# Quantum Information Technologies (QuInTec)

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Quantum information technologies are attracting much attention and have given rise to several strategic quantum initiatives worldwide. The state of São Paulo has a strong academic community developing various aspects of quantum information science and a vibrant private sector which could greatly benefit from a well devised program to join efforts and develop cutting edge technologies. We aim to create a FAPESP quantum initiative, centered around: (i) fostering private sector-academy collaborations towards the development of short- and mid-term technologies; (ii) creating an attractive environment to bring talented young researchers and entrepreneurs to the state of São Paulo; (iii) educating a highly skilled workforce to further develop quantum information science and technology; (iv) enhancing international visibility and competitiveness, both from scientific and economic perspectives; (v) increase public awareness and understanding of quantum science in order to promote responsible research and innovation.

## 1 Timeliness of a quantum initiative in São Paulo

In a study commissioned by the European Physical Society and published in 2019, it was estimated that Physics-based industries made a net contribution to the economy of at least € 1.45 trillion per year, from 2011 to 2016[1]. A similar study by the American Physical Society estimated a contribution of US$ 2.3 trillion in 2016, and that 6% of total employment in the U.S. was provided by such companies[2]. The impact of quantum physics on much of the technology developed in the 20th century can hardly be overstated. A second quantum "revolution" is currently underway, relying on information-theoretic advances of the last 25 or 30 years. This is spurring quantum initiatives in many countries and will certainly lead to disruptive technologies that will reshape the economic landscape in the years ahead. The state of São Paulo must prepare for this new landscape by embracing and developing novel quantum technologies on its own. The existence of a world-class scientific community of researchers working on fundamentals of quantum information is a strong asset which must not be wasted. A FAPESP-led quantum initiative will foster needed partnerships between private-sector companies and academic researchers, as well as provide incentives for the creation of startup companies in this promising field.

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1 https://cdn.ymaws.com/www.eps.org/resource/resmgr/policy/eps_pp_physics_ecov5_full.pdf
2 https://www.aps.org/programs/industrial/index.cfm

## 2 What is meant by Quantum Technologies?

A very broad definition of quantum technologies is found in the German Federal Ministry of Education and Research publication called Quantum Technologies -- from basic research to market[3]: "If our world is a quantum world, it follows that we must be able to use quantum systems to help us to understand our world better and organise it more efficiently. This is what quantum technologies are about." As much as we agree with this definition, a more focused and goal-oriented vision is needed. We organize emerging quantum technologies into three main categories: information processing, communication, and sensing. Each of these raises its own challenges and opportunities. In Figure 1, these areas are schematically represented, together with a few examples of building blocks currently being developed in São Paulo state.

