Quantum Technology in Norway
Proposal for a National Funding Strategy

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Summary

Quantum technology holds the promise to revolutionize our technological future with applications in fields ranging from information and communication technology to medical imaging and drug design. In this document we provide a brief but broad overview of the field, including its potential impact in more general terms. We evaluate Norway's current position in the global, European and Nordic landscape of quantum technology, and based on this we suggest a funding strategy which, if followed, could keep Norway on track to partake of the upcoming technological revolution.

Our main suggestion is the implementation of two funding instruments, through the Research Council of Norway: (i) a thematic area within a call and (ii) a dedicated call for projects within quantum technology. In our opinion, these instruments would be very effective ways to allocate resources to the growing quantum technology community in Norway. As a short-term effect, they would enable a more dynamic and fertile participation by the Norwegian research community in academic and industrial activities within the Nordic countries as well as at the international level. As a long-term effect, the Norwegian research community would be in a position to foster collaborative efforts, for instance united in a Center of Excellence, and offer strong educational programs, together ensuring that Norway will not fall behind in the quantum-technological future.

This document is the result of a grassroot cooperation of a diverse group of researchers with expertise and interest in quantum technology. The reader should feel free to contact any of the authors for more information.

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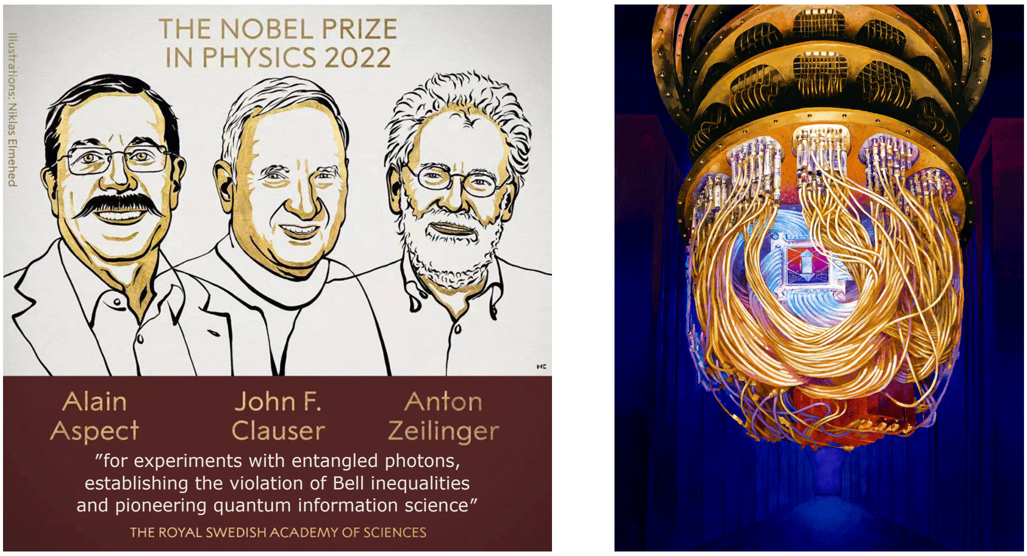
Background

Recently, the potential of quantum phenomena for technological applications has risen to prominence on the global scene, prompting a surge of activities both at the academic level and by public and private stakeholders [1]. This has been termed by analysts and experts the **second quantum revolution**, echoing the first one, which can be considered as one of the pillars of modern-day technology, with inventions such as the transistor, the laser, and nuclear magnetic resonance imaging, to name a few.

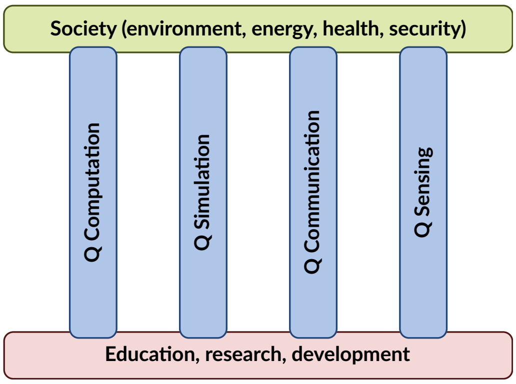
The current interest in the technological potential of the most counterintuitive aspects of quantum physics (such as *superposition* and *entanglement*) is evidenced by the volume of investments made, both by private companies and at the governmental level: The total investments worldwide in quantum technologies have shown an exponential growth in the past decade, exceeding 2.35 billion USD in 2022 [1]. Also the Nobel Prize committee recently emphasized the importance of the development of quantum technology from the academic perspective: The 2022 Nobel Prize in Physics was awarded "*for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science*" [2]. It is exciting to witness how truly fundamental quantum phenomena are currently being transformed into resources for radically new *technologies* with applications in fields ranging from communication security to the green transition.



