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Article

Bibliometric Analysis in the Field of Quantum Technology

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Abstract: The second quantum technological revolution started around 1980 with the control of single quantum particles and their interaction on an individual basis. These experimental achievements enabled physicists, engineers, and computer scientists to utilize long-known quantum features—especially superposition and entanglement of single quantum states—for a whole range of practical applications. We use a publication set of 54,598 papers from Web of Science, published between 1980 and 2018, to investigate the time development of four main subfields of quantum technology in terms of numbers and shares of publications, as well as the occurrence of topics and their relation to the 25 top contributing countries. Three successive time periods are distinguished in the analyses by their short doubling times in relation to the whole Web of Science. The periods can be characterized by the publication of pioneering works, the exploration of research topics, and the maturing of quantum technology, respectively. Compared to the USA, China's contribution to the worldwide publication output is overproportionate, but not in the segment of highly cited papers.

Keywords: quantum information; quantum metrology; quantum communication; quantum computing; scientometrics; bibliometrics

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1. Introduction

At the end of the 19th century, there was a prevalent opinion that the building of physics was complete, and nothing new was left to be discovered. However, since approximately the turn of the 20th century, certain new phenomena that apparently could not be interpreted in the theoretical frame of classical physics shattered this notion and initiated an unexpected revolution. The revolution started with Planck's quantum hypothesis to derive the correct black body radiation [1,2] and Einstein's explanation of the photoelectric effect [3]. Both led to a full-grown quantum theory in the mathematical formulations of the matrix mechanics of Heisenberg, Born, and Jordan [4], as well as of Schrödinger's wave mechanics [5]. The primary innovative and non-classical ingredients of the new theory were the following: (i) a superposition of states was now possible, which had not been thinkable in the classical framework; (ii) the time evolution of quantum systems was no longer deterministic and, therefore, required a probabilistic description; (iii) objective properties, e.g., location and speed at the same time, were no longer existent apart from a determining measurement; and (iv), most counter-intuitively, particles that are not locally connected could now correspond via their common wave function—the so-called entanglement.

Quantum theory turned out to be highly consistent with experiment and formed the basis for the development of solid state physics and for a first quantum technological revolution. This development led to such applications as lasers, transistors, nuclear power plants, solar cells, and superconducting magnets in nuclear magnetic resonance (NMR) devices and particle accelerators. These applications have in common the exploitation of quantum behavior—such as the tunneling effect—of great ensembles of particles.

In the late 1970s and early 1980s, scientists learned to prepare and control systems of single quantum particles, such as atoms, electrons, and photons. The scientists let the particles interact on an individual basis. This ability sparked a second quantum revolution, when physicists, engineers, and computer scientists worked together to utilize the long-known quantum features—especially superposition and entanglement of single quantum states—for a whole range of practical "next generation" applications. These applications may be summarized as "quantum engineering" or "quantum technology 2.0" (QT 2.0).

The present study provides a bibliometric analysis of QT 2.0, methodologically following previous studies dealing with research fields such as climate change [6], specific aspects thereof [7–9], and density functional theory (DFT) [10]. The dataset used in this study has been analyzed in the white paper by Bornmann et al. [11], but only for the time period 2000–2016 and with a focus on Germany. The present study analyzes QT 2.0 over the time period 1980–2018 with an international perspective on the topic.

2. Quantum Technology 2.0: Foci of Research in Four Subfields

QT 2.0 can be structured in various ways [12–14]. We prefer to broadly divide them into four fields, which have substantial overlaps, but do not cover all possible quantum technologies: (i) quantum information science; (ii) quantum metrology, sensing, imaging, and control; (iii) quantum communication and cryptography; and (iv) quantum computation.

(i) Quantum information science is the basis for the whole of QT 2.0. It is mainly the study of the "second-order" effects of quantum theory, firstly recognized by Einstein, Podolsky, and Rosen [15] in their famous EPR gedankenexperiment: quantum systems can exhibit non-local, entangled correlations unknown in the classical world, which Einstein opposed as "spooky action at a distance", insisting that the quantum theory must be incomplete. Alternatives, e.g., so-called local hidden-variable theories, were proposed; Bell proved, 30 years later, that these were obliged to fulfill his famous inequality [16]. Since it takes very carefully engineered quantum states to realize and measure these effects, it took another decade to ascertain their experimental determination [17–19]; the violation of Bell's inequality ruled out local hidden-variables theories. Subsequently, it became feasible to think of applications of quantum information processing. A milestone year on the path to exploiting quantum entanglement was 1994: non-local photon correlations over a long optical fiber could be experimentally demonstrated [20] and could, prospectively, after some improvements, be used for quantum cryptography. Furthermore, an algorithm for a future quantum computer that could solve a very difficult numerical problem exponentially faster than all classical computer algorithms known at that time [21] was presented.

A basic prerequisite for quantum information technology is the concept of a qubit or quantum bit. This is the quantum mechanical generalization of a classical bit, which can be physically realized as a two-state device (e.g., a ground state level and an excited level of an ion in an ion-trap, the spin of an electron in a quantum dot, a photon with vertical or horizontal polarization). According to quantum mechanics, a qubit can stay in a coherent superposition of both states as long as it is not measured. This would "force" the system into one of the two states. With several qubits, one can form quantum gates, registers, and circuits for computational purposes as building blocks for quantum processors. The engineering challenge is the layout of hardware systems that can handle many qubits, store them, and keep them stable enough to perform several computation cycles in order to realize a quantum computer. Not only quantum computing, but also other quantum technologies are inextricably connected with quantum information science. Especially in quantum communications, the use of photons (quantum optics) is prevalent because of their weak interaction with matter and therefore long coherence times. These times are needed for the transportation of quantum information [16].

(ii) Quantum metrology and sensing offer measurement techniques that provide higher precision than the same measurement performed in a classical framework. One well-known example of quantum metrology that had been around for a long time is the atomic clock [22], which uses a characteristic transition frequency in the electromagnetic spectrum of atoms as a standard. The new generation of quantum logic clocks achieves a previously unknown accuracy by exploiting the sensitivity of quantum entanglement against disturbances, measured, e.g., in a single ion [23]. Quantum-enabled high-precision measurements using, e.g., the Josephson effect and the quantum Hall effect, have been essential for the recently completed redefinition of the SI unit system via natural constants [24]. Other new devices of quantum sensing are atom interferometry-based gravimeters [25] or magnetic field sensors based on quantum defects in diamonds, which are sensitive enough to detect changes in single nerve cells [26]. Quantum tomography is a mathematical technique to reconstruct quantum states via a sufficient set of measurements [27]. An important application is the characterization of optical signals, including the signal gain and loss of optical devices [28]. Another relevant application is the reliable determination of the actual states of the qubits in quantum computing and quantum information theory [29,30]. Quantum imaging is a new subfield of quantum optics. It exploits quantum correlations such as quantum entanglement of the electromagnetic field to image objects with a resolution or other imaging criteria that are beyond what is possible in classical optics. In that area, the special technique of "ghost imaging" is using light that has never physically interacted with the object to be imaged [31]. Control of quantum systems is, e.g., achieved via manipulation of quantum interferences of the wave functions of coherent laser beams. It is dominantly guided by the so-called quantum optimal control theory [32].

(iii) Quantum communication and cryptography were started with the publication of the BB84 protocol for quantum key exchange by Bennett and Brassard [33]. It is based on an idea by Wiesner from the early 1970s that had for a long time been unpublished [34,35]: Heisenberg's uncertainty principle would prevent undercover eavesdropping. Later, Ekert introduced the use of entangled qubits (quantum bits) into quantum key distribution [36]. Due to the no-cloning theorem of quantum mechanics, it is not possible—in contrast to the classical case—to replicate a quantum state exactly [37]; it can be done either approximately or exactly only with a certain probability. Therefore, the information encoded in transferred qubits cannot be identically copied. Quantum networks consist of quantum processors as nodes which exchange qubits over quantum communication channels as edges. They are, therefore, a necessary ingredient of quantum computing. Secure communication in quantum networks is essential for the long-range transmission of quantum information, usually by quantum teleportation. This idea was introduced by Bennett et al. [38]. Only four years later, it was experimentally demonstrated by Boschi et al. [39] and Bouwmeester et al. [40] independently via entangled photons—the significance of the former being controversial [41]. Another seven years later, entangled photons were used as the basis for an unbreakable communication code in order to perform a secure money transaction between two banks in Austria [42]. An extended quantum network leads to a quantum internet, which in addition needs quantum repeaters. They do not work like classical repeaters due to the no-cloning theorem. They rather build upon entanglement swapping and distillation and need to store qubits in quantum memory units [43]. A recent milestone was the achievement of all three scientific goals in launching the first quantum satellite, called Micius, by China: a quantum entanglement distribution over a long distance [44], a satellite-to-ground quantum key distribution between China and Austria by implementing the BB84 protocol [45], and quantum teleportation [46].

(iv) Quantum computing promises a quantum leap in computational power since previous speed-ups on the basis of semiconductor technology as described by Moore's law [47] appear to come to an end [48–50]. The original idea of quantum computing was expressed by Feynman [51] (this is the transcript of a talk given by Feynman in 1981): Quantum systems as, e.g., molecules should be simulated by letting a model quantum system evolve and calculate the system in question. That was a new approach—rather different from implementing the classical algorithms, e.g., of quantum chemistry. The classical algorithms consume a high number of computational resources. The first implementation of quantum simulation was the quantum variant of simulated annealing. This is a widely used Monte Carlo optimization algorithm for finding extrema of multidimensional functions by mimicking the thermalization dynamics of a system which is slowly cooled. Thermal excitations allow the system to escape out of local minima. In quantum annealing, this possibility is much greater by including the tunneling effect [52]. In 2011, the Canadian enterprise D-Wave announced to have built the first commercial quantum annealer [53]. The greatest success of this kind of device is the recent (until then not feasible) simulation of magnetic phase transitions in a 3D lattice of qubits [54]. Due to the susceptibility of quantum computers to decoherence and noise, a substantial performance improvement can be achieved by the implementation of quantum error correction [55].

Others try to implement a universal model of quantum computation using quantum logic gates in superconducting electronic circuits. These attempts are most prominent in popular science presentations and in the media. They are reporting on the efforts and successes of global players as Google, IBM, and others to reach quantum supremacy. Quantum supremacy means that a programmable quantum device can solve a problem that no classical computer can feasibly solve. In 2019, Google claimed to have reached this goal [56] with its quantum processor for a very special problem: this processor checked the outputs from a quantum random-number generator within minutes, for which the world's largest supercomputer would take thousands of years. A third standard model of quantum computation is the quantum cellular automata, a quantization of classical cellular automata. They are capable of simulating quantum dynamical systems intractable by classical means [57].

New algorithms and software are necessary to exploit the advantages of quantum computing. A quantum algorithm in a narrow sense is an algorithm that exploits quantum features such as entanglement or superposition, which cannot be ingredients of a classical algorithm. The very first example of a quantum algorithm provably faster than its classical counterpart was given by Deutsch in 1985 [58], but the most prominent examples with practical usefulness are Shor's algorithm for factoring numbers [21] and Grover's algorithm for searching unsorted databases [59]. However, there are dozens of other quantum algorithms [60,61]. Quantum software comprises the assembling and orchestration of computer instructions to whole programs that can be run on a quantum computer. Even new high-level programming languages are being developed which especially help to express the quantum algorithms (see https://en.wikipedia.org/wiki/Quantum_programming#Quantum_programming_languages for a list of languages—accessed on 29 July 2021).