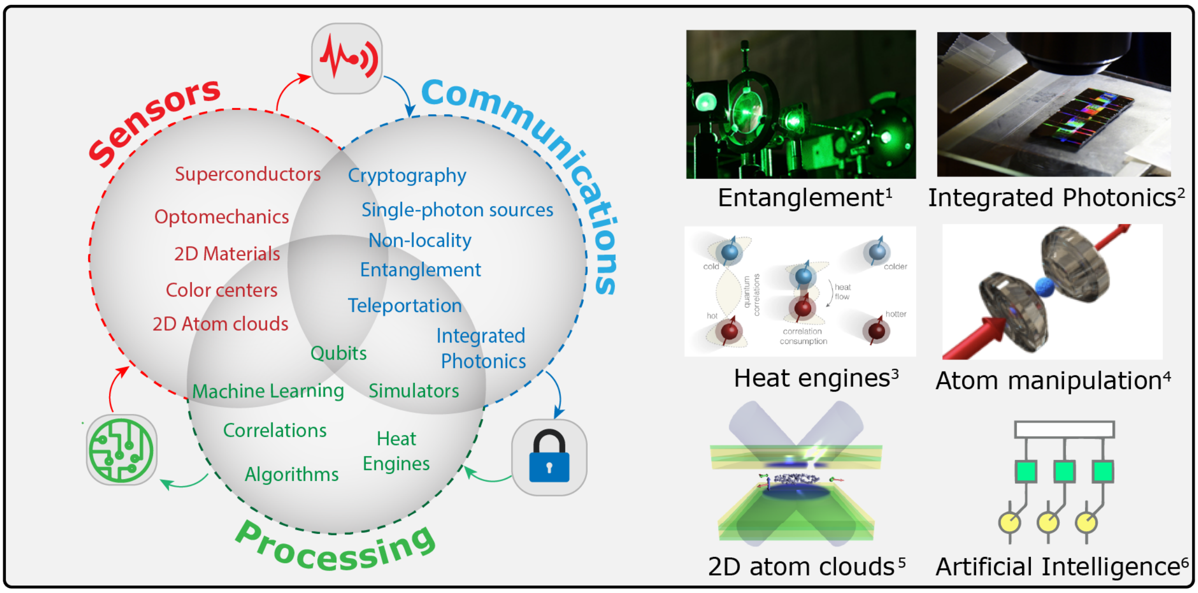


Figure 1. (left) Interbreeding of emerging Quantum technologies. (right) Examples of quantum technologies under development in SP. (1) USP São Paulo; (2) Unicamp; (3) UFABC; (4) UFscar; (5) USP São Carlos; (6) UNESP.

## 3 Global initiatives and State of the art

Advances in computational platforms, which have fueled most of the XXth century technological innovations, are based on the evolution of the physical systems used for information processing. The increase in the number of elements capable of carrying out logical operations within processors has followed an exponential law. The tendency to miniaturize these elements, the transistors, finally approaches physical limits given by the dimensions of individual atoms. In this regime, the laws of quantum mechanics are needed to describe the behavior of matter. For more than thirty years, physicists have realized that new avenues for information processing could be opened up with the appropriate use of the quantum nature of matter.

There are major challenges, both fundamental and technological, for the implementation of universal quantum computers. Much progress has been made and large computing

[3] https://www.bmbf.de/upload_filestore/pub/Quantum_technologies.pdf

companies, such as Google, IBM, Intel, and Microsoft, are investing significant resources in their development. The broader field of quantum information technologies, comprising quantum computing, quantum communication, quantum metrology, quantum sensors etc. is considered strategic.
In quantum computing, 2016 saw the birth of quantum cloud computation, through IBM-Q[4] (later followed by important players like Alibaba[5], D-Wave[6], Rigetti[7], Amazon[8], and Microsoft[9]). In 2019, Google AI Quantum claimed to have reached the "quantum supremacy" regime [Arute (2019)]. The 53 qubit noisy intermediate scale quantum processor Sycamore solved in 200 seconds a problem that would require 2.5 days[10] on the best supercomputer in the world. In 2020, IBM already launched a 63 qubit processor and unveiled a road map proposing at least doubling sizes for each year, planning to reach more than a thousand qubits by 2023[11]. IonQ announced what they claim to be the best quantum processor to date (using trapped ions), and also foresee at least doubling its capacities each year.

China is a clear leader in the development of quantum communications [Qiu (2014), Zhang (2018)]. The satellite Micius, launched in 2016, is a grand technological achievement[12], which has allowed two-way secure communication establishing a relay between China and Europe[13] [Liao (2018)]. Two Chinese cities, more than a thousand kilometers apart, were also connected with no need for a relay. In landlines, Beijing, Shanghai, Jinan, Hefei, and other cities are connected since 2018, using 32 secure nodes to relay cryptographic keys which can be used, e.g., by banks[14].

Such exciting prospects gave rise to quantum initiatives around the world. In 2016, European scientists published the Quantum Manifesto[15], followed by a Quantum Road Map[16], which led to the launch of the European Quantum Flagship[17], in 2017 [Acín (2018)]. This is a 10 year and 1 billion Euro initiative, following the examples of Graphene Flagship and Human Brain Project.

In 2017, *The Economist* focused on quantum technology in its first *Technology Quarterly*[18]. They capture the high expectations with a very clever pun: "the odds are good, the goods odd."