Left: The 2022 Nobel laureates in physics: Alain Aspect, John F. Clauser and Anton Zeilinger (source: The Nobel foundation). *Right*: Google Sycamore quantum processor used in Ref. [3] (source: Google).

Four pillars

In this second quantum-driven technological revolution, four main pillars of quantum technologies are conventionally identified (quantum computation, quantum simulation, quantum communication, and quantum sensing and metrology), all of which being firmly rooted in basic research and development but potentially having a far-reaching impact on society as a whole. The main ideas behind these four technologies can be summarized as follows:



The four pillars of quantum technology.

Quantum computation The basic idea of quantum computation is to store and process information encoded in quantum-mechanical two-level systems, so-called *quantum bits*, instead of the classical bits we use in regular computers. The fundamental importance of quantum computation is rooted in the fact that there exist relevant problems which are intractable for any conventional classical computer (including supercomputers), but could be solved by a computer able to exploit the laws of quantum physics for computational purposes [4].

Arguably, one of the most celebrated quantum computing algorithms is the prime factoring algorithm discovered by Peter Shor [5], which could potentially be used to break the RSA encryption commonly used for secure communication. However, the advent of both quantum cryptographic encryption schemes (using entanglement to make communication intrinsically secure, see below) and classical but quantum-safe ("post-quantum") cryptography has rendered Shor's algorithm more interesting from a conceptual perspective than an applied one. In more general terms, the central benefit of quantum computation consists in the exploitation of the intrinsic (quantum) parallelism provided by entangled quantum systems, combined with their interference properties. Broadly speaking, the expectation is that complex optimization problems present natural candidates for the application of general-purpose quantum computers. Examples range from, e.g., air traffic scheduling and fleet management to protein folding calculations and analysis and prediction of financial markets, but also include the study of systems in which quantum mechanical phenomena are dominating, as is often the case in material science.

Quantum advantage, i.e., the actual ability of a quantum computer to solve a problem that is classically intractable, has been claimed first by Google in 2019 [3], on a rather abstract problem. While this achievement presented an important milestone in the development of quantum computing, researchers are still working around the world to build more powerful and reliable quantum hardware platforms and develop quantum algorithms of more direct practical relevance. Such research focuses on many different aspects of quantum computation, including building and manipulating physical qubits, error correction, quantum software stacks, compilers, quantum operating systems, quantum algorithm design, and finding groundbreaking real-world applications. Recently, noisy intermediate-scale quantum (NISQ) computers are attracting much attention, since they potentially represent an early generation of quantum devices that, despite their imperfections and limited qubit counts, might offer promising opportunities for exploring quantum computation and algorithms.

Quantum simulation Quantum simulation refers to the analog simulation of quantum systems whose behavior is not known (such as biomolecules or complex materials), through the manipulation—"by analogy"—of a controllable quantum system (the quantum simulator).

Quantum simulation can be regarded as a form of quantum computation that, while not allowing *universal* quantum computation, does not suffer from the stringent hardware requirements of the latter and thus can conceivably be implemented in the near future. As in the case of a more general-purpose quantum computer, applications tend to address optimization problems, with many relevant applications within, e.g., machine learning and the chemical industry. Specific example applications include accelerating and optimizing the design of chemical compounds for the development of drugs, new materials, or fertilizers.

Quantum communication Another field in which quantum physics can play an important role is communication security. The key concept here is that a quantum system is very sensitive to external disturbances, and this sensitivity can be harnessed to protect the exchange of information between two parties.

The potential breaking of RSA encryption security by quantum computers, as previously mentioned, creates a necessity of devising efficient countermeasures, including quantum and classical (post-quantum) cryptographic solutions. Quantum communication and quantum key distribution play a crucial role in this definition of a provably secure communication infrastructure. Around the world, we are therefore witnessing the development of quantum communication networks based on the exchange of quantum-cryptographic keys, which are intrinsically secure. While commercially available solutions are already in the market, investments in research and development aim at the further extension of quantum networks. EuroQCI plans a pan-European network connecting EU capitals for a total network length of 44 000 km. In parallel, and from a different perspective, classical quantum-safe algorithms are being developed to protect conventional networks from potential future quantum hacking attacks.

Quantum sensing and metrology The fourth pillar consists in the possibility of exploiting quantum effects for extremely accurate sensing and measurement purposes and for the definition of metrological quantities and relations [6].

Examples of quantum sensing include applications in microscopy, medical imaging, force sensing, and electromagnetic sensing. In all these applications, the fundamental idea is that it is possible to exploit quantum properties such as squeezing and entanglement to improve on the sensitivity provided by conventional sensors [7].

On a slightly different note, the application of quantum physics to metrology relies, somewhat counterintuitively, on the "robustness" of specific quantum phenomena to impurities and imperfections. One example in this sense is given by the possibility of defining the resistance standard using the quantum Hall effect [8].

