" perception (see p. 8 of the EU Commission's *2030 Digital Compass (COM(2021) 118 final)* of 9 March 2021). https://ec.europa.eu/info/sites/info/files/communication-digital-compass-2030_en.pdf to Quantum Glory (the relationship between the science of quantum physics and the glory of God, see also footnote 10) and the dawn of a Quantum Era (Bosch Research Blog, post by Georgy Samsonidze, 16 February 2021, p. 8. https://www.bosch.com/stories/how-quantum-computing-can-tilt-the-computational-landscape/

[2] A very easy to read, almost colloquial but still informative introduction is by Dr. Lance Eliot, *Here's How Quantum Computer Supremacy will Impact Self-Driving Cars*. https://www.forbes.com/sites/lanceeliot/2019/11/14/heres-how-quantum-supremacy-will-impact-self-driving-cars/ which makes the reader "quantum conversant".

[3] Burkacky, O., Mohr, N., Pautasso, L. (2020, September 2). *Will quantum computing drive the automotive future?* McKinsey & Company. https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/will-quantum-computing-drive-the-automotive-future

Possible applications or use cases in the automotive industry

Fields of application or use cases for the automotive industry are manifold. They are likely to resolve some of the key challenges of the automotive industry.

The following list is assembled from various recent publications on this topic (so the reader should not be surprised about some repetition, but each bullet point has a different focus):

- traffic congestion (anticipating and avoiding bottlenecks),[4]
- fuel cell optimization,
- level 5 autonomous driving by, *inter alia*, improving navigation to calculate the fastest route more effectively and in real time,
- advance product development, namely battery technology,
- improving the fuel efficiency of shared mobility fleets[5],
- machine learning of traffic patterns,
- artificial intelligence for mobility solutions,
- security of connected driving,
- boosting transition into the electric vehicle era, by accelerating R&D of novel technologies, in particular cooling of EV batteries,
- simulations (heat and mass transfer, fluid dynamics, material properties at the atomic levels) – relevant for development of battery and fuel cell materials,
- risk mitigation or prevention of quantum hacking of communications in autonomous vehicles, electronics and industrial IoT,
- investigating and optimizing crash behaviour, cabin soundproofing,
- route optimisation,
- durability of materials,
- predicting traffic with such precision that accidents may be avoided (a task requiring significant computer capacity),
- over the air communication (V2V or V2C) for downloading data (traffic information) and uploading driving data and encryption of data locally in the self-driving car and in the cloud, thus providing safety for commuter cars[6],
- optimizing routing of warehouse robots,
- increasing the accuracy of demand forecasting for suppliers along the supply chain by simulating complex economic scenarios[7] (e.g. could the current semiconductor and steel supply shortages have been avoided or mitigated?).

Many automotive industry players are already fully involved in exploring quantum computing applications and use cases. OEMs and Tier 1 suppliers which are known to belong to these players are amongst others:

Volkswagen	Daimler
Ford	BMW
Toyota	Bosch[8]

[4] For details, see Istvan Barabasi (2018, May 4). *How to Compensate for Traffic Congestions in Big Cities by Optimizing the Path Vehicles Take*. http://csis.pace.edu/~ctappert/srd2018/2018PDF/a6.pdf

[5] A good recent overview by Jamie Thomson, Isabell Page (2020, December 17). *How quantum computing can drive an autonomous future*. Messe Berlin GmbH. https://www.intelligent-mobility-xperience.com/how-quantum-computing-can-drive-an-autonomous-future-a-987692/

[6] Akrout, M. (2020, March). *Will quantum computing be the next generation of automotive technology?* Prescouter. https://www.prescouter.com/2020/03/will-quantum-computing-be-the-next-generation-of-automotive-technology/

[7] Burkacky, O., Mohr, N., Pautasso, L. (2020, September 2). *Will quantum computing drive the automotive future?* McKinsey & Company. https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/will-quantum-computing-drive-the-automotive-future

[8] For a good summary of what they are involved in, see the Exhibit 3 in Burkacky, O., Mohr, N., Pautasso, L. (2020, September 2). *Will quantum computing drive the automotive future?* McKinsey & Company. https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/will-quantum-computing-drive-the-automotive-future