In recent years, some bibliometric studies have been published on QT. Tolcheev [62] published a bibliometric study on QT including a very broad set of papers (by comprising all papers that use "quantum" in their title, abstract, or keywords since the year 2000). In contrast, the present study has a more focused view by including papers from specific technology-relevant subfields. Tolcheev's particular attention was directed to the assessment of the publication output of Russian scientists concerning the main WoS Subject Categories and the degree of international collaboration. Another study on QT by Chen et al. [63] uses the field of quantum information as an application case for a new method. This method focuses on the scientometric comparison of the Quantum Center of Excellence of the Chinese Academy of Sciences with three other outstanding international research units. The authors were interested in the internal team structure, collaborations, and prospective development. Olijnyk [64] was interested in China's involvement in the area of quantum cryptography between 2001 and 2017 and witnessed China taking on a leading role. Dhawan et al. [65] focused on the global publication output in quantum computing research between 2007 and 2016 and reported results concerning the top contributing countries very similar to ours (see Section 5. Discussion).

Seskir and Aydinoglu [66] followed an approach similar to the approach of this study. They applied an elaborate search query to publications in the WoS until June 2019, informed by expert knowledge, but different from ours (cf. Section 3.3). Their handling of the topics was not as detailed as ours, where we tried to suppress noisy terms, and therefore they arrived at a coarser partitioning of subfields: quantum cryptography and communication, quantum computing and information theory, and the physical realizations of the respective concepts. Apart from the identification of a core set of QT 2.0 literature, they also tried to identify the key players on the level of countries and institutions by analyzing their collaboration patterns. They identified the same top 25 countries as we did (cf. Section 4.3).

3. Methods and Dataset

3.1. Data Sources

The bibliometric data used in our study are from three sources: (1) the online version of the Web of Science (WoS) database provided by Clarivate Analytics (Philadelphia, PA, USA), (2) the bibliometric in-house database of the Max Planck Society (MPG), developed and maintained in cooperation with the Max Planck Digital Library (MPDL, Munich), and (3) the bibliometric in-house database of the Competence Centre for Bibliometrics (CCB, see: http://www.bibliometrie.info/ (accessed on 1 August 2021)). Both in-house databases were derived from the Science Citation Index Expanded (SCI-E), Social Sciences Citation Index (SSCI), Arts and Humanities Citation Index (AHCI), Conference Proceedings Citation Index—Science (CPCI-S), and Conference Proceedings Citation Index—Social Science & Humanities (CPCI-SSH) prepared by Clarivate Analytics. The availability of bibliometric data and the syntax the WoS offers, to formulate the complex queries detailed in Section 3.3, have both motivated our choice of database.

3.2. Search Procedure

The analyses considered publications of the document types "Article", "Conference Proceeding", and "Review". The results are based on 54,598 papers published between 1980 and 2018 in the field of QT 2.0. The search queries that we used for compiling the dataset including the publications for the different subfields of QT 2.0 are listed and explained in the following. For each of the different subfields in general, effects of earlier truncation, usage of quotation marks, and different proximity operators were tested. We carefully considered the different result sets. Our main goal was to have a sufficient recall and high precision. The final publication set does not comprise all QT 2.0 publications, nor does it exclude all irrelevant publications, as will be pointed out in the following. A completely "valid" publication set is not achievable on such a scale. However, with our carefully formulated WoS search query, we are confident that we captured most of the relevant publications regarding QT 2.0 while including only very few irrelevant publications. In particular, we excluded on purpose the very large literature related to quantum physics and quantum chemistry that is not linked to the field of QT 2.0.

The searches were done on 25 May 2020 via the online version of WoS and yielded 54,848 publications starting in 1980 until the end of 2018. All WoS internal identifiers (UTs)—except for 247—could be accessed via the in-house custom database of the MPG in its version from December 2019.

3.3. Search Queries for Fields of QT 2.0

In the following, we explain the WoS search queries tailored for the different relevant subfields within the four different fields of QT 2.0 to gain a maximum precision and a high recall (which is not easily guaranteed). We compared result sets of searching in different data fields (i.e., topic or title) and with different proximity operators (i.e., quoting search terms or using the operators AND, NEAR, or SAME). Since we did not find a useful query for title-only searches, our search queries use the topic field "ts" which comprises title, abstract, and keywords. The use of proximity operators had to be done differently for each QT 2.0 subfield. The search formulations are ordered by field. All queries are combined by the OR operator in the WoS online database.

3.3.1. Quantum Information Science and Quantum Technology in General (Q INFO)

(1) Quantum information science

ts = (“quantum information*” OR “von Neumann mutual information” OR “quantum mutual information” OR “quantum fisher information”)

This broad search yields a lot of hits, but successfully excludes non-relevant ones. In quantum information theory, quantum mutual information, also called von Neumann mutual information, is a quantum generalization of the Shannon mutual information and measures the correlation between subsystems of a quantum state [67]. Quantum Fisher information is the quantum analogue of the classical Fisher information of mathematical statistics and determines the bound for measurement precision. Therefore, it is a matter of choice whether to assign it to quantum information science or quantum metrology, sensing, imaging, and control. Use of a narrow proximity operator, e.g., NEAR/1, would result in many irrelevant publications from other fields that contain compound terms such as, e.g., “quantum chemical information” in the context of quantum chemistry or studies using the “Quantum Geographic Information System” for regional localization of diseases or geological events.

(2) Quantum technology in general

ts = (quantum NEAR/2 technolog*)

We added this general search to the first basic and broader topic of quantum information science. Only a few of the papers have the concept in their title, but in many of them QT is explicitly envisaged as a field of application of the physical phenomena described. The proximity operator is tuned to cover relevant compound terms such as “quantum optical technologies” or “quantum key distribution technologies” and to exclude irrelevant hits due to compound terms such as “quantum-inspired classical computing technology” or “quantum-dot-based display technology”. More than a third of the results of QT contain the concept of quantum information.

(3) Quantum theory in connection with qubits

ts = (“quantum theory” SAME (qubit* OR “quantum bit*”))

Quantum theory, the theoretical basis of QT, is a very broad field. Therefore, we decided to include only publications which contain “quantum theory” and “qubit*” or “quantum bit*” in the same field of the topic.

3.3.2. Quantum Metrology, Sensing, Imaging, and Control (Q METR)

(1) Quantum metrology

ts = ((quantum NEAR/10 metrology) OR (quantum NEAR/1 tomograph*) OR “atomic clock*” OR “ion clock*” OR “quantum clock*” OR “quantum gravimeter*”)

The first proximity operator is also needed to retrieve titles such as “quantum-enhanced metrology” and especially relevant, but wordier, mentions in the abstract or title such as, e.g., “A study of quantum Hall devices with different working magnetic fields for primary resistance metrology”. A greater distance between search terms would reduce the precision too much. The second proximity operator is also needed to include papers that contain phrases such as “quantum process tomography” or “quantum state tomography”. The publication set regarding quantum clocks is a very special case that cannot be retrieved sufficiently by general search terms. Therefore, the specific search terms “atomic clock*” and “ion clock*” were included.

(2) Quantum sensing

ts = ((Quantum NEAR/1 Sensing) OR (Quantum near/1 Sensor*))

Using a quoted search term for this subfield would exclude too many relevant publications. The chosen proximity operator yields desired results such as “quantum-enhanced sensing”, “quantum plasmonic sensing”, or even “quanta image sensor”. (When using proximity operators both plural and singular forms are found.) Using a broader proximity operator such as NEAR/2 would yield too many irrelevant hits such as “quantum dot-based sensors” or “quantum cascade laser sensor”.

(3) Quantum imaging

ts = ((“quantum imag*”) OR “ghost imag*”)

For quantum imaging, it was possible to capture most of the relevant publications using two quoted and truncated strings. Usage of the NEAR/1 operator would have yielded, e.g., the fear of “images of ghosts” in psychiatric literature or “quantum dot imaging”. This does not exploit QT 2.0 features but is widely used in biological and chemical research because of the well-tunable emission spectra of quantum dots. Additionally, imaging quantum effects in a broader sense are excluded.

(4) Quantum control

ts = (“quantum control*” OR “control* of quantum” OR “control over quantum” OR “quantum optimal control” OR “quantum state control” OR “control* quantum” OR “control* the quantum” OR “quantum coherent control”)

For the subfield quantum control, we decided to use multiple quoted search terms because “quantum NEAR/1 control” would have led to too many irrelevant hits due to compound terms such as “quantum path control” in quantum chemistry.

3.3.3. Quantum Communication and Cryptography (Q COMM)

(1) Quantum communication and networking

ts = (“quantum communication*” OR “quantum network*” OR “quantum optical communication” OR “quantum state transmission*” OR ((“quantum memor*” OR “quantum storage*”) NEAR/5 photon*) OR “quantum repeater*” OR “quantum internet” OR (“quantum teleport*” AND (“qubit*” OR “quantum bit*” OR “entangle*”)))

The quoted strings “quantum communication*”, “quantum network*”, “quantum optical communication”, and “quantum state transmission*” yield a rather accurate basis for this subfield. However, network-related publications regarding optical storage are missing. We included them by requiring that the term “photon*” appears within five words of the search terms “quantum memory” and “quantum storage”. The optical storage is especially important for quantum communication. The qualification of quantum teleportation (a basic procedure in quantum communication) with qubit or entanglement narrows the focus down to technological applications as opposed to theoretical or experimental work.

(2) Quantum cryptography

ts = (“quantum crypto*” OR pqcrypto* OR “quantum key distribution” OR “quantum encrypt*” OR ((“quantum secur*” OR “quantum secre*”) NOT (“quantum secreted” OR “quantum secretion”)))

The quoted search term “quantum crypto*” provides a good basis for this subfield. However, additional search terms, e.g., “pqcrypto*” (for post-quantum cryptography), “quantum key distribution”, and “quantum encrypt*” were necessary for obtaining an acceptable recall. Further relevant publications containing “quantum secur*” or “quantum secre*” were included while irrelevant publications, mainly from biology, with the compound terms “quantum secreted” or “quantum secretion” were excluded.

3.3.4. Quantum Computing (Q COMP)

(1) Quantum computing

ts = (“quantum comput*” OR “quantum supremacy” OR “quantum error correction” OR “quantum annealer” OR (quantum NEAR/2 (automata OR automaton)) OR “quantum clon* machine*”)

The term “quantum annealer” in the search formulation points to more actual technical realizations than the more abstract term “quantum annealing”. The proximity operator with automata is so chosen as to include, e.g., the generalized concept of quantum-enabled finite automata and of quantum cellular automata as well as the "Cellular Automaton Interpretation of Quantum Mechanics" [68] or "quantum evolutionary cellular automata" or "cellular automaton, based on quantum states". The capabilities of quantum cloning machines [69] are important for the processing of qubits in quantum computers. Therefore, we added the last search term to cover such literature, too.

(2) Quantum hardware systems

ts = ("quantum hardware" OR "quantum device*" OR "quantum circuit" OR "quantum processor*" OR "quantum register*")

In the case of this subfield, we managed to progress with a combination of general and specific quoted search terms.