1 SWOT analysis of quantum technology for Norway

Our first objective is to evaluate the position of Norway in the international landscape of quantum technology (QT), by conducting a comprehensive SWOT analysis. The analysis focuses on both academia and businesses, and is aimed at assessing Norway's competitive position. Our goal is to gain insights into the current situation, which will allow us to make informed decisions about future actions. Through this SWOT analysis, we hope to identify areas of strength, address weaknesses, pursue opportunities, and mitigate potential threats.

STRENGTHS

- Several internationally recognized research groups
- Existing study programs already contain a number of relevant courses
- National coordination and dialogue across sectors
- Strong interest in developing the field (academia, industry, political)
- Existing Nordic and international connections

WEAKNESSES

- Below critical mass to attract/hire top researchers
- Activity delayed compared to most other countries
- Little experimental activity and limited access to hardware
- Lack of a national QT strategy

OPPORTUNITIES

- Develop study programs on all levels to educate the "quantum workforce"
- Funding instruments dedicated to foster development of quantum technology
- Collaboration with industry and startup ecosystem
- Develop new products and business

THREATS

- Norwegian businesses and industry could lose their competitiveness
- Lack of public funding or funding cuts
- Quantum "winter," i.e., drop of interest due to slower than expected development
- Lack of national quantum computing hardware

Based on this overview, we conclude that the largest current threat for Norway is the risk that Norwegian businesses and industry could lose their competitiveness if they do not partake in the rapid global advancement of quantum technologies, which have the potential to revolutionize fields such as data analysis, drug development, material science, sensing, and communication.

Worldwide there is currently a surge in research and development in the field, meaning that countries and companies that fail to invest in a structured way may find themselves unable to compete with those that do, as quantum technologies will become increasingly commonplace. Norway still lacks a clear strategy or agenda for investment in this field, and Norwegian businesses thus risk falling behind and losing their edge in the global marketplace. The consequences of failing to act could be severe. Norwegian businesses may struggle to attract top talent in quantum-related fields, and may find it difficult to secure partnerships with international companies that have already made significant investments in these technologies. They may also miss out on the potential benefits that quantum technologies can offer, such as faster and more secure data processing, and new avenues for innovation, growth and the green transition.

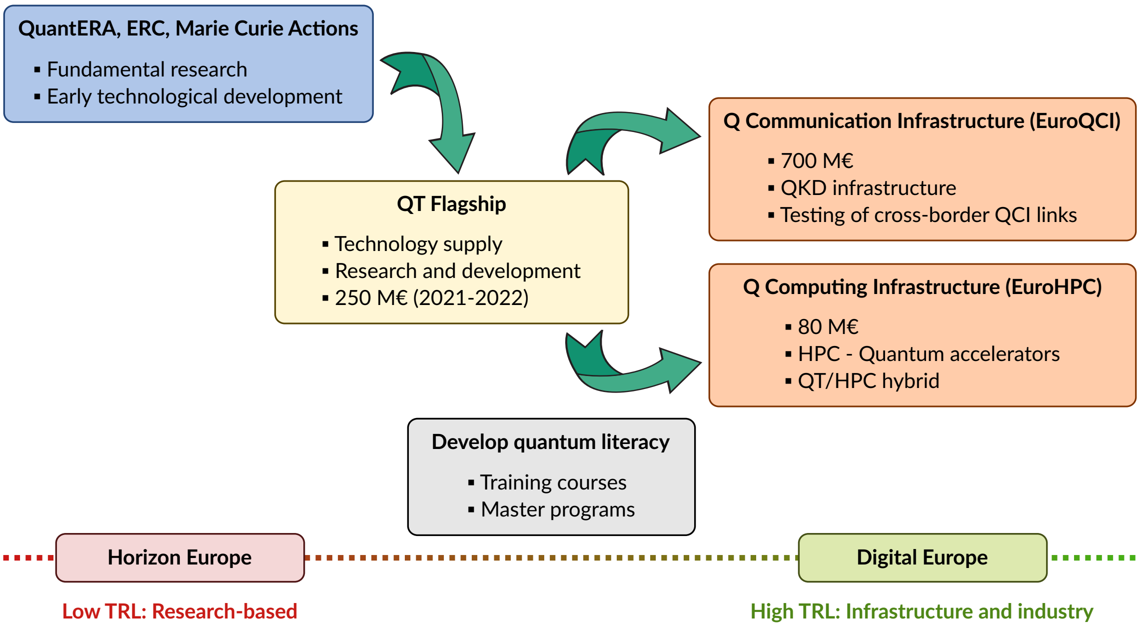
To avoid this scenario to become reality, it is critical that Norway develops a clear plan for investing in quantum technologies, to ensure that Norwegian businesses remain at the forefront of innovation and maintain their position as a leader in the global business community. This plan should identify why quantum technologies are important, how they can be used to create value, and where investment should be focused. It should also include measures to build a strong ecosystem for quantum education, research and development, including partnerships between businesses, universities, and government organizations. We believe that an investment in research will lay a good foundation for that.

