Europäisches Patentamt
European Patent Office
Office européen des brevets

Quantum computing

Insight report

January 2023

epo.org

Executive summary

This report is the second publication in a series of EPO patent insight reports related to quantum technologies.[1] It summarises the results of patent analyses in the field of quantum computing which were jointly carried out by subject-matter specialists and patent knowledge experts at the European Patent Office (EPO).

The objective of this report is to provide an overview of important patent trends in the field of quantum computing and the following sub-sectors: “physical realisations of quantum computing”, “quantum error correction/mitigation”, and “quantum computing and artificial intelligence/machine learning”.

For this study, publicly available patent information based on the EPO’s databases for worldwide patent data was analysed. Patent information constitutes a very rich source of technical information on inventions for which patent protection was sought based on commercial expectations of the applicants. Patent information often includes technical and other information that is not available from any other source.

This report may be helpful as a source of information in the area of quantum computing. The methodology on which this report is based can be used freely, i.e. everyone can adapt the chosen search and analysis approach to their needs, for example to follow trends and developments in other established or emerging technical fields.

The increase in the number of inventions in the field of quantum computing has developed dynamically in recent years. The number of inventions in that field multiplied over the last 10 years, which is well above the generally observed increase in all fields of technology. The figure on the next page shows the number so-called International Patent Families in the field of quantum computing and in all technical fields, as a function of the year when the underlying inventions were made publicly available for the first time.

Patent applicants in the field of quantum computing strongly build on the following patent application routes: International patent applications that may result in patent protection in more than 150 countries worldwide, US applications, JP applications, EP applications and CN applications. With more than 20 per cent over the last 10 years, the share of International patent applications in that field is clearly above average when compared to the share attributed to the International patent application route in all fields of technology. This higher share may be interpreted as an indication of the high economic expectations of the patent applicants with regard to the technologies in question, as well as a corresponding multinational commercialisation strategy.

Although International Patent Families with patent applications filed by more than one patent applicant are in the minority in the field of quantum computing, these cases are of particular interest as they provide indications of cooperation between different companies or between companies and academic institutions, either within the same country or across national borders. A closer analysis of International Patent Families with at least 1 EP patent family member and at least 2 patent applicants provided interesting insight into the cooperation between applicants. About two thirds of the

The EPO patent insight report on quantum computing in a nutshell:

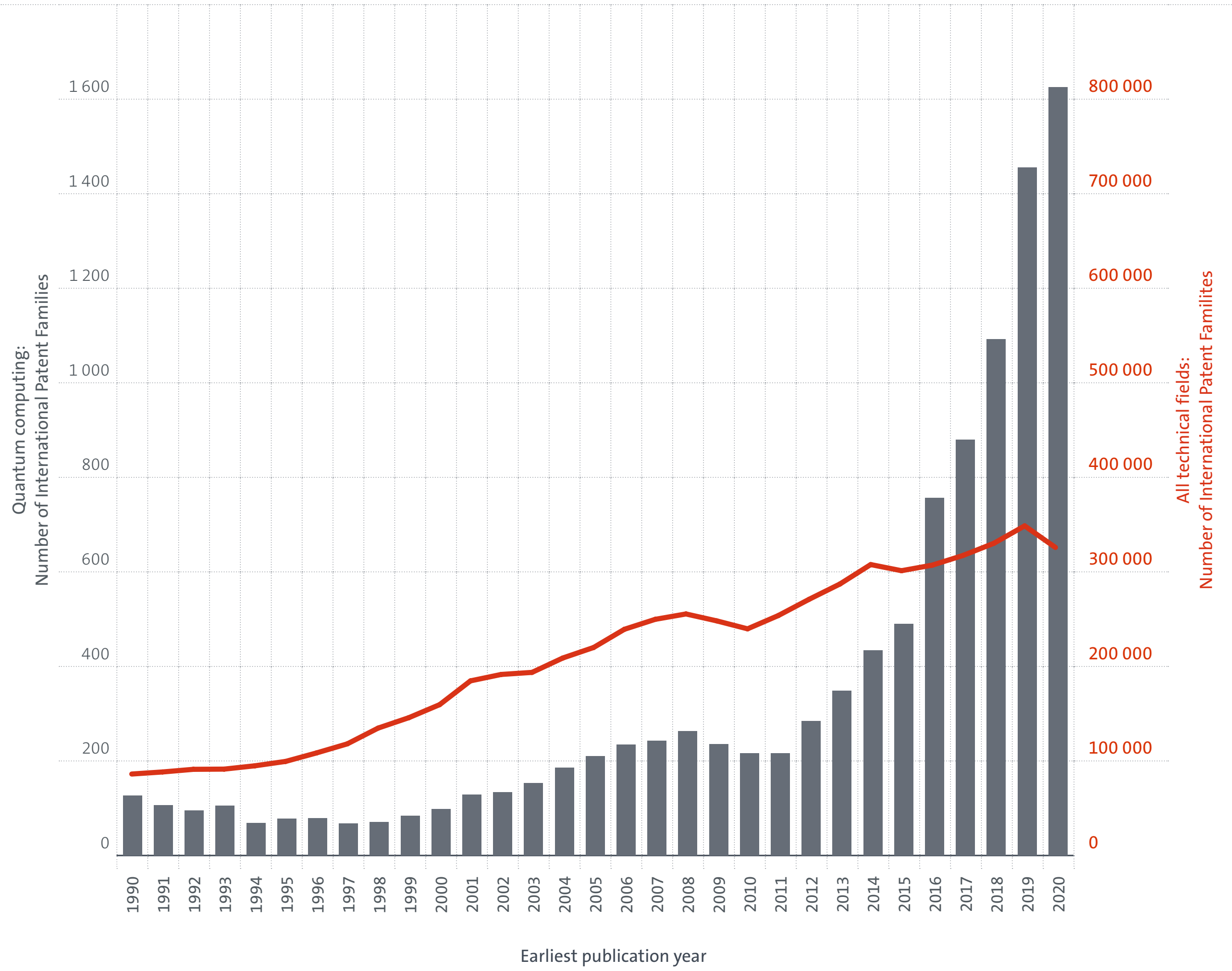
- Number of inventions in the field of quantum computing multiplied over the last decade
- Higher growth rate than in all fields of technology in general
- Above-average share of International patent applications, suggesting high economic expectations with regard to the technologies in question and multinational commercialisation strategy
- Dynamic patent trend in the sub-sectors “physical realisations of quantum computing”, “quantum error correction/mitigation” and “quantum computing and artificial intelligence/machine learning”, where the number of inventions also multiplied
- Roughly one out of ten European patent applications in the field of quantum computing have several patent applicants, suggesting active cooperation between them. The patent applicants come from all continents, with a clear focus on the same region or continent.

1 More information about EPO patent insight reports and the list of currently available reports is available at epo.org/insight-reports

Figure

Quantum computing: Number of International Patent Families per earliest publication year

Number of inventions per earliest publication year in the field of quantum computing, by limitation to International Patent Families. International Patent Families group patent documents related to the same or similar inventions published by at least 2 patent authorities. It is generally assumed that patent applicants attribute greater economic potential to the underlying inventions of these patent families, and that they tend to seek more extensive commercialisation from a geographical point of view.



Source: authors' calculations

patent families with joint patent applications where one applicant is located in a contracting state of the European Patent Convention (EPC)[2] have a second applicant also from an EPC contracting state. In about one quarter of the joint patent families with an EPC applicant, another applicant from North America, mainly from the United States, is observed. These results suggest relatively close cooperation within the same region and weaker cooperation between applicants on different continents. The analysis of the country of residence of the inventors mentioned in the joint patent applications reveals a similar picture.

The dynamic patent trend in the field of quantum computing as a whole can also be observed in the sub-sectors we looked at, namely "physical realisations of quantum computing", "quantum error correction/mitigation" and "quantum computing and artificial intelligence/machine learning", where the number

2 More information about EPC contracting states is available at epo.org/about-us/foundation/member-states.html.

of inventions also multiplied over the last years. The dynamic development in the latter sub-sector only began in the last decade and is even higher than in the other sub-sectors and in the whole field at the moment.

That sub-sector is also special with respect to the most active applicants. While the list of most active patent applicants in the whole field and in the sub-sectors "physical realisations of quantum computing" and "quantum error correction/mitigation" is headed by IBM and other US-based companies playing an increasingly prominent role in recent years, the diversity of origin remains high in the sub-sector "quantum computing and artificial intelligence/machine learning".

In view of the high momentum in the field of quantum computing and the fact that the dedicated sub-domain for quantum computing in the Cooperative Patent Classification system will be fully in place in the medium term, the EPO considers updating this report in the future and having a closer look into how the sub-sectors covered in this report and other sub-sectors in the field of quantum computing will have developed and diversified.

Contents

Abbreviations

AI	Artificial intelligence
CPC	Cooperative Patent Classification
DNA	Deoxyribonucleic acid
DOCDB	EPO worldwide bibliographic data
EPO	European Patent Office
EPC	European Patent Convention
IPC	International Patent Classification
ML	Machine learning
PCT	Patent Cooperation Treaty
QC	Quantum computing
WIPO	World Intellectual Property Organization

Glossary

DOCDB patent family	Set of patent documents related to patent applications covering the same technical content
Espacenet	Free of charge online patent searching service by the EPO. Includes information on more than 140 million documents from 100 patent offices. Espacenet is available at worldwide.espacenet.com.
International patent application	Patent application filed under the Patent Cooperation Treaty. An International patent application may result in patent protection in more than 150 countries.
International Patent Family	A patent family having patent family members published by at least two different patent authorities.
Invention	Practical technical solution to a problem
Jurisdiction	Country (territory) for which a patent or related intellectual property right may be granted by the corresponding intellectual property office.
Patent	Legal title giving the patent owner(s) the right to exclude others from using the protected invention in a commercial context. A patent builds on what is called the "patent specification", which discloses the relevant details defining the protected invention along with other relevant information.
Patent application	In the field of patent information, the expression "patent application" is used for both the patent application itself and the patent application published as a document.
Patent classification system	Set of so-called patent classification symbols assigned to categorise the technical subject-matter of a patent or utility model. There are various patent classification systems used today by national, regional and international patent offices. Two patent classification systems are of particular importance: The International Patent Classification (IPC) system is a hierarchical patent classification system which is used by more than 100 patent offices on all continents. It breaks down technologies into eight sections with several hierarchical sub-levels. The IPC scheme has approximately 75,000 subdivisions and is updated on an annual basis. The Cooperative Patent Classification (CPC) system builds on the IPC system and provides a more granular and detailed classification structure. The CPC system has more than 250,000 subdivisions and is updated four times a year. It is used by more than 30 patent offices worldwide.
Patent family	A set of patent documents covering the same or similar technical content. The size of a patent family (family size) refers to the number of patent documents in that patent family.
Priority application	Inventions can be protected by patents and utility models in more than one country. Once an applicant has filed a first application, the so-called priority application, in a member state of the Paris Convention, the applicant has 12 months to file applications for the same invention in other member states of the convention. During this period, the original filing date can be claimed as the effective filing date, or "priority date", for subsequent applications.
Qubit	Basic unit of quantum information. A qubit, or quantum bit, is the analogue of the bit in classic computing but with significantly different properties.

1. Introduction

1.1 About this report

Quantum computing is on everyone's lips. That is no wonder, as this technology promises major advances in many technical areas such as drug development, materials research and secure data transmission based on principles of quantum communication.

Quantum computing is developing more and more dynamically, with a large number of active companies and funding programmes. The Quantum Flagship initiative, which was set up by the European Commission and makes an important contribution to research and commercialisation of quantum computing technologies (see Figure 1), should be mentioned here as an important example.

The momentum in the field of quantum computing can already be seen today in the considerable number of commercially promising start-ups. In light of the high momentum, it is not easy to keep track of the most important technical developments and players.

The aim of this report is to provide an overview of important patent trends in the field of quantum computing. For this purpose, the report relies on publicly available patent information, which constitutes a very rich source of technical information on inventions for which patent protection was sought based on commercial expectations of the applicants. Patent information often includes technical information that is not available from any other source.

To gather relevant patent information as the basis for this report, search strategies have been developed using meaningful keywords and relevant patent classification symbols. These search strategies, which are designed to strike a balance between completeness and a small

Figure 1

The Quantum Flagship intiative

QUANTUM FLAGSHIP

Launched in 2018, the Quantum Flagship initiative is one of the largest and most ambitious research initiatives established by the European Union. It aims at consolidating and expanding scientific excellence and leadership in Europe in the area of quantum technologies. The initiative brings together more than 5,000 scientists and engineers, entrepreneurs and policymakers.

Equipped with more than 1 billion euros over a period of more than 10 years, it aims at consolidating Europe's role as a leader in the field of quantum technologies. For this purpose, the following goals shall be achieved:

- to foster a competitive European quantum industry
- to expand scientific excellence in the field of quantum research
- to make Europe an attractive region for businesses and investments in quantum technologies
- to use quantum technologies for better solutions to important challenges, e.g. in the environment, health and data security area

The activities of the Quantum Flagship initiative centre around the following main fields: basic quantum research, quantum computing, quantum simulation, quantum metrology and sensing, and quantum communication.

Valuing the important role of the Quantum Flagship initiative and of quantum technologies for economy and society in Europe, the EPO has developed a series of EPO patent insight reports on quantum technologies aligned with the main topics of the initiative:

Topic	Publication year
Quantum metrology and sensing	2019
Quantum computing (this report)	2023
Quantum simulation	2023 (planned)
Quantum communication	2024 (planned)

Once published, these reports and supplementary information are made available at epo.org/insight-reports.

fraction of unrelated documents in the result sets, were then used to create a basic data set of relevant patent documents from the EPO's databases for worldwide patent data. This basic data set formed the basis for the subsequent patent analyses.

This report may be helpful as a source of information on the area of quantum computing. The methodology on which this report is based can be used freely, i.e. everyone can adapt the chosen search and analysis approach to their needs, for example to follow trends and developments in other established or emerging technical fields.

1.2 Introduction to quantum computing

Quantum Computing (QC) is becoming increasingly active with large technology companies such as IBM, Google, Amazon, and Microsoft investing in this computing technology. The first noisy intermediate-scale quantum (NISQ) computers are up and running, and are also made widely available for use, for example through offering QC services in the cloud, and by the provisioning of a full programming toolchain.

QC is highly advantageous when its inherent parallelism can be exploited and when it has a significant computational advantage over a classical parallel implementation (on classical parallel/distributed computing systems). This advantage is referred to as "quantum supremacy".

