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The Quantum Computer – A Future Subject of Media Studies?

The quantum computer is regarded as a key technology for the twenty-first century. Presently both large companies in the technological sector and lavishly financed research programs of various nation-states are driving development of these machines. Quantum computers are based on the idea of making insights from quantum physics utilizable for the processing of information. They are at center of the hope to develop completely new technologies – so-called quantum technologies – through informatics' use of quantum effects. A “quantum fever”¹ has broken out and more than a few observers see the “next revolution”² looming.

Such discourses are well known to media studies by reason of its reflections on change and upheaval in the history of media³. A semantics of revolution, which holds out the prospect of radical changes for very different spheres of society, is often combined with a conceptual dependence on preexisting information technologies⁴. But in understanding contemporary developments it is crucial to note that even if innovation expectations are presently focused on quantum computers, they are certainly not limited to these machines. In the professional discourse there is already discussion of technologies such as a “quantum Internet”⁵, innovative “quantum sensing”⁶ and “quantum cryptography”⁷ procedures. Conspicuous in these debates is that research on the link between quantum physics and information theory is fundamentally concerned with questions pertaining to the mediality of the processes described⁸. To put it more pointedly, one can currently observe the emergence of a paradigm of

quantum-based mediality that is concretized in a whole series of specific quantum technologies and which finds its most visible expression in the quantum computer.

In media studies there are already some analyses of quantum computers.⁹ In view of developments in the research field, however, any theorization of the quantum computer as a “new” medium has still yet to emerge as well as any media-theoretical and media-historical reappraisal of links between quantum physics and media technology.¹⁰ The present paper therefore suggests that a prospect for future research would be to enter into the discussion on “quantum media” in a very general way and to commence this discourse with a description of the quantum computer as a media technology of the future. To this purpose, the first section will give an initial overview of the underlying physical insights and functioning of quantum computers. The second part will then use the debate on so-called “quantum supremacy” to discuss exemplary imagination processes that can be presently identified with regard to the quantum computer. The third part will expand our view to a more general consideration of quantum media and their archeology, then to conclude there will be a brief summary which will emphasize the consequences for research in media studies.

On the Theory and History of Quantum Computers

It was a marginal phenomenon, a physical detail which gave rise to the supplementation of late-nineteenth century physics with quantum physics and thus heralding a turning point. Then the world of atoms was added – a world about which classic physics (already appearing both established and complete) could not make any meaningful statements.

The primal scene consisted of explaining what color a body glows when it is heated. We know the phenomenon from the glow of wood-burning stoves, the glow of glass as it is being formed, and from pictures of forges when the metal block goes from a deep red to orange to light yellow as it grows hotter, and we also know it from the color of sunlight. Max Planck, who was perhaps the personification of a classic physicist, could not avoid incorporating into the theory of radiation color an element that suddenly brought the hitherto insufficient law of radiation into conformity with the measurements. He introduced the quantum hypothesis, the assertion that energy is not forever finely distributable but is always only existent in measured packets. Surprisingly this hypothesis ultimately aligned theory and experiment. This was incompatible with classical physics, so Planck was thoroughly displeased. It was therefore only after a long struggle that in 1901 he made his proposal public¹¹. This indivisible amount of energy, the quantum of electromagnetic action, was subsequently named after him as “Planck constant” and in 1918 he received the Nobel Prize in physics for his discovery. Planck’s constant is actually very small, which is also why science had managed to overlook it up until that point. If its numerical value is written down then it is only in the 27th place after the decimal point that something other than a zero appears, thus playing virtually no role in any facet of our daily experience – though it is indeed relevant on very small scales, for atoms and their components.

Albert Einstein came to similar assumptions and conclusions when he investigated with what energies electrons are driven from metal when it is irradiated with light. Today this is called the “photoelectric effect” and is to be found in every digital camera. It was for this work and *not* his theory of relativity that Einstein was awarded the Nobel Prize in 1921. In 1905 he put forward the presupposition “that the energy of light is discontinuously distributed in space”¹² and thus demonstrated his special gift for

drawing fundamental conclusions from seemingly peripheral observations. In any event this meant nothing less than that light was an aggregate of very tiny particles, which in turn raised the curtain on the era of particle physics that completely dominates physics today.

The time around 1900 was also that of spectroscopy – the analysis of the glow of atoms and molecules. There was a great deal of empirical data on this, but there was no theoretical basis to be derived from classic physics. The breakthrough here only came about by transferring the quantum hypothesis to atomic structure¹³ and for which Niels Bohr received the Nobel Prize in 1922. Bohr forbade the electrons of the atomic shell to adopt arbitrary energy state, but only multiples of Planck's constant, and which succeeded in explaining two things at once.

Firstly Bohr's atomic model made it comprehensible as to just why matter is stable at all and why electrons – contrary to the prediction of electrodynamics – do not continuously radiate energy as they circle the nucleus, only to fall with a crash into this nucleus then discharge and terminate the whole atom in a flash. This is because electrons only exchange their energy in packets and always retain a residual quantum of kinetic energy in the atom when they are closest to its nucleus. This is no small theoretical gain, for our macroscopic world ultimately consists of atoms and molecules, and when we look around us then everything is fairly stable – at least if no atom bomb happens to be exploding. Secondly this mechanism suddenly explained the typical colors that atoms radiate when they are stimulated. Bohr's atomic model precisely predicted the spectral lines of hydrogen and could thus be empirically confirmed.

There had to be a new theory of motion on the smallest of scales to account for these oddities, and thus we arrive at the fundamentals of quantum mechanics and quantum computing. It was above all Werner Heisenberg and Erwin Schrödinger who formulated

this new theory of motion and for which they won the Nobel Prize in 1932 and 1933 respectively. Quantum mechanics has been gradually perfected and in theoretical physics its predictions are among the most rigorously tested at the experimental level. Yet the basic assumptions are so abstruse that it is better not to take them for direct statements about nature but for what they are: theory – statements about the description of nature.