2 Global/EU/Nordic landscape of quantum technology

Global In the global landscape of quantum technology, the most prominent role is arguably played by the United States, Canada, China and, especially in the academic realm, by EU countries. We think that the trend of establishing initiatives on a large scale—QT will be included in both the US *CHIPS and Science Act* [9] and in the EU *Chips Act* [10]—, in which both private and public stakeholders are considering the relevance of quantum physics for future technologies, naturally leads to the emergence of large-investment initiatives.

Europe Focusing on the European situation—analogous initiatives are under way in the US and China— we see that in 2018 the EU started its *QT Flagship*, with a total budget of over 1 000 M€. The flagship is aimed at providing a series of funding instruments for initiatives supporting both fundamental and applied research.

At the fundamental level, ERC and Marie Curie actions (MSCA) guarantee funding for blue-sky research on topics with relatively low technology readiness level (TRL), while other instruments, such as Horizon Europe EIC programmes, focus on the transition from basic to applied research. Instruments focusing on more applied aspects of quantum technology include EuroQCI (Quantum Communication Infrastructure, 700 M€), EuroHPC (focusing on all aspects of high-performance computing, and also quantum computing and quantum-high performance hybrids, 80 M€ for QT/HP hybrids) and QuantERA (focusing both on fundamental and applied aspects). When it comes to the latter, Norwegian applicants have been particularly successful, until Norway decided not to participate in the 2023 call.



EU funding structure for quantum technologies, centered around the QT Flagship (figure adapted from qt.eu).

Within Europe, a central role is played by the QT Flagship, whose mission is to bring quantum technologies from a laboratory setting to the market, strengthening the leading role of European science in quantum research. Over the last two years (2021–2022), the flagship alone, covering areas comprising technology supply as well as fundamental research and development, invested 250 M€. The QT Flagship, while being part of Horizon Europe, acts in close synergy with EuroQCI and EuroHPC mentioned above.

In addition, regional agreements between countries are emerging, one example being a recent agreement signed by the Dutch, French, and German governments, aimed at strengthening their collaboration in the field.

Nordics In 2022, a Nordic consortium emerged, consisting of scientists from Denmark, Finland, Norway and Sweden. A group of researchers in the field, comprising more than 20 institutions, decided to establish *Nordic Quantum*, a consortium that has the ambition to present itself as a global player in QT, while maintaining a close interaction with other stakeholders, both at the continental level and outside. Activities of this consortium will be rather broad, including joint PhD and postdoc positions, visiting researcher programs, thematic training networks, and infrastructure coordination.

Within the Nordic region, Finland, Sweden and Denmark already have well-established and solid programs in the field. Some examples are given by:

1. **Finland.** Finland has established a Center of Excellence in Quantum Technology (2018–2025, funding 12 M€/yr), comprising three research organizations and three companies.
2. **Sweden**. In Sweden, the main hub for QT is the Wallenberg Center for Quantum Technology (WACQT, 12 years, 130 M€). The main goal of WACQT is the definition of an excellence program in quantum science and the coordination of the efforts for realizing a quantum computer; a related program with a focus on theory is the Wallenberg Initiative on Networks and Quantum Information (WINQ, 10 years, 17.5 M€).
3. **Denmark**. Denmark hosts a Microsoft Quantum Lab, the newly-established DIANA NATO Quantum Center, the DTU center for QT, the Quantum for Life Centre at the University of Copenhagen, and the Novo Nordisk Quantum Computing Programme (in collaboration with the University of Copenhagen, 12 years, 200 M€).

3 Activities in Norway

At the moment, research on quantum technology in Norway is mainly focused on the theoretical side (with some exceptions), although most of our research groups have close collaborations with experimentalists abroad. The range of activities is rather broad and bound to expand to different themes in the near future. Topics currently covered include: quantum condensed matter physics directed toward quantum computing and sensing applications, quantum materials (experimental), quantum computational and sensing applications of optomechanical systems and vacancies in semiconductor materials (experimental), quantum and post-quantum cryptography, quantum software engineering, integration of HPC and quantum computation, NISQ computers as open quantum systems, quantum information theory, quantum algorithm design, quantum error correction theory, as well as didactic research on quantum computing education. Although there has not been a dedicated thematic call on quantum technology so far, in a presentation at the end of 2022, Pål Malm from RCN estimated that there were slightly over 30 funded RCN projects that were in some way related to QT, considering the period 2017–2022, and two Centers of Excellence with activities in the field (QuSpin at NTNU, 2017–2027, 266 MNOK and Hylleraas at UiO/UiT, 2017–2027, 275 MNOK). Currently, we count 7 active Researcher Projects within QT, out of a total of 1 681 Researcher Projects funded by RCN.