Quantum Computing

Some Introductory Remarks

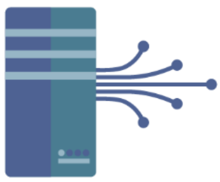
As stated above, quantum computers are exponentially faster than traditional/digital computer technology because they operate on the basis of quantum physics where subatomic particles (and in quantum computers the qubits instead of bits) exist in more states than one state which allows for an unimaginable simultaneous multiplication of computation steps and processes. The addition of one qubit to a quantum computer doubles its computing power; the same effect could only be achieved with a classical supercomputer by doubling its system size.[9]

When we start to look into quantum computing in greater detail, we quickly learn the key difference to a traditional computer: Its bits are expressed in a binary code by a “1” or a “0”. Quantum computing, in contrast, uses quantum bits or “qubits” for short; they can also have these binary values “0” or “1” or hold both of them at the same time which is called superposition.

Further, two separate and apart qubits can become linked together and correlated like mirror images of each other; this is called entanglement. Information is “transported” without passing through time or space; rather, the information in one qubit is simultaneously in another qubit because entanglement causes one qubit to be what the other is. In other words, there is no “transfer” of knowledge from one to the other qubit; the other has it simultaneously.

Thus, quantum computing is based on the multi-dimensional nature of physical objects – admittedly, at subatomic size – which are permanently connected in a different, hard to imagine, virtually invisible reality, which experimentally, however, may be made visible and is real. By quantum computing, data are “transported”, computed, stored dramatically faster than in traditional computing. Sounds spooky? Sounds unreal? You can’t logically imagine it! And yet it is all true and proven, both theoretically/mathematically and experimentally.

Quantum computing is built on and uses the principles of quantum physics (or quantum mechanics) such as superposition and entanglement to perform the computation steps. To properly consider and understand the legal risks arising from quantum computing, it seems worthwhile to be aware of and have a rudimentary understanding of the underlying principles of quantum physics/quantum mechanics.



[9] Bosch Research Blog, post by Georgy Samsonidze, 16 February 2021, p. 6. https://www.bosch.com/stories/how-quantum-computing-can-tilt-the-computational-landscape/

Quantum Physics

Some Basics

Physics is the field of science which explores the nature of the physical world we live in.[10] Physicists are fascinated by the nature of matter. They want to know what the universe is made of and what holds it together. Physics concerns itself with matter, energy, force, motion, space, time, gravity, mass and electrical charge. The physicist explores these relationships between all the realities and seeks to arrive at an exact mathematical description of the correct characteristics and sources of nature. What is the nature of matter and what is the smallest constituent part of matter?

Quantum physics concerns itself with this study of the constituent elements of nature which are divided into discrete units or packets of energy called quanta. The world of the quantum is the world of subatomic particles that interact with one another in the smallest scale of the universe. To grasp the nature of the quantum world we must reduce our scale or thinking down to the infinitesimally small.

A quantum particle is an indivisible unit or packet of energy – the word quanta describes the mathematically determined quantity of energy (such as an electron or a photon). Max Planck got the 1918 Nobel Prize in 1919 for discovering that all of nature is made up of these indivisible quanta of energy. There are many different kinds of quanta such as photons, i.e. electromagnetic radiation, or particles like electrons or positrons (which carry certain amounts of quantum energy).[11]

Photons are the elementary particles light consists of, i.e. (as Albert Einstein proposed) the units/quanta of energy of electromagnetic radiation. Further, photons also have properties of spatially localized, discrete waves so that they may be considered wave packets. The amount of energy a single photon carries is proportional to its electromagnetic frequency and hence inversely proportional to the wavelength.

All matter such as solid-state bodies, liquids and gases are made up of atoms or molecules, molecules being a group of several atoms. For instance, the very simple water molecule H_2O consists of two hydrogen atoms and one oxygen atom coupled together to form a molecule. A hydrogen atom consists of a single electron and a single proton. This is the simplest atom that exists. Generally, atoms consist of the nucleus and the cloud of electrons being distributed (jiggling or oscillating) around the nucleus.