The first basic assumption is to formulate the theory as a linear one. This is hardly unusual, it too holds for classic mechanics. In this branch of physics, which we know so well, there is namely that certain aspect entailing the superimposition of movements. For instance in the trajectory of a projectile we find a steady, uniform, force-free motion straight ahead, which is superimposed on the free fall downward as accelerated by the earth's gravitational pull. Each type of motion has its own dimension: x (front-back) for the straight-line uniform movement and z (up-down) for the accelerated movement. This also exists in quantum mechanics, though its originators conceived an entirely different mathematical space for it than the familiar three-dimensional one, to which classically the fourth dimension of time is added. It is an abstract space that, depending on the problem, can have anywhere from one, two or three to infinitely many dimensions: the Hilbert space. Let us take a typical component of a quantum computer: an electron with its peculiar angular momentum – the spin. This spin turns the electron into a tiny magnet because its rotation sets the electron's charge in motion and thereby produces a magnetic moment. The magnetic moment can be measured in an external magnetic field and that measurement always results in up or down (the little magnetic needle points up or down) with the electron rotating to the left or to the right. One cannot with certainty predict which value is measured in the experiment, sometimes it is the one and sometimes the other, like the flip of a coin.

From this the linear theory of quantum mechanics now constructs its abstract space with exactly two dimensions whose basic states are $|\text{up}\rangle$ and $|\text{down}\rangle$. Both of these states are solutions to their equation of motion, the Schrödinger equation, and because of its/ linearity also their sum – which is exactly what linearity means. A single electron is then described as a vector sum – as in classic mechanics with its x and z components – but consisting of $|\text{up}\rangle$ and $|\text{down}\rangle$:

$$|\text{electron}\rangle = a^*|\text{up}\rangle + b^*|\text{down}\rangle.$$

The states of electrons described in the abstract Hilbert space are thus superpositions of their basic states, which classic physics cannot permit in this way. For who has ever seen a top spinning in a leftward and rightward direction at the same time? This superposition would prove very useful in quantum computers.

So in quantum mechanics the objects are superpositions, weighted sums, of their basic states. The Schrödinger equation describes what happens to them in a given physical situation, i.e. what happens when forces are at work and time elapses, and the final result is once more a certain changed superposition of the basic states. The measurement finally follows, which itself can no longer be described via the theory of quantum mechanics. It overrides the theory, forms its blind spot, in that it then again only verifies one of the basic states: $|\text{up}\rangle$ or $|\text{down}\rangle$. The theory of quantum mechanics is therefore only valid so long as no measurement is done. It must not be looked at in order to not destroying the fragile quantum phenomena, a phenomenon which gave occasion to a wide spectrum of bizarre interpretations¹⁴ and all kinds of parascientific esoteric-consciousness physics, but also advanced feminist positions like that of Karen Barad's agential realism¹⁵ which is explicitly based on Niels Bohr's natural philosophy.

And this is where the very difficult work of interpretation begins. How does one go from alleged superposition states to the purely measured basic states? In the case of electrons the present scholarly view – the so-called Copenhagen interpretation – states that from the initially assumed coefficients $a(t=0)$ and $b(t=0)$ of the superposition – the starting conditions – Schrödinger's quantum-mechanical wave equation continuously and deterministically calculates the $a(t)$ and $b(t)$ of the superposition at the end, at the time of measurement. And it is from the latter that the probability of encountering the electron as a pure $|\text{up}\rangle$ or pure $|\text{down}\rangle$ can be determined¹⁶. If the magnitude of $a(t)$ is greater than that of $b(t)$ then an $|\text{up}\rangle$ is measured more frequently than a $|\text{down}\rangle$. There are always only probability statements of the measurements of pure states. The Geiger counter rattles when it detects nuclear decay; measurements in the laboratory, for example on electrons, are noisy individual events in their entirety; in the laboratory the measured quantum-mechanical phenomena are always subject to statistics, random processes.

This leads to the paradoxical situation that a continuous wave equation – that of Schrödinger – calculates the probabilities of particle properties. The theory thus calls for the paradoxical coexistence of a wave image with a particle image. The states of quantum-mechanical objects continuously change in a wave-like fashion before the measurement. Should this take place, then they appear as whole particles. This is also the reason why, although we are dealing with particles, that interference patterns exist¹⁷.

This is the material from which quantum computers are built¹⁸. Their elementary objects are not binary switches, bits, 1 or 0, but quantum-mechanical objects such as spin systems with binary basic states that may yet overlap. The quantum switches, qubits, may simultaneously be $|1\rangle$ und $|0\rangle$ in the theory:

$$|\text{qubit}\rangle = a|1\rangle + b|0\rangle$$

If they are subjected to a targeted quantum-mechanical experiment in which they are sent through “quantum gates” then the Schrödinger equation calculates the physical result of a new mixture of $|1\rangle$ und $|0\rangle$. The experiment carries out a calculation – and this is the trick – that is performed in parallel with all possible combinations of the initial states of the qubits.

For a register of qubits with a length of, let us say, eight, the quantum computer simultaneously calculates the results of the inputs $|0,0,0,0,0,0,0,0\rangle$ over $|0,0,0,0,0,0,0,1\rangle$ to $|1,1,1,1,1,1,1,1\rangle$, which makes 256 different inputs, if the register's qubits are accordingly prepared as superpositions of their two basic states. The longer the register is then the more dramatic is the efficiency increase as compared to a digital computer, which possesses registers of ordinary bits that can only adopt one state at a time and which in turn must be strictly processed one after the other.

The theory of the quantum computer is quantum mechanics. Special quantum-physical experiments realize the switching elements of quantum computers – the quantum gates. Quantum mechanics describes the continuous development of the states of qubits in Hilbert space, which are projected at the end in the act of measurement onto binary, discrete measuring events. Quantum computers are analog computers. They can only embody those calculations for which a physical experiment can be concocted, so they are not universal¹⁹. Searching and sorting operations are their domain, but also the decomposition of large numbers into their prime factors and optimization problems²⁰.

But to put it quite simply, two basic problems show how difficult the construction of a quantum computer is. On the one hand, research is confronted with the mathematical-

symbolic question of having to clarify for which classes of computational problems and on the basis of which algorithms a quantum computer can even offer a significant speed-up advantage in comparison to traditional computers²¹. On the other hand, from a physical-material standpoint, the question arises as to which machines can technically realize and stabilize the quantum effects necessary for qubits – and various approaches are pursued here²². An analysis of quantum computers cannot simply continue that of digital computers, it must start afresh – indeed in physics – because findings with regard to digital computers can hardly be of assistance when it is the quantum computer which is to be understood. Quantum computers are no longer as closely related to logic, the symbolic and the text as the digital computer, about which media studies has already argued extensively. A look at the history of computers, at the analog computer, is much more helpful here than to focus on the men and women who cracked the code of the German Wehrmacht in the Second World War.