(3) Quantum simulation

ts = ("quantum simulat*" AND (qubit* OR "quantum bit*" OR "quantum comput*") OR "quantum simulator*") OR (ts = "quantum simulat*" AND wc = (quantum science technology OR computer science theory methods))

The term "quantum simulation" often means the simulation of quantum systems performed by classical means. Therefore, the term is widely used in various large fields such as, e.g., quantum chemistry. Thus, we needed to restrict it somehow. We decided to use search terms and two relevant WoS subject categories emphasizing the quantum nature of the simulation itself.

(4) Quantum algorithms

ts = "quantum algorithm*"

We decided to capture the subfield of quantum algorithms with a single quoted search term. Broader queries, e.g., using NEAR/1, would also capture irrelevant publications due to compound terms such as "quantum-inspired algorithm".

(5) Quantum software

ts = ("quantum software" OR "quantum cod*" OR "quantum program*")

In the case of "quantum software", too many irrelevant publications would be included if a broader search query was used. There is no significant overlap with quantum algorithms, but one third of the results are also found in quantum computing.

3.4. Publication Output and Citation Impact Indicators

We analyzed the number of papers (full counting) broken down by year, field of QT 2.0, and country. Citation impact analyses are based on time- and field-normalized indicators. We focused on the share of papers belonging to the 10% most frequently cited papers in the corresponding publication year, document type, and subject area. In case of more than one paper with a citation count at the required threshold of 10%, these papers are assigned fractionally to the top 10% publication set. This procedure ensures that there are exactly 10% top 10% papers in each subject area [70]. The top 10% indicator is a standard field-normalized indicator in bibliometrics [71]. The citation window relates to the period from publication until the end of 2018.

3.5. Mapping of Research Topics

Besides indicators such as publication output and citation count as measures of scientific activity and impact, techniques of text mining are also used in bibliometric studies. The analysis of keywords in a corpus of publications can identify important research topics and reveal their change and development over time. This analysis can be managed with the software VOSviewer [72]. The software produces networks based on bibliographic coupling. The nodes in these networks are keywords, their size signifies the number of corresponding publications, and the distance between nodes is proportional to their relatedness regarding cited references. Keywords of papers citing similar literature are located closer to each other. The nodes are divided into classes of similarity, displayed by clusters of different colors. The network can be controlled by some adjustable parameters such as minimal cluster size or resolution.

4. Results

In this study, we are interested in answering several research questions. (i) How did QT 2.0 and its subfields grow overall and compared to each other from 1980 to 2018? (ii) How did their topical foci change over time? (iii) What are the top contributing countries in QT 2.0 and its subfields since 2000? (iv) How are research topics and author countries related?

4.1. Respective Shares of Fields

We retrieved 54,598 publications using the search queries. Table 1 shows the number of papers in the four fields and their percentages of the total number of publications. We applied whole counting and many papers were assigned to more than one field. Therefore, the percentages add up to more than 100% and the percentage of papers belonging to only one field is only about 84%. A graph of the mutual overlap of the four fields is given in Figure 1.

Table 1. Number and percentage of papers in four fields of QT 2.0.

Field of QT 2.0	Number of Papers	Percentage of the Number of Distinct Papers	Number and Percentage of One-Field-Only Papers
Q INFO	16,300	29.85%	9706 (59.55%)
Q METR	12,531	22.95%	9766 (77.93%)
Q COMM	13,985	25.61%	9809 (70.14%)
Q COMP	21,786	39.90%	16,545 (75.94%)
Sum of all fields	-	118.77%	45,826 (83.93%)

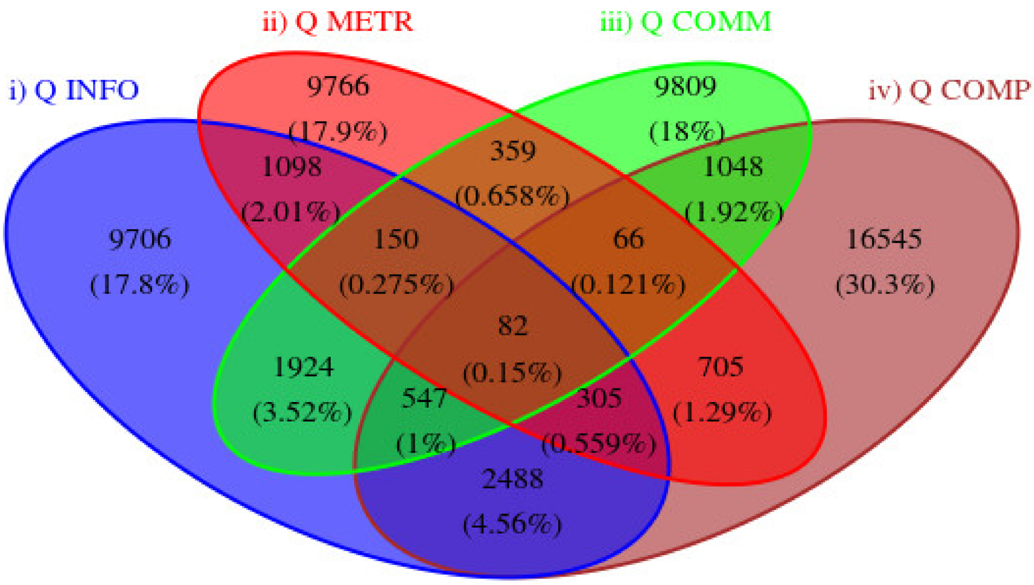

Figure 1. Venn diagram of mutual overlaps of the four fields of QT 2.0.

4.2. Overall Growth and Growth in Terms of Fields

Figure 2 shows the annual publication numbers for QT 2.0 and its four fields for the period from 1990 to 2018. The numbers are collected in Appendix A.2 in Table A1.

The annual numbers of publications on QT 2.0 before 1990 never exceeded a dozen per year—most of them about Q METR. This can be explained by the efforts and achievements in manipulation, controlling, and measuring of single quantum systems. The first decade is excluded from the following comparative analyses because the number of documents is small and their thematic focus is nearly exclusively on Q METR.

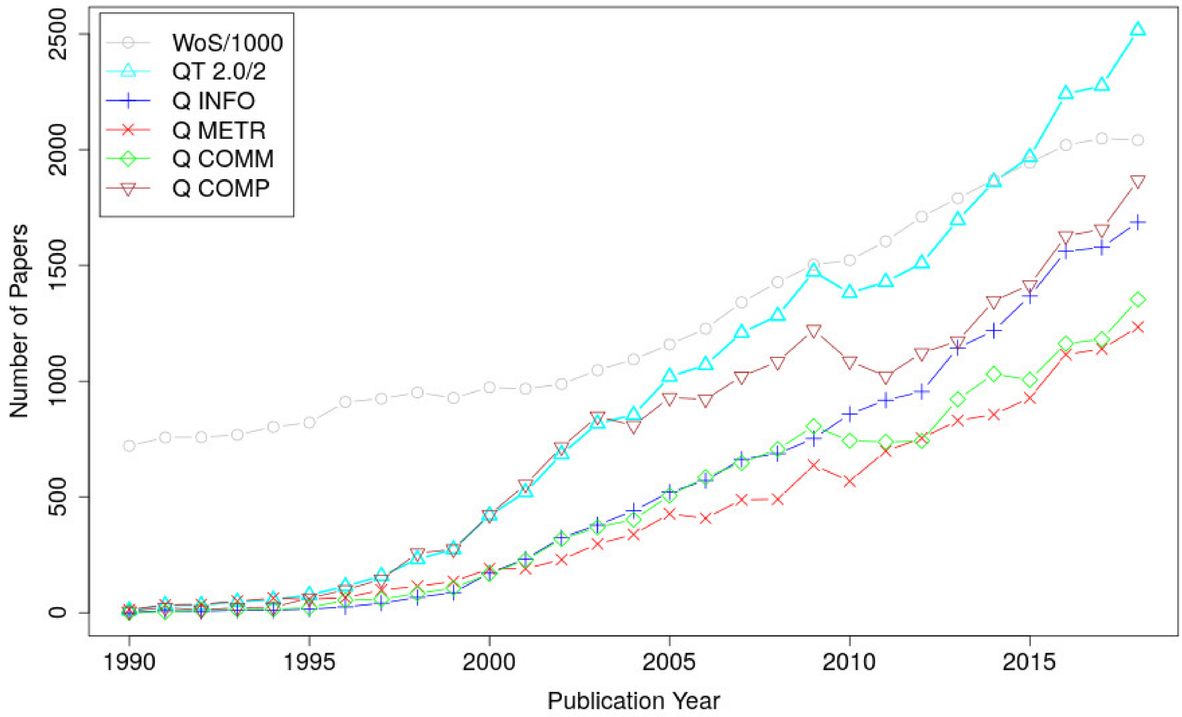

Figure 2. Annual numbers of publications of QT 2.0 and its four fields between 1990 and 2018 (in earlier years the annual numbers of all fields together never exceed 12) compared to the number of articles, reviews, and conference proceedings in the whole WoS. The numbers for QT 2.0 and the whole WoS are scaled by factors 2 and 1000, respectively, for better comparison.

An exponential growth of publications per year occurred between 1990 and 2000, mainly caused by Q METR and Q COMP (see Figure 2 and Table A1). Additionally, Q INFO emerged as a significant research field. The year 1994 is seen by Dowling and Milburn [16] as the birth year of the quantum information revolution. This year is associated with a significant experimental step towards practical quantum key distribution [20] and the publication of Shor's quantum algorithm [21] with an exponentially better performance than the then available classical algorithms for integer factorization. Together with the introduction of teleportation [38], they give ample reason for the significant increases in Q COMP from 1994 to 1995 (more than doubling and overtaking Q METR) and of Q INFO and Q COMM from 1995 to 1996 (nearly doubling and more than doubling, respectively). Q INFO and Q COMM continue in nearly linear growth. In the first decade of the century, Q COMP is clearly the most strongly represented field, with about twice as many papers as each of the fields Q INFO and Q COMM. Q INFO and Q COMM have strong interconnections, coming to the fore especially in this decade. The remarkable peak in 2009 is probably due to the online demonstration by D-Wave Systems of their quantum simulator at the Supercomputer Conference SC'07 [73]. This demonstration sparked hectic activity in the field but also sceptical reactions which probably are responsible for the decline in 2010 and 2011 [62]. The final years are characterized by a steady linear growth and nearly constant shares of the four fields.

Figure 3 offers a different view on the development of the four fields between 1990 and 2018 by displaying their respective percentages of the total counts of the papers of all four fields—partly counted multiple times due to overlaps of the four fields (see Figure 1).

During the first years, Q METR, is clearly dominating, but joined by Q COMP fairly soon thereafter. From about the year 2000 onwards, Q COMP and the strongly related Q INFO together have an annual share of about 60% of all QT 2.0 papers.