In 2020, a company called Qureca[19] listed relevant quantum initiatives around the world: in addition to China, the U.S. and Europe, they list Canada, UK, France, Netherlands,

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[4] https://quantum-computing.ibm.com
[5] https://damo.alibaba.com/labs/quantum
[6] https://www.dwavesys.com/take-leap
[7] https://www.rigetti.com/
[8] https://aws.amazon.com/braket/
[9] https://www.microsoft.com/en-us/quantum
[10] https://www.ibm.com/blogs/research/2019/10/on-quantum-supremacy/
[11] https://www.ibm.com/blogs/research/2020/09/ibm-quantum-roadmap/
[12] https://www.bbc.com/news/world-asia-china-37091833
[13] https://physics.aps.org/articles/v11/7
[14] https://spectrum.ieee.org/telecom/security/chinas-2000km-quantum-link-is-almost-complete
[15] https://qt.eu/app/uploads/2018/04/93056_Quantum-Manifesto_WEB.pdf,
[16] http://qurope.eu/h2020/qtflagship/roadmap2016
[17] https://qt.eu/about-quantum-flagship/
[18] https://www.economist.com/weeklyedition/2017-03-11

Germany, Russia, Korea, Japan, Singapore, Australia, India and Israel, as illustrated in Figure 2. Each of these initiatives describes some specific targets and reveals the common reasoning of not missing out on a relevant technological wave and to compete for protagonism in its developments.

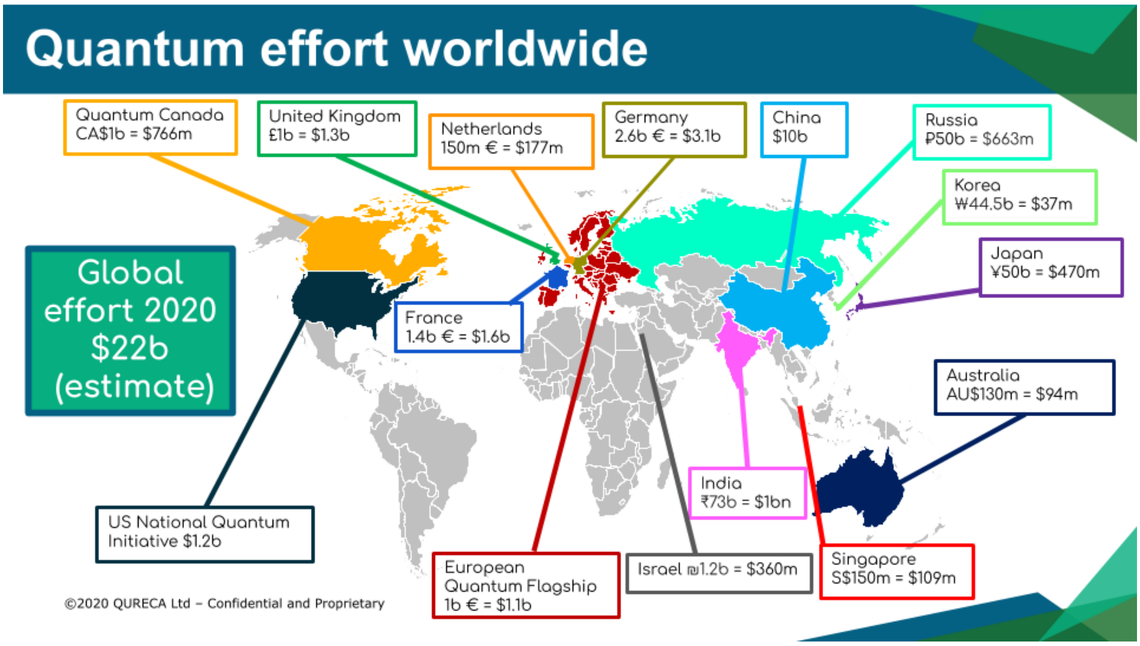


Figure 2. Funding of quantum initiatives worldwide, as organized by QuRECA[20]

China is investing US$ 10 billion in building a National Laboratory for Quantum Information Science in Hefei[21], the European Union approved a € 1 billion Flagship Initiative, and the U.S. Congress passed the Quantum National Initiative Act in December 2018[22], allocating US$ 1.2 billion to support the development of quantum computers.

While Brazil appeared in The Economist's world funding map of 2015, the country is absent from Qureca's map. Indeed, no strategic initiative exists in Brazil, even though funding for quantum information science still persists, albeit at very low levels. We are confident that the quality and strength of our academic community is a valuable asset that must be connected with relevant targets for economic players, and that São Paulo State is the natural starting place for such an endeavor.