Quantum computers also bear the epistemological burden of quantum mechanics and its counterintuitive postulates: wave-particle dualism, the superposition of paradoxical states like with Schrödinger's cat²³, spooky action at a distance²⁴ and the retroactive probability interpretation of a deterministic theory. In the case of an interpretation, media studies must grapple not only with physics but with spiritualism and esotericism, which sometimes run riot in the discourse on quantum mechanics, a subject ironically treated by Hillgärtner and Wiemer²⁵.

In September 2019 there was growing evidence that a Google research team had achieved an epoch-making breakthrough in the sphere of quantum computing. It was by way of a NASA server that journalists from the *Financial Times* stumbled across a paper entitled *Quantum Supremacy Using a Programmable Superconducting Processor*²⁶ which had apparently been released by mistake. A flood of articles soon followed in which the supposed sensation was interpreted and classified for a broad public. The tenor of reports was that Google's team might have proven that the vision of a quantum computer was gradually transforming into a technological reality with potentially massive consequences for all of society.

As future possibilities associated with quantum computers, these potential consequences indicate a nexus of ideas, expectations, hopes and fears that, as a process of the collective imagination, is presently giving social shape to a future technology such as the quantum computer. In science and technology studies such collective imagination processes are called "sociotechnical imaginaries"²⁷, "models"²⁸ or "technical futures"²⁹. Their achievement is to constitute ideas shared by groups of heterogeneous actors about a future that is considered desirable³⁰.

With respect to the Google team's paper, the concept and title *Quantum Supremacy* serves as a focal point for these imaginative processes. Coined in 2012 by John Preskill, "quantum supremacy" is a shorthand for how quantum computers have significant speed advantages in doing complex calculations (while also having lower energy costs) as compared to the strongest existing traditional super computers. According to Preskill's criterion, this arithmetic problem may be explicitly designed for the purpose of this demonstration of supremacy, i.e. it requires no practical application³¹. Yet why all the fuss about quantum computers if quantum supremacy is merely a mathematical game bereft of all utility?

In principle, quantum computers are an interesting future technology for science and industry because their qubits permit them to deal with complexities that cannot be handled by traditional computer systems.³² Crucial for this is a “separation between quantum and classic complexity”³³ which was even viewed by Preskill as the driving force behind the development of quantum computers in general³⁴. The Google team’s paper claims to have demonstrated the supremacy of a quantum computer based on Google’s Sycamore processor with 53 qubits³⁵. This involved the solution of a highly specialized mathematical task in two hundred seconds and for which the presently fastest classic supercomputers would require some ten thousand years³⁶. Just why the Google team can celebrate its success as an epoch-making “milestone”³⁷ can be explained³⁸ with reference to the importance of quantum supremacy within the expert discourse.

In the course of expositing his criteria, Preskill postulates that the demonstration of quantum supremacy would show that there exists no unknown physical law which would in principle forestall the possible future supremacy of quantum computers³⁹. Once this evidence is adduced – and this is precisely the claim that the Google team makes for itself⁴⁰ – then it follows that a certain era in the history of the development of quantum computers would be ushered in, namely the era of so-called Noisy Intermediate-Scale Quantum Technologies (NISQ). NISQ is a diachronic term that Preskill⁴¹ outlined in a paper with the title “Quantum Computing in the NISQ Era and Beyond.” The NISQ era is a phase in which quantum computers are superior to classic computers in terms of useless applications but remain noisy because the stabilization of qubits is still very susceptible to mistakes. The word “intermediate” refers to the quantity of qubits. According to Preskill, one can realistically expect systems with a range of between fifty and a few hundred qubits, whereas the classic supercomputer’s

limits in terms of performance is presumed to be some fifty qubits⁴². Once these NISQs are realized then the real future of quantum computing will begin. Yet Preskill notes that the appearance of these systems is a “significant step toward the more powerful quantum technologies of the future”⁴³.

Against the background of these future expectations within the specialist community, the Google team’s claim to have demonstrated quantum supremacy is not only legitimate but quite remarkable. Evidence would seem to have been provided that the future machine “quantum computer” is in the process of increasingly realizing the potential that has been ascribed to it ever since its inception⁴⁴. What therefore makes this example of the historical significance of quantum supremacy with respect to the future so important from the standpoint of media studies is not only the specialist physics discussion itself but the associated mobilization of overarching imaginaries and technical futures. It is by virtue of these that a comparison can be made between ideas about the future of quantum computers within the specialist discourse and an increasingly larger number of general social expectations for these machines⁴⁵.

As an expert in the field, however, Preskill is much more reserved than many a thing which is now already being discussed in public about the future of quantum computing. In his description of NISQs he notes that quantum computers are much too different (or too “alien”) with respect to classic computers for us to say anything with certainty about the future development of these machines⁴⁶. Thus it is plausible to presuppose that they could indeed have certain social effects in the next decades; but to what extent these effects might be commercially useful, for example, is still completely open to conjecture⁴⁷.

Preskill’s provisos nonetheless underscore the strategic character of a category like NISQ and thus confirm the social significance of shared ideas about the future. As a

shared vision of the development of quantum computers, Preskill's formulation of quantum supremacy is based on an imaginary timeline, which as such drives laboratory research and within which the appearance of NISQs first attains the significance of a historical milestone. Essential to this is the assumption that with the appearance of NISQs the hitherto unclear future of quantum computers will become more real in its possibilities. In futurology this process is called the emergence of "futuribles"⁴⁸. Futuribles are possibilities handed down in utopias and similar forms of discourse, which due to an event (discovery or invention) change their status from unrealizable possibilities that still lie in the distant future to realizable possibilities now looming in the near future. Older utopias, in the present case older media utopias, then prove to be *ex post* sources of information in light of new possibilities and serve to influence the imaginaries of these now real possibilities.