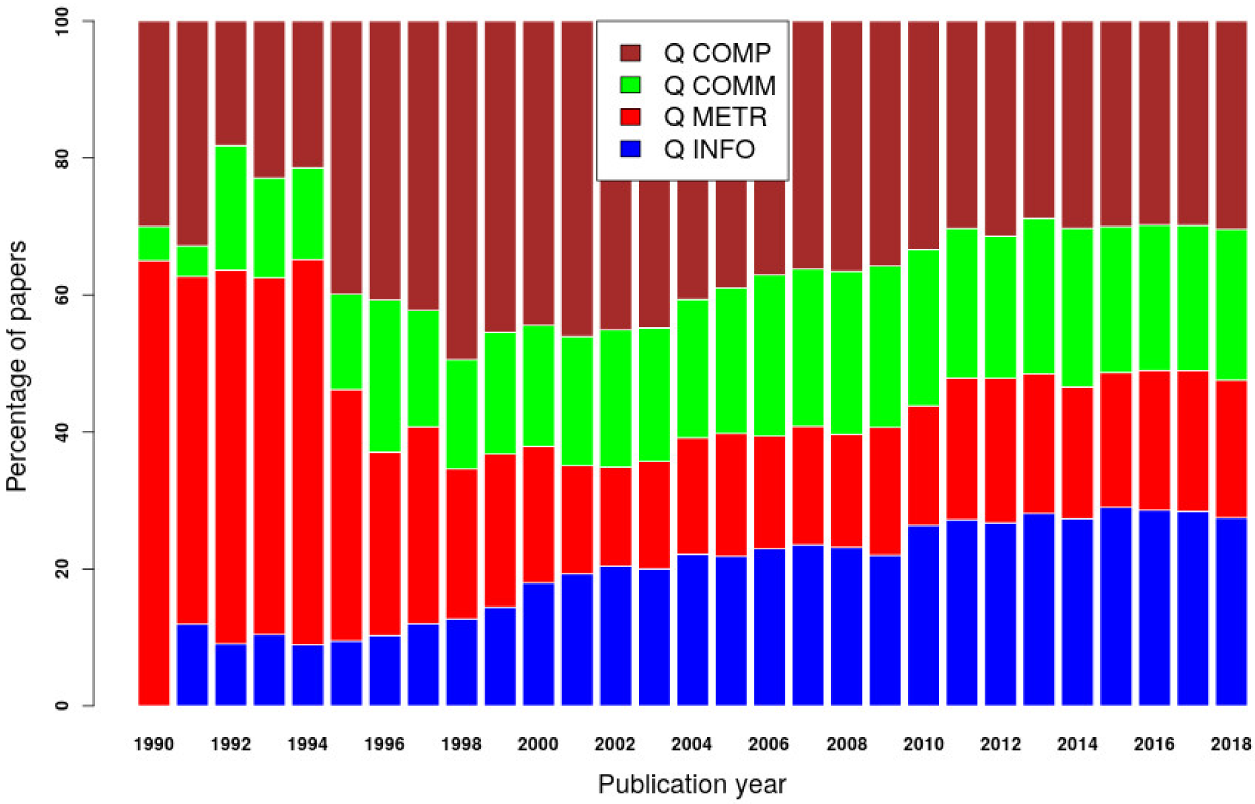

Figure 3. Annual percentages of the four different fields of QT 2.0 from 1990 to 2018.

To study the time evolution, we divide the period into three phases: (1) from 1980 to 1999; (2) from 2000 to 2011; and (3) from 2012 to 2018. The numbers of papers in the last two periods are in the same order of magnitude, with 24,322 and 28,132. With 2144 papers, the first (pioneering) phase has less than a 10th of the number of papers in the other periods. This division into three periods seems suitable to us for presenting the output of publications and the mapping of research topics.

A measure of the growth of the research fields during the three periods is the doubling time (see Table 2). The four fields have very similar values to the total QT 2.0. The very short doubling time of two years is characteristic for the first period until 1999, slowing down to four years in the second period, and slowing down to seven years during the most recent period. The last doubling time is comparable to the 5–6 years which Haunschild, Bornmann, and Marx [10] found for the climate change literature until 2014. However, this time is significantly shorter than the 12–13 years for the overall growth of the WoS records. Bornmann and Mutz [74] calculated an even longer doubling time of nearly twenty-four (24) years for WoS in the period from 1980 to 2012 by applying a non-linear segmented regression analysis. During the twenty (20) years from 1991 to 2010, the annual number of publications grew by a factor of 42, compared to a factor of ten for the climate change corpus and to a factor of about two for the whole WoS.

Table 2. Doubling times in years for all QT 2.0 papers and four fields for the years 1980–1999, 1980–2011, and 1980–2018 compared to the whole WoS publication record.

Years	All QT Papers	Q INFO	Q METR	Q COMM	Q COMP	WoS
1980–1999	2–3	1–2	3–4	1–2	1–2	7–8
1980–2011	4–5	4–5	4–5	4–5	5–6	11–12
1980–2018	6–7	5–6	6–7	6–7	7–8	12–13

4.3. Contributing Countries

Many countries are contributing research on QT 2.0 by collaborating with each other. Table 3 lists the 25 top publishing countries with at least 500 papers published between 2000 and 2018 in QT 2.0. Multiple authors of a single paper from the same country are counted only once, but multi-author papers are fully assigned to several countries so that the total sum exceeds the number of papers in our dataset. The 25 countries in the table include more than 90% of the authors, the USA and China alone cover one third, and two thirds are covered by the first eight countries. The last column shows the corresponding shares of the countries in the whole WoS in the same period.

Table 3. The 25 top publishing countries with at least 500 papers in QT 2.0 for the years 2000 to 2018. The table shows the number of papers, their percentage, and the national share of the whole WoS.

Country	Country Code	#QT 2.0	%QT 2.0	%WoS
USA	us	13,489	18.59	24.29
China	cn	12,110	16.69	9.79
Germany	de	5291	7.29	5.59
UK	gb	4639	6.39	6.57
Japan	jp	3982	5.49	4.76
Canada	ca	3044	4.20	3.45
Italy	it	2894	3.99	3.32
France	fr	2558	3.53	3.82
Australia	au	2413	3.33	2.59
India	in	1711	2.36	2.51
Russian Federation	ru	1687	2.32	1.68
Spain	es	1580	2.18	2.64
Switzerland	ch	1470	2.03	1.39
Austria	at	1213	1.67	0.76
Singapore	sg	1074	1.48	0.56
Brazil	br	1031	1.42	1.70
South Korea	kr	998	1.38	2.21
Poland	pl	991	1.37	1.16
Netherlands	nl	945	1.30	1.90
Israel	il	813	1.12	0.72
Iran	ir	719	0.99	0.91
Denmark	dk	623	0.86	0.77
Sweden	se	585	0.81	1.24
Taiwan	tw	535	0.74	1.25
Czech Republic	cz	530	0.73	0.62

Analogous evaluations have been made for the four fields of QT 2.0 separately (the results are not shown). They give a similar picture with nearly the same countries dominating. The same 22 countries are among the top 25 countries in QT 2.0 as a whole and all four fields, even when we focus on the top 10% most cited papers in QT 2.0 and its four fields. For both cases (either all papers or only top 10% papers), we calculated two numbers, indicative of the relative publication output of these countries, measured against an "expectation value" based on the countries' overall WoS shares. The first number is the difference in the last two columns in Table 3 (%QT-%WoS); positive and negative signs indicate more or less publication activity than expected, repectively. The second one is the corresponding quotient (%QT/%WoS). The quotient is identical to the so-called activity index (AI), introduced by Frame [75], which in turn is a variant of the revealed comparative advantage (RCA) used in economics [76]. AIs greater than 1.0 indicate national publication outputs higher than expected (from the whole WoS). Both indicators are presented as radar charts in Figure 4. For each indicator, there is one plot including all papers (on the left) and one including only the top 10% papers (on the right). In each radar chart, the 22 common countries are denoted by their respective country codes, starting at the top with the country with the most publications in QT 2.0 (USA) and descending clockwise. In each radar chart, the dividing values between under and over achievement are marked by a gray dashed line at the value 0 for the difference and 1 for the AI.

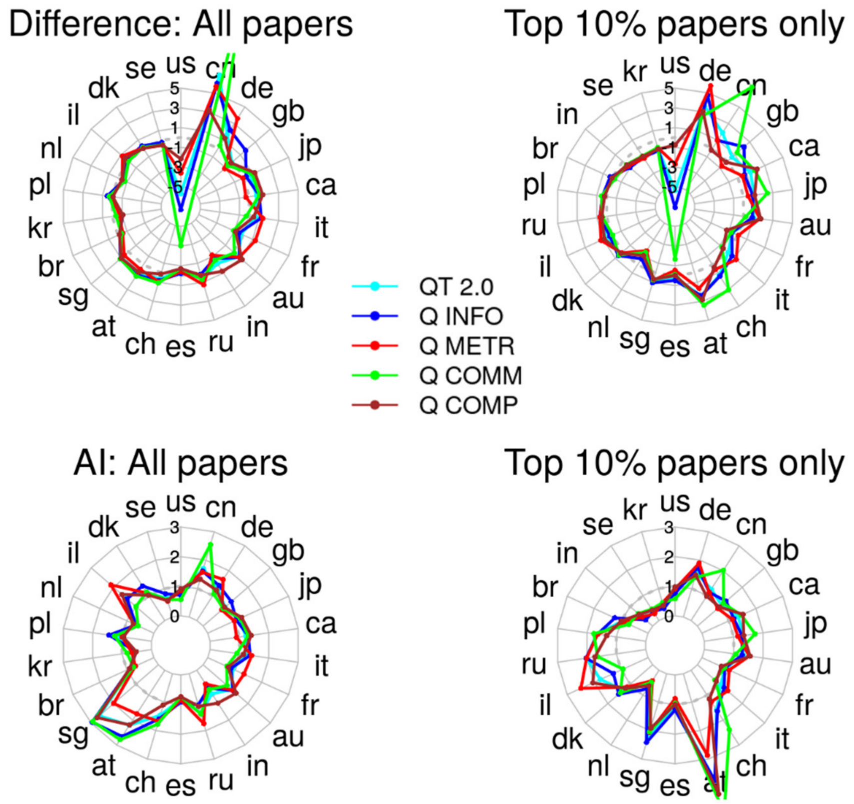

Figure 4. Radar charts of the differences (upper graphs) and quotients (activity indices, lower graphs) of the national shares of papers in QT 2.0 and its four fields from 2000 to 2018. On the left side, all papers are included; on the right side, only the top 10% most cited papers in the time period 2000–2016 are included. The 22 countries, which are among the top 25 in all fields and the whole QT 2.0, are denoted by their country codes, and ordered clockwise in descending order of the number of publications. The gray dashed lines at 0 and 1 indicate the expected output of the country.