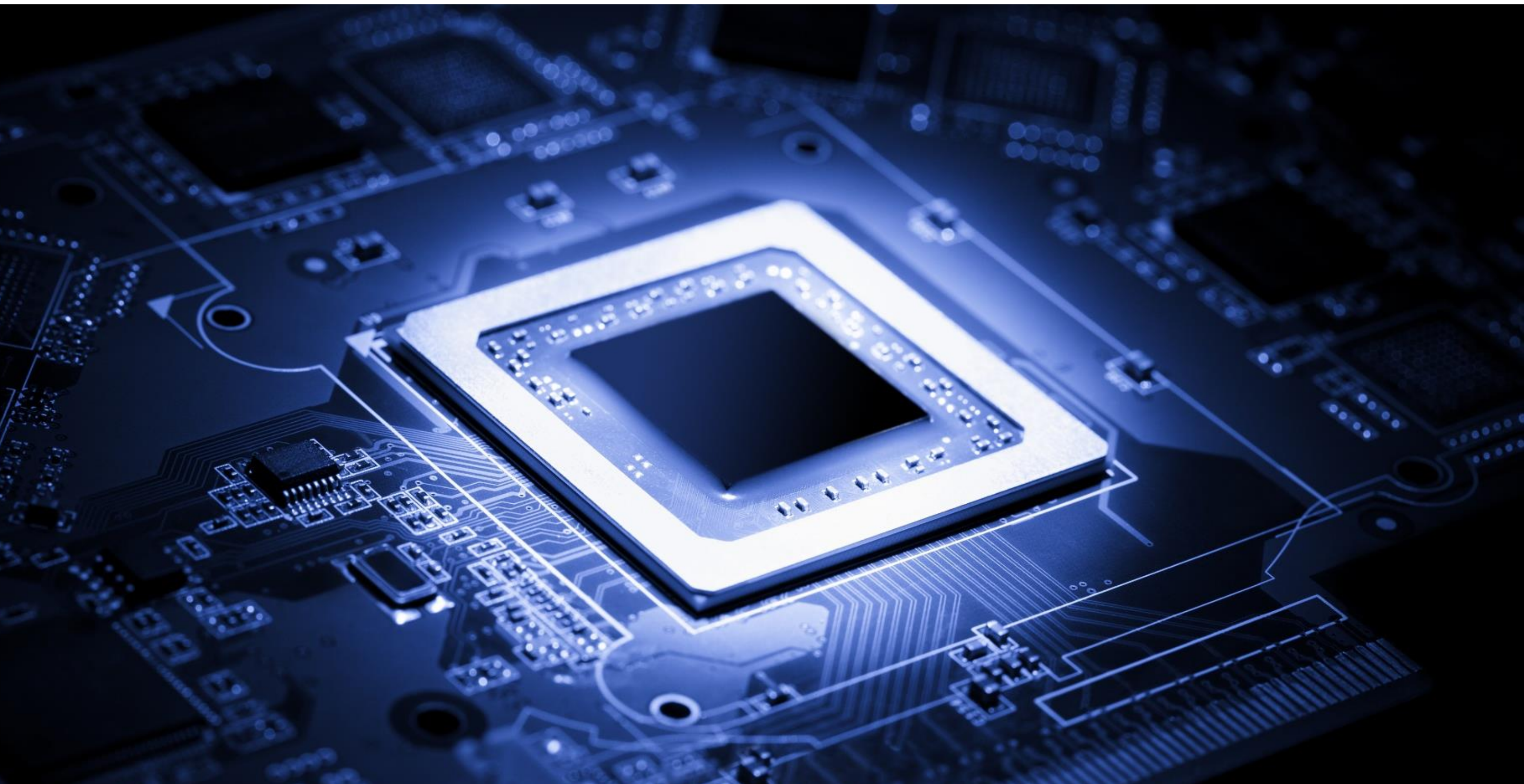
[10] Sections III. and IV. on Quantum Physics are inspired by and adapted from chapters 2 and 3 of Phil Mason's book *Quantum Glory: The Science of Heaven Invading Earth* (2010), an exploration and discussion of the intersection between science and spirituality through the lens of the biblical worldview.
[11] Many thanks to my partner Felix Harbsmeier, a patent attorney and trained physicist, for some very helpful comments on this and the following section.

The nucleus of the atom consists of one or a bundle of positively charged protons and neutrons (that have no charge) tightly bonded together by the nuclear forces to form the core at the heart of the atom. The electron is much smaller in size than the proton and the neutron and has considerably less mass. Protons and neutrons are almost 2000 times heavier than electrons. The negatively charged electrons are bound to the positively charged nucleus of the atom (because of its positively charged protons). Even though they are bound together by electromagnetic force between them, the electrons violently oscillate around the nucleus, occasionally extending to the atom's outer fringes.