International collaboration is one of the characterizing traits of the Norwegian QT community and funding instruments such as QuantERA have in this sense been fundamental for our activity. In the latest call in which Norwegian researchers were allowed to participate (2021), three (ConSpiQuOS, DQUANT, MQSens) out of at least five submitted project proposals involving Norwegian partners were awarded funding. As also discussed in the "Proposed initiatives" section, we would recommend similar instruments to be considered in the future. These include International Partnerships for Excellent Education, Research and Innovation (INTPART) from the Research Council of Norway to support cooperation with countries outside the EU such as the USA, Canada, and Japan.

Norwegian researchers also participate in a Nordic project, NordiQuEst, that will build a Nordic-Estonian quantum computing infrastructure connecting Nordic quantum computers (QAL 9000 at Chalmers, Sweden and Helmi at VTT, Finland) with high-performance computing (HPC) infrastructures (LUMI in Finland and eX3 at Simula). Norwegian researchers also participate in EuroHPC joint undertakings, e.g., in the LUMI-Q project that will procure a European quantum computer and connect it to Karolina, a classical HPC system. In both NordiQuEst and LUMI-Q, quantum software testing tools that emerged from a research project funded by the Research Council of Norway will be integrated. Moreover, Norwegian researchers will contribute to quantum computing use cases in both projects.

3.1 Ambition

It is crucial to define how the QT Norwegian research environment can further develop and establish an effective dialogue with its peers abroad, particularly the other Nordic countries, the EU, and selected countries outside the EU (e.g., the USA, Japan, and Canada). To this end, we have identified some of the main goals of our scientific community, both covering the educational aspects and the more general challenge of creating a healthy community (involving academia, industry and society) in quantum technology. When compared to neighboring countries, the Norwegian level of activities is somewhat limited. While, on the one hand, this represents a drawback, it also allows us to build essentially *ex novo* a more effective teaching and research environment, building upon the experience, for instance, of our Nordic neighbors.

The necessities of the national quantum community depend on the time frame taken into account. In general, the following short-term needs can be identified:

1. **Increased awareness** among different stakeholders, including
    a) academic decision-makers, persuading them of the present (not only future) technological relevance of the field and of the necessity of a strong dialogue between academia and industry;
    b) national policy makers, allowing them to recognize the strategic value of quantum technology;
    c) industrial partners, to raise awareness about the disruptive role quantum technology is anticipated to play and the need to partake in this revolution in order to stay competitive;
    d) the general public, making sure that the promise (and risks) of quantum technology are communicated in a clear and non-hyped way.
2. **A strengthened academic QT community**, both facilitating quantum technology activities amongst dedicated researchers already in place and also favoring an international recruitment process, aimed at attracting the best talents in the field.

3. **Adequate financial instruments** for the national community to access large-scale European funding instruments (co-fund calls).

On a longer time scale, the community can aim to have an ecosystem of spin-off companies arising from the collaboration between academia and industry, and, when the right level of technological maturity is reached, define user-based collaborations with the industry.

3.1.1 Norwegian Collaboration

One of the central aspects to the development of a Norwegian QT community is the need for a regular **interaction between researchers** in the field. To this end, we are in the process of establishing a website (www.quantumnorway.no), allowing the community to exchange information such as events, recent publications, and job offers. Furthermore, we believe that a regular (maybe yearly) **scientific meeting** could foster collaboration, easier exchange of early-career researchers (PhD and postdoctoral researchers), and a general feeling of community. The role of the academic community should also extend towards collaboration with industry in identifying needs, potential new applications, and methodologies.

Monthly seminars, yearly gatherings, and jointly organized events, such as an autumn school for PhD students, and joint supervision of Master thesis projects contributed to tying the involved research groups together in the past few years. However, larger funding for such collaborative quantum-efforts would make it possible to extend the activity considerably, through, e.g., extra PhD positions and more frequent joint events. One recent initiative is the founding of the Gemini Center on Quantum Computing, which was established by NTNU, the University of Oslo, and SINTEF in 2020. Simula (since 2021) and Simula UiB (since 2022) have become associate partners. Another node in the Norwegian quantum ecosystem is the OsloMet Quantum Hub, with whom Simula is also affiliated, along with other partners in academia and industry. All such initiatives could benefit greatly from larger funding.

3.1.2 Education

One of the crucial challenges that has emerged globally in the last few years is the considerable lack of workforce in the field (the “talent gap”) [1]. University capacity covers only around a third of the current demand, and in this context upskilling study programs could address this problem.

The Norwegian perspective on this issue should be twofold: On the one hand, the educational offer should help building a coherent national QT community (spanning both academia and industry) that can effectively interact and establish partnerships with international partners. Furthermore, in this context also a national security aspect should be taken into account: Communication security experts should possess the right background to work in the context of a quantum communication infrastructure.

We therefore believe that it is essential to boost our teaching offer in quantum technology, at all (PhD, Master, and Bachelor) levels. If planned appropriately, this could cover both the specific needs of a future Norwegian QT industry and provide a highly-trained “science, technology, engineering and mathematics” (STEM) workforce with a broader scientific background—a professional figure that the Norwegian industry has manifested interest for.