The most striking insight from these figures is the very different assessment of the two leading countries with very similar output, the USA and China, in comparison with the whole WoS: while the USA is less active in QT 2.0 than in other WoS-covered research fields (QT 2.0: difference = −5.7%, AI = 0.77), China is much more active in QT 2.0 than in other fields (QT 2.0: difference = +6.9%, AI = 1.71). The difference is most pronounced in the field Q COMM (difference = +15.2%, AI = 2.5). With respect to the top 10% papers, the strong research focus of China on QT 2.0 is dampened considerably (QT 2.0: difference = +1.9%, AI = 1.26; Q COMM: difference = +7.4%, AI = 2.0). Germany has climbed from the third to the second rank in number of publications. It also shows a higher share of research activity in QT 2.0 than China (QT 2.0: difference = +2.5%, AI = 1.39). When only highly cited papers are considered, Germany has comparable strengths in all four fields. Figure 4 shows that Austria, Singapore, and Switzerland contributed rather unexpected high shares of QT 2.0 research in comparison with their research activities as a whole. Austria has an overall AI of above 2 in QT 2.0 and Q COMP, and of nearly 3 in Q COMM and Q INFO. The AIs even exceeded this, if focusing on the top 10% papers, leading to values of more than 4. These high AIs can be explained by the high activities of the groups in Vienna and Innsbruck concerning quantum teleportation. Singapore has AI values of nearly 3 in the three fields Q INFO, Q COMM, and Q COMP. Switzerland's AI value of about 1.6 is mainly caused by a high value of 2.4 in Q COMM.

4.4. Visualization of the Time Evolution of Research Topics

For the various time periods, we have created keyword maps based on author keywords and keywords plus assigned by Clarivate Analytics to papers. Usually, we prefer to use author keywords, but in the oldest period there is only a very small percentage of papers with author keywords. The number of papers with either author keywords or keywords plus amounts to about 70% (see Table 4). A common thesaurus file (https://s.gwdg.de/4DDxsp (accessed on 1 August 2021)) was used to unify singular/plural forms of words and synonyms as detailed in Table A2 in Appendix A.3. The minimal number of occurrences of a keyword is chosen such that about 100 keywords are displayed for each period. We chose default values as VOSviewer parameters for clustering. For the minimal cluster size, however, we used a value of 5 which resulted in a well-interpretable network. All VOSviewer maps are provided to the reader as online versions [77] via URLs. They can be used for an interactive inspection, e.g., by zooming in on the clusters.

Table 4. Occurrences of author keywords and keywords plus in three periods.

Time Period	Total Numberof Papers	Occurrences of Author Keywords (Percentage)	Occurrences of Keywords Plus (Percentage)	Occurrences of Either Type of Keywords (Percentage)
1980–1999	2144	445 (20.8%)	1350 (63.0%)	1500 (70.0%)
2000–2011	24,322	10,197 (41.9%)	19,549 (80.4%)	21,888 (90.0%)
2012–2018	28,132	13,766 (48.9%)	22,902 (81.4%)	26,033 (92.5%)

Figure 5 displays an overall co-occurrence map of 100 keywords occurring at least 298 times for the period from 1980 to 2018. Maps with about 100 keywords usually are a good compromise between maintaining readability of the map and displaying most of the content. In the figure, the four fields of QT 2.0 are nicely discernible by the keywords in four clusters, whose colors are kept consistent in all networks. In the following explanations of Figures 5–9, those keywords that are also found in the respective co-occurrence maps are written in italics:

- Red (Q METR): The manipulation of single atoms, molecules, and even (electron) spins as in quantum dots and the quantum control using light fields of coherence (lasers) lead to the realization of single qubits and of very high-precision quantum clocks.
- Brown (Q COMP): Quantum computing and computers build on quantum circuits with logic gates realized as trapped ions, anyons, or in NMR devices. On this hardware, quantum algorithms have been implemented that are much in need of quantum error correction.

- Blue (Q INFO): Quantum entanglement of states is a major subject of quantum information science, also investigating entropy and channel capacity in a generalization of Shannon's information theory.
- Green (Q COMM): Quantum communication is built upon the quantum teleportation of pairs of entangled states, often realized by single photons, as a basis for quantum cryptography and quantum key distribution.

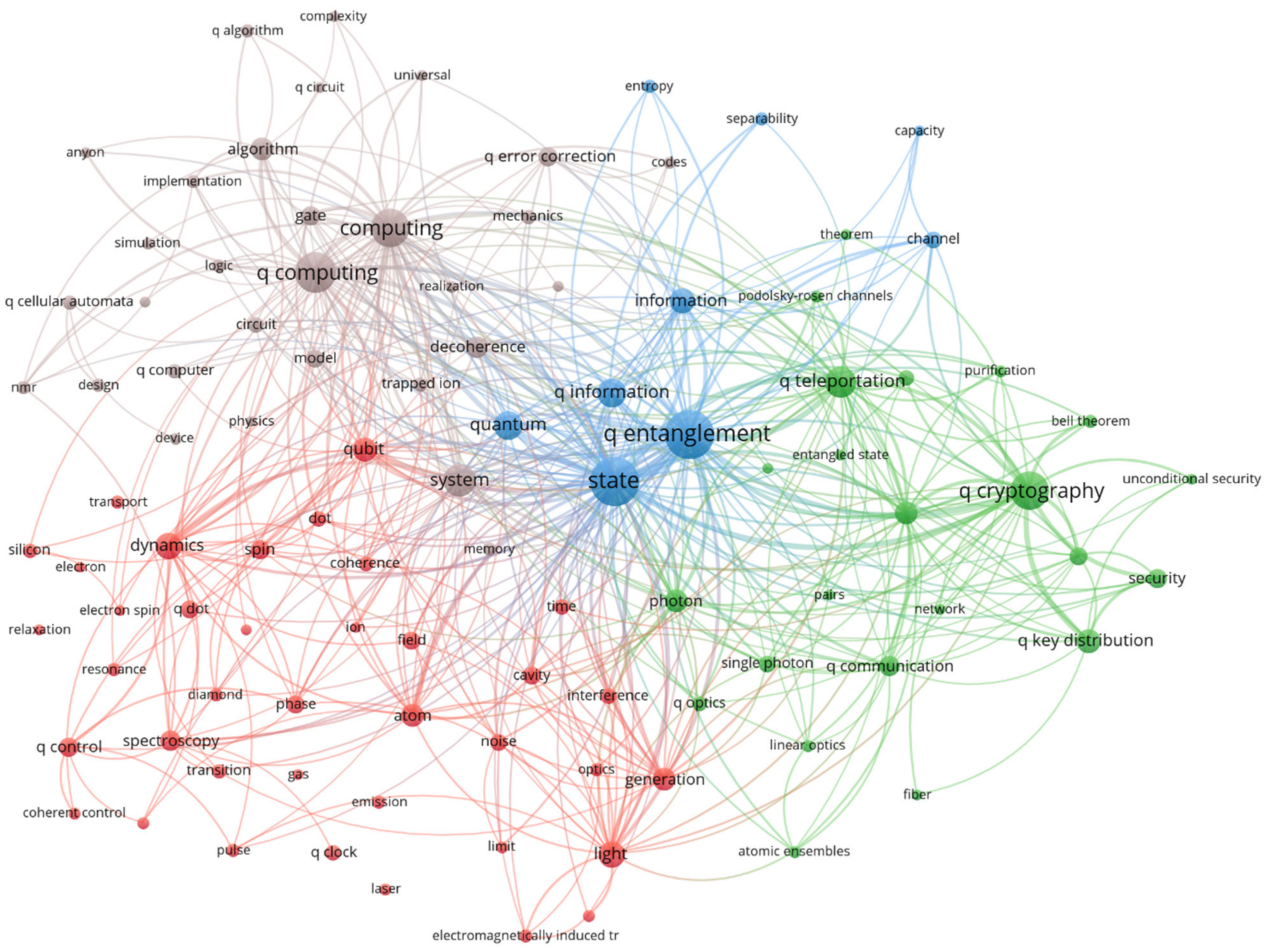

Figure 5. Co-occurrence map of the top 100 keywords (author keywords and keywords plus from 1980 to 2018) with four topical clusters, using the VOSviewer parameters resolution = 1.0 and minimal cluster size = 5. (The two biggest unnamed green nodes belong to the keywords communication and key distribution, respectively.) For better readability, in compound keywords quantum is abbreviated to q. Readers interested in an in-depth analysis of our publication set can use VOSviewer interactively and zoom in on the clusters. An online version is provided at https://s.gwdg.de/1Bg9EB (accessed on 1 August 2021) (cluster colors probably differ).

Figure 6 displays the co-occurrence map of 95 keywords occurring at least 12 times in the period from 1980 to 1999. From the five clusters, two can be associated with the field Q METR: the red cluster contains keywords such as spectroscopy, atom, quantum clock, frequency standard, and gravity; the keywords in the violet cluster point in the direction of quantum control in molecular dynamics, using, e.g., laser pulses. This field dominated the 1980s. The keyword quantum metrology itself does not occur before 2001, coined as a named concept only in retrospect. Since 1981, five publications contained the term in their title but were cited only two times in the first period. The green cluster is focused on Q COMM. The most frequent keywords quantum cryptography, (quantum) communication, quantum entanglement, quantum teleportation, and bell theorem point to pioneering experiments [8,20] as well as the proposal and realization of quantum communication protocols and quantum teleportation in the 1980s and 1990s [33,38,40]. The brown cluster belongs to Q COMP. The most prominent keywords are quantum computing, logic gate, quantum error correction, and algorithm. The yellow cluster contains keywords that relate to quantum hardware and methods of its realization. Keywords are quantum device, quantum dot, quantum cellular automata, and gaas (meaning the semiconductor GaAs, frequently used in creating quantum dot cellular automata). The keywords in the brown and yellow clusters indicate the efforts to realize quantum gates and circuits using a variety of techniques in the earlier years of the period. There was hope for efficient quantum algorithms in later years, triggered by Shor's algorithm [21]. The field Q INFO is not explicitly visible (apart from the keyword information in the green cluster). However, it is implicitly present in the strong connections between the green and brown clusters (Q COMM and Q COMP) via keywords such as decoherence, quantum entanglement, and quantum error correction.