A revealing picture emerges with respect to Preskill's discussion of NISQs. The demonstration of quantum supremacy and the appearance of NISQs marks the starting point for the future of the quantum computer within the professional community. Yet the indeterminacy and alien nature of these technologies is also established, which in turn emphasizes the significance of those imaginaries currently available. Conspicuous here is that in order to compensate for this alienness, in the expert discourse there is a borrowing from older utopias and visions of the present "classic" media culture. This becomes clear with a view to the distinction between analog and digital, whose careers of course go well beyond computer technology in the narrower sense⁴⁹ and which, due to the triumph of digital media, is now being adduced as a guiding distinction for entire social analyses such as that of "digital society"⁵⁰

The fact that the imaginations around quantum computers make use of the analog/digital distinction in entirely different ways as a category to describe these new

technologies, can be seen in the aforementioned example of the analog character of qubits, which suggests that quantum computers could be paradigmatic “post-digital” machines. Nevertheless, the imaginations with respect to possible scenarios for practical application of these “post-digital” computers still remain indebted to the mediality of classic digital computers. This can be exemplified with a view to one of the central “cores of fascination” that linked up with computers in the twentieth century, namely “simulation”⁵¹ and which is currently being discussed in the specialist discourse, especially with the example of the simulation of quantum dynamics, e.g. molecules in chemistry.

In two sections of his paper “Quantum Computing in the NISQ Era and Beyond,” Preskill⁵² states that the simulation of quantum dynamics – which is extremely difficult with classic computers for reasons of complexity theory – could be the real future potential of quantum computers. On the occasion of a short exposition of possible technical solutions, he distinguishes between an analog and a digital quantum simulator:

“When we speak of an analog quantum simulator we mean a system with many qubits whose dynamics resemble the dynamics of a model system we are trying to study and understand. By contrast, a digital quantum simulator is a gate-based universal quantum computer which can be used to simulate any physical system of interest when suitably programmed and can also be used for other purposes. Analog quantum simulation has been a very vibrant area of research for the past fifteen years, whereas digital quantum simulation with general purpose circuit-based quantum computers is just now getting started”.⁵³

Here Preskill is using a semiotically inspired variant of the distinction between analog and digital, which moreover seizes upon the model of the digital computer as a universally programmable machine and projects it onto a possible application of the new quantum technologies.

While this example gives a brief glimpse into the recourse to established media history so as to describe future developments, it also illustrates that – if a universally programmable quantum computer joins the ranks of an entire genealogy of future quantum technologies used for medial purposes (here: simulation) – the question already posed above also arises in intensified form: What traces have quantum physics and its demonstrated effects already left behind in media history?

If one seeks to explain the history of quantum media from the presently imagined future of the quantum computer as a future technology that is still alien at its core,⁵⁴ then one must show how the relationship between quantum physics and media history developed. Emergence of the quantum computer obligates media studies to review the history of “quantum media.”

Notes on a Media Archeology of Quantum Media

The concept “quantum media” would be pointless if it were to denote the manifest fact that media – insofar as they are also material and technological artifacts (alongside institutions, programs, content, practices etc.) – ultimately consist of the same elementary particles as all other material objects. Nor is it to be employed here for

various media arrangements through which knowledge of quantum phenomena can be generated⁵⁵.

We would instead propose that in addition to a) media whose origin is independent of quantum-mechanical knowledge, there are b) first-stage quantum media and c) second-stage quantum media. Our suggestion is therefore to structure media history in terms of the (as previously emphasized) absolutely central role of quantum theory in the twentieth century.

a) For example one can term photography a non-quantum medium, a technology that arose in the nineteenth century long before the first steps taken by Max Planck in the field of quantum mechanics. Its development required no quantum-mechanical knowledge and was empirically found, as it were, through experiments with light-sensitive silver-halide emulsions⁵⁶. However this example is complex. Photo-chemical effects had long been observed and made useful in countless photographic experiments, but a conclusive theoretical explanation was only possible in the twentieth century with the aid of quantum theory⁵⁷. In other words – and this will come as no surprise – photography was ultimately based on quantum effects to make them usable, but no explicit quantum theory was required. The same held true for electricity as the basis of all electronic media. Electrical functionality was known relatively early on and could therefore be used in practice, even though a consistent explanation for electromagnetic phenomena was first found in the twentieth century with the onset of quantum electrodynamics⁵⁸.

b) With the development of quantum mechanics in the twentieth century there has been a correspondingly rapid development of technologies that presuppose this knowledge:

“The twentieth-century revolution is not digitalization but quantum mechanics, which enabled the former’s technical implementation in the first place”⁵⁹. In other words: “By some estimates, 30 percent of the United States’ gross national product is said to derive from technologies based on quantum theory. Without the insights provided by quantum mechanics, there would be no cell phones, no CD players, no portable computers. Quantum mechanics is not a branch of physics; it is physics”⁶⁰. So the laser that scans the disc in a CD (or DVD or Blu-Ray etc.) player is an example of stimulated emission, which was first predicted in 1916 by Albert Einstein with quantum-theoretical arguments⁶¹. The laser was and is also a condition for the manufacture of holographs – for instance as security features on countless banknotes and credit cards in the simple form of so-called rainbow holograms. And it was Einstein, as early as 1905, who provided a quantum-theoretical explanation for the photoelectric effect which ultimately led – via the work of Boyle and Smith (2009 Nobel Prize) – to the very image sensors found in digital cameras and scanners.⁶² Semiconductor technology, which in the form of the transistor is fundamental to modern computer technology, can be theoretically described through the use of quantum mechanics. Yet these examples also show that quantum-mechanical knowledge is not often directly necessary (more practical concepts from chemistry or solid-state physics are frequently more helpful) or that technologies do not arise directly from the theoretical concepts⁶³ – and to investigate such transitions from knowledge to a concrete technology is an excellent field of application for media-archeological processes⁶⁴.

- c) So although twentieth-century media history was already in essence a history of quantum-mechanical knowledge, a “quantum revolution” is now being proclaimed: The computer gave birth to the quantum computer, cryptography gave birth to

quantum cryptography, and the Internet gave birth to the quantum Internet⁶⁵. Has a watershed change taken place? Or is it merely sensationalist rhetoric like that which has accompanied the digital age for some time now⁶⁶? Although language and money, for instance, have always been digital codes and the nineteenth century had a decidedly digital medium in the guise of telegraphy, there is presently much talk of “digitalization” – as if everything prior had been analog.⁶⁷ But is this much-vaunted digitalization not rather the dissemination of microelectronic and thus ultimately quantum-based technologies – that is to say, not rather a “quantum mechanization”?