In this regard, it should be noted that courses in quantum computing, quantum information theory and quantum technology topics are already on the curriculum at several Norwegian higher education institutions—mostly at Master and PhD levels, with recent entries also at the Bachelor level. An international Master program in quantum technology (funded by The Norwegian Directorate for Higher Education and Skills) has also been established. A number of Master projects related to quantum information technology are in progress as we speak, and we see signs of a growing interest in the topic in the current generation of students, but also in people at companies who would like to acquire skills in quantum sciences and technology. Thus, we identify a need to solidify this offer and set up tailored courses and possibly entire study programs dedicated to quantum science. These would be interdisciplinary programs which require coordination between institutions and funding of study places.

Concrete plans in this sense could include cross-university programs in quantum technology, potentially supported by national, Nordic and EU activities (Research Council of Norway, Nordic Quantum, or Marie Curie actions). From the societal point of view, it is important that the QT community contributes to disseminating the concepts around quantum technology to the general public, outlining the risks (e.g., concerning information security) and the opportunities (e.g., the benefits of quantum technology in the future of drug design).

In the context of the Nordic Quantum collaboration, we have the ambition of making the Nordics the most quantum-literate region in the world and this ambition should be echoed at the national level. Society at large should know what quantum technology is and should be able to make informed decisions based on reliable scientific information.

Looking at other Nordic countries, as an example, we note that Denmark launched its first education program toward an MSc degree in Quantum Information Science in January 2023. The program is based at the University of Copenhagen and is shared between the Department of Mathematical Sciences, the Niels Bohr Institute, and the Department of Computer Science, and it will also have an instruction component at the Technical University of Denmark. The rationale is simple: to ensure that the society has a qualified quantum sciences and technologies workforce.

3.1.3 Nordic collaboration

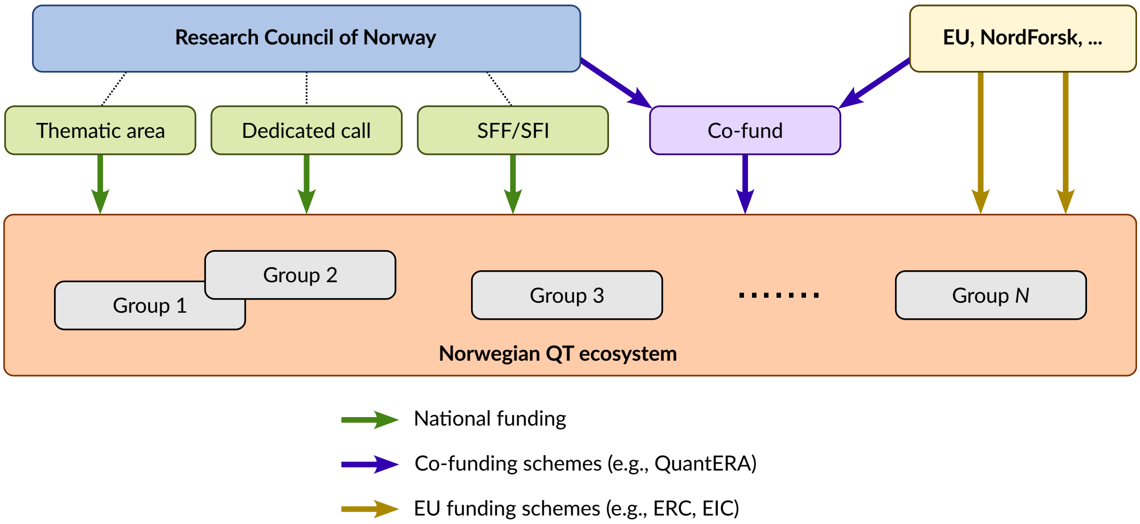
As mentioned in the previous sections, we think that near-future QT activities in Norway should be strongly coordinated with other Nordic partners. This will allow us to follow the best practices of our neighbors, benefiting from their strong reputation and success in the field. Concomitantly, we think that the Norwegian community has a strong potential for growth: while small, it hosts groups with a reputation for world-leading research. One of our goals is to reach a large enough "critical mass" to effectively access large-scale funding opportunities at the EU level. In this spirit, we have participated in the definition of the Nordic Quantum consortium, which will allow us to participate in large-scale calls such as the Marie Curie co-fund actions and EIC calls.

4 Proposed initiatives

Given the context outlined above and with a view to the definition of potential funding instruments that could be implemented through the Research Council of Norway, we have identified two main possibilities for funding for the near future: (a) a thematic area within a call, see (4.1), and (b) a dedicated call to quantum technology, see (4.2). In our opinion, these options would be very efficient tools for a successful allocation of resources to the quantum technology community. As a long term effect, the Norwegian research community would be able to foster collaborative groups that could be competitive in calls for Centers of Excellence, more on which follows in (4.3).