To which extent an electron may be distributed at larger distances from the nucleus depends on the energy the respective electron has, and this energy can be absorbed by an electron only in quanta and not continuously. Similarly, the constituents of the nucleus, i.e. the protons and neutrons may also assume quantized energy levels.

Therefore, because the energy of its constituted parts is quantized, the atom is made up of quantum energy and therefore also, the entire universe is made up of quanta (or quantities) of energy. Quantum physics is therefore the study of the physical world at a scale of these quanta!

Often, the initiation into the world of quantum physics/mechanics causes the reaction of shock, mystery or "weird". The discoveries of quantum theory went against all instinctive understanding that we humans have developed through our regular interaction with the classical world of physics. Physicists, however, are absolutely certain of the properties of the quantum world because the predictions of quantum physics are tested and validated mathematically; the mathematical predictions of quantum mechanics yield results that are in agreement with experimental findings. And the fact that quantum theory fits experiments is what validates the theory. But why experiments should give such peculiar results is a mystery: no one can relationally explain the mystery of what they have discovered in the world of quantum mechanics. Let's look at some such principles of quantum physics:



Quantum Physics

Some Principles

Electrons wildly jiggle around the nucleus of the atom, as we already saw. They, therefore, cannot be precisely measured in terms of their position and their momentum: this is the Uncertainty Principle of quantum mechanics (discovered and identified by Heisenberg). This Uncertainty Principle rules over all possible states of the quantum field. The Uncertainty Principle teaches that is impossible to precisely know where an electron is at any moment in time. It can be – and probably is – at more than one spatial/geographical place at the same time; and that it may never stop moving would also follow from the Uncertainty Principle (as otherwise there would be certainty).

The Wave-Particle Duality is one of the most striking features of the quantum world and it states: There is no fundamental difference in the make-up and behaviour of energy and matter. Elementary particles of both energy and matter behave depending on the experiment like either particles or waves. Joseph John Thomson won the Nobel Prize in 1906 for proving that electrons are particles. His son George Paget Thomson won the Nobel Prize in 1937 for proving that electrons are waves. Both father and son are correct.

Light travels as a wave but departs and arrives like a particle. Light thus acts like a wave when one type of experiment is done but acts like a stream of particles when a different type of experiments is performed. This dual nature of light eventually came to be known as the Wave-Particle Duality.

In the 20th century, electrons which so far had been assumed to constitute matter were also shown to exhibit wave-like phenomena. The so-called Double Slit Experiment (see below at 5.) essentially confirmed that matter also exhibits this same Wave-Particle Duality. In other words: It was discovered and confirmed experimentally that an electron is both, a particle of matter AND a wave of energy. From this reality all the other principles of quantum mechanics follow.

The question then, of course, is how can something simultaneously be a wave and a particle? We can accept that something in the macroscopic world is either one or the other but not both at the same time! This is the "shock" of quantum physics.

The principle of quantum superposition claims that while we do not know what the state of an object is it is actually in all possible states simultaneously as long as we do not look or check. It is nothing more than a cloud of ambiguous possibilities.

However, when someone looks to take a measurement, it is the very act of the measurement (observation) that causes the electron to be limited to a single possibility (the so-called observer effect). Whenever physicists seek to measure something at the quantum level, they collapse the superposition, forcing the electron into a single state; measuring actually destroys the superposition forcing the electron into a single state.

Thus, as regards light: physicists are collapsing the superposition of the light from being particle and wave at the same time to (or: from) being one or the other, depending on the kind of experiment they are subjecting the photon to.

The key characteristic of quantum mechanics is "Entanglement" though. If a subatomic particle decays (falls apart/is split) into two particles, these resulting particles will remain linked or connected as "partners for life" with one another – they remain "entangled". Let's take two photons as an example of such subatomic particles; they are created when a photon decays.[12] The resulting two photons are entangled photons, i.e. their total energy will be equal to the mass/energy of the original photon.[13] The resulting pair of photons are sent off in opposite directions with identical

[12] For instance, when an electron and a positron (the anti-particle of the electron) hit each other.

[13] I.e. the electron and the positron in our example.