The present NISQ era is characterised by a limited number of independently addressable and undisturbed qubits – the basic unit of quantum information – with sufficiently long coherence times that is not sufficient for tackling many practical computational problems with quantum supremacy. These limitations nevertheless trigger innovation themselves, such as NISQ-targeted quantum circuit decompositions for circuit synthesis and error mitigation/correction techniques.

An important model of quantum computation is called "quantum circuit", in analogy to the classical computational (logic) circuit diagrams with (Boolean) logic gates. A quantum circuit comprises sequences of operators defined to initialise, manipulate and readout the state of qubits. Such quantum circuits need to be compiled/synthesised from a "high-level" language via a sort of "quantum machine code" to hardware-level instructions, which are analogue signals (voltages/frequencies) for manipulating the physical qubits.

As opposed to a classical bit, which can be in one of two states during computation, a qubit can be in a superposition of states and only "collapses" into a final state when subject to a measurement. Programming a quantum computer and the development of quantum algorithms is both an art and a science, that is crafting a sequence of qubit-manipulations that are probabilistic in nature such that, at the end of the computational process, the desired result is achieved with highest probability.

The probabilistic nature of QC focuses the applications of quantum computers to certain areas, in which a high combinatorial complexity of the computational task is typically present and where the combinatorial problem-solving capacity of the inherently probabilistic quantum computations can be exploited. Complex simulations and molecular/drug design are prominent examples, as well as machine learning, metrology and cryptoanalysis.

In general, the developments of QC cover models of quantum computing, physical realisations/architectures, quantum algorithms/optimisation, quantum error mitigation/correction and quantum programming/platforms. The constructional details of individual components of a quantum computer are overreaching into fields such as semiconductors, ion traps, resonators, cryostats, cabling, interfaces and more.

At present, quantum computers fill entire rooms. But as history has demonstrated with the technological development in integrated circuits for classical computers, the promise of a wider availability of quantum computers in the future is already being worked on today.

Further reading

Boston Consulting Group, The next decade in quantum computing – and how to play, 2018

S.J. Devitt et al., Quantum error correction for beginners, Reports on Progress in Physics, Volume 76 076001, 2013

M.I. Dyakonov. Will We Ever Have a Quantum Computer? Springer, Cham, 2020

A.G. Fowler et al., Surface codes: Towards practical large-scale quantum computation, Phys. Rev. A Volume 86 032324, 2012

McKinsey & Company, Quantum computing use cases are getting real — what you need to know, 2021

A. Montanaro, Quantum algorithms: An overview, npj Quantum Information, 2 15023, 2016

J. Preskill, Quantum computing 40 years later, arXiv:2106.10522, 2021

S. Resch and U.R. Karpuzcu. Quantum computing: An overview across the system stack, arXiv:1905.07240, 2019

S. Yarkoni, et al., Quantum annealing for industry applications: Introduction and review, Rep. Prog. Phys. 85 104001, 2022

2. Methodology and sources of patent information used

2.1 Using patent information

Patents are essentially economic rights which confer on patent holders the right to exclude others from using the patented invention. Patents are commercial assets which can help attract investment, secure licensing deals and provide market exclusivity.

Patent systems foster innovation, technology diffusion and economic growth by allowing patent holders to secure investments in research and development, education and infrastructure, and by requiring them to disclose their inventions to the public in return. With that, patent information is at the core of any patent system.

Patent information enables others to build on the published inventions of other inventors and also avoid the mistake of investing in developing a solution for a problem that has already been solved by others and is potentially protected. Patent information contains a wealth of technical and other information, much of which cannot be found in any other source.

The EPO alone, as the leading provider of high-quality patent information worldwide, has collected, standardised and harmonised information on more than 140 million patent documents from more than 100 countries in its databases, amounting to more than a billion records. And these databases grow by tens of millions of records every year.

Patent information from these databases is available via numerous free-of-charge and commercial patent information services by patent offices and service providers worldwide. The information may be used for various analyses, e.g. to explore technical trends and the filing strategy of applicants, or to calculate indicators for innovation activity, commercialisation and knowledge transfer.

2.2 Methodology for this EPO patent insight report

This EPO patent insight report is designed to provide useful insights into the field of quantum computing and specific sub-sectors. It is based on publicly available patent information and acts as a snapshot of the technologies, taken in the light of patent information.

The methodology of this report is essentially based on a three-step process:

Step 1: Creating and tuning a basic data set	A basic data set is created, usually based on various individual search concepts, e.g. building on patent classification symbols for specific technologies and on keywords. Typically, unrelated patent documents will have to be removed from the result set in an automated or manual manner to increase the quality of the basic data set. The creation of a meaningful basic data set is key because sound patent analytics in step 2 requires a sound basis.
Step 2: Patent analytics	In this step, patent analyses are performed on the basic data set, e.g. by aggregating the data to patent families as a representative of inventions, by creating descriptive statistics, testing hypotheses or recognising patterns in the data.
Step 3: Further processing and visualisation	In this third step, the data is further analysed and processed. Results are visualised and summarised.

The methodology underlying this report and the details are free to use. With that, anyone can apply the proposed analytical approach to reveal trends and prospects in the same or other areas of technology, and adapt the approach to their own needs.

2.3 Patent retrieval

For this EPO patent insight report, EPO subject-matter experts developed numerous search concepts to identify patent documents that relate to each of the following important sub-sectors: quantum computing in general; physical realisations of quantum computing; quantum error correction/mitigation techniques; quantum computing and artificial intelligence/machine learning (AI/ML). The latter sub-sector was selected because it is considered to represent a rather recent trend whereas the other sub-sectors were selected for their long-standing relevance in the field of quantum computing.

Each search concept is a combination of patent classification symbols and/or full-text queries (see Box 1 and Annex), primarily designed for the EPO's inhouse search tools (see section 2.3.1), though they can be translated into search statements for other search tools publicly available on the internet, such as the EPO's search interface Espacenet.[3]

The patent classification symbols used for this study efficiently capture documents with a focus on quantum computing, as opposed to, for example, more general technical improvements that may be useful in the field of quantum computing as well as other technical domains, and accordingly extend beyond the field of quantum computing. Such technical improvements with a broader scope may be discussed under the more general umbrella of the "quantum computing ecosystem", or in the context of "quantum technologies".

A current limitation of the QC-related patent classification symbols lies in the fact that not all QC-related patent documents have yet been assigned QC-related patent classification symbols in the dedicated CPC classification sub-domain, which was defined in 2022 (see Box 1). The reason for this is the pending reclassification of patent documents in this field by the competent patent offices. Another reason is the fact that not all patent experts in related technical fields are aware of the specific patent classification symbols, as is also frequently the case for other emerging technologies. Further automation of the classification process is expected to help advance the full classification of patent documents.

For the time being, we augmented the search concepts with keyword-based search terms to mitigate the effect of the currently pending classification of QC-related patent documents. For this purpose, it was accepted that keyword-based searches are generally less specific and accurate than those based on patent classification symbols, of which the assignment is systematically controlled. In this context, it is also important to note that not all Asian patent documents are fully classified according to the CPC classification scheme at the moment, and keyword-based searches in the machine-translated full text of these documents may give rise to unrelated patent documents in the result set.

The search results retrieved using our search concepts will grow over time due to the dynamic nature of the technical field and of the patent databases, as patent documents related to quantum computing are continuously added to these databases. Thanks to their collaborative nature, our search concepts will also grow and develop. Accordingly, we are considering to update this report in the future, which would also give us the opportunity to produce more fine-grained analysis of QC-related patent trends, e.g. along the lines of the detailed structure of the said CPC classification sub-domain for quantum computing.

3 Available at: worldwide.espacenet.com

Box 1: quantum computing and patent classification schemes

Patent offices assign so-called patent classification symbols to categorise the technical subject-matter of a patent or utility model. Patent classification symbols are defined as part of what are known as "patent classification systems". There are various patent classification systems used today by national, regional and international patent offices.

Two patent classification systems are of particular importance:

The **International Patent Classification (IPC)** system is a hierarchical patent classification system which is used by more than 100 patent offices on all continents. It breaks down technologies into eight sections with several hierarchical sub-levels. The IPC system has approximately 75,000 subdivisions and is updated on an annual basis. Further information on the IPC system is available at wipo.int/classifications/ipc/en/.

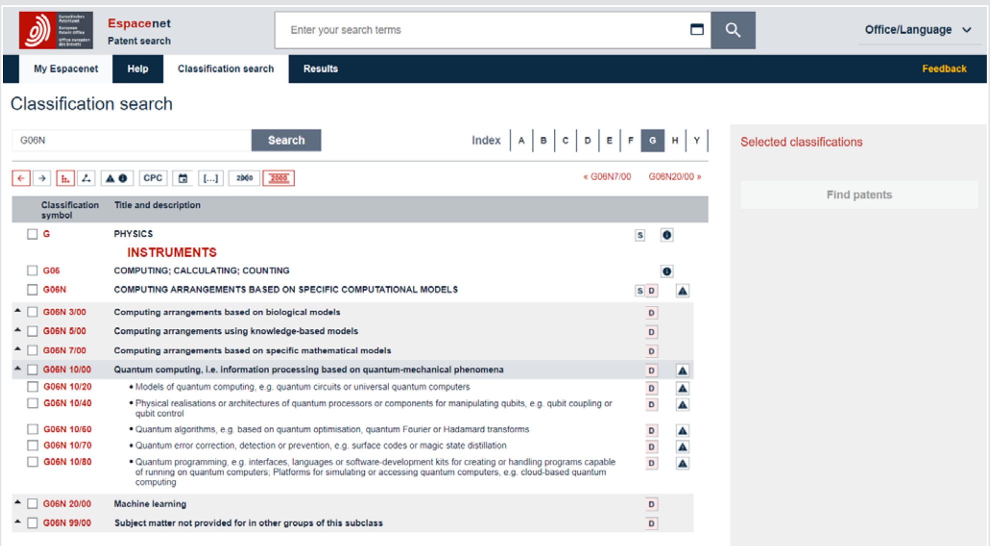
The **Cooperative Patent Classification (CPC)** system builds on the IPC system and provides a more granular and detailed classification structure. The CPC system has more than 250,000 subdivisions and is updated four times a year. It is used by more than 30 patent offices worldwide. Detailed information about the CPC system is available at cooperativepatentclassification.org/.

IPC and CPC classification symbols can be used to quickly retrieve relevant patent documents using search interfaces such as Espacenet, for example.

Both patent classification schemes comprise the subclass G06N for computing arrangements based on specific computational models including quantum computing, artificial intelligence/machine learning (e.g. neural networks) and other unconventional computing techniques, such as DNA computing (see below a snapshot of the CPC browser in Espacenet for this sub-domain).

A specific sub-division covering quantum computing has existed in the CPC system since its creation in 2013, which traces back to an equivalent sub-division in one of the predecessors of the CPC system, the European patent CLAssification (ECLA). Due to increased patenting activity in the field of quantum computing, this sub-division was also introduced into the IPC system as "G06N 10/00" in 2019. Additional subgroups for this sub-division were created in 2022 in order to more efficiently index/classify the rapid developments in various main sub-areas of quantum computing (see screenshot below for these sub-areas).

Further sub-divisions in the CPC system covering specific examples in these main areas are expected in 2023 (see also the definitions of current CPC symbols, e.g. via the D feature in the CPC browser in Espacenet). These additional sub-divisions will enable patent information users to perform more targeted searches for prior art in the field of quantum computing. They will also allow for more fine-grained analyses of patent trends in this rapidly developing field of technology.



2.3.1 Data sources and tools used

The quality of patent analyses largely depends on the completeness, correctness and timely availability of relevant patent information in the patent databases from which the basic data set for the subsequent analysis is extracted.

Absolute completeness of the relevant patent information is not possible, as not all patent-related data is available from all patent offices.

However, there are several patent databases that have very good or excellent coverage of patent information from the main patent offices. These patent databases mostly rely on EPO worldwide patent data as a central source of prior art patent information.

EPO worldwide patent data includes bibliographic and other information on more than 140 million patent documents from more than 100 patent authorities on all continents. It is available via the EPO patent information products and services,[4] and via other major free of charge and commercial search interfaces for patent information.

For this EPO patent insight report, patent searches to create the basic data set for subsequent patent analyses were carried out using EPO worldwide patent data via the EPO's internal data platforms and search interfaces such as ANSERA.[5]

The resulting basic data set was combined with added value data contained in the EPO's PATSTAT product line[6], which provided the advanced basis for the patent analytics part, and was used for further processing and visualisation of the data.

4 More information is available at epo.org/searching-for-patents.html

5 See Y.Tang Demey & D. Golzio, Search strategies at the European Patent Office, World Patent Information 63 101989, 2020 https://doi.org/10.1016/j.wpi.2020.101989

6 See epo.org/patstat; version of the PATSTAT product line used for this study: Spring 2022 Edition

3. Analysis

This chapter presents the results of our analyses regarding the field of quantum computing and selected sub-sectors, and discusses possible interpretations.

For this purpose, we will first take a look at filing trends in the field of quantum computing and compare the findings with the overall situation in all fields of technology. We will then look at the main jurisdictions for which protection was sought, at the most active applicants and at co-applicant behaviour in order to shed light on cooperation between different applicants and across borders.

Subsequently, we will look at the situation and the results of our analyses in the following sub-sectors: physical realisations of quantum computing, quantum error correction/mitigation and quantum computing and artificial intelligence/machine learning.

3.1 Quantum computing in general

The number of patent applications in the field of quantum computing has developed dynamically in recent years.

Figure 2 shows the number of inventions, approximated by DOCDB patent families[7], in the field of quantum computing, as a function of the earliest publication date. This date was chosen to represent the moment when the inventions were first available to the public and could stimulate research activities by others and influence the commercial strategy by competitors. With this, the earliest publication date is of fundamental importance for the technical and economic development of a technical field.

The figure shows a very steep increase in the number of inventions over the last decade. This increase is all the more remarkable because it is well above the generally observed increase in the number of inventions in all fields of technology (see right-hand scale in Figure 2).

Figure 2 also shows a weak increase in the number of inventions in the 2000s. This effect may have been triggered by scientific publications regarding quantum computing technologies that were considered fundamental in the scientific community, and which raised economic expectations and led to patent applications regarding these technologies. Another possible explanation of this upswing concerns the field of adiabatic quantum computing, which was considered a promising technology at the time and led to a wave of patent applications during this period. In the latter case, the wave would have faded away after a few years or would have been superimposed by the strong increase in the number of inventions related to quantum computing observed in the last decade.