It can nonetheless be argued that the quantum computer (in its various technical manifestations) is able to overcome the central principle of so-called digitalization, namely binary coding, which has hitherto been seminal for computers⁶⁸ – at least in the sense that a given qubit can now be 0 and 1 at the same time. This means that although microchips are already based on quantum-mechanical knowledge (on the basis of silicon as a semiconductor) the form of information processing (clearly separated in 0 or 1) remains classic. In quantum computers the form of information processing itself is realized through the use of quantum effects and the same holds true for quantum cryptography. In this sense – insofar as quantum computers and quantum cryptography are methods for the transmission, storage and processing of information and hence media – we can speak of second-stage quantum media (e.g. in contrast to “normal” computers as first-stage quantum media).

From the standpoint of media history, this first of all means that the binary-digital Von Neumann machines used so far do not signal the “end of media history.”⁶⁹ New technologies are obviously emerging and these can be integrated into a media-historical perspective. Kittler describes media history as an escalation: “In a strategic

chain of escalation, the telegraph appeared in order to surpass the speed of messenger postal services, radio was developed to solve the problem of vulnerable undersea cables; and the computer emerged to make possible the codification of secret – and interceptable – radio communications.”⁷⁰ Quantum computers would then be the answer to network communication encrypted with PGP (Pretty Good Privacy) and related procedures deployed by criminals and terrorists, for these can no longer be deciphered by conventional computers (at least they require too much time). In Winston’s words this would be a “supervening social necessity”⁷¹ which drives the development of quantum computers.⁷² It is no accident that one of the first algorithms for the then still hypothetical quantum computer was one that addressed prime factorization⁷³ – and many of the encryptions used today are based on the difficulty of such factorization⁷⁴. The home banking of respectable citizens would no longer be secure, however, if such criminal elements had access to quantum computers. Yet there are also more complex encryption procedures that can supposedly withstand quantum computers⁷⁵, but for this very reason we should privilege their development.

The situation would be even more complicated if there were functional quantum-cryptography procedures that theoretically allowed for absolutely unobservable secret communication.⁷⁶ There already exist commercial solutions,⁷⁷ though these can still be hacked⁷⁸. But if functioning quantum-cryptography existed then it would enable absolutely secure political and military communication, perhaps absolutely secure home banking as well, but possibly also enabling unobservable criminal and terrorist communication. Should there now be, in Winston’s words, a “suppression of radical potential”⁷⁹? Will the use of quantum computers as well as quantum cryptography have

to be strongly regulated in the future? What shifts in the distribution of observability and unobservability will this trigger?

However, encryption is by no means the sole “necessity” that drives the development of quantum computers – perhaps not even the most important one. The fact that large digital companies such as Google advance the development of quantum computers is related to the assumption that quantum computers can search through large amounts of data a great deal faster as well as more effectively so as to make patterns recognizable than can conventional computers⁸⁰. The connection with the business models of Google and Facebook et al. is obvious.

We can only speculate as to just which futuristic media technologies in the sphere of artificial intelligence⁸¹ or new holographic display technologies that until now have likewise suffered from the problem of too large and too complex data volumes⁸² might someday be made possible by the high computing speed of quantum computers. In terms of media theory it should once more be noted that with the quantum computer, despite all the talk of digitalization, analog technologies are returning: “Quantum computers are analog devices”⁸³. The essentially long-known fact that “digital” does not come after “analog” and that in reality both versions appear mostly in mixed form⁸⁴ is once more confirmed. Quantum computers will presumably not replace conventional binary-digital computers in the future, but both technologies will instead coexist because they have different strengths and weaknesses in specific areas.⁸⁵ For many tasks the classic computer will continue to be sufficient or even more suitable – special computer problems will then perhaps be delegated to an integrated quantum chip.

It was furthermore discussed whether the use of entanglements⁸⁶ affects the notion of the channel, being central to that of communication at least since Shannon and Weaver: “All information is thus dedicated to the materiality in which codes are

transmitted (or noisy). By contrast, Anton Zeilinger applies his quantum-physical approach, which is based on the entanglement of two distant particles and thus the expendability of a media theory of the channel⁸⁷ Yet instead of making the notion of channel obsolete, with entanglement channels are duplicated into quantum channels and classic channels⁸⁸ so that superluminal communication remains impossible, as it initially seemed in view of entanglement phenomena. The media theory of the channel is thus not rendered superfluous but instead enhanced through another type of channel.

Conclusion: The Prospects for Research in media studies

What can media studies garner from all this? We can first of all ascertain that quantum computers are a technology of the future that has emerged from the media culture of classic digital computers and will integrate their potential application into this culture long term. At the same time, many feel that quantum computers have the potential to transcend this culture in a way that is still unclear. Particularly unclear is just what practices will develop. That is not something which can be predicted, but for precisely this reason it is necessary that we describe on a broader basis the collective socio-technical imagination processes surrounding quantum computers. A symptom in this respect is the appearance of quantum computers that point media studies – in a thoroughly surprising way – to the still unwritten history of quantum media.

The goal must be to systematically work through the cross references to already existing research. At the same time, however, the history of quantum media also poses a theoretical challenge that has still only been confronted by theories such as Karan

Barad's agential realism⁸⁹. The degree to which historical understanding and theoretical reflection intermesh is demonstrated in particular by classification of the quantum computer as a sui generis analog computer against the background of a general history of quantum media.

It is therefore unsurprising that media studies is being faced with the perhaps still very latent question – while other fields, such as philosophy of the mind, are confronted by it in a very immediate and explicit fashion – as to just what quantum physics can tell us of natural phenomena such as consciousness⁹⁰, that is to say, phenomena which are characterized by information processing. Cosmological mind games such as that black holes or other natural phenomena can be used for calculation⁹¹ amusing as the ironic flash-forward of a future quantum-based “instant communion medium”⁹². But they have a serious core inasmuch as quantum computers could in fact challenge us to re-conceive the relationship between information processing and matter both historically and systematically.

¹ Christian Schubert, "Im Quantenfieber," (2019)

<https://www.faz.net/aktuell/wirtschaft/unternehmen/wie-die-quantentechnologie-die-wirtschaft-bewegt-16527306.html>.