4.1 Thematic area within a call

One of the main difficulties encountered by Norwegian researchers in the field in recent calls is the lack of a specific thematic area within calls, such as the "Researcher Projects" call. We think



Sketch of possible funding instruments by the Research Council of Norway, along with the role played by international sources for funding and co-funding.

that the establishment of a dedicated "quantum technology" thematic area within a call would stimulate many new initiatives and would also facilitate the evaluation of proposals in the field by appropriate panels (which has not always been the case in the past). This, while being a relatively simple measure, would ensure a fair competition between groups in QT and have the direct effect of stimulating the growth of the community. Since most groups in the university sector have their strengths in theoretical research, the funding would initially predominantly go to the hiring of junior members of staff, PhD students, and postdocs (instead of experimental equipment), which has a potential trickle-down effect towards the creation of startup companies in the field. For the institute sector, it is vital to allow for stable funding of permanent staff within the areas to allow for a sustainable research activity over time.

To facilitate cooperation with selected countries outside the EU, having a dedicated topic related to QT within the INTPART program from the Research Council could help the Norwegian community to cooperate with countries such as the US, Japan, and Canada, which are more advanced within QT than Norway. Fostering collaboration between stakeholders in Norway and major global players could foster a thriving environment for the research community in Norway.

4.2 Dedicated call

Along the same lines, it would be conceivable to define a dedicated quantum technology call. This instrument, in addition to the positive aspects of the thematic area, would be a clear statement of the relevance of quantum technology in the Norwegian academic and industrial landscape. Dedicated funding for establishing a robust Norwegian infrastructure for experimental research aimed at the concrete development of quantum technologies is also of paramount importance. Such endeavors would serve to: (i) unite parts of the Norwegian quantum technology community under a common objective, (ii) enhance the recruitment of exceptional young researchers, and (iii) attract substantial funding from national, Nordic, and European public agencies, as well as private foundations and investors.

4.3 Center of excellence

Thematic and dedicated calls like the ones suggested above will help to strengthen the QT community in Norway. This would then present an important step toward the application for a Center of Excellence (SFF) or (depending on the maturity of industry involvement) a Center for Research-based Innovation (SFI). As there is an urgent need for preparing the future workforce for the onset of the second quantum revolution, we also envision a future application for a Center for Excellence in Education (SFU) aiming at addressing this knowledge gap. The creation of a Center of Excellence would allow to scale up the activities in the field, allowing the national QT community to further benefit from international partnerships and to prepare the Norwegian industry to take full advantage of the latest developments in QT. A Norwegian Quantum Center of Excellence could be part of the network European National Quantum Initiatives (see Appendix B).

4.4 Topics

One of the most important aspects of devising the right funding instruments for the quantum technology sector is the definition of the boundaries of what should be included.

A tentative list of topics includes:

1. Quantum computation:
   a) Hardware platforms. Innovative ideas in the field: known and new platforms, hybrid platforms;
   b) Algorithms. NISQ algorithms, NISQ computers as open quantum systems, quantum error correction algorithms, applications, fault tolerant quantum algorithms;
   c) Quantum information theory;
   d) Infrastructures. High-performance computing and quantum computing interfaces;
   e) Quantum software engineering.
2. Quantum communication:
   a) Hardware. Novel platforms and resources;
   b) Software. Cryptography, post-quantum cryptography.
3. Quantum sensing: Microscopy, force sensing, electromagnetic sensing.
4. Quantum metrology: Metrological standardization through quantum phenomena.
5. Fundamental aspects of quantum physics, condensed matter physics, quantum optics, and atomic physics.
6. Education and education research on relevant topics.

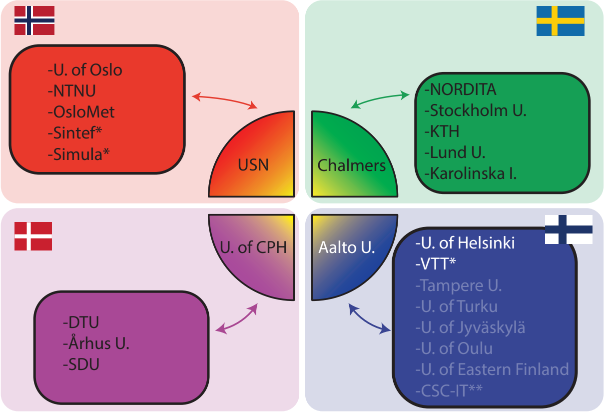
Appendices

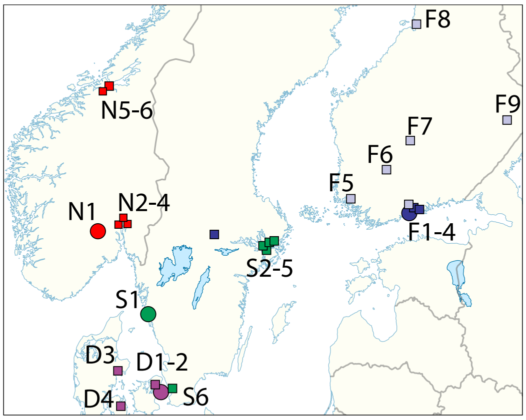
In the following appendices, we include an overview of the Nordic Quantum consortium (from the NordForsk University cooperation call) and a statement concerning the creation of a European Network of quantum initiatives.