## 4 Quantum information science in São Paulo

The development of emerging quantum technologies depends on the presence of a strong research community. In São Paulo, we already have a renowned community of researchers in the field of quantum information, including several early career faculty. In fact, two successive National Institutes of Science and Technology (INCT) in Quantum Information

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19 https://www.qureca.com/, https://www.qureca.com/overview-on-quantum-initiatives-worldwide/
20 https://www.qureca.com/overview-on-quantum-initiatives-worldwide/
21 https://www.wired.co.uk/article/quantum-computing-china-us
22 https://www.quantum.gov/, https://www.congress.gov/bill/115th-congress/house-bill/6227/text

projects were coordinated by Prof. Amir Caldeira, from UNICAMP. The current INCT in Quantum Information is based in Rio de Janeiro, but has a significant participation of researchers from São Paulo. Relevant research groups in the field are found in the major universities in the State: Unicamp (IFGW, IMECC, FEEC), USP in São Paulo city (IFUSP) and in São Carlos (EESC and IFSC), UFSCar, UFABC, and Unesp (in Araraquara and Bauru). FAPESP provided support and currently funds research through thematic projects and several young researcher (JP) projects, directly linked to the field, in addition to fellowships for undergraduates, graduate students, and postdocs. The creation of platforms for implementing quantum computation is not a priority at this time, although there is a team at UFABC working with trapped ions and a young investigator developing superconducting qubits at Unicamp. There are several theoretical and experimental groups addressing aspects of the fundamentals of quantum information and their applications, as summarized in the following list:

- Implementations of computer and communication protocols in quantum optics or condensed matter systems, among others (theory and experiment);
- Investigation of quantum algorithms and implementation in available commercial platforms such as cloud-based quantum computers;
- Theoretical and experimental research on quantum cryptography and quantum communication;
- Generation of single photons via quantum dots and 2D materials and applications in quantum random number generators and quantum cryptography;
- Use of platforms such as optical systems, whether with individual photons or macroscopic beams, optomechanical and nanophotonic systems, diamond color centers, superconducting qubits, among others and applications in quantum information processing;
- Use of cold atomic ensembles for applications in quantum sensing and quantum metrology, as atomic clocks and atomic gravimeters;

A preliminary survey reveals at least 30 principal investigators, with their respective groups, in SP (at universities or research centers), working directly with one or more of the above topics. Considering a somewhat broader range of researchers related to this topic, a compilation of the research throughput within the last 10 years was evaluated and summarized in panels a and b of Figure 3. Beyond the steady increase in the number of citations of these 960 (~96/year) publications, their impact is quite remarkable: the h-index for these publications is 58 and confirms the potential impact of the proposed program. In panel b, a significant number of publications in high-impact journals is also noticeable, which is an indication of this community’s commitment to the highest scientific standards.

# 5 Societal issues and economic perspectives for Sao Paulo State

Novel quantum technologies hold promises of strong impacts on industry, government and people's lives. Yet, the general audience has little grasp of the fundamental science driving such innovations. The dissemination of quantum charlatanism in social media is disturbing and may lead to novel conspiracy theories about the purposes and eventual benefits of emerging technologies.