² Bastian Benrath, "Quantencomputer: Die nächste Revolution," (2020),

<https://www.faz.net/aktuell/wirtschaft/netzkonferenz-dld/quantencomputer-die-naechste-revolution-16585851.html>.

³ Jens Schröter, Gregor Schwering, "Modelle des Medienwandels und der Mediengeschichtsschreibung," in *Handbuch Medienwissenschaft. Unter Mitarbeit von Simon Ruschmeyer und Elisabeth Walke*, ed. Jens Schröter (Stuttgart: J.B. Metzler, 2014):179-190.

⁴ Gabriele Balbi, "Old and New Media: Theorizing Their Relationships in Media Historiography," in *Theorien des Medienwandels*, ed. Susanne Kinnebrock, Christian Schwarzenegger and Thomas Birkner (Cologne: Halem, 2015):231-249.

⁵ Gösta Fürnkranz, *The Quantum Internet. Ultrafast and Safe from Hackers* (Cham: Springer, 2019).

⁶ John Preskill, "Quantum Computing in the NISQ Era and Beyond," (2018):6, <https://quantum-journal.org/papers/q-2018-08-06-79/>.

⁷ Preskill, "Quantum Computing in the NISQ Era and Beyond":6.

⁸ Jeffrey Bub, "Quantum Entanglement and Information," (2019), <https://plato.stanford.edu/archives/spr2019/entries/qt-entangle/>.

⁹ Martin Warnke, "Quantum Computing," in *HyperKult II. Zur Ortsbestimmung analoger und digitaler Medien*, ed. Martin Warnke, Wolfgang Coy and Georg Christoph Tholen (Bielefeld: transcript, 2005):151-172. ; Martin Warnke, "Quantencomputer: Taktlos", in *Kulturtechniken der Synchronisation*, ed. Christian Kassung and Thomas Macho (Paderborn: Wilhelm Fink, 2013):269-287.; Martin Warnke, "Quantencomputer/Quantenkryptographie," in *Handbuch Medienwissenschaft*, ed. Jens Schröter (Stuttgart: J.B. Metzler, 2014):369-371.

¹⁰ Here too we have the first contributions (e.g. Anne Dippel and Martin Wanke, *Interferences and Events: On Epistemic Shifts in Physics through Computer Simulations*, (Lüneburg: meson press, 2017).); but as compared with the very nuanced discussion on the implications of quantum physics in philosophy, the debate in media studies is relatively straightforward. In 2013, Hillgärtner and Wiemer came out with a wonderful metatext on the motif of future "quantum media" and their utopian potential (Harald Hillgärtner and Serjoscha Wiemer, "Materialien zur Quantenkommunikation," in *Das Medium meiner Träume*, ed. Ralf Adelman and Ulrike Bergermann (Berlin: Verbrecher, 2013):51-76.).

¹¹ Max Planck, "On the Theory of the Energy Distribution Law of the Normal Spectrum", in *The Old Quantum Theory: The Commonwealth and International Library: Selected Readings in Physics*, ed. D. Ter Haar (Oxford/London i.a.: Pergamon Press, 1967):82-90.

¹² Albert Einstein, "On a Heuristic Point of View Concerning the Production and Transformation of Light," in *Einstein's Miraculous Year. Five Papers that Changed the Face of Physics*, ed. John Stachel (Princeton: Princeton University Press, 1998):177-198, here 178.

¹³ Niels Bohr, "I: On the Constitution of Atoms and Molecules," *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science* 26, no. 151(1913):1-25.

¹⁴ Everett in 1956 with his multiverse: Hugh Everett III, *The Theory of Universal Wavefunction*, PhD thesis (Princeton University, 1956).

¹⁵ Karen Barad, *Meeting the Universe Halfway: Quantum Physics and the Entanglement of Matter and Meaning* (Durham/London: Duke University Press, 2007). There are other theoretical approaches that take recourse to quantum theory: See François Laruelle, *Anti-Badiou. On the Introduction of Maoism into Philosophy* (London etc.: Bloomsbury, 2013), who proposes a "quantum theory of philosophy" (xxiv). See also David Orrell, "A Quantum Theory of Money and Value," *Economic Thought* 5, no. 2 (2016):19-28.

¹⁶ Max Born, "Zur Quantenmechanik der Stoßvorgänge," *Zeitschrift für Physik* 37, no. 12 (1926):863-867.

¹⁷ Dippel and Wanke, *Interferences and Events: On Epistemic Shifts in Physics through Computer Simulations*.

¹⁸ Colin P. Williams and Scott H. Clearwater, *Ultimate Zero and One – Computing at the Quantum Frontier* (New York: Copernicus, 2000).; Wanke, "Quantencomputer: Taktlos".; Wanke, "Quantencomputer/ Quantenkryptographie".

¹⁹ Wanke, "Quantum computing".

²⁰ Williams and Clearwater, *Ultimate Zero and One – Computing at the Quantum Frontier*.

²¹ Amit Schröter and Michael Cuffaro, "Quantum Computing," (2019):11, <https://plato.stanford.edu/archives/win2019/entries/qt-quantcomp/>.

²² An overview is provided by Christian J. Meier, *Eine kurze Geschichte des Quantencomputers: Wie bizarre Quantenphysik eine neue Technologie erschafft* (Hannover: Heise, 2015):87-122. For the various possibilities of realizing qubits, see especially:107-109.

²³ Trimmer, John D., "The present situation in quantum mechanics: a translation of Schrödinger's cat paradox paper", *Proceedings of the American Philosophical Society* 124, no. 5, (1980):328.

²⁴ *The Born-Einstein Letters: Friendship, Politics and Physics in Uncertain Time: Correspondence Between Albert Einstein and Max and Hedwig Born from 1916 to 1955*, trans. Irene Born (Macmillan, 1971):158.

²⁵ Hillgärtner and Wiemer, "Materialien zur Quantenkommunikation".

²⁶ Franke Arute et al., "Quantum Supremacy Using a Programmable Superconduction Processor," *Nature* 574 (2019):505-511.

²⁷ Sheila Jasanoff, "Future Imperfect. Science, Technology, and the Imagination of Modernity," in *Dreamscapes of modernity: Sociotechnical Imaginaries and the Fabrication of Power* (Chicago/London: Univ. of Chicago Press, 2015).