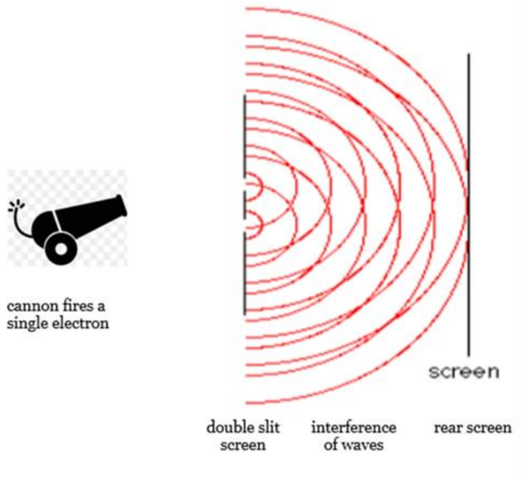
polarisation or spin.[14] Even if these two (entangled) photons move far away from each other, they, nevertheless, remain connected or entangled and able to always "communicate" with each other.[15]

The spin is identical, but the direction of the movement is opposite. If one entangled particle or photon is spinning "upwards", the other will spin "downwards". If one entangled particle is measured (observed) as being nudged in the "up" direction, the entangled partner is simultaneously caused to spin in the "down" direction. The measurement at one place of one particle affects the other particle at another place directly, instantaneously, even if it is far away. Spatial separation, as we perceive it, seems to be non-existent. Therefore, whatever happens to one entangled particle affects its entangled partner! And without any time delay – not even the time it would take light to travel from one to the other particle. Thus, also the concept of time, as we know it, does not seem to exist. The two entangled particles affect each other immediately, simultaneously, instantaneously without the smallest gap. Regardless of the distance between two entangled particles, what happens to one of them happens to the other as well.[16]

As we have referred above under 2 and 3 to the double slit experiment and the observer effect, it seems useful to explain them as follows:

So, what is the double slit experiment? If one electron (a matter particle) is fired through a (gold foil) screen with two extremely narrow slits, it travels through both slits at the same time and creates interference waves which show up on the rear screen. The single electron is set to exist in a superposition of two states. As soon as it is fired, it spreads out in a broad wave pattern.

The obvious interference pattern reveals that a single electron, spread out into a wave, passes through both slits simultaneously and creates an interference pattern where the electron in its wave form actually interferes with itself, resulting in a fringe pattern appearing on the rear screen. In particular, the initial wave of the electron is generating two separate waves in the centre of the slits and these two waves collide or interfere with one another as becomes visible on the rear screen.



This changes though if a (particular) detector is switched on.

The act of observing/measurement mysteriously collapses the dual nature of the electron into a particle state so that it only passes through a single slit much like a bullet passes through a doorway in a wall. The detector is placed behind the double slit screen and can determine which slit the electron passed through. So it is clear that when observed/measured the electron acts like a single particle passing through one slit only! This is the so-called "Observer Effect".

When an electron is fired and it is being observed (because the detector is activated), the superposition of its two states collapses into a definite particle state; no interference waves are recorded on the rear screen. When it is not being observed (because the detector is not activated), it remains in a superposition of two states (as at 5.1).

This problem simply cannot be explained rationally – how does the electron – intuitively – know that it is being observed? How does it know there is a detector hidden behind the double slit screen? How does it know when the detector is not switched on (so that it can pass through both slits without being observed)?[17]

[14] All particles have a property known "spin" as they rotate on an axis.

[15] Einstein is often quoted as having called (and derided) entanglement "spooky action at a distance" ("spukhafte Fernwirkung") in a letter to Max Born, dated 3 March 1947, because it seemed to be contradictory to his theory of relativity as regards the speed limit on the transmission of information inherent in it.

[16] On Entanglement generally and in-depth: Amir D. Aczel, Entanglement: *The Greatest Mystery in Physics*, 2002, especially p. 250; Entanglement is so challenging to our thinking about nature and the tangible/perceivable reality as we know it that one secular author has called it "the God Effect". Brian Clegg, *The God Effect: Quantum Entanglement, Science's Strangest Phenomenon*, 2006, pp. 1-2.

[17] So, there are electrons/atoms with an in-built capacity to know when they are being observed? Is there a conscious awareness in atoms causing them to materialise in the presence of a conscious observer? Electrons cannot be tricked – the electrons appear to sense exactly what is going on around them.