Figure 2 takes into account patent families with patent applications which have been filed in a single national jurisdiction as well as in multiple jurisdictions. For the latter kind of patent families, it is generally assumed that patent applicants attribute greater economic potential to the underlying inventions, and that they tend to seek more extensive commercialisation from a geographical point of view.

Accordingly, we have focused our analysis on this category of patent families, which are generally referred to as International Patent Families. When plotting the number of International Patent Families for quantum computing as a function of the earliest publication year, the dynamics described earlier become even more apparent. While the number of inventions for all fields of technology is continuously increasing, the increase in the field of quantum computing is far above average (Figure 3). Furthermore, there are no signs that this development will slow down in the next few years.

A closer look at International Patent Families in the field of quantum computing shows that the patent family members are not evenly distributed across all patent authorities. Rather, it can be seen that patent applicants set a strong focus on the following patent application routes: International applications[8], US applications, JP applications, EP applications and CN applications (see Figure 4).

EP applications are a special case. The European Patent Convention (EPC) has established a single application procedure for obtaining patent protection in Europe.

7 A DOCDB patent family is a set of patent documents related to patent applications covering the same technical content.

8 I.e. patent applications filed under the Patent Cooperation Treaty (PCT). Correspondingly, these patent application are often referred to as PCT, or international, applications. See wipo.int/pct/en for more information.

With just one patent application, applicants can protect their invention not only in all the 39 contracting states that have acceded to the EPC but also in one extension state and four validation states.[9] Figure 7 shows the percentage of EP patents in International Patent Families in the field of quantum computing that were validated and maintained in a EPC member state, extension state or validation state. The figure provides an indication of the importance of a country as a location of research and production, and as a market in the field of quantum computing, according to patent holders in that field.[10]

Figure 5 shows the percentages of these patent application routes for all patent application routes chosen for inventions in quantum computing. It illustrates the consistently high proportion of U.S. patent applications over the last decades, reflecting the importance of the United States in the field of quantum computing both in terms of the development of technologies in this field and as an important market for these technologies. Also worth noting is the continuing high share of EP applications and the increasing share of CN patent applications.

As is evident from Figure 5, the percentage of international patent applications in the field of quantum computing increased in recent years. And what is more, the share of international patent applications in that field is clearly above average if compared with the share attributed to the international patent application route in all fields of technology (see Figure 6). This higher share may be interpreted as an indication of the high economic expectations of the patent applicants with regard to the technologies in question, as well as a corresponding multinational commercialisation strategy.

An important indicator of the strategic orientation and success of patent filing strategies in the field of quantum computing is the percentage of granted IP rights.

Figure 8 shows the percentage of International Patent Families in the field of quantum computing with at least one granted patent regarding within CN, EP, JP, US jurisdictions, or PCT applications leading to a granted patent in a national or regional phase. The situation in the field of quantum computing generally follows the trend observed in all fields of technology, with a modestly higher percentage in earlier years and slightly lower percentages in recent years.

The most active applicants in the field of quantum computing are companies, with a high proportion of enterprises, mainly from the United States and Japan (see Table 1). Exceptions are a small number of US-based universities and a non-profit organisation that maintains a relationship with US universities. The list of most active applicants is headed by IBM, followed by Toshiba (including Nuflare Technology), Intel and Microsoft.

The picture becomes more nuanced when looking at the development over the last decades in more detail (see Table 2). In the 2000s, the Canadian-based company D-Wave Systems was very active in the field, with a focus on adiabatic quantum computing. Such activity might have induced a certain momentum across the whole domain and attracted the interest of other applicants (e.g. from the United States and Japan). In this decade, only companies were among the top 10 most active applicants. In the 2010s, by contrast, two universities, the Massachusetts Institute of Technology (MIT) and Harvard University, attracted attention among the most active patent applicants whereas the rest was dominated by large companies. In recent years, the share of US universities has grown, while the rest has continued to be dominated by large companies.

A closer look at the International Patent Families in the field of quantum computing shows that most patent applications in these families were filed by a single patent applicant. Although International Patent Families with patent applications filed by more than one patent applicant are in the minority (about one third), these cases are of particular interest as they provide indications of cooperation between different companies or between companies and academic institutions, either within the same country or across national borders. For this reason, we have taken a closer look at International Patent Families that include at least one EP patent family member, as reliable information on the origin/country of residence is available for these cases. Given that reliable information on the country of residence of the applicant was available mainly for EP applications, the co-applicants analysis has been focused on this kind of application.

Of the more than 13,000 International Patent Families in the field of quantum computing, more than 6,000 patent families have at least 1 EP family member. Of these patent families, more than 500 patent families have more than 1 patent applicant. This corresponds to a share of about

9 See epo.org/applying/european.html for more information about the European patent application route.

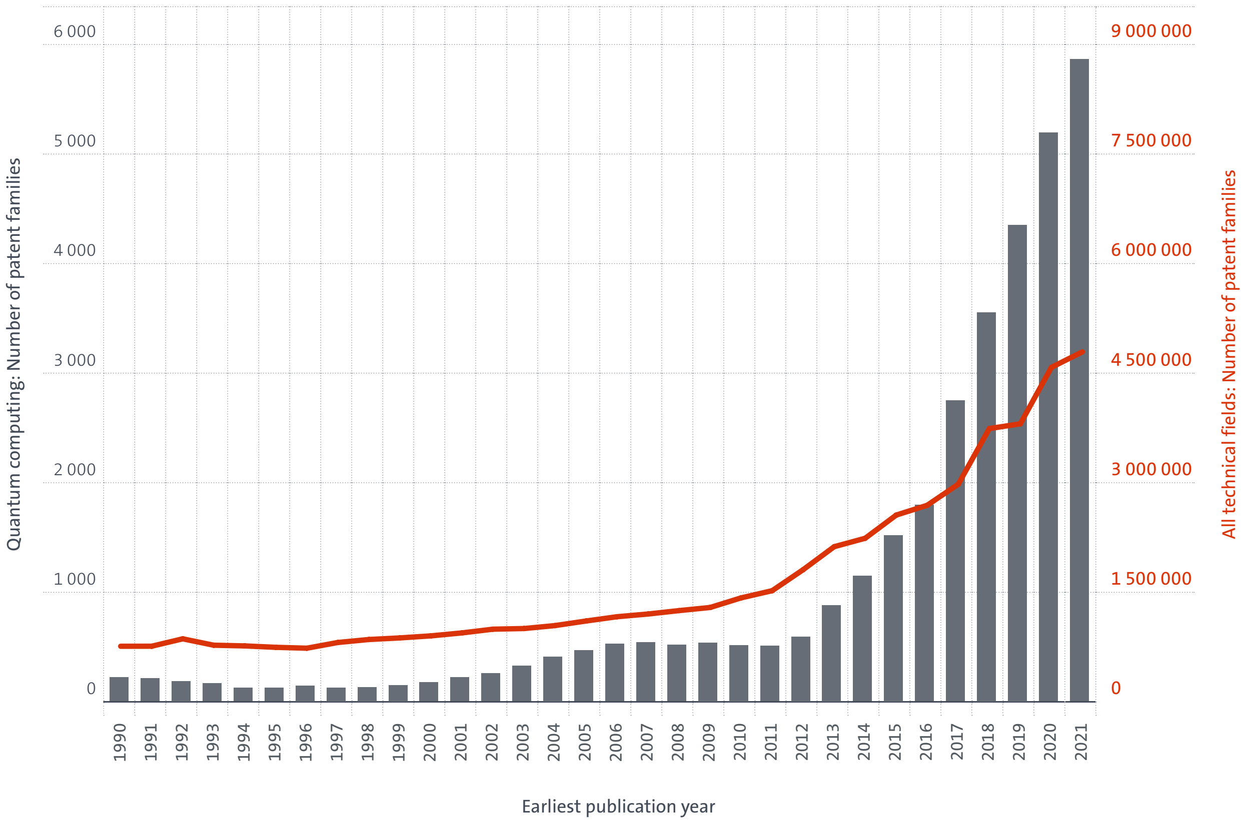
10 This figure is based on procedural information related to the payment of maintenance fees for EP patents in these countries, as available via the EPO worldwide legal event data (INPADOC) service.

one tenth. A closer analysis of the country of residence of the applicants in these patent families with joint patent applications shows that the patent applicants come from all continents, with a clear preference for joint patent applications with geographically relatively close patent applicants, i.e. from the same regional structure or from the same continent. For example, about two thirds of the patent families with joint patent applications where one applicant is located in a contracting state of the European Patent Convention have a second applicant also from one of these states (see Figure 9). In about one quarter of the joint patent families with an applicant from an EPC state, a second applicant from North America is observed. These results suggest relatively close cooperation within the same region and weaker cooperation between applicants on different continents. A similar picture results from the analysis of the origin/country of residence of the inventors mentioned in the joint patent applications (see Figure 10).

Cross-border cooperation can be observed not only on the geographical level but also between different sectors to which the patent applicants can be assigned according to their nature as companies, universities, etc.[11] Figure 11 shows the result of the analysis of joint patent applications in terms of the origin/country of residence, further broken down according to sector allocation for patent applicants located in Europe. It shows that European applicants from one sector tend to cooperate more frequently with other European patent applicants from the same sector. However, there is also cooperation with European patent applicants from other sectors.

Figure 2

Number of DOCDB patent families per earliest publication year in the field of quantum computing

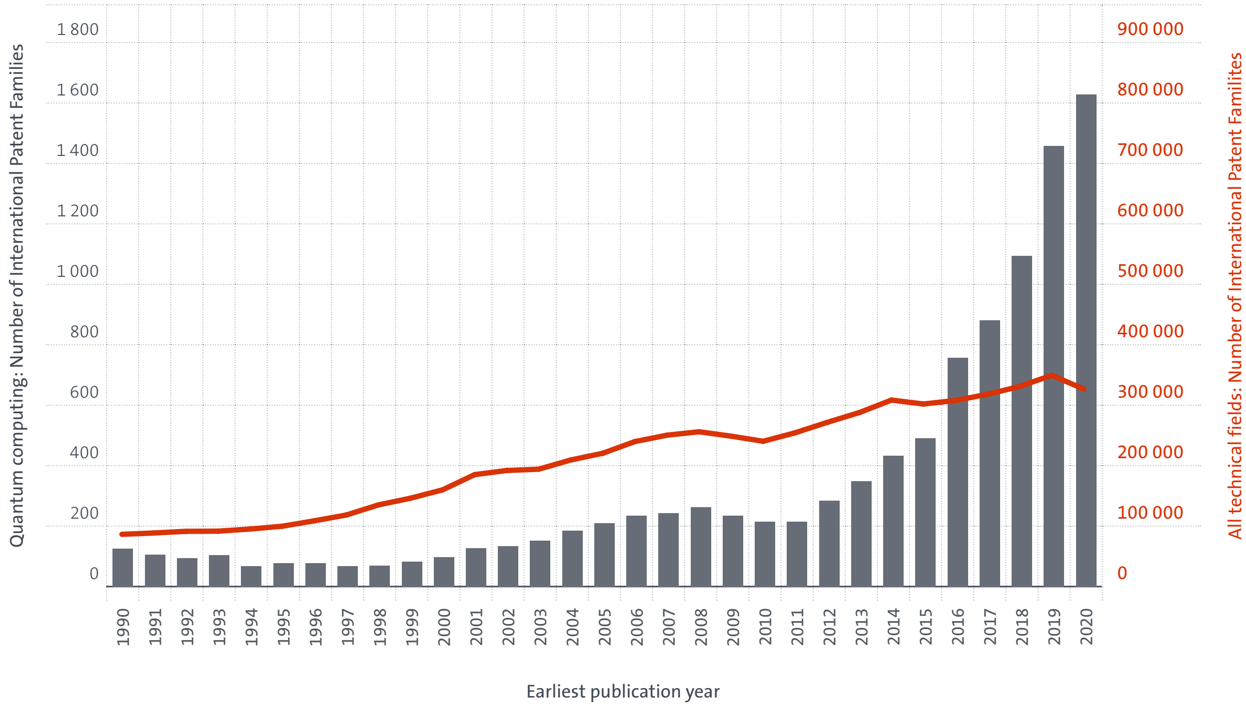


Source: authors' calculations

11 More detailed information on the sector allocation concept regarding patent applicants is available in: European Commission, Patent Statistics at Eurostat: Methods for Regionalisation, Sector Allocation and Name Harmonisation, chapter 3, 2011

Figure 3

Number of inventions per earliest publication year in the field of quantum computing, with limitation to International Patent Families

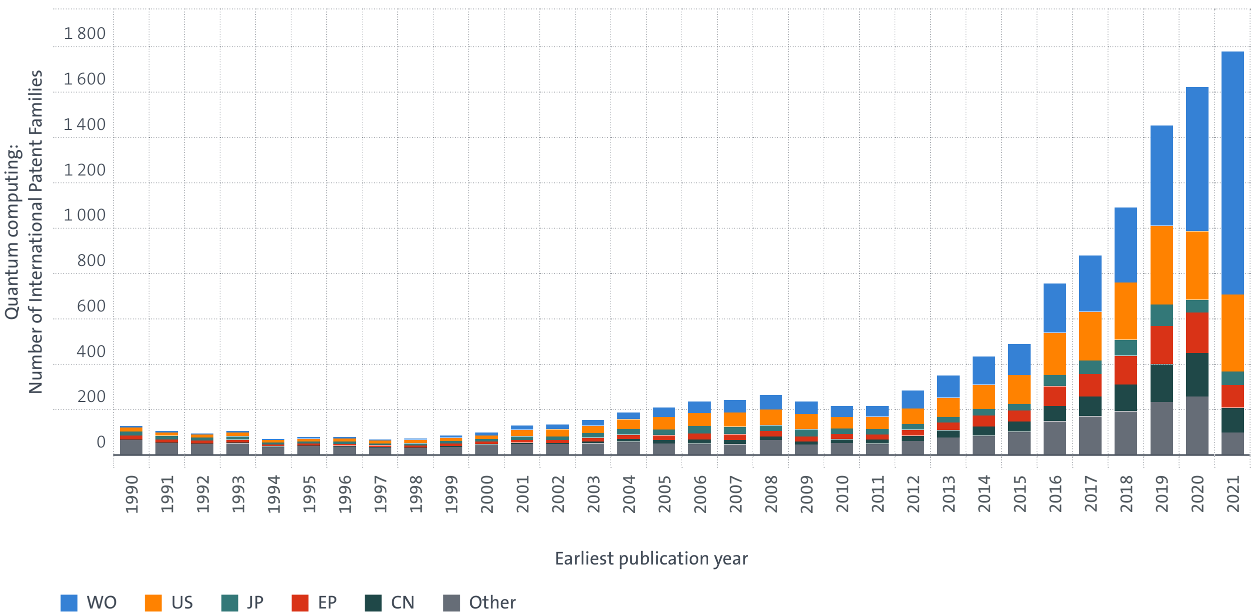


Source: authors' calculations

Figure 4

Breakdown of filing statistics in the field of quantum computing as to publishing patent authorities, per earliest publication year