²⁸ "Leitbild" in the german text by Katharina D. Giesel, *Leitbilder in den Sozialwissenschaften: Begriffe, Theorien und Forschungskonzepte* (Wiesbaden: Springer VS, 2007).

²⁹ Armin Grunwald, *Technikzukünfte als Medium von Zukunftsdebatten und Technikgestaltung* (Karlsruhe: Karlsruher Institut für Technologie, 2012).

³⁰ See Jasanoff, "Future Imperfect. Science, Technology, and the Imagination of Modernity" and also Christoph Ernst and Jens Schröter, *Media Futures: Theory and Aesthetics*, (London: Palgrave, 2021 , forthcoming).

³¹ John Preskill, "Quantum Computing and Entanglement Frontier: Rapporteur talk at the 25th Solvay Conference," (2012), <https://arxiv.org/abs/1203.5813>.; Preskill, "Quantum Computing in the NISQ Era and Beyond.":7, John Preskill, "Why I Called it 'Quantum Supremacy'," (2019), <https://www.quantamagazine.org/john-preskill-explains-quantum-supremacy-20191002/>.

³² The possibility of a quantum computer was already being weighed in the 1970s and 1980s. Then in the 1990s came the working out of examples for mathematical problems where quantum computers could prove superior, see Hagar and Cuffaro, "Quantum Computing," :9-11.

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- ³³ Preskill, "Quantum Computing and Entanglement Frontier: Rapporteur talk at the 25th Solvay Conference":3.
- ³⁴ Preskill, "Quantum Computing and Entanglement Frontier: Rapporteur talk at the 25th Solvay Conference":14. In discussions of quantum computers there are two distinct forms of the distinction between 'classic vs. non-classic:' within the history of physics and within the history of computing.
- ³⁵ Arute et al., "Quantum Supremacy Using a Programmable Superconduction Processor":506.
- ³⁶ Arute et al., "Quantum Supremacy Using a Programmable Superconduction Processor":505.
- ³⁷ Arute et al., "Quantum Supremacy Using a Programmable Superconduction Processor":505.
- ³⁸ What one can also gather from press reports is that a team from Google's competitor IBM instantly objected that with the proper algorithms the task could also be completed in two and a half days by classic computers. See Edwin Pednault, John Gunnels, Dmitri Maslov and Jay Gambetta, "On 'Quantum Supremacy'," (2019), <https://www.ibm.com/blogs/research/2019/10/on-quantum-supremacy/10.04.2020>.
- ³⁹ Preskill, "Quantum Computing and Entanglement Frontier: Rapporteur talk at the 25th Solvay Conference":2.
- ⁴⁰ Arute et al., "Quantum Supremacy Using a Programmable Superconduction Processor":505.
- ⁴¹ Preskill, "Quantum Computing in the NISQ Era and Beyond".
- ⁴² Preskill, "Quantum Computing in the NISQ Era and Beyond":5.
- ⁴³ Preskill, "Quantum Computing in the NISQ Era and Beyond":1.
- ⁴⁴ E.g. Meier, *Eine kurze Geschichte des Quantencomputers: Wie bizarre Quantenphysik eine neue Technologie erschafft*.
- ⁴⁵ see too Ernst and Schröter, *Media Futures: Theory and Aesthetics*, forthcoming.
- ⁴⁶ Preskill, "Quantum Computing in the NISQ Era and Beyond":1.
- ⁴⁷ Preskill, "Quantum Computing in the NISQ Era and Beyond":1,5.
- ⁴⁸ Bertrand de Jouvenel, *The Art of Conjecture*, trans. Nikita Lary (New York: Basic Books, 1967):18f.
- ⁴⁹ Jens Schröter, "Analogue/ Digital – Opposition or Continuum?," https://www.academia.edu/41750875/Analogue_Digital_Opposition_or_Continuum.
- ⁵⁰ Armin Nassehi, *Muster: Theorie der digitalen Gesellschaft* (Munich: C. H. Beck, 2019).
- ⁵¹ Nicola Glaubitz, Henning Groscurth, Katja Hoffmann, Jörgen Schäfer, Jens Schröter, Gregor Schwering and Jochen Venus, *Eine Theorie der Medienumbrüche 1900/2000* (Siegen: Universi, 2011):103-117.
- ⁵² Preskill, "Quantum Computing in the NISQ Era and Beyond":13.
- ⁵³ Preskill, "Quantum Computing in the NISQ Era and Beyond":13.
- ⁵⁴ Science fiction offers interesting material for analyzing current imaginations around quantum computers. One could mention the novels *Hologrammatica* and *Qube* by Tom Hillebrand (2018/2020) where quantum computers are portrayed as brain replacement and extension, i.e. an "extension of men" in McLuhan's sense. Also having attracted much attention is the *Trisolaris* trilogy by Cixin Liu, (Liu, *The three-body problem*, trans. Ken Liu (New York: Macmillan, 2014); Liu, *The dark forest*, trans. Joel Martinsen (New York: Macmillan, 2015) and Liu, *Death's end*, trans. Ken Liu (New York: Macmillan, 2016)), where among other things quantum computers in the form of "Sophons" are deployed as weapons in the war between Earth and extraterrestrials – as weapons in an *information* war because the Sophons are believed to block development of new physical knowledge on the one hand, while still being able to observe all earthly communication on the other. Thus, in both fictitious depictions, quantum computers are imagined as media as a matter of course (also Ernst and Schröter, *Media Futures: Theory and Aesthetics*., forthcoming)
- ⁵⁵ Peter Galison, *Image and Logic: A Material Culutre of Microphysics* (Chicago/London: Chicago Up, 1997).
- ⁵⁶ for a fine study that traces Talbot's experimental struggle with photography see Larry Schaaf, *The Photographic Art of Henry Fox Talbot* (Princeton: Princeton UP, 2000).
- ⁵⁷ See H. Sponer, "Der photochemische Primärprozess," *Zeitschrift für angewandte Chemie* 43 (1930):823-830.
- ⁵⁸ Richard Feynmann, *QED. The Strange Theory of Light and Matter* (Princeton/Oxford: Princeton UP, 2006).
- ⁵⁹ Wolfgang Hagen, "Die Entropie der Fotografie: Skizzen zu einer Genealogie der digital-elektronischen Bildaufzeichnung," in *Paradigma Fotografie: Fotokritik am Ende des fotografischen Zeitalters* 1, ed. Herta Wolf (Frankfurt a.M.: Suhrkamp, 2002):222.
- ⁶⁰ Cited in Barad, *Meeting the Universe Halfway: Quantum Physics and the Entanglement of Matter and Meaning*:252.
- ⁶¹ Albert Einstein, "On the Quantum Theory of Radiation," in *The Old Quantum Theory: The Commonwealth and International Library: Selected Readings in Physics*, ed. D. Ter Haar (Oxford/London i.a.: Pergamon Press, 1967):167-183.