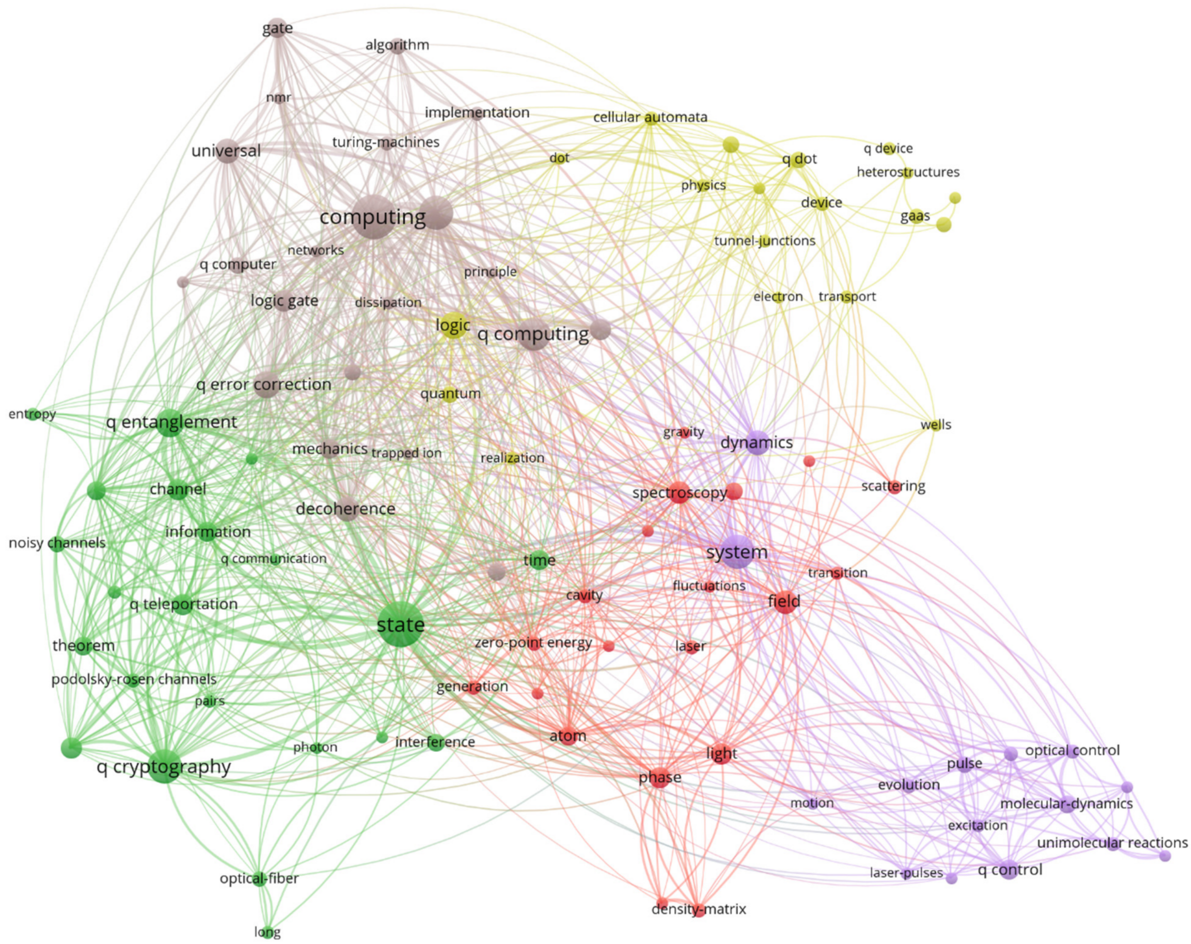

Figure 6. Co-occurrence map of the top 95 keywords (author keywords and keywords plus from 1980 to 1999) with five topical clusters, using the VOSviewer parameters resolution = 1.0 and minimal cluster size = 5. (The unnamed big brown node belongs to the keyword computer.) For better readability, in compound keywords the term quantum is abbreviated to q. Readers interested in an in-depth analysis of our publication set can use VOSviewer interactively and zoom in on the clusters. An online version is provided at https://s.gwdg.de/SfpspR (accessed on 1 August 2021) (cluster colors probably differ).

Figure 7 displays the co-occurrence map of 98 keywords occurring at least 134 times in the period from 2000 to 2011. About 60% of the keywords are the same as in Figure 6. In Figure 7, the keywords are distributed over three clusters (instead of five in Figure 6). The red cluster in Figure 7 can be interpreted as a merging of the two Q METR clusters (red and violet) from Figure 6. Furthermore, research on quantum hardware is no longer separated into its own cluster but is incorporated in the brown cluster (Q COMP). For example, the keywords nmr and trapped-ion point to different approaches for realizing quantum circuits. The green cluster includes the keywords quantum entanglement, quantum cryptography, quantum teleportation, and quantum information. The keywords indicate that the cluster comprises Q COMM and much of Q INFO together. Moreover, quantum key distribution and questions of security come to the fore in this decade with the first secure money transaction using QT 2.0 [42].

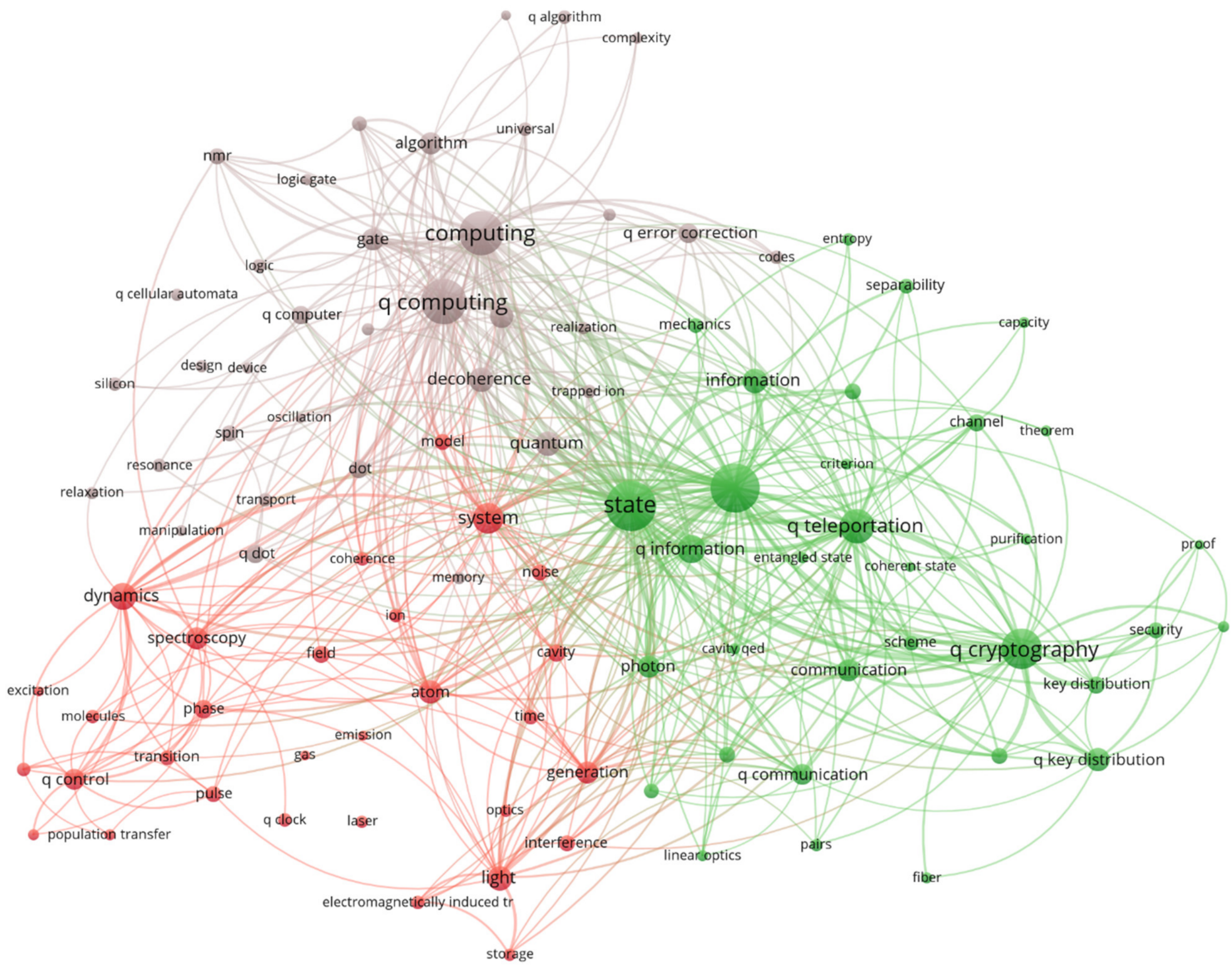

Figure 7. Co-occurrence map of the top 98 keywords (author keywords and keywords plus from 2000 to 2011) with three topical clusters, using the VOSviewer parameters resolution = 1.0 and minimal cluster size = 5. The unnamed big green node belongs to the keyword quantum entanglement. For better readability, in compound keywords the term quantum is abbreviated to q. Readers interested in an in-depth analysis of our publication set can use VOSviewer interactively and zoom in on the clusters. An online version is provided at https://s.gwdg.de/DvXJnY (accessed on 1 August 2021) (cluster colors probably differ).

Figure 8 displays the co-occurrence map of 100 keywords occurring at least 168 times each between 2012 and 2018. Eighty percent of the keywords are the same as in Figure 7, but they are distributed over five distinct clusters in Figure 8. The graph for this period is similar to the overall graph, but with an additional orange cluster. The red cluster can still be assigned to Q METR, which now also contains the keyword quantum metrology. The blue cluster located between the brown (Q COMP), green (Q COMM), and red cluster (Q METR) contains keywords such as quantum entanglement, quantum information, and entropy. This warrants an assignment of the cluster to Q INFO as a field at the interface of the other three fields of QT 2.0. The new orange cluster located between the red and green clusters constitutes an interface area between the two fields Q METR and Q COMM: quantum optics and quantum memory using photons.

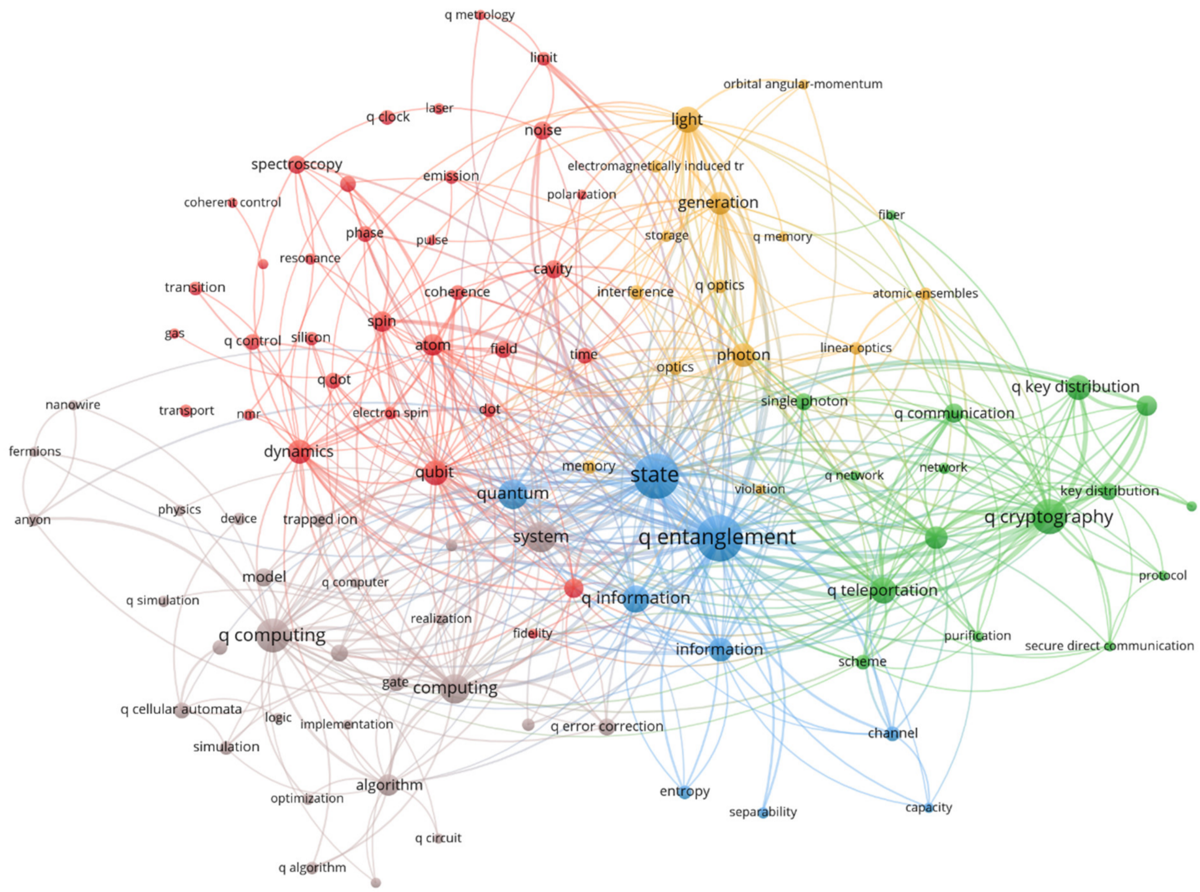

Figure 8. Co-occurrence map of the top 100 keywords (author keywords and keywords plus from 2012 to 2018) with five topical clusters, using the VOSviewer parameters resolution = 1.0 and minimal cluster size = 5. For better readability, in compound keywords the term quantum is abbreviated to q. Readers interested in an in-depth analysis of our publication set can use VOSviewer interactively and zoom in on the clusters. An online version is provided at https://s.gwdg.de/N5TmUa (accessed on 1 August 2021) (cluster colors probably differ).