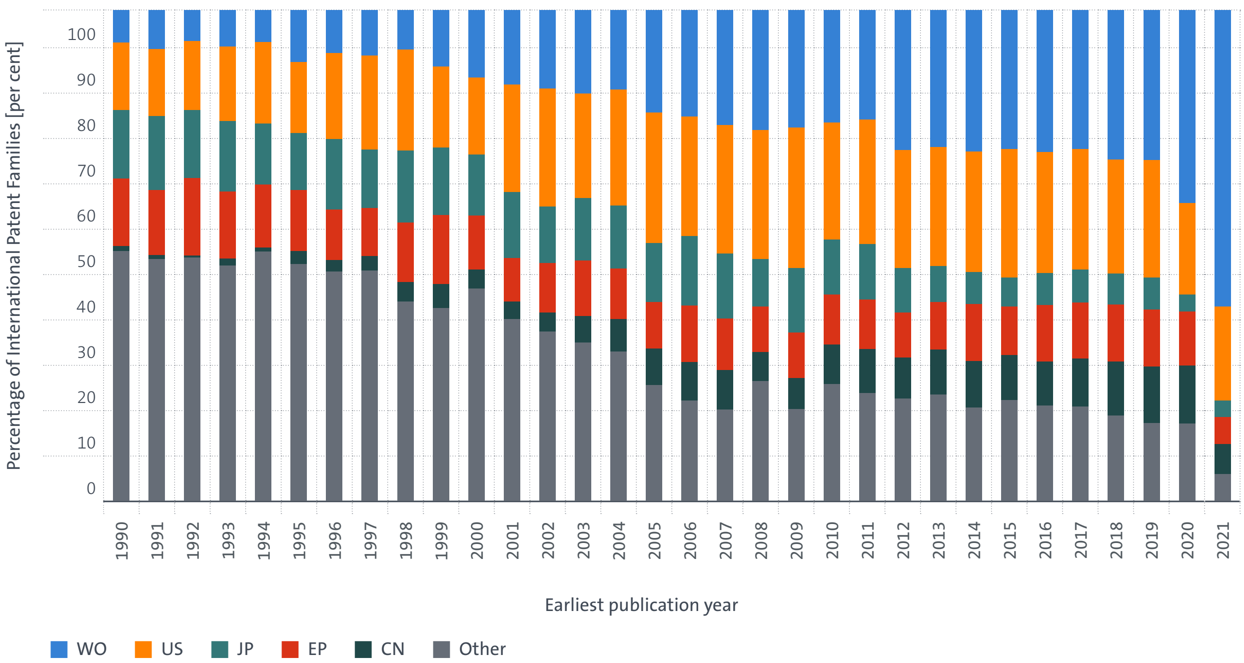
Fractional counting as to patent authorities was used. For each patent authority, only one patent publication in the patent family was counted, which helps to avoid double counting and overrepresenting the patent authority.



Source: authors' calculations

Figure 5

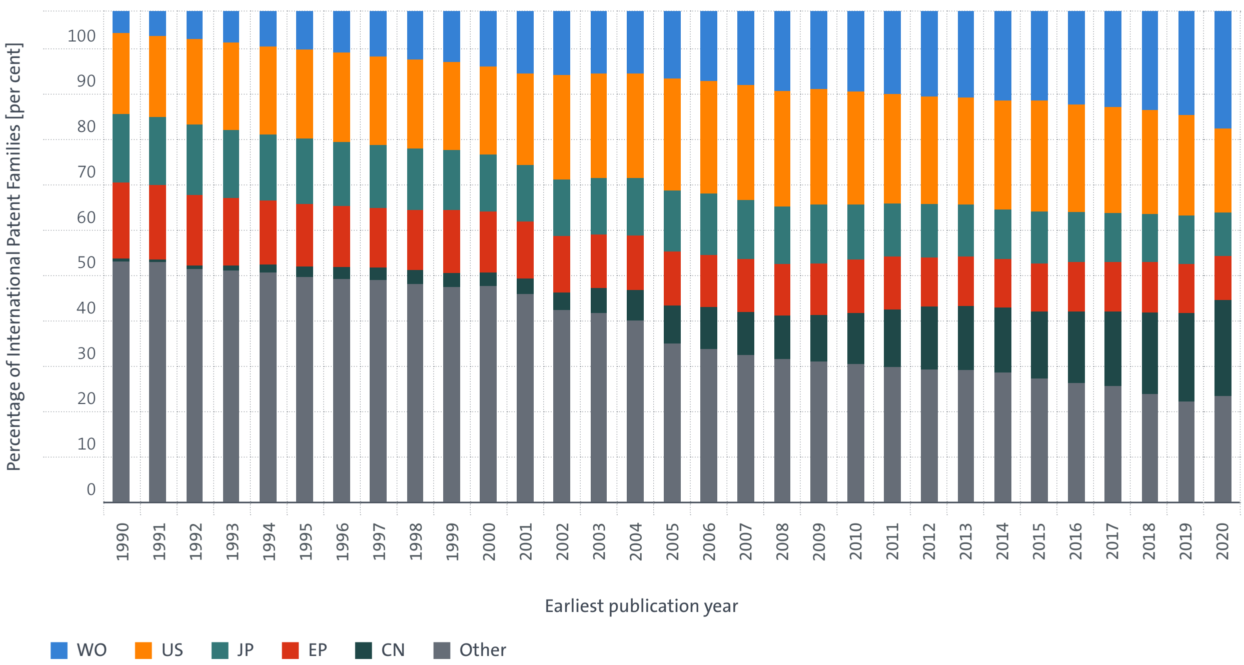
Breakdown of filing statistics in the field of quantum computing as to publishing authorities, per earliest publication year



Source: authors' calculations

Figure 6

Breakdown of filing statistics in all technical fields as to publishing authorities, per earliest publication year



Source: authors' calculations

Figure 7

Percentage of granted EP patents in International Patent Families in the field of quantum computing which were validated and maintained in a member state of the European Patent Convention, in an extension state or in a validation state.

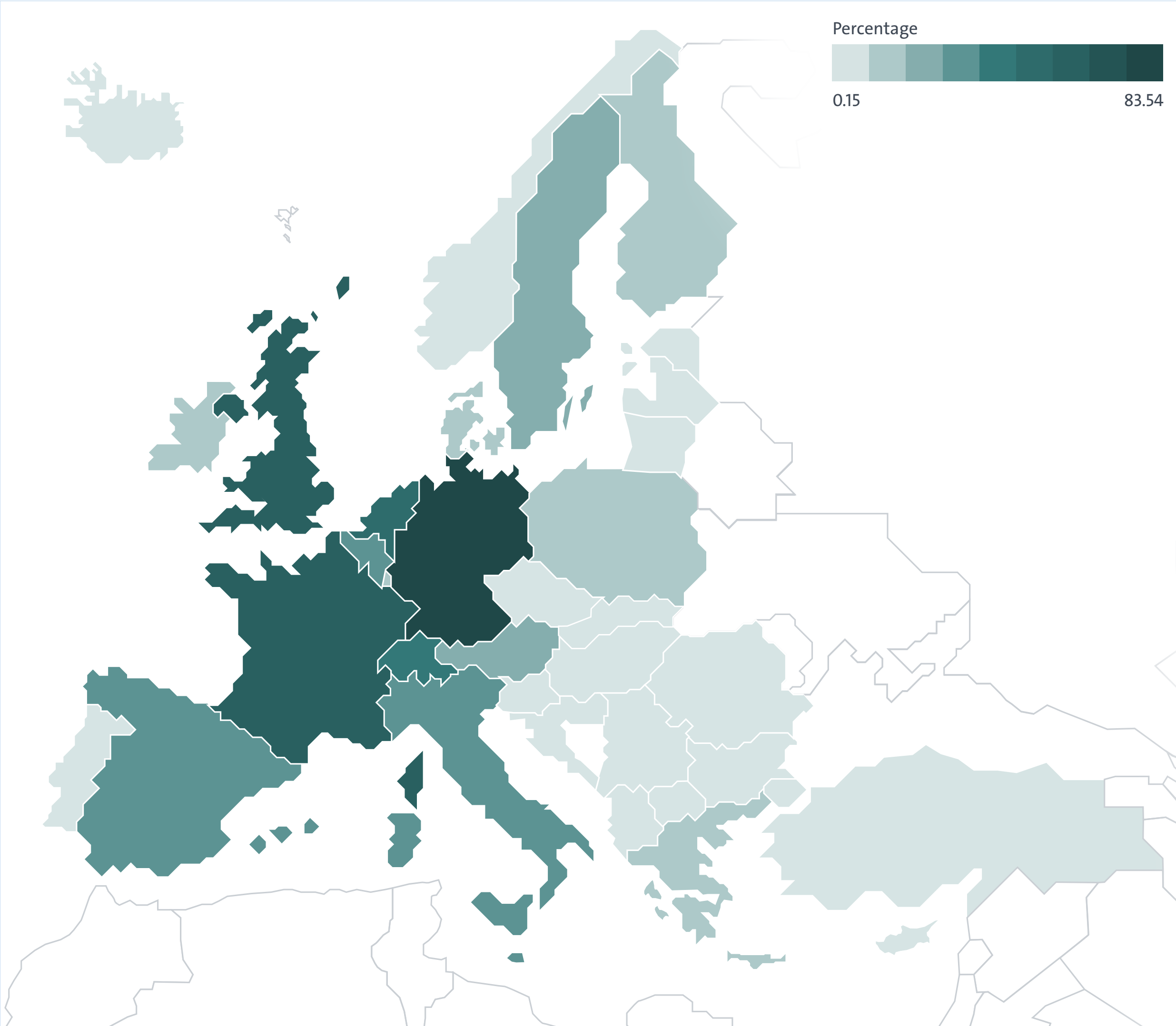
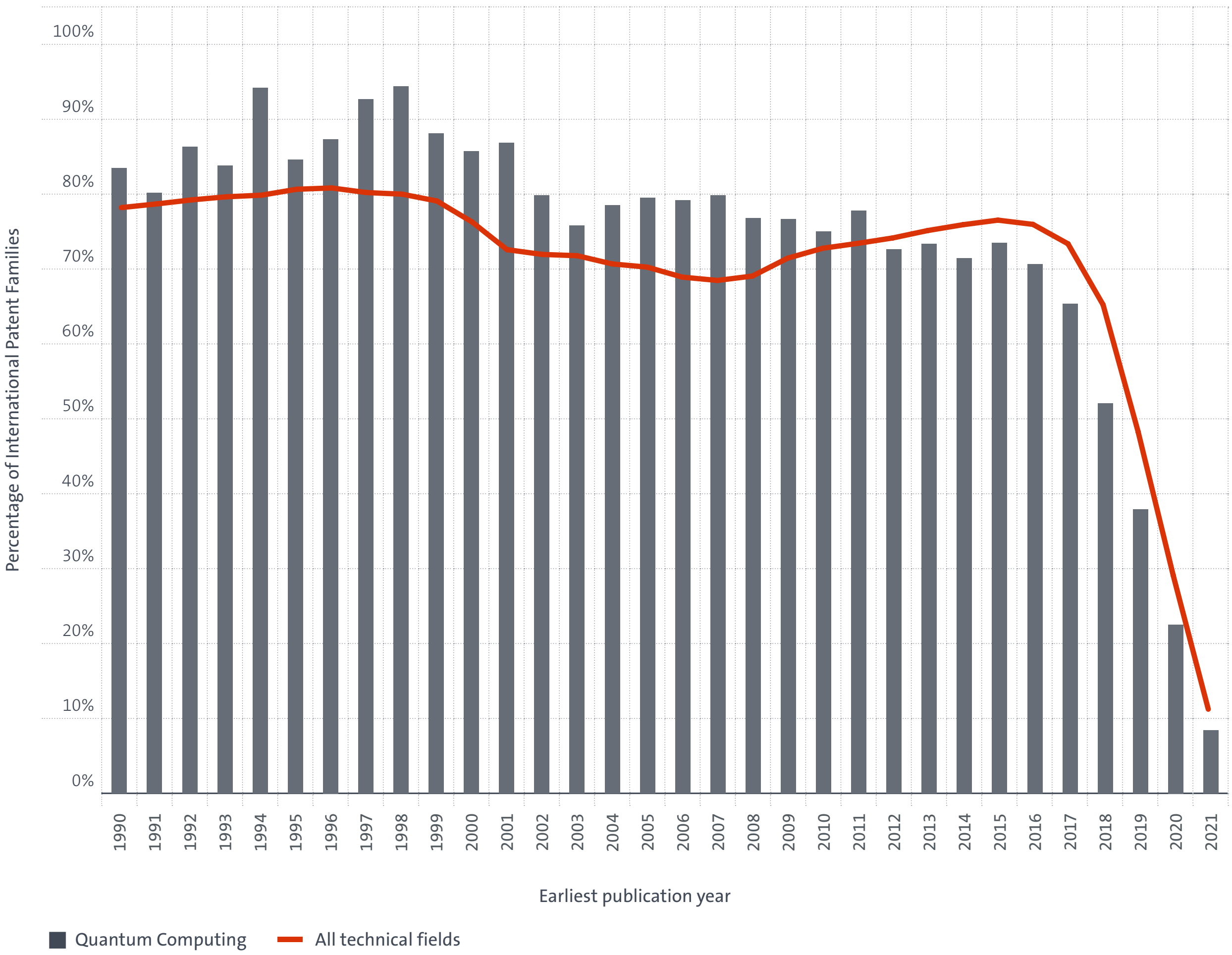


Figure 8

Percentage of International Patent Families in the field of quantum computing with at least one granted patent regarding CN, EP, JP, US, or PCT application leading to a granted patent in a national or regional phase, per earliest publication year.

The decline in recent years can be explained with the fact that the application and granting procedures in the field of quantum computing may take several years before a patent is granted, similar to many other fields of technology. With that, many patent applications filed in recent years have not completely passed the procedure.