Quantum Computing

Applications and Challenges

The principles of quantum physics or quantum mechanics are fully applicable in quantum computing – just that we do not discuss particles, electrons or photons but qubits instead. And qubits operate on the basis of superposition of two basic quantum states (whereby qubits are able to carry out parallel computing operations) on the basis of entanglement to the effect that the state of any qubit that is in a pair or group of qubits is fully correlated to the state of the other(s), especially as regards their physical properties: position, spin, polarization and if one entangled qubit is measured (observed), other entangled qubit(s) also collapse. In fact, the measurement of a qubit causes the collapse of the quantum state of the qubit into a bit. In other words: The qubits are fragile and lose their quantum state when measured (observed).

But there are other key differences between classic bits and qubits: In theory (i.e. in a perfectly isolated qubit), there is a definite system-like phase relation between different states which is said to be "coherent". In practice, however, due to the influences of the physical environment on the qubit and its interactions with the qubit, the coherence is gradually and over time lost. This process is called quantum decoherence.

Against the background of these quantum physical principles of superposition, entanglement and the measurement (or observer) effects as well as the possible environmental influences upon them it is easy to imagine that actually building a fully functionable, large-scale quantum computer faces several challenges:

1. First of all, a qubit or a semiconductor qubit needs to be realized at all, then their quality needs to be improved.

2. Quantum computers rely on quantum algorithms, for which quantum circuits are required which are sequences of elementary quantum gates applied to qubits. Semiconductor qubits and quantum gates have usually and typically limited coherence time, usually much shorter than required to execute quantum algorithms.

3. To actually perform computations, qubits need to be controlled with great precision, either electrically (charge qubits) and/or by magnetic fields (spin qubits). The volatile nature of qubits and the fact that they interact with other qubits (which interactions cause multiple calculations to take place at the same time) makes controlling qubits and their interactions so very important but also complex and challenging. Large-scale computers require hundreds of thousands or even millions of qubits. The maximum qubit numbers operating and being handled in a computer grew from 16 in 2019 to 64 in 2020.[18] This illustrates the hugeness of the task.

[18] A. Luckow, J. Klepsch, J. Pichlmeier, *Quantum Computing: Towards Industry Reference Problems*, Digitale Welt 2/2021, p. 38. https://digitaleweltmagazin.de/d/magazin/DW_21_02.pdf

4. Equally, error and fault factors need to be reduced or even avoided. This requires shielding the quantum computer and its qubits from environmental influences (commonly referred to a "quantum noise"). Such "noise" causes the electric and magnetic fields in the qubit to fluctuate; thereby a dephasing and decoherence of the qubit state are effected.

   Noise reduction is achieved by refrigeration at very low temperatures, ultra-high vacuum for purposes of isolation, shielding from stray radiation and the use of control pulses to negate errors.

   Thus, improvement (shortening) of the decoherence time by reducing or avoiding environmental noise is critical for the performance of a large-scale quantum computer.

5. For their proper operation, qubits need to be kept at very low temperatures[19]. This requires large-size cooling systems and lots of power. Higher temperatures, though, decrease performance of the qubit as regards decoherence, noise and fidelity.

6. The interface between qubits and classical electronics for their control as well as readouts.

7. Development of special algorithms (quantum algorithms).

8. The lack of quantum programming languages and the need for their development.

9. Short running times of larger numbers of qubits required (not least for quantum error correction/QEC purposes) for the use of large-scale quantum computers.

As discussed, quantum computing qubits are extremely fragile in comparison to bits. Slightest disturbances may cause errors. Shielding the current generation of computers from outside influences, *inter alia*, by having them run in isolated operating environments and at very low temperatures is one way of avoiding errors. The other is quantum error corrections – they exist but are highly energy and resource consuming and are not yet ready for implementation in a vehicle; rather, many significant engineering challenges are still ahead.[20]

Quantum error correction is thus one of the fundamental issues of building and operating any (large-scale) quantum computers. In particular, as the volatile state of the qubits may be the reason that input is lost or changed with the consequence of faulty/defective results of the computing process.[21]

[19] Quantum computers require cooling down with liquid helium to -273.13° Celsius, cf. S. Ghose, *The future of quantum computing*, Bosch Global, 10 September 2020. https://www.bosch.com/stories/future-of-quantum-computing/

[20] Shohini Ghose (2020, September 17). *Are you Ready for the Quantum Computing Revolution?* Harvard Business Review. https://hbr.org/2020/09/are-you-ready-for-the-quantum-computing-revolution: It is not even clear when or even if the full power of quantum computing will be accessible.