When we inspect the topic maps for the three periods, we see continuity and persistence of clusters as well as a change in the focus and occurrence of keywords. From the first to the second period, only 60 out of 99 keywords in the maps are identical. From 1980 to 1999 (https://s.gwdg.de/WOaY1F (accessed on 1 August 2021)), the focus had been on the preparation, manipulation, and control of single quantum systems at the atomic scale and the pioneering work on building materials, devices, and sensors for quantum metrology. From the year 2000 to 2011 (https://s.gwdg.de/y668Y5 (accessed on 1 August 2021)), the focus had, on the one hand, switched to the advanced design of hardware components for real quantum computers and the development of algorithms utilizing quantum properties. On the other hand, the exploitation of quantum effects such as entanglement for secure communication using quantum key distribution had become prominent, favorably utilizing quantum optics of single photons. From the second to the third period, i.e., the year 2012 to 2018 (https://s.gwdg.de/nnrm9Y (accessed on 1 August 2021)), nearly 80% of the keywords remain the same (78 out of 99 and 101 keywords, respectively). There are only slight changes in the main direction of research, but some keywords moved into the new clusters of Q INFO and quantum optics. For example, memory and storage are located in the clusters Q COMP and Q METR in the second period; both keywords are connected with quantum optics in the third period. This connection probably exists because of their importance for optical quantum communication networks. The keyword quantum simulation appears only on the third map in the Q COMP cluster. This coincides with the enlarged efforts to build a quantum simulator as the fulfillment of Feynman's vision of a quantum computer [53,54].

4.5. Visualization of the Geographical Distribution of Research Topics

Figure 9 shows a combination of the approaches taken in the previous two sections. For the period from the year 1980 to 2018, we have produced a co-occurrence map of countries (denoted by their two-letter country code with a prefixed "@") with at least 400 occurrences (multiple co-authorships of the same country on a paper are counted only once) as well as a map of keywords (author keywords and keywords plus assigned by Clarivate Analytics) with at least 300 occurrences. These thresholds lead to the top 25 countries in Table 3 and to 104 keywords, sorted into five topical clusters (by using the VOSviewer parameters resolution = 1.1 and minimal cluster size = 5). Four clusters in the figure can be assigned to the four fields of QT 2.0. The fifth cluster comprises quantum optics, which is also visible in the keyword map of the most recent period (orange cluster in Figure 8). This last cluster does not contain any of the 25 top countries, but there are many connections to keywords and countries of the neighboring clusters Q METR, Q COMM, and Q INFO. These connections confirm its interface function that was also detected for the third time period in Figure 8. About ten countries are assigned to the clusters Q METR and Q INFO, respectively. Three countries are assigned to Q COMP and Q COMM each. In case of Q COMP, India (@in) and Iran (@ir, just above node @in) are mainly connected to the design of logic gates and circuits.

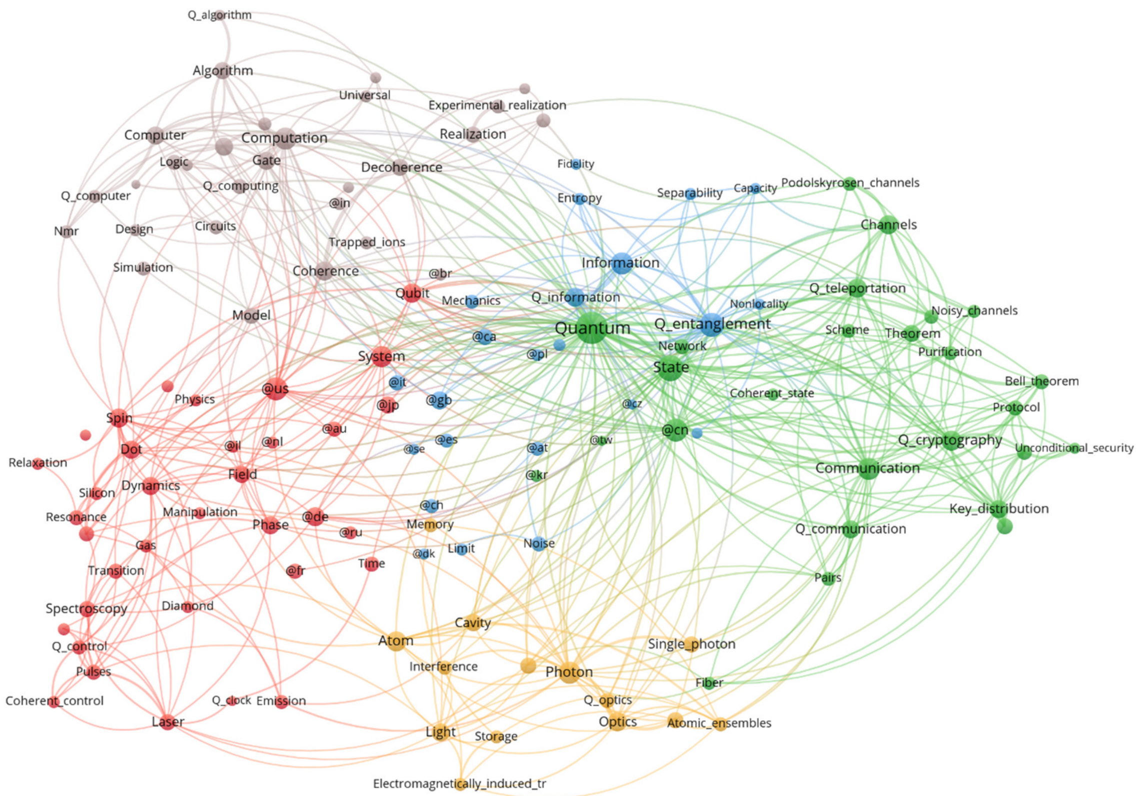

Figure 9. Co-occurrence map of (1) the top 25 countries of Table 3 (denoted by their two-letter country code with a prefixed "@") with at least 400 occurrences and (2) the top 104 keywords (author keywords and keywords plus) with at least 300 occurrences in the total publication set from 1980 to 2018. The map shows five topical clusters, using the VOSviewer parameters resolution = 1.1 and minimal cluster size = 5. For better readability, in compound keywords the term quantum is abbreviated to Q. An online version is provided at https://s.gwdg.de/IULOc3 (accessed on 1 August 2021) (cluster colors probably differ).

We now compare the assessment of the countries in the radar charts for all QT 2.0 papers in Figure 4 with their placement and connections in the co-occurrence map in Figure 9. The large node of China (@cn) in the green cluster (Q COMM) mirrors the dominance of China with respect to the total number of papers and AI. Germany (@de) with the third highest publication output and the highest values in Q METR in the radar charts is consequently located prominently in the red cluster. Germany has significant contributions to quantum optics and is connected to some other countries in the blue cluster (Q INFO). Q INFO is the field of Germany's second highest AI. Germany's connections to two other countries in the red cluster may have contributed to their noticeably high AIs of about 2, which is in contrast to their small share of all QT 2.0 publications: Russia (@ru) with nearly 2.5% also has contributions to quantum optics and to the green cluster of Q COMM with Russia's second highest AI; Israel (@il) with just over 1% has the strongest connection to quantum control and the USA (@us).

We would like to emphasize two other countries. These countries have, with 2.5%, a small share of all QT 2.0 papers, but a high AI of about 3 in Q INFO and Q COMM. Singapore (@sg, the unnamed blue node left below "Quantum") has an especially high AI of about 3 in Q INFO and Q COMM. In the map, consequently, it can be found in the blue cluster of Q INFO connected with quantum entanglement and information and with the UK (@gb). Singapore is additionally connected with the green cluster of Q COMM and its major contributor China. Austria's (@at) activities, especially in Innsbruck and Vienna, are mirrored by its placement in the blue cluster Q INFO which is strongly connected to quantum entanglement. It is also connected to the green Q COMM keywords communication and pairs of photons (quantum optics, orange cluster).

5. Discussion

This bibliometric study on QT 2.0 identified four main subject fields, namely Q INFO, Q METR, Q COMM, and Q COMP. For these four fields, we analyzed their respective share, their respective growth in the QT 2.0 publication set compared to one another and to the overall growth of QT 2.0, and the main contributing countries by comparing their actual to their expected publication output based on the countries' overall WoS shares. We provided insight into the time evolution and geographical distribution of specific research topics through several topic maps. We presented visualizations of the co-occurrence of keywords during the whole period plus the three distinctive partial periods 1980–1999 (the pioneering years), 2000–2011 (the exploration years), and 2012–2018 (the maturing years), as well as of keywords and countries combined.

Of the 54,598 publications in our dataset, the four fields have shares from about one fifth (Q METR) to two fifths (Q COMP) (see Table 1). In the first decade considered here, less than 100 publications appeared, most of them in the field Q METR with its pioneering works on preparing and controlling single quantum systems. During the second decade, the 1990s, Q COMP joined Q METR in driving the exponential growth, leading to the ongoing dominance of Q COMP in the new millennium (see Figure 2). Between 1980 and 1999, the doubling time of QT 2.0 was between 2 and 3 years as opposed to the doubling time of the whole WoS of 7 to 8 years. During the periods until 2011 and until 2018, respectively, the doubling times still were about half as long as in the whole WoS, with 4 to 5 years and 6 to 7 years, respectively (see Table 2). Tolcheev [62] found for a much broader publication set of all publications containing "quantum" in their title, abstract, or keywords and for the top 15 countries a doubling time of over 17 years from the year 2000 to 2016. In the most recent decade, QT 2.0 therefore seems to be a very active research area that is steadily evolving at a rapid pace.

We also analyzed the main contributing countries to QT 2.0. We focused on a time period with a substantial annual number of papers from the year 1990 until 2018. We looked at the top 25 contributing countries in more detail and compared their publication output in QT 2.0 and its four fields to the expected output from the whole WoS (see Figure 4). Singling out Q COMP, the top ten contributing countries are the same as in

Dhawan, Gupta, and Bhusan [65], even if their less detailed search retrieves only a small part of the field. We visualized the geographical distribution of research topics with a co-occurrence map of countries and keywords in Figure 9. The main result is the sharp contrast of the USA and China, which are the greatest contributors to QT 2.0. The USA shows a much smaller contribution to QT 2.0 than could be expected from their otherwise leading role in science. China has a far overproportionate contribution, especially in the field of Q COMM—corroborated by its hub-like function in the topical map and confirming the findings of Olijnyk [64]. Germany can be found on the third rank of contributors with a much higher than expected share of QT 2.0 publications. By focusing on highly cited publications, China's share and AI are significantly diminished. In the high-impact range, Germany goes up by one rank to the second place, contributing substantially in each of the four fields, but notably in Q METR. This result is confirmed by the country's location in the corresponding cluster in the topic map.