Source: authors' calculations

Table 1

Most active applicants in the field of quantum computing

Applicant	Country of residence	Sector	Number of International Patent Families
IBM	US	Company	401
Toshiba/Nuflare Technology	JP	Company	312
Intel	US	Company	254
Microsoft	US	Company	246
Nokia/Here Global	FI/NL	Company	230
Harvard University	US	University	185
Hitachi	JP	Company	178
Google	US	Company	165
MIT (Massachusetts Institute Of Technology)	US	University	163
NEC	JP	Company	158
Samsung	KR	Company	151
Sony	JP	Company	139
Fujitsu	JP	Company	131
Northrop Grumman	US	Company	129
University of California	US	University	122
D-Wave Systems	CA	Company	113
Qualcomm	US	Company	109
Philips	NL	Company	108
Alibaba Group	CN	Company	89
The Broad Institute	US	Non-Profit Organisation	87

Table 2

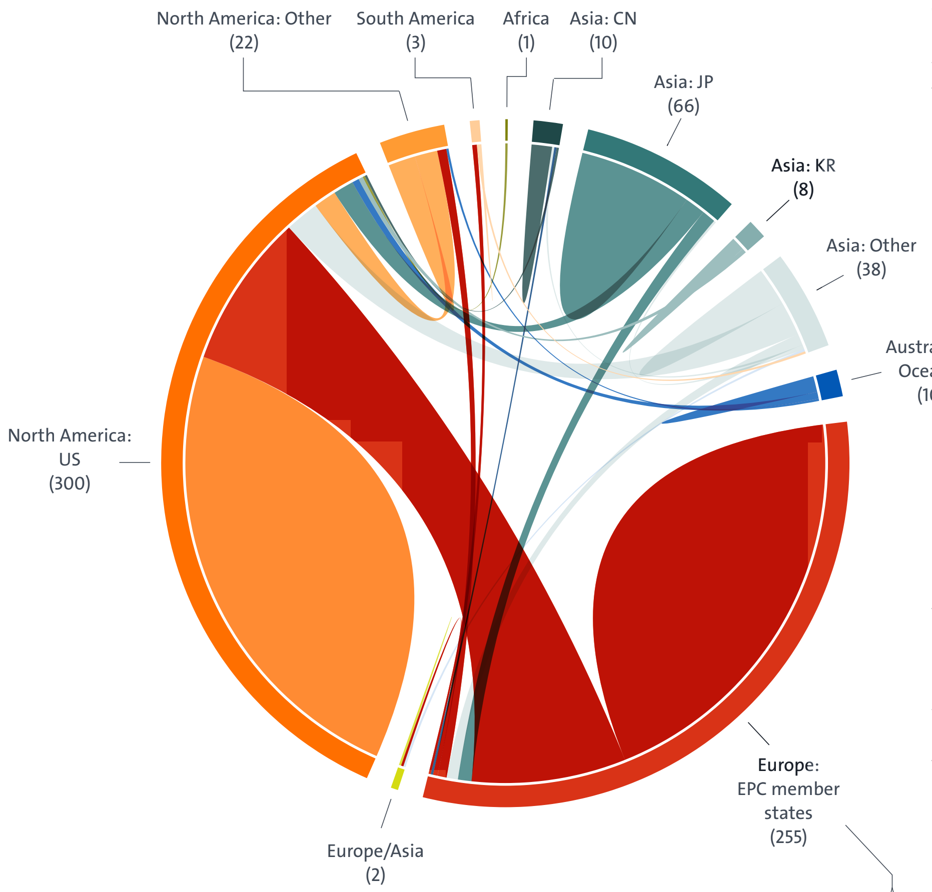
Breakdown for most active applicants in the field of quantum computing, for the periods 2000-2009, 2010-2019 and 2020-2021

Applicant	Country of residence	Sector	Number of International Patent Families
2000-2009			
D-Wave Systems	CA	Company	57
NEC	JP	Company	49
Toshiba/Nuflare Technology	JP	Company	47
Microsoft	US	Company	47
MagiQ Technologies	US	Company	41
Hewlett-Packard	US	Company	41
Samsung	KR	Company	38
Sony	JP	Company	37
Japan Science And Technology Agency	JP	Company	35
Fujitsu	JP	Company	33
2010-2019			
Intel	US	Company	200
Toshiba/Nuflare Technology	JP	Company	173
Nokia/Here Global	FI/NL	Company	157
IBM	US	Company	121
Harvard University	US	University	117
Microsoft	US	Company	113
Google	US	Company	110
MIT (Massachusetts Institute Of Technology)	US	University	104
Northrop Grumman	US	Company	98
Alibaba Group	CN	Company	80
2020-2021			
IBM	US	Company	187
Microsoft	US	Company	86
Nokia/Here Global	FI/NL	Company	73
Toshiba/Nuflare Technology	JP	Company	61
Harvard University	US	University	57
Fujitsu	JP	Company	56
Intel	US	Company	51
Google	US	Company	50
University of California	US	University	44
MIT (Massachusetts Institute Of Technology)	US	University	41

Figure 9

Co-applicant pattern in the field of quantum computing, for International Patent Families with at least one EP patent family member: Breakdown regarding the country of residence, and displayed as Chord diagram

Countries of residence are grouped on the continent level. A special focus is set on Europe, for which the country of residence is further broken down.



These chord diagrams represent the inter-relationships between applicants from different countries of residence in the light of joint EP patent applications in the field of quantum computing.

In the upper diagram, countries of residence are grouped on the continental level, with some sub-divisions.

Each continent and sub-division is represented by a segment around the circumference of the circle, which are in different colours to make the diagram easier to read. The chords between the segments represent the number of joint applications. Their thickness reflects the number of International Patent Families with EP applications filed by applicants from the continents or sub-division that are connected by the chord. The thicker the chord, the higher the number of International Patent Families.

The numbers in brackets after each continent and sub-division indicate the number of International Patent Families with EP applications filed by at least one applicant from that continent or sub-division. Example: in the field of quantum computing, there are 255 International Patent Families with EP applications filed by at least one applicant from an EPC state.

The lower diagram shows a more detailed breakdown of applicants from EPC states. The diagram represents the co-applicant behaviour of applicants from EPC states who jointly filed EP applications in the field of quantum computing. The thickness of the chords is a measure of the number of International Patent Families with applicants from the EPC states that they connect.

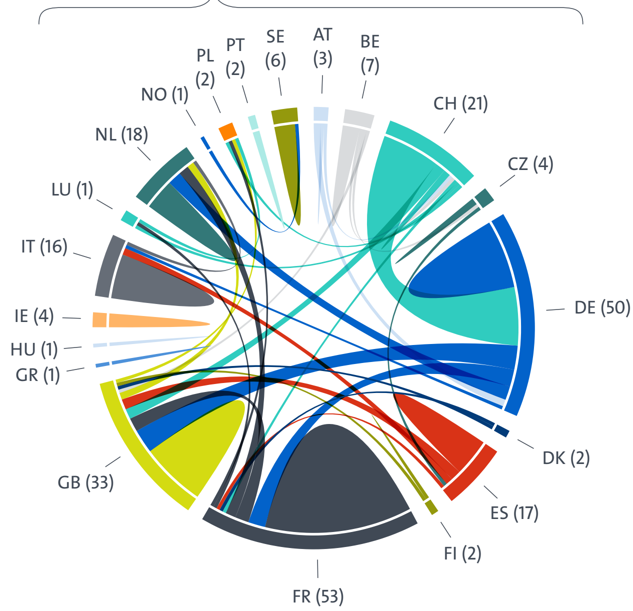
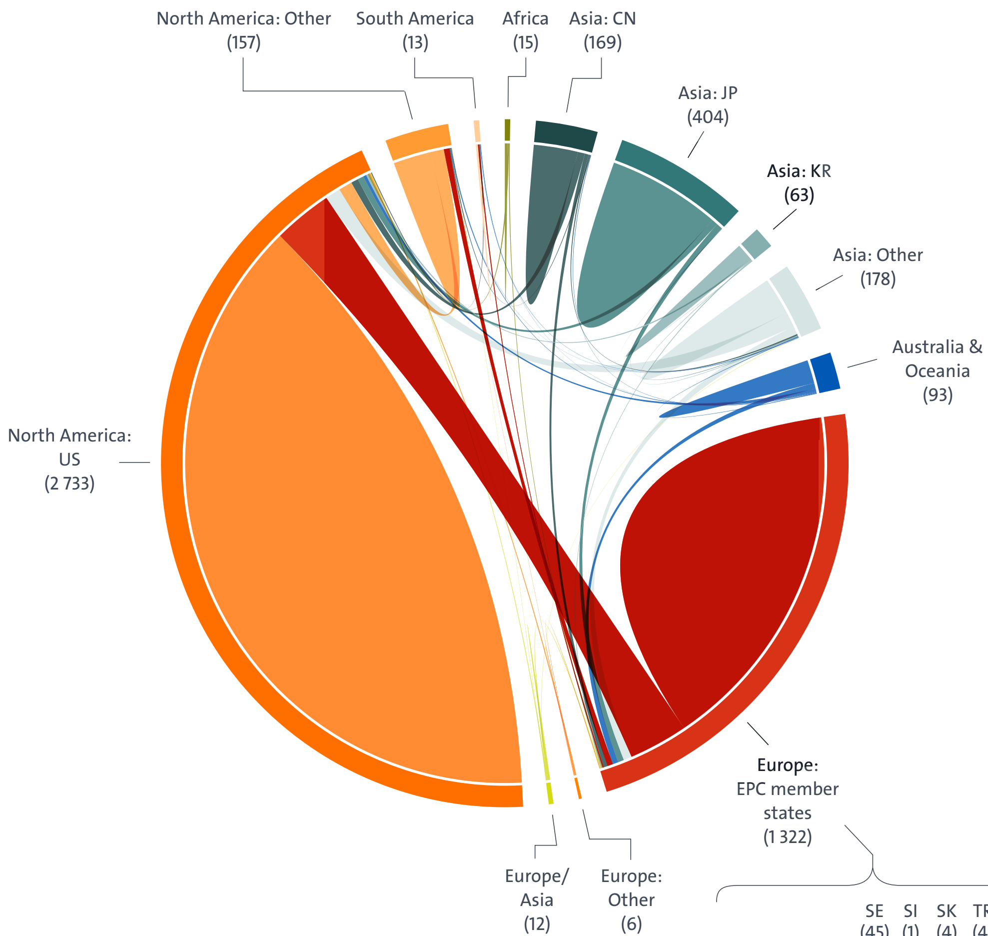
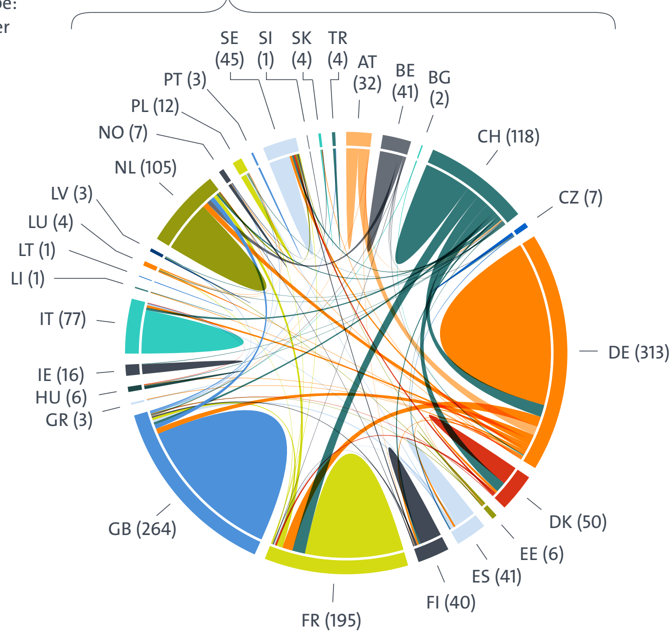


Figure 10

Co-inventor pattern in the field of quantum computing, for International Patent Families with at least one EP patent family member: Breakdown regarding the country of residence, and displayed as Chord diagram

Countries of residence are grouped on the continent level, with a further breakdown for EPC states.



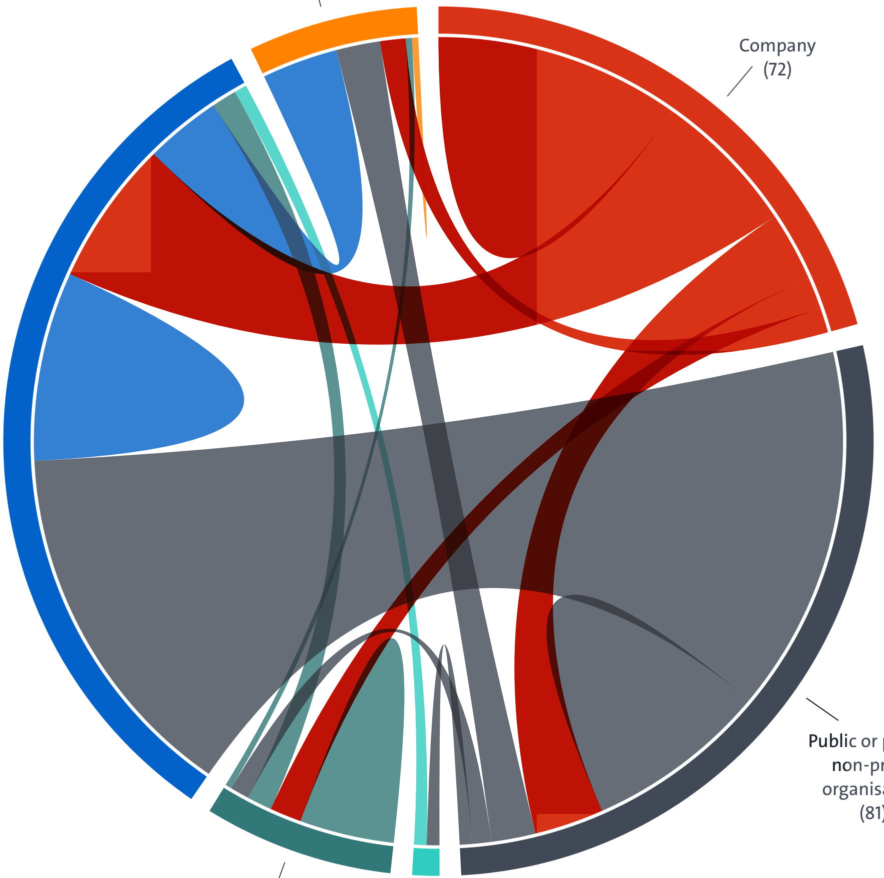


These chord diagrams represent the inter-relationships between inventors from different countries of residence in the light of joint EP patent applications in the field of quantum computing (see explanatory box in Figure 9 for this type of diagram).