[21] Much of the proceeding text has been influenced by and adapted or summarized from the following two papers which also provide a much more in-depth analysis of the issues discussed above: R. Nikandish, E. Blokhina, R.B. Staszewski (2020, December 16). *CMOS Quantum Computing: Toward A Quantum Computer System-on-Chip*. Cornell University. https://arxiv.org/pdf/2012.09021.pdf and Travis S. Humble (2018, October 5). *Consumer Applications of Quantum Computing: A Promising Approach for Secure Computation, Trusted Data Storage, and Efficient Applications*. U.S. Department of Energy/Office of Scientific and Technical Information. https://www.osti.gov/pages/biblio/1490615

Quantum Error Correction (QEC)

QEC comprises the method in quantum computing to protect quantum information – i.e. the quantum states of a qubit from unwanted environmental interaction (decoherence) and other forms of quantum noise.

QEC is essential for dealing with noise but also with faulty quantum gates and faulty measurements, among others. QEC is very much achieved by protecting information even when individual qubits get corrupted; in facts, errors must be detected and corrected without measuring the qubits as otherwise the qubits' coexisting possibilities would be collapsed into definite realities; but traditional "0" or "1" bits cannot sustain quantum computations. However, by means of "quantum error-correcting codes" (detected/proved by Peter W. Shor in 1995) error rates can theoretically be pushed close to zero.

Quantum error-correcting codes work in such a way that information is not stored in individual qubits but in patterns of high entanglement among many qubits. Thus, any qubits for "real" computations need exceedingly greater numbers of "ancillary" qubits for OEC purposes. This requires both a far greater capacity (and size) of large-scale quantum computer hardware than currently exists and far more efficient codes. Therefore, QEC is still a major area of design, development and research.

The challenges of QEC are indicated above; for present purposes it should suffice and details be reserved for another paper at another time.

Legal Implications and Risks of Quantum Computing

If we look at the specifics of quantum computing and, in particular, at some of the key differences to traditional computing arising from quantum physics, it quickly should become clear that there may also be some new and major risks which may be much harder to generally assess and deal with contractually.

Most of us outside the small circles of (quantum) physicists and quantum computer specialists will find it quite challenging to comprehend fully or at least sufficiently all that is ongoing in any quantum computer calculations and computation processes (remember Einstein's dictum above at footnote 15). To press any of these physics-based new technological aspects into legal concepts and legal doctrine requires some deep thinking about the combination of both. This is a mere start on some likely issues.

Contract Issues

In contractual terms, it is likely that the development of and reliance on cloud-based business models for the use/licensing of software will (need to) extend to quantum computing. Considering the technical requirements for the set up and operation of a quantum computer on any company's premises, "renting" or "leasing" hardware (space), software or data processing services and use them from a distance would seem the sensible and likely way forward. Cloud computing services (like software as a service, platform as a service or infrastructure as a service) may be blueprints for such offerings. So finding appropriate contract wording for the business model for and access to quantum computing is a key issue to be addressed.

In light of the capacities of quantum computing, new questions and challenges will arise regarding effective copyright protection of software (source code). Reverse engineering and circumvention of software protection measurements will be much easier. It is too early to judge whether this may need to be addressed in legislative changes (and, if so, in which), but right holders / licensors certainly need to consider whether they need to reflect this in their licensing contracts.[22]

Considering that quantum computers will operate much faster, how will their performance be measured for the purposes of figuring out whether and how they comply with contractual performance criteria and, conversely, how will a lesser performance be measured, proven and be compensated for?

A related question would arise as to how service levels would be figured out and agreed in the first place and then be measured as to whether they are complied with or not given the unpredictable possibilities of quantum computing (entanglement, observer effect, QEC to name a few novelties of this technology with which the market and the lawyer would need to deal)

[22] Many thanks to my partner Fabian Niemann, a specialist on IT, Copyright and Data for some helpful insights and comments here and elsewhere in this paper.

The ideas of superposition and entanglement in quantum physics and quantum computing shatter the traditional understanding of causation, in the first place in a "natural/scientific" way, but then also, of course, in a legal sense.