⁶² In smartphones CMOS sensors tend to be used – which are constructed differently, but are likewise based on the photoelectric effect.

⁶³ That would also explain why in many media histories (e.g. Brian Winston, *Media Technology and Society: A History from the Telegraph to the Internet* (London/New York: Routledge, 1998) quantum mechanics is never mentioned or only in passing.

⁶⁴ See Hagen, "Die Entropie der Fotografie: Skizzen zu einer Genealogie der digital-elektronischen Bildaufzeichnung".

⁶⁵ Fürnkranz, *The Quantum Internet*.

⁶⁶ See Schröter, "Analogue / Digital – Opposition or Continuum?".

⁶⁷ Nonsensical coinages such as "analog book" – e.g. in contrast to the e-book – are being propagated.

⁶⁸ But the binary principle is historically contingent and ubiquitous by mere fact of its simple circuitry-wise implementation (see Schröter, "Analogue/ Digital – Opposition or Continuum?").

⁶⁹ At least one passage in Kittler can be interpreted in this fashion: "Before the end, something is coming to an end. The general digitization of channels and information erases the differences among individual media. [...] [A] total media link on a digital base will erase the very concept of medium." (Friedrich Kittler: *Gramophone Film Typewriter*, transl. by Geoffrey Winthrop-Young and Michael Wutz (Stanford: Stanford University Press, 1999):1f.).

⁷⁰ Friedrich Kittler, "On the Implementation of Knowledge – Toward a Theory of Hardware," (1999), <http://hydra.humanities.uci.edu/kittler/implement.html>.

⁷¹ Winston, *Media Technology and Society: A History from the Telegraph to the Internet*: 6.

⁷² Winkler's media-historical model (Hartmut Winkler, *Docuverse: Zur Medientheorie der Computer* (München: Boer, 1997)), in which new media respond to the "desires" produced by old media, would also make it possible to describe the desire for quantum computers as precisely that desire to somehow master the accumulated mass of data from earlier digital media.

⁷³ See Peter W. Shor, "Polynomial-Time Algorithms for Prime Factorization and Discrete Logarithms on a Quantum Computer," *SIAM Journal on Computing* 26, No.5 (1997):1484-1509.

⁷⁴ See Jens Schröter, "Technik und Krieg. Fragen und Überlegungen zur militärischen Herkunft von Computertechnologien am Beispiel des Internets" in *Die Medien und ihre Technik: Theorien – Modelle – Geschichte*, ed. Harro Segeberg (Marburg: Schüren, 2004):368f.

⁷⁵ See Daniel Bernstein, Johannes Buchmann and Erik Damen, *Post-quantum Cryptography*, (Berlin/Heidelberg: Springer, 2009).

⁷⁶ The history and principle of quantum cryptography is explained in Simon Singh, *The Code Book: The Evolution Of Secrecy From Mary, Queen Of Scots To Quantum Cryptography* (New York: Anchor, 1999), Chapter 8, see also Fürnkranz, *The Quantum Internet*,

⁷⁷ For example see <https://www.idquantique.com/> (15 February 2020).

⁷⁸ See Lars Lydersen, Carlos Wiechers, Christoffer Wittmann, Dominique Elser, Johannes Skaar and Vadim Makarov, "Hacking Commercial Quantum Cryptography Systems by Tailored Bright Illumination," *Nature Photonics* 4, no. 10 (2010):686-689.

⁷⁹ Winston, *Media Technology and Society: A History from the Telegraph to the Internet*: 11.

⁸⁰ See Abhishek Pandey and V. Ramesh, "Quantum Computing for Big Data Analysis," *Indian Journal of Science* 14, no. 43 (2015):98-104.

⁸¹ See Seth Lloyd, Mahoud Mohseni and Patrick Rebentrost, "Quantum Algorithms for Supervised and Unsupervised Machine Learning," (2013), <https://arxiv.org/pdf/1307.0411.pdf>.

⁸² See Winston, *Media Technology and Society: A History from the Telegraph to the Internet*:341.

⁸³ Mark Friesen, Robert Joynt and M.A. Eriksson, "Pseudo-digital Quantum Bits," (2002), <https://arxiv.org/pdf/quant-ph/0208105.pdf>:1.

⁸⁴ See Schröter, "Analogue/ Digital – Opposition or Continuum?".

⁸⁵ As a general rule, old media do not disappear but change their function and continue to exist in special niches (a good example of this is analog records).

⁸⁶ See Fürnkranz, *The Quantum Internet*:43-49.

⁸⁷ Wolfgang Ernst, "Den A/D-Umbruch aktiv denken – Medienarchäologisch, Kulturtechnisch," in *Analog / Digital – Opposition oder Kontinuum?: Zur Theorie und Geschichte einer Unterscheidung*, ed. Jens Schröter and Alexander Böhnke (Bielefeld: transcript, 2004):58. For the very strange phenomenon of entanglement, see also Bub, "Quantum Entanglement and Information".

⁸⁸ See Fürnkranz, *The Quantum Internet*:86.

⁸⁹ See Barad, *Meeting the Universe Halfway: Quantum Physics and the Entanglement of Matter and Meaning*.

⁹⁰ Harald Atmanspacher, "Quantum Approaches to Consciousness," (2019), <https://plato.stanford.edu/archives/win2019/entries/qt-consciousness/>.

⁹¹ Meier, *Eine kurze Geschichte des Quantencomputers: Wie bizarre Quantenphysik eine neue Technologie erschafft*: 155-165.

⁹² Hillgärtner and Wiemer, "Materialien zur Quantenkommunikation,":74.