The numbers in brackets after each continent, sub-division and country indicate the number of International Patent Families with EP applications that have at least one inventor from these entities.

Figure 11

Co-applicant pattern in the field of quantum computing, for International Patent Families with at least one EP patent family member: Further breakdown of the origin/country of residence according to the sector allocation of applicants from EPC states



This chord diagram represents the inter-relationships between applicants from EPC states in the light of joint EP patent applications in the field of quantum computing (see explanatory box in Figure 9 for general information on chord diagrams). The data in this diagram is grouped according to the sector allocation of the applicants.

The numbers in brackets after each sector indicate the number of International Patent Families with EP applications filed by applicants from EPC states belonging to that sector.

3.2 Physical realisations of quantum computing

Box 2: physical realisations of quantum computing

Physically realising a quantum computer is when the ideas of how to make it work meet the realities and the limitations of the world we live in. All computational models and algorithms need an infrastructure, that is a computing system, on which they are implemented. Classical algorithms have the classical computers we know from day-to-day life, which ultimately manipulate bits, the most basic units of information in classical computing. Quantum algorithms manipulate qubits as the basic units of quantum information. While transistors and semiconductors dominate the field of classical bits when it comes to the physical realisation, the landscape is more diverse for qubits. This is a manifestation of the still emerging character of the technology, as the best way to build the qubits of a quantum computer is yet to be found. Various issues, such as scalability, noise, coherence time and computational speed must be simultaneously addressed.

Indeed, there is still a long way to go. While users need thousands of stable qubits for their increasingly demanding and ambitious applications, quantum computers are still limited to a few dozen qubits. But the physical concepts to implement quantum computers are developing quickly, and while is not evident which technique, or techniques, will win the race, several promising paths have been and continue to be explored.

In principle, it is possible to use any quantum-mechanical system which has two identifiable states as a qubit. Within the quantum mechanics formalism, these two states are denoted |0> and |1> and together form the computational basis. What's more, for a given quantum-mechanical system, there may be several ways to encode the two states of a qubit. For example, when one considers the electron, a quantum particle, in a potential well (the "particle in a box"), the states of the associated qubit might be for example represented by the number of electrons in the box (e.g., |0> stands for no electron being inside the box and |1> for at least one electron being inside in the box), but also by the intrinsic angular momentum of the electron, that is by the spin of the electron (e.g., |0> stands for the spin being directed up and |1> for the spin being directed down).

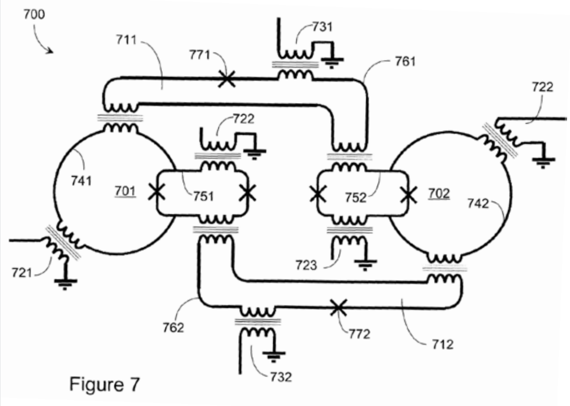
We have already mentioned the electron as a first quantum-mechanical system usable as physical realisation of a qubit. Quite a few other others are possible. For example, the spin property is also exposed by the nucleus of an electron, and the nuclear spin can be used for encoding two states, namely the spin up and the spin down states. Similarly, a photon, a quantum of light, may have two directions of polarisation: the vertical polarisation and the horizontal polarisation, respectively, might encode the two computational basis states.

Another important category of physical realisations of qubits benefits from the miniaturisation trend in the world of semiconductors and electronic circuits. Indeed, the downsizing of transistors inside microprocessors under the pressure of Moore's law ended up resulting in dimensions so small that they caused quantum effects to manifest – at times as a nuisance but at other times as a remarkable opportunity. Focusing on the latter, qubits may be realised by using semiconductors, and in particular quantum boxes in which individual electrons are trapped: the so-called quantum dots. By combining quantum dots, even more complex encoding of qubit states can be achieved, for example as singlet-triplet qubits.

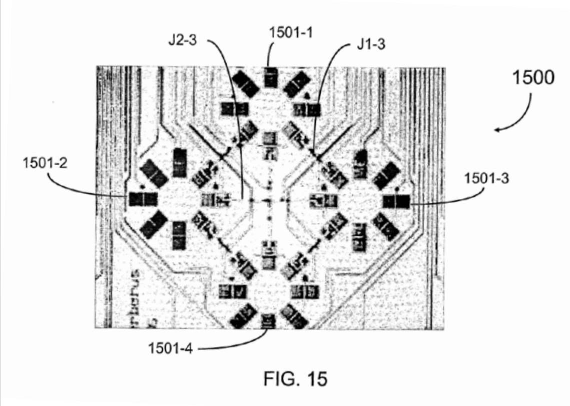
Still, the quantum effects sufficiently manifest themselves not only for elementary particles, but even for larger systems. Superconducting-based qubits, such as the charge qubit (e.g., the transmon), the flux qubit (e.g, the fluxmon), and the phase qubit were all successfully demonstrated.

Crystals expose a lattice structure on which it is as well possible to encode states of qubits. Nitrogen-vacancy centres (or NV centres) are crystallographic point defects in diamond, wherein a nitrogen atom has substituted for a carbon atom and neighbours a lattice vacancy. Charge states or spin states of NV centres can encode a computational basis.

There are the topological qubits as well, which rely on non-abelian anyons, a special breed of two-dimensional quasiparticles, whose world lines when rotating around one another form braids. Their non-abelian character allows for their use in encoding the computational basis of a qubit. As the non-abelian anyons still elude attempts to find and control them, this physical realisation remains for the time being a theoretical one. It allows us though to end this short introduction on a (quantum) leap towards the future.



EP2145294A1:
two superconducting qubits with two couplers



EP1851693A1:
actual photograph of four coupled qubits

The strong increase in the number of patent families in the last decades observed for the field of quantum computing also shows in the sub-sector of physical realisations of quantum computing, with a smaller upswing in the 2000s and a very pronounced increase in the last decade. The development in this sub-sector is also clearly above the trend that can be observed in all areas of technology (Figure 12).

Figure 12 (right scale) also shows the share of International Patent Families related to physical realisation of quantum computing in relation to all International Patent Families in the field of quantum computing. The share of inventions related to physical realisations of quantum computing rose to over 20 percent of all inventions in the whole field in the 2000s during the aforementioned small upswing, fell to about one tenth when this wave came to an end, and rose again steadily to about 20 percent in the last decade.

A look at the members of the International Patent Families in the field of physical realisations of quantum computing shows that, similar to the field of quantum computing as a whole, patent applicants mainly file patent applications via the following application routes: International applications, US applications, JP applications, EP applications and CN applications (see Figure 13). Figure 13 reflects the consistently high proportion of US patent applications in the International Patent Families in that field, which corresponds to the importance of the United States as a country of residence of important patent applicants but also as a market for physical realisations of quantum computing.

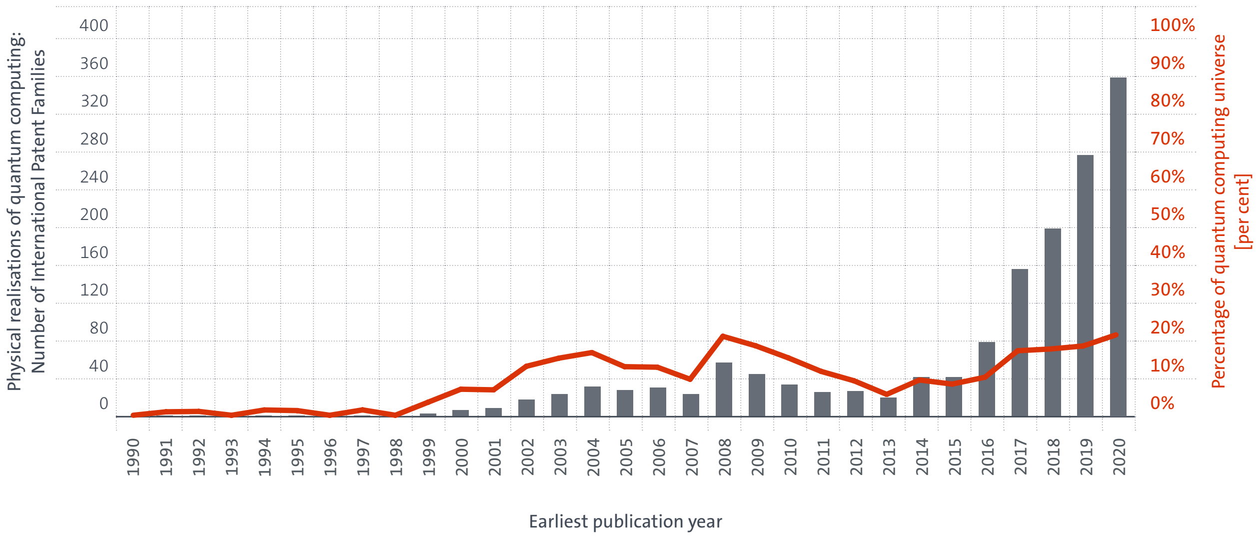
Figure 14 shows the percentage of International Patent Families in the field of physical realisations of quantum computing with at least one granted patent regarding CN, EP, JP, US, or PCT applications leading to a granted patent in a national or regional phase. Similar to the field of quantum computing as a whole, the situation in the field of physical realisations of quantum computing largely follows the trend observed in all fields of technology, with a higher percentage in earlier years. The scattered and partly thinned out course in early years can be explained with the rather low number of inventions in that period in the field.

The prominent position of the United States in that field also shows in the analysis of the most active patent applicants (Table 3). IBM heads the list, followed by other US companies. Companies from Canada, Japan, China and Australia are also among the most active patent applicants. Some US universities, notably the Massachusetts Institute of Technology and Yale University, have played a role of some importance, too.

A more detailed breakdown of the data over time shows that US patent applicants have played an increasingly prominent role in recent decades (see Table 4). In the 2000s, the period of the first upswing, the list of the most active patent applicants was headed by companies from Canada, the United States, Japan and Australia. In the following years, the picture has shifted in favour of US applicants.

Figure 12

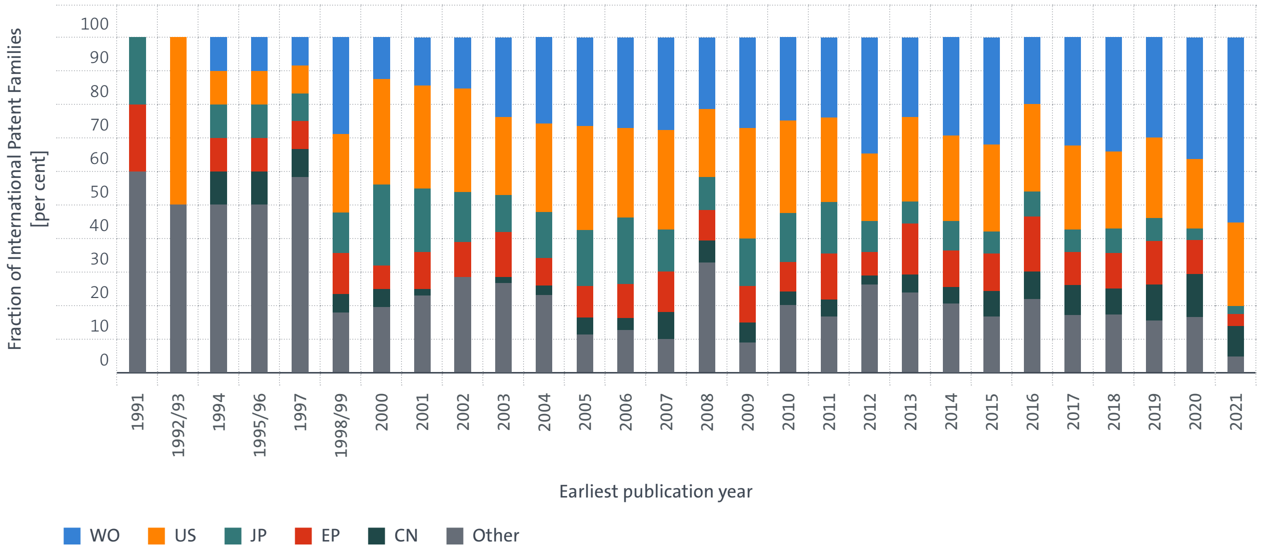
Number of inventions per earliest publication year related to physical realisations of quantum computing



Source: authors' calculations

Figure 13

Breakdown of filing statistics related to physical realisations of quantum computing as to publishing authorities, per earliest publication year



Source: authors' calculations

Table 3

Most active applicants related to physical realisations of quantum computing

Applicant	Country of residence	Sector	Number of International Patent Families
IBM	US	Company	230
Intel	US	Company	123
Microsoft	US	Company	122
Google	US	Company	114
D-Wave Systems	CA	Company	111
Northrop Grumman	US	Company	87
Toshiba/Nuflare Technology	JP	Company	47
MIT (Massachusetts Institute Of Technology)	US	University	33
Hitachi	JP	Company	32
Rigetti & Company	US	Company	30
Zapata Computing	US	Company	24
Yale University	US	University	23
Herr, Quentin P.		Individual	21
Qualcomm	US	Company	20
IonQ	US	Company	20
Hewlett-Packard	US	Company	20
Tencent Technology	CN	Company	19
NewSouth Innovations	AU	Company	18
NEC	JP	Company	18
Naaman, Ofer		Individual	18