Appendix A: Nordic Quantum consortium

Nordic Quantum national hubs

N1 University of South-Eastern Norway (Norway)
S1 Chalmers University (Sweden)
D1 University of Copenhagen (Denmark)
F1 Aalto University (Finland)





The four Nordic Quantum hubs are meant to act as initial reference points for consortium applications aimed at establishing the backbone of the Nordic Quantum consortium.

Nordic Quantum associated partners

Norway

N2 University of Oslo
N3 Oslo Metropolitan University - OsloMet
N4 Simula*
N5 NTNU
N6 SINTEF*

Sweden

S2 NORDITA
S3 Stockholm University
S4 Royal Institute of Technology - KTH
S5 Karolinska Institute
S6 Lund University

Denmark

D2 Technical University of Denmark - DTU
D3 Aarhus University
D4 University of Southern Denmark - SDU

Finland

F2 University of Helsinki
F3 VTT*
F4 CSC-IT**
F5 University of Turku
F6 Tampere University
F7 University of Jyväskylä
F8 University of Oulu
F9 University of Eastern Finland

* research institutes not directly affiliated to universities
** non-profit IT Center for Science (state & university ownership)
for Finland: in gray, institutions which, at present, are not part of the InstituteQ

Appendix B: European NQI statement

Towards a European Network of National Quantum Initiatives

Endorsed by the Quantum Community Network on 16/01/2023

Over recent years, Europe saw the emergence of several national initiatives dedicated to the development of Quantum Technologies, in Belgium, Bulgaria, Czech Republic, Finland, France, Greece, Hungary, Italy, Latvia, Netherlands, Slovakia, Switzerland and UK. Significant resources have been committed for advancing quantum computation, quantum simulation, quantum communications, and quantum sensing and metrology, as well as to the corresponding enabling sciences and technologies, training, and innovation. In Denmark and Sweden, similar initiatives have emerged funded by national private foundations. Overall, currently this corresponds to a total investment in excess of 5.7 billion Euro over a period of 5 years.

These national quantum initiatives (NQI) in Europe happen when the European Commission (EC) is expanding its own agenda and investments in Quantum Technologies (QT), now including the Quantum Flagship, the European Quantum Communication Infrastructure (EuroQCI), the European Quantum Computation and Simulation Infrastructure (EuroQCS), as well as actions for open testing and experimentation, and for pilot production capabilities, and a dedicated European Innovation Council (EIC) Pathfinder Challenge. There will be also a quantum component in the European Chips Act, as well as, efforts in training and innovation, and in setting up relations with major players outside Europe. Further to these top-down initiatives by the EC, QT have also been very successful in finding support from major bottom-up funding opportunities, e.g. the European Research Council (ERC), Marie Skłodowska-Curie Actions, the ERAnet QuantERA programme, and the European Metrology Programme for Innovation and Research (EMPIR).

In order to fully exploit these very important developments at the national and European levels, an unprecedented degree of coordination is now required, with a clear engagement of the NQI managers at the Member States (MS) government levels. This new layer of policy coordination is needed to ensure that all the EC and MS initiatives and infrastructures listed above can grow and expand in a coherent, sustainable and integrated way across the entire Union. This is particularly relevant for the EuroQCS and EuroQCI infrastructures, which have an intrinsic transnational dimension, making it mandatory that the plurality of MS voices can be heard.

We thus propose the creation of a **European Network of National Quantum Initiatives** contributing to the coherent development of all QT efforts in Europe, with the goals to:

- increase the national and international impact and visibility of all actions involving Quantum Technologies within Europe.
- promote bilateral and multilateral cooperation between different NQIs at the level of research & development, innovation, education, and training, exploiting the synergies between academia and industry.
- establish a common interface between NQIs and the European Commission, and promote the alignment of the different strategies and a regulatory framework in Quantum Technologies.
- exchange good practices in the development of national agendas, and contribute to the emergence of national quantum initiatives in all EU countries.
- establish a coordinated basis for cooperation with major players outside Europe and for promoting the creation of international standards in Quantum Technologies.
- develop joint engagement with the public, including to promote Quantum Technologies as a career perspective and contribute to fill the skills gap across Europe.

Overall, this will allow Europe to achieve a sustainable and integrated development of Quantum Technologies, making it autonomous, competitive, and sovereign at a global scale.

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