Similarly, foreseeing and contractually taking into account (by limiting or excluding any kind of damages) the defects and losses which may arise from any quantum computing processes and operations may need to be thought through afresh vis-à-vis current concepts: Whereas contract lawyers currently think of different kinds of defects, breaches of contract and losses/damages and provide contractually for them, this ability to deal with known issues or contemplating new issues may no longer work with quantum computing (at all or as easily as at present).

Irrespective of the way any company will use quantum computing, what level of expertise will their employees/"IT specialists" need to have and (in case of dispute) be able to show or even prove in order to avoid any accusation of contributory negligence? This may apply, in particular, to operational matters (input etc.), maintenance, QEC.

Supply Chain Issues

Today the Tier1 supplier already often receives parts comprising electronic or digital gadgets, software, algorithms supplied by a (often directed) Tier2 supplier, which the Tier1 supplier has neither the know-how or expertise nor the technical or other resources to test or validate in any meaningful, in particular, in-depth way. These issues will be exacerbated by the supply of quantum computing products.

Similarly, any recourse along the supply chain will become more difficult as neither causation nor fault are easily established or even proved along the supply chain. And especially those "in between" without owing contractually or impliedly any special expertise on quantum computing may even more easily escape liability; this would result in the recourse along the supply chain perhaps being more easily interrupted than today.

In the circumstances, OEMs may be well advised to enter into agreements with directed Tier2 suppliers in future – something they avoid as much as possible today.

Cybersecurity and Privacy

The quantum uncertainty and the probabilistic nature of quantum physics are the cause that quantum information/information in quantum systems cannot be precisely copied. Therefore, quantum keys for encryption cannot be hacked for encryption is based on the laws of physics and not on the mathematical algorithms of today. Conversely, the powerful quantum computation possibilities of tomorrow may crack today's mathematical encryption techniques.[23]

Does that mean that for instance all autonomous driving technology must be quantum-based to be safe from hackers?

The easy breach of encryption and the likelihood of cybersecurity being compromised may have an impact on the storage and use of any form of data, in particular Big Data. It may also have very severe implications for the safety of personal data/privacy and the (continued) usefulness of data protection regimes like the GDPR.

Current data protection laws and guidance require encryption in many circumstances. Will this at all be possible in the future?

Further, anonymization of personal data may become difficult and often impossible. Many industries and, more generally, technological progress rely on the possibilities to use data without the limitation of (current) data protection laws. What happens if there is hardly any anonymous data anymore? Possibly, quantum computing requires a change of data protection laws. In any case, it requires a fresh look at anonymisation and data protection issues more generally.

[23] Ghose, S. (2020, September 17). *Are you Ready for the Quantum Computing Revolution?* Harvard Business Review. https://hbr.org/2020/09/are-you-ready-for-the-quantum-computing-revolution

Regulation and Norms

In view of some broader general concerns about the use of quantum computing and even the discussion of risks for society at large[24], there may be some regulation at national or international level.

In addition, it remains to be seen whether and in which scopes there may be sector-specific or industry specific regulation in future.

Furthermore, norms like ISO 26262 on functional safety of electrical and/or electronic systems that are installed in serial production of road vehicles (covering the entire automotive product development cycle from specification to design, implementation, integration, verification, valuation and production release) may need to be adapted to the use of quantum computing per se or as part of any of these product development steps; or a similar norm specifically for quantum computing may need to be issued.

Also, we should not be surprised if any of the players in the automotive related quantum computing field – especially the OEMs – will duly issue their own (work) norms.

Competition law

Competition law concerns may arise if it should appear over time that only a very limited number of companies may ultimately have credible offerings in quantum computing that would generally or in certain areas of application (like, for instance, cryptography) dominate the market. In view of the many start-ups, big tech companies and sector-specific players (like the aforementioned automotive companies) investing in this area, no real prognosis of the likelihood of such competition law concerns seems possible at present. But perhaps there may also be issues of "access to quantum computing".[25]

[24] Monica Zent provides some interesting thoughts for probing and a broader legal framework (Zent, M. (2019, December 16). *INSIGHT: Quantum Computing – A Blueprint for a Proactive Public Policy, Legal Framework*. Bloomberg Law. https://news.bloomberglaw.com/us-law-week/insight-quantum-computing-a-blueprint-for-a-proactive-public-policy-legal-framework

[25] Writing this article was inspired by reading chapter 5 of Kris Vallotton's book *Spiritual Intelligence* (2020) which discusses a Christian perspective on science and tech innovation by means of the example of quantum computing.

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