For the small countries Austria and Switzerland, our current study finds a very high AI, notably in the field Q COMM. The other small country with an extremely high AI, Singapore, scores especially high in Q INFO and Q COMM. In the topic map, the blue cluster of Q INFO has stronger connections to the keywords (quantum) computation and information as well as entanglement.

The other two noticeable countries with high AI values, especially in Q METR, are Russia (about 2) and Israel (2 to 2.5). In the topic map, Russian research relates to quantum optics and keywords of the Q INFO and the Q COMM clusters as well as to the countries Germany and the USA. This seems to be in accordance with a recent collection of papers on "Quantum technologies in Russia" in the journal Quantum Electronics [78]. Here, research activities of the recent past and the prospective future focus on the development of optical quantum memory, of single–photon light sources, and of magnetometers based on NV centers in diamond. Congruently, Fedorov et al. [79] list as main focal topics quantum communication as well as quantum metrology and sensing, besides quantum computing and simulation. These topics are supposed to receive a development boost by a recent huge governmental funding plan [80]. The strong collaboration of Russian scientists with scientists from Germany and the USA which we found in this study agrees with the findings of Tolcheev [62]. Israel has a strong connection to quantum control, spin, and the USA.

Our findings about the top publishing countries in QT 2.0 agree with national funding initiatives. The journal Quantum Science and Technology reported in 2019 that ten of the eleven top countries in Table 3 had launched high-budget initiatives in order to consolidate and substantially enhance their efforts and achievements in QT 2.0: the USA [81], China [82], Japan [83], Australia [84], Canada [85], the Russian Federation [79], the European Union—represented by some of its member states [86]—and the UK [87].

In this study, we also investigated the time evolution of research topics, visualized by co-occurrence maps for different time periods. The map for the period from the year 1980 to 2018 shows clearly distinguishable clusters for the four QT 2.0 fields. The maps for the three partial periods reveal changes in the focal areas over time. The years 1980 to 1999 were the pioneering years with breakthroughs in the manipulation and measurement of single quantum systems, the design of quantum logic gates, first quantum algorithms, and the first quantum teleportation. The years 2000 to 2011 were characterized by an emphasis on security issues in quantum communication and multiple approaches to building the first quantum computers. The period from the year 2012 to 2018 displays nearly the same keywords as the previous period, indicating a maturing of QT 2.0 and a steady work on improving promising approaches.

This study has focused on QT 2.0 and its four fields in their mutual relation and development over time, and their occurrence in the main contributing countries as well as the geographical distribution and the time development of research topics. As many other similarly designed bibliometric studies, this study has some limitations. (1) The precision of the search queries is affected by ambivalent meanings of terms that are not qualified by the term quantum, such as information, computing, etc. (2) For the topic maps, we used mixed keyword types in order to get a reasonable coverage. During the first two decades, however, the share of papers with any keyword is just above 70%. (3) The term "quantum cellular automata" (QCA) is ambiguous. It might mean the implementation of classical cellular automata on systems of quantum dots as a replacement for classical computation using CMOS technology [88]. However, it may also denote an abstract model of cellular automata performing true quantum computations, initially proposed by Feynman [51]. In order to better differentiate between the two meanings, some authors refer to the former as "quantum dot cellular automata". There are about 1500 hits in our dataset for this term, but the two meanings are not clearly distinguishable. Thus, we accepted a substantial number of false positives to not miss the quantum concept. (4) One of the reviewers pointed out as a limitation of our study the poorer coverage of computer science in the WoS database, causing a systematic underestimation of the contribution of computer scientists to QT 2.0, especially to Q COMP and Q COMM. This is a well-known disadvantage, mainly caused by less coverage of conference papers which are an important publication channel in computer science. The seminal (conference) paper of quantum cryptography [33] is therefore not contained in our dataset. In our study, with a high degree of aggregation, this circumstance does not seem to distort the overall picture of the long dominance of Q COMP and Q COMM, but more detailed bibliometric studies of quantum computation or quantum communication should consider the use of databases with a higher coverage of computer science.

Future studies could focus on the further development of QT 2.0 research in the featured countries, such as the USA, China, Germany, Austria, Singapore, and other countries that now put great efforts and financial means into quantum science and technology. The competition between China and the USA and the discrepancy in their expected activity we reported in Section 4.3 are especially worthy of further attention. A related question is the transfer of QT 2.0 research into the area of (commercial) applications. This would require the use of another database that relates to, e.g., patents. From the viewpoint of research topics, the further growth of a field like quantum optics that came up more clearly in the maturing period of QT 2.0 could warrant a closer look.

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Appendix A

Appendix A.1 Combined Search String

The following search string combines the separate topic searches for the different fields of QT 2.0:

ts = (“quantum theory” SAME (qubit* OR “quantum bit*”)) OR ts = (“quantum hardware” OR “quantum device*” OR “quantum circuit” OR “quantum processor*” OR “quantum register*”) OR ts = (“quantum software” OR “quantum cod*” OR “quantum program*”) OR ts = (“quantum control*” OR “control* of quantum” OR “control over quantum” OR “quantum optimal control” OR “quantum state control” OR “control* quantum” OR “control* the quantum” OR “quantum coherent control”) OR ts = ((“quantum imag*”) OR “ghost imag*”) OR ts = ((quantum NEAR/1 sensing) OR (quantum NEAR/1 sensor*)) OR ts = ((quantum NEAR/10 metrology) OR (quantum NEAR/1 tomograph*) OR “atomic clock*” OR “ion clock*” OR “quantum clock*” OR “quantum gravimeter*”) OR ts = (“quantum simulat*” AND (qubit* OR “quantum bit*” OR “quantum comput*”) OR “quantum simulator*”) OR (ts = “quantum simulat*” AND wc = (“quantum science technology” OR “computer science theory methods”)) OR ts = (“quantum information*” OR “von Neumann mutual information” OR “quantum mutual information” OR “quantum Fisher information”) OR ts = (“quantum crypto*” OR pqcrypto* OR “quantum key distribution” OR “quantum encrypt*” OR ((“quantum secur*” OR “quantum secre*”) NOT (“quantum secreted” OR “quantum secretion”))) OR ts = (“quantum communication*” OR “quantum network*” OR “quantum optical communication” OR “quantum state transmission*” OR ((“quantum memor*” OR “quantum storage*”) NEAR/5 photon*) OR “quantum repeater*” OR “quantum internet” OR (“quantum teleport*” AND (“qubit*” OR “quantum bit*” OR “entangle*”))) OR ts = “quantum algorithm*” OR ts = (“quantum comput*” OR “quantum supremacy” OR “quantum error correction” OR “quantum annealer” OR (quantum NEAR/2 (automata OR automaton)) OR “quantum clon* machine*”) OR ts = (quantum NEAR/2 technolog*)

Appendix A.2 Publication Output Data

Table A1. Annual numbers of publications between 1980 and 2018 in QT 2.0 and its four fields as well as the whole WoS, restricted to the document types article, review, and conference proceeding and to the five chosen indices SCI-E, SSCI, AHCI, CPCI-S, and CPCI-SSH. The last line gives the resp. share of each field of the total publication set.

Publication Year	All Papers	Q INFO	Q METR	Q COMM	Q COMP	Sum of All Fields	WoS
1980	8	1	7	0	0	8	445,586
1981	5	0	4	1	0	5	465,913
1982	6	1	5	0	0	6	486,256
1983	7	0	5	0	2	7	512,149
1984	3	0	0	1	2	3	526,237
1985	10	1	6	0	3	10	533,260
1986	9	0	5	0	4	9	536,412
1987	6	1	3	0	2	6	553,109
1988	12	1	6	3	3	13	578,654
1989	12	0	8	0	4	12	651,038
1990	20	0	13	1	6	20	720,896
1991	66	8	34	3	22	67	756,930
1992	65	6	36	12	12	66	758,014
1993	95	10	50	14	22	96	768,353
1994	112	10	63	15	24	112	802,416
1995	153	15	58	22	63	158	820,972

Table A1. *Cont.*

Publication Year	All Papers	Q INFO	Q METR	Q COMM	Q COMP	Sum of All Fields	WoS
1996	228	25	65	54	99	243	910,249
1997	317	41	98	58	144	341	924,489
1998	462	66	114	83	257	520	951,072
1999	548	87	135	107	274	603	927,431
2000	841	171	190	168	423	952	973,109
2001	1041	232	190	227	554	1203	967,076
2002	1369	324	229	318	715	1586	987,912
2003	1634	379	297	369	848	1893	1,047,409
2004	1709	440	338	402	808	1988	1,094,068
2005	2039	521	427	506	929	2383	1,158,342
2006	2140	571	408	585	922	2486	1,226,838
2007	2418	663	488	647	1021	2819	1,340,147
2008	2565	687	490	706	1084	2967	1,428,198
2009	2946	752	637	805	1222	3416	1,503,129
2010	2762	858	568	743	1086	3255	1,522,424
2011	2858	918	698	738	1022	3376	1,604,339
2012	3018	955	754	742	1122	3573	1,710,599
2013	3391	1144	830	922	1173	4069	1,790,367
2014	3722	1218	856	1031	1347	4452	1,869,915
2015	3937	1368	928	1006	1416	4718	1,943,877
2016	4481	1561	1115	1162	1627	5465	2,019,730
2017	4552	1578	1139	1181	1656	5554	2,048,110
2018	5031	1687	1234	1353	1868	6142	2,041,007
Total	54,598	16,300	12,531	13,985	21,786	64,602	41,906,032
Share of total papers		0.30	0.23	0.26	0.40	1.18	

Appendix A.3 Description of VOSviewer Thesaurus File

Table A2. Description of the common thesaurus file (https://s.gwdg.de/4DDxsp (accessed on 1 August 2021)) applied to the VOSviewer keyword maps Figures 5–8. All terms on the maps are unified concerning singular/plural writing. Sometimes the plural form has been chosen if its more common (cellular automata) or if no singular form has been found. One stopword ("cannot") has been removed. Hyphens have been removed from cellular-automata, electron-spin, error-correction, single-photon, and nuclear-magnetic-resonance. Some terms, definitely used in the QT 2.0 context, have been prefixed by "quantum" (entanglement, teleportation, cryptography). The remaining changes concerning synonyms and abbreviations are listed in the table.

Unified Term in Keyword Maps	Mapped Terms
bb84 protocol	bb84
cavity qed	cavity quantum electrodynamics
ghost image	ghosts
nmr	nuclear magnetic resonance
noisy quantum channel	noisy channel
q cellular automata	(quantum-)dot cellular automata, qca
q clock	atomic clock, rubidium atomic clock
q computing	quantum computation
q error correction	error correcting/correction (code), qec
q key distribution	quantum key distribution (qkd), qkd
q tomography	quantum state tomography

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