Table 4

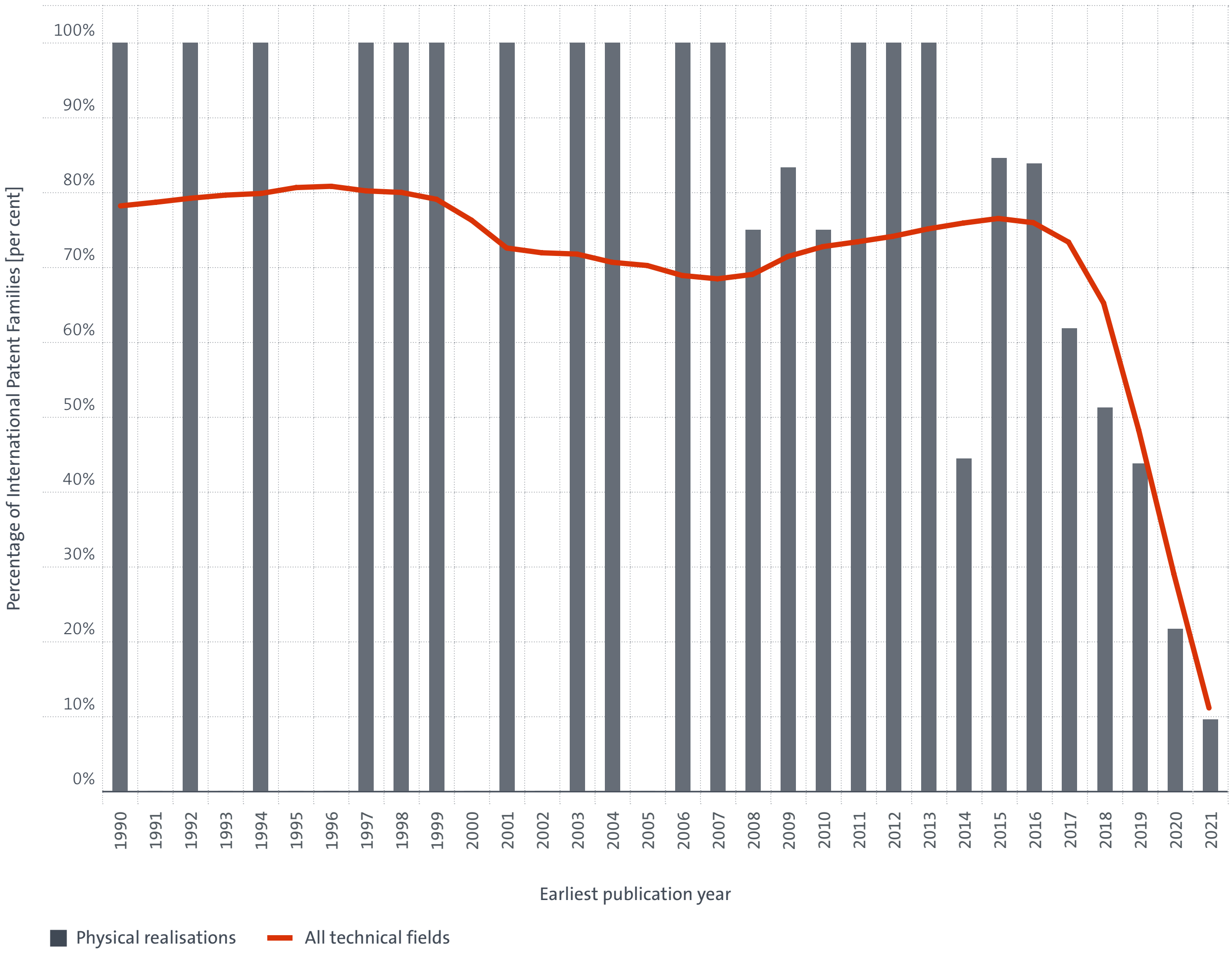
Breakdown for most active applicants related to physical realisations of quantum computing, for the periods 2000-2009, 2010-2019 and 2020-2021

Applicant	Country of residence	Sector	Number of International Patent Families
2000-2009			
D-Wave Systems	CA	Company	57
Qualcomm	US	Company	20
Hewlett-Packard	US	Company	20
Toshiba/Nuflare Technology	JP	Company	14
Rose, Geordie		Individual	13
Hitachi	JP	Company	13
Munro, William J.		Individual	12
Japan Science And Technology Agency	JP	Non-Profit Organisation	12
Qucor	AU	Company	11
Spiller, Timothy P.		Individual	10
2010-2019			
Intel	US	Company	118
IBM	US	Company	98
Google	US	Company	74
Northrop Grumman	US	Company	72
Microsoft	US	Company	52
D-Wave Systems	CA	Company	40
Toshiba/Nuflare Technology	JP	Company	22
Rigetti & Company	US	Company	20
Yale University	US	University	19
Herr, Quentin P.		Individual	18
2020-2021			
IBM	US	Company	128
Microsoft	US	Company	69
Google	US	Company	40
Zapata Computing	US	Company	24
Tencent Technology	CN	Company	18
IonQ	US	Company	17
MIT (Massachusetts Institute Of Technology)	US	University	16
D-Wave Systems	CA	Company	14
Honeywell	US	Company	13
Northrop Grumman	US	Company	12

Figure 14

Percentage of International Patent Families in the field of physical realisations of quantum computing with at least one granted patent regarding CN, EP, JP, US, or PCT application leading to a granted patent in a national or regional phase, per earliest publication year

See Figure 8 for a comment on the decline of the percentage in recent years.



Source: authors' calculations

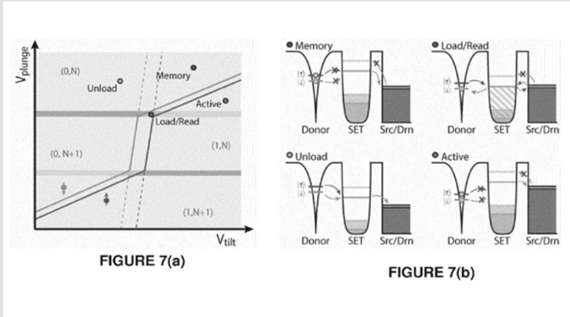
3.3 Quantum error correction/mitigation

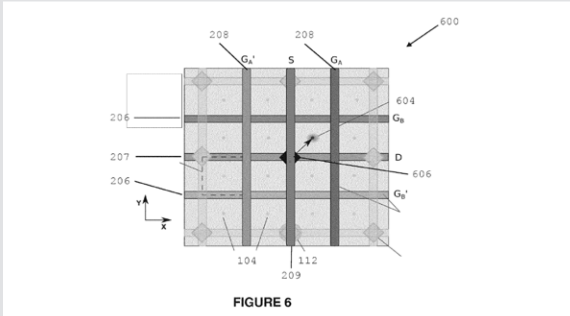
Box 3: quantum error correction/mitigation

Present quantum computers (of the NISQ era) are subject to various sources of errors, such as qubit decoherence (i.e., the unwanted collapse the qubit's state) due to (electromagnetic) noise, errors at qubit gates and errors in the measurement of the qubits' state, for example. These errors limit the complexity (depth) of the quantum circuits that can be implemented at present. Besides attempts to achieve fault tolerance, quantum error mitigation/correction provides mechanisms that employ error correction principles such as redundancy (surface codes, topological quantum computing) but also robust statistical principles of sampling/measuring states (operator decompositions, scheduling independently executable sub-operators) to address the drawbacks of present quantum computer technology.

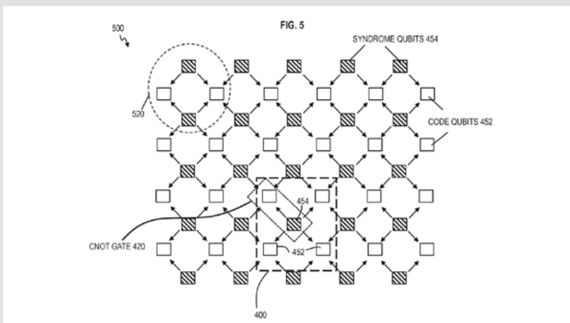
The development of error correction/mitigation principles for quantum computing not only involves algorithmic concepts but also concrete hardware structures for the different underlying technologies used to realise qubits to build a quantum computer. A quantum computer with hundreds of thousands, preferably millions of qubits, requires the capability of implementing quantum error correction given the constraints of the qubit-technology used. For example, if separate control lines are used for each individual qubit, the cost in terms of space required for control lines would scale prohibitively with the number of qubits. This is a serious limitation for a quantum computer with qubits based on superconductivity, for example, because of the necessary interface to a vacuumised extreme low temperature chamber.

For a quantum processor with a qubits' state encoded in the nuclear or electron spin of donor atoms embedded in a semi conducting structure, a structure of control elements arranged to control the qubits that has a limited number of control elements is devised in the European Patent EP3016034B1. The architecture uses multiplexed control lines and the structure and elements allow it to perform the operations required in surface code syndrome extraction for error correction (Fig. 6 in that document). The "data"-qubits are encoded using the donor atoms, and further donor atoms used as so-called "ancilla"-qubits are arranged to facilitate





quantum error correction. The state of both data and ancilla qubits is encoded in the nuclear spin of respective donor atoms. Donor electron and nuclear spins can be changed simultaneously using a global magnetic field externally applied to the entire structure. This provides an advantage in respect to architectures which require a local application of the magnetic field to each qubit. The arrangement of the control structure allows controlling a plurality of qubits simultaneously, especially in patterns distributed across the matrix. The structure can be controlled to load or unload an electron to or from each of the donor atoms and simultaneously on multiple donor atoms, thereby changing the state of a respective qubit (Fig. 7 in the said document).



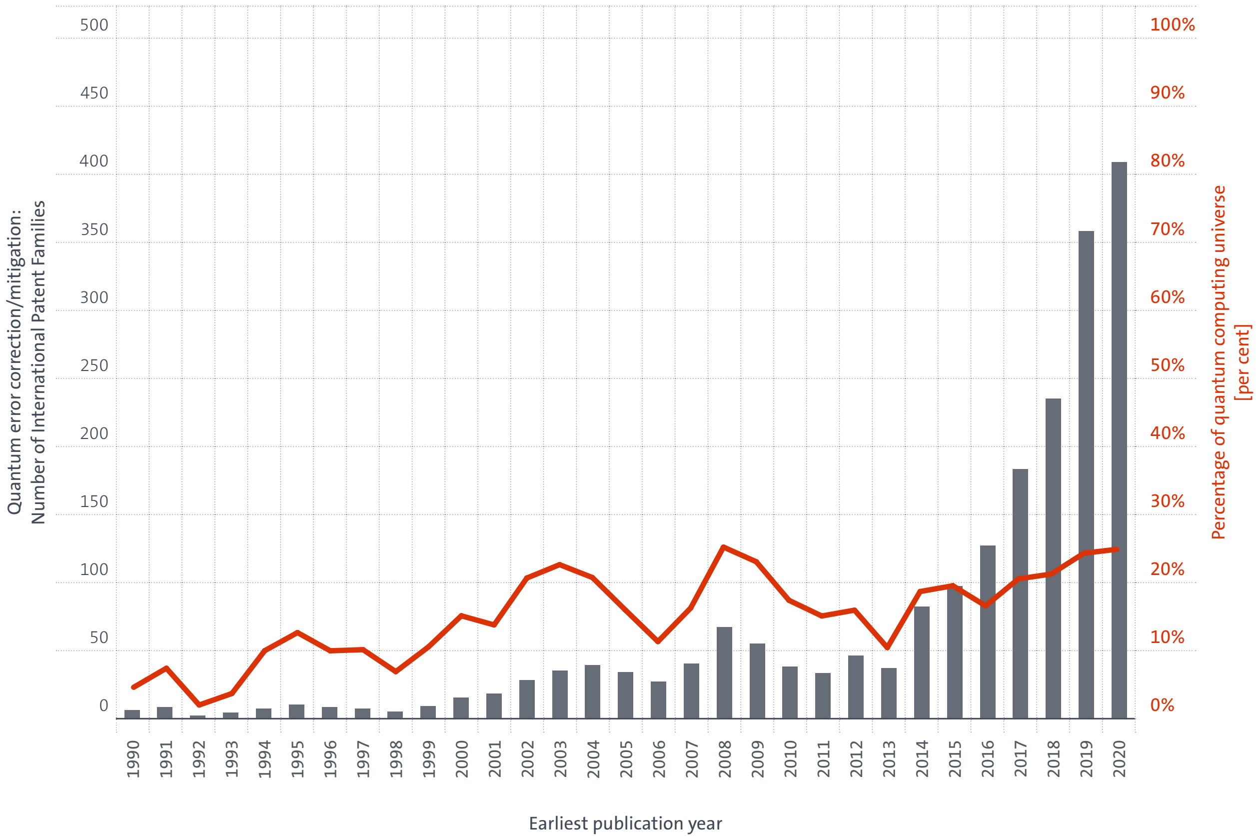
EP3602421A1:
lattice arrangement with both code and syndrome qubits

Similar to the sub-sector of physical realisations of quantum computing, and presumably interrelated to some extent technology-wise, the sub-sector of quantum error correction/mitigation has also developed very dynamically, with a weak upswing in the 2000s and a very strong increase in the last decade (Figure 15). The share of inventions in this sub-sector in relation to the field of quantum computing as a whole has seen largely continuous development during the period under consideration (Figure 15, right-hand scale).

The list of the most active patent applicants is again headed by IBM, followed by other applicants from the United States, Japan, Canada and Korea (see Table 5). A closer look at the development over time shows, similar to the sub-sector of physical realisations of quantum computing, that US-based companies have played an increasingly prominent role in recent year whereas in the 2000s, the period of the first upswing, the list of the most active patent applicants was significantly more diverse in terms of their origin (Table 6).

Figure 15

Number of inventions per earliest publication year related to quantum error correction/mitigation



Source: authors' calculations

Table 5

Most active applicants related to quantum error correction/mitigation

Applicant	Country of residence	Sector	Number of International Patent Families
IBM	US	Company	144
Google	US	Company	97
Toshiba/Nuflare Technology	JP	Company	94
Microsoft	US	Company	90
Intel	US	Company	77
MIT (Massachusetts Institute Of Technology)	US	University	59
D-Wave Systems	CA	Company	57
Harvard University	US	University	51
Sony	JP	Company	32
Northrop Grumman	US	Company	31
The Broad Institute	US	Non-Profit Organisation	27
Hitachi	JP	Company	27
Zapata Computing	US	Company	24
Rigetti & Company	US	Company	23
NEC	JP	Company	23
Pure Storage	US	Company	22
MagiQ Technologies	US	Company	22
Samsung	KR	Company	21
University of California	US	University	20
Hewlett-Packard	US	Company	20

Table 6

Breakdown for most active applicants related to quantum error correction/mitigation, for the periods 2000-2009, 2010-2019 and 2020-2021

Applicant	Country of residence	Sector	Number of International Patent Families
2000-2009			
D-Wave Systems	CA	Company	36
MagiQ Technologies	US	Company	22
Hewlett-Packard	US	Company	19
Toshiba/Nuflare Technology	JP	Company	16
NEC	JP	Company	14
Silverbrook Research	AU	Company	13
Silverbrook, Kia		Individual	12
Sony	JP	Company	10
Beausoleil, Raymond G.		Individual	10
Trifonov, Alexej		Individual	9
2010-2019			
Toshiba/Nuflare Technology	JP	Company	60
Google	US	Company	60
Intel	US	Company	55
Microsoft	US	Company	46
IBM	US	Company	46
Harvard University	US	University	37
MIT (Massachusetts Institute Of Technology)	US	University	36
The Broad Institute	US	Non-Profit Organisation	22
Northrop Grumman	US	Company	22
Alibaba Group	CN	Company	18
2020-2021			
IBM	US	Company	78
Microsoft	US	Company	39
Google	US	Company	34
Zapata Computing	US	Company	24
Intel	US	Company	21
Tencent Technology	CN	Company	18
MIT (Massachusetts Institute Of Technology)	US	University	18
Toshiba/Nuflare Technology	JP	Company	16
Pure Storage	US	Company	12
Harvard University	US	University	12

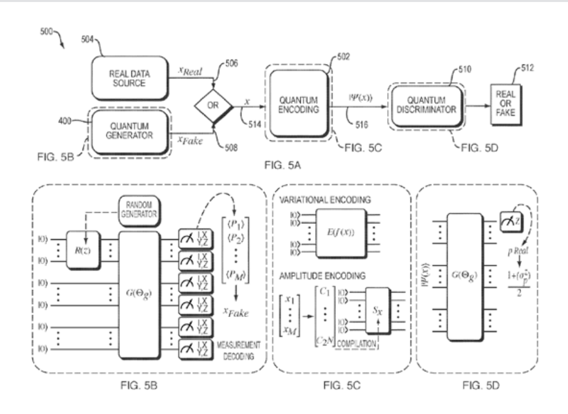
3.4 Quantum computing and artificial intelligence/machine learning

Box 4: quantum computing and artificial intelligence/machine learning

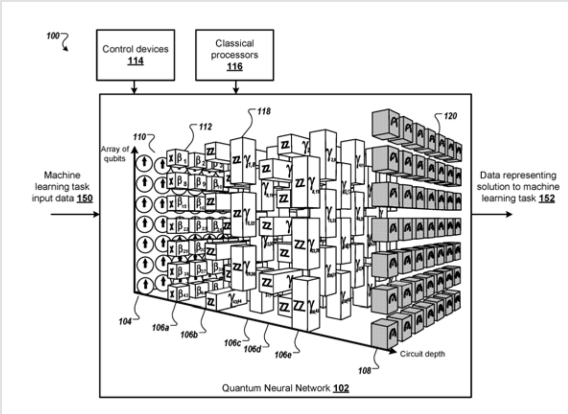
Quantum parallelism already evidences that quantum computing is particularly adapted to implement Artificial Intelligence/Machine Learning (AI/ML) techniques – as neural networks, for example, are often presented as "embarrassingly parallel" – but the connection between the two emerging technologies goes beyond this initial observation. For example, the equivalence between graphical models (e.g. generative neural networks) and spin-based models (e.g. Ising or Pott models) is long-known and well-documented in statistical physics, and such analogies lead to a deeper, more direct adaptation of QC to AI/ML.

A wide variety of solutions have already been proposed in the scientific and patent literatures (see figures), though such innovations are at the very edge of two emerging technologies. As QC typically involve "hybrid" systems, with quantum as well as classical components, these solutions may implement the data and/or the AI/ML model (or its training when applicable) in the classical or quantum realm. This also applies to quantum optimisation in general (e.g. quantum annealing, variational quantum eigen-solvers (VQEs) or QAOA), typically based on variational techniques and particularly adapted to solve AI/ML problems.

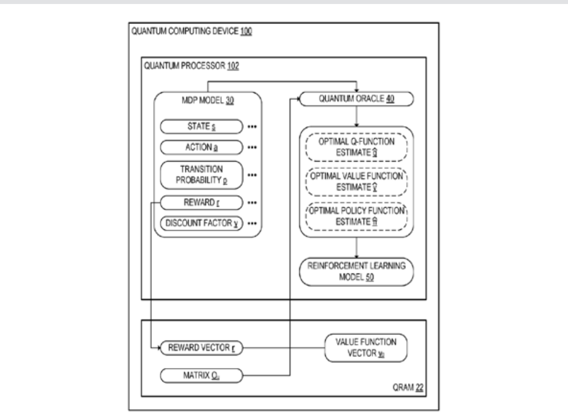
Another solid opening for AI/ML techniques is in their applications to QC-related data, parameters or variables, with similar success expected as in other area thanks to their application-independent nature.



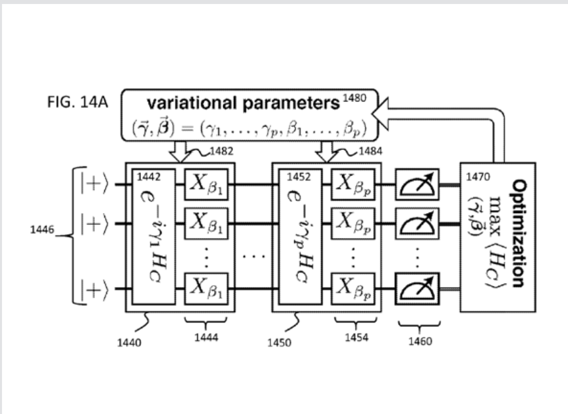
EP3864586A1:
quantum generative adversarial networks (QGAN);



EP3619655A1:
quantum neural networks (QNN)



WO2022164548A1:
quantum reinforcement learning (QRL);



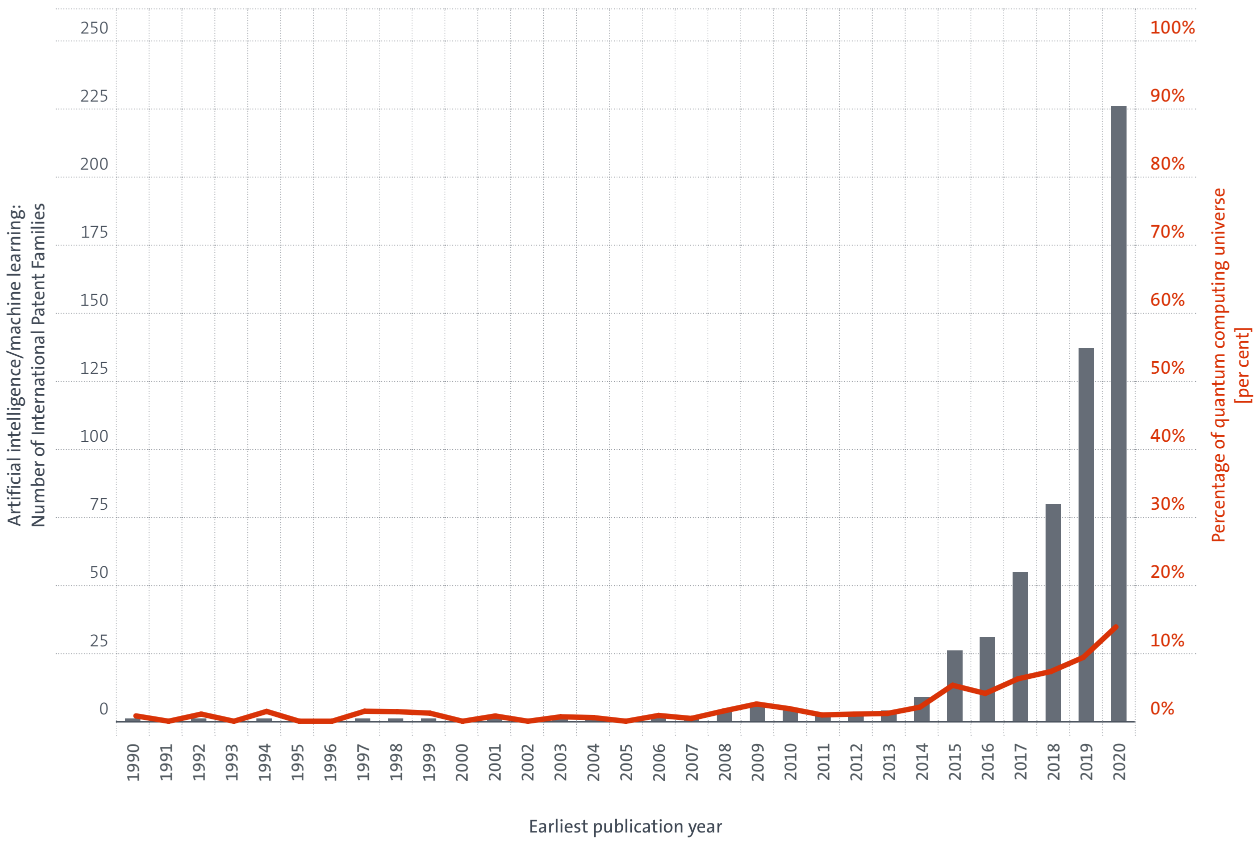
EP3844631A1:
quantum approximate optimisation algorithm (QAOA)

The "quantum computing and artificial intelligence/machine learning" sub-sector differs notably from the other sub-sectors examined and from the field of quantum computing as a whole. While an initial, minimal upswing in patent applications could be observed for this sub-sector in the 2000s, the actual dynamic development only began in the last decade (Figure 16). Remarkably, the momentum in this sub-sector is even higher than in the other sub-sectors or the field of quantum computing as a whole. With this far above-average momentum, the share of inventions in the sub-sector compared to the whole field is also rising, and is currently about 15 percent (Figure 16, right scale).

As in the other sub-sectors considered, IBM leads the list of the most active patent applicants, followed by patent applicants from Japan, the United States, Europe, Canada and China (Table 7). Compared to the other sub-sectors being looked at, in which US-based companies have played an increasingly prominent role in recent years, the diversity regarding the country of origin of the most active patent applicants in the sub-sector "quantum computing and artificial intelligence/machine learning" has clearly been higher over the last decade (Table 8).

Figure 16

Number of inventions per earliest publication year related to quantum computing and artificial intelligence/machine learning



Source: authors' calculations

Table 7

Most active applicants related to quantum computing and artificial intelligence/machine learning

Applicant	Country of residence	Sector	Number of International Patent Families
IBM	US	Company	55
Fujitsu	JP	Company	47
Microsoft	US	Company	38
Accenture Global Solutions	IE	Company	31
Hitachi	JP	Company	31
Google	US	Company	30
1QB Information Technologies	CA	Company	28
Nokia/Here Global	FI/NL	Company	25
Zapata Computing	US	Company	19
D-Wave Systems	CA	Company	19
Toshiba/Nuflare Technology	JP	Company	12
Intel	US	Company	12
Tencent Technology	CN	Company	11
Facebook	US	Company	11
Sony	JP	Company	9
Harvard University	US	University	9
NEC	JP	Company	8
Rigetti & Company	US	Company	8
Denso	JP	Company	8
Alibaba Group	CN	Company	8

Table 8

Breakdown for most active applicants related to quantum computing and artificial intelligence/machine learning, for the periods 2000-2009, 2010-2019 and 2020-2021

Applicant	Country of residence	Sector	Number of International Patent Families
2000-2009			
Sugishima, Kenji		Individual	3
Patel, Sukesh		Individual	3
Tokyo Electron	JP	Company	3
D-Wave Systems	CA	Company	3
Kaushal, Sanjeev		Individual	3
2010-2019			
Hitachi	JP	Company	21
1QB Information Technologies	CA	Company	21
Google	US	Company	20
IBM	US	Company	17
Microsoft	US	Company	16
Nokia/Here Global	FI/NL	Company	13
D-Wave Systems	CA	Company	13
Accenture Global Solutions	IE	Company	11
Intel	US	Company	8
Alibaba Group	CN	Company	6
2020-2021			
Fujitsu	JP	Company	42
IBM	US	Company	38
Microsoft	US	Company	21
Accenture Global Solutions	IE	Company	20
Zapata Computing	US	Company	19
Nokia/Here Global	FI/NL	Company	12
Facebook	US	Company	11
Hitachi	JP	Company	10
Toshiba/Nuflare Technology	JP	Company	10
Google	US	Company	10

4. Conclusions and outlook

This study shows that, while patent application numbers are still rather low, the momentum in the field of quantum computing is very high and clearly above average with respect to the general increase in patent application numbers in all fields of technology.

This study had a special focus on the sub-sectors “physical realisation of quantum computers”, “quantum error correction/mitigation” and “quantum computing and artificial intelligence/machine learning”. While all three sub-sectors have a high momentum as to the number of patent applications – similar to quantum computing as a whole – the sub-sector “quantum computing and artificial intelligence/machine learning” is characterised by an even stronger dynamic.

While the list of most active patent applicants in the whole field and in the sub-sectors is headed by IBM and other US-based companies playing an increasingly prominent role in recent years, the diversity of origin remains high in the sub-sector of “quantum computing and artificial intelligence/machine learning”.

In view of the high momentum in the field of quantum computing and the fact that the dedicated CPC classification domain for quantum computing will be fully in place in the medium term, the EPO considers updating this report in the future and having a closer look into how the sub-sectors covered in this report and other sub-sectors in the field of quantum computing will have developed and diversified.

Annex

Notes on the limits of the study

This study provides a snapshot of the field of quantum computing, taken in the light of patent data.[12] The methodology on which this report is based can be used freely, i.e. everyone can adapt the chosen search and analysis approach to their needs, for example to follow trends and developments in other established or emerging technical fields.

This study makes use of publicly available EPO worldwide patent data, EPO-internal and publicly available search and analysis tools.

Like many patent analyses, this study is based on search queries combining key words and patent classification symbols.

For most patent analyses, it is impossible to simultaneously reach 100 percent recall – i.e. to retrieve as many relevant documents as possible – or 100 percent precision – i.e. to exclude as many non-relevant documents as possible. This study is not an exception. The search queries chosen to create the basic data set for the field of quantum computing as a whole and for the sub-sectors were designed to strike a balance between recall and precision, to provide a meaningful overview of the field.

12 Date of extraction of the basic data set from the EPO's internal data platform: September 2022. The basic data set was combined with data from the EPO's PATSTAT product line (Spring 2022 Edition), which uses backfile data of the EPO's master documentation database (DOCDB) extracted in January 2022.

Published and edited by
European Patent Office
Munich
Germany

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Design
European Patent Office

The report can be downloaded from:
epo.org/insight-quantum-computing

ISBN 978-3-89605-370-1