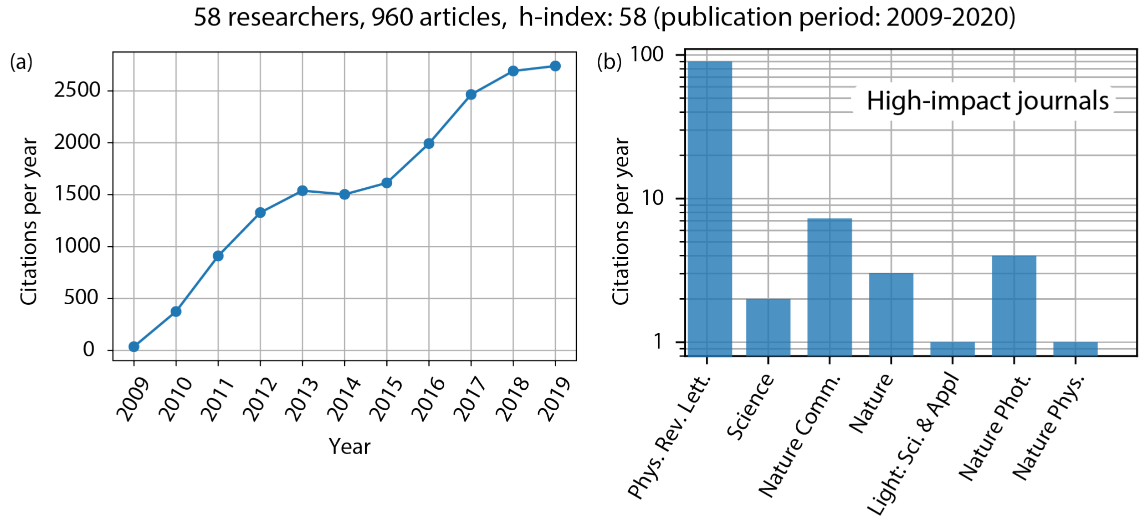


Figure 3. Research throughput of researchers working on quantum technologies and related topics. (a) Number of citations per year. (b) Number of articles in high impact journals. Source: SCOPUS (27/10/2020). Only articles with at least one of the authors affiliated in Brazil were considered.

It is important to boost efforts to make quantum science a familiar topic in the broader population. Quantum information-theoretic views may help the general audience by focusing on quantum mechanics as a novel information theory with less emphasis on its counterintuitive physical predictions [Fuchs (2009), Amaral (2018)].

In a special issue of *Ethics and Information Technologies* [Vermaas (2017)], six authors address policy and ethical issues related to the technological advances that are foreseen, the awareness that must be promoted and policy forums which need to be created. The concept of responsible research and innovation is based on sufficient understanding by all stakeholders for adequate societal debate on public policies to be undertaken.

In order for FAPESP to launch a quantum initiative in the state of São Paulo, we believe that it is of utmost importance to gauge the economic revenue that can be generated by emerging technologies. Interest by large companies is naturally aroused by the development of quantum computing and the already available cloud-based resources. Yet, it is hard to argue that direct economic benefits are to be gained from cloud quantum computing within the next five years, since demonstrations of quantum advantage for practical applications are still currently beyond capabilities of the best processors. On the other hand, smaller scale emerging technologies, such as quantum communications (and byproducts, such as true quantum random number generators), and quantum sensing can be developed within shorter time frames and targeted at the solution of local problems. Of particular interest in the state of São Paulo are sensing technologies for agricultural applications[23], as well as

[23] https://www.insidequantumtechnology.com/news/quantum-tech-one-six-inventions-will-transform-farming/, https://www.newscientist.com/video/2202405-how-quantum-sensors-can-improve-our-lives-and-agriculture/

underground mapping with gravimeters. Magnetic sensing holds promise for numerous applications, including medical imaging.

## 6 Strategic role of Fapesp

As already mentioned and described above, emerging quantum technologies are getting large funding boosts worldwide and will change the industrial landscape in coming years. In the state of São Paulo, we have the most dynamic economic players in the country, from industry to agriculture to finance. Those businesses will need to shift to quantum technologies in the near-term future in order to remain internationally competitive. Our state has built a solid academic reputation, with international recognition, in quantum information science. We need to tap into the enormous potential of such intellectual assets in order to harness the economic benefits of emerging quantum technologies.

FAPESP has a crucial role to play in driving partnerships between universities and the private sector to focus on the development of disruptive technologies which are within reach. We believe that a program on quantum information technologies can significantly enrich the industrial landscape in São Paulo.

We propose a plan to launch such an initiative, beginning with a six-month (plus?) effort to prepare a detailed roadmap of quantum information technologies which can be developed within a timeframe of 5-10 years, with an estimate of economic revenue that can be generated and of jobs to be created. Preparation of this roadmap will require joint efforts from quantum information researchers, economists, private sector partners, government partners, and FAPESP governance. FAPESP can play an important role in this phase by organizing workshops among the different stakeholders, among other efforts.

We believe that this program will attract investments from the private sector, in order to benefit from the state's intellectual assets under such a strategic program. FAPESP should use seed money to promote workshops aimed at the solution of specific industrial, agricultural, and health problems identified in the roadmap (and beyond). There should be ample opportunity to fund startup companies in novel quantum technologies, under the PIPE program.

An effort should be made to improve teaching of quantum science in high schools and to organize scientific outreach to promote wider understanding of quantum science. The Program should include calls for proposals to conduct research in Education and Philosophy departments with this purpose.

São Paulo State must be seen as an attractive destination for young and talented people to pursue careers in quantum information science and technology. Private sector partners will need a well-educated expert workforce and FAPESP should contribute by awarding undergraduate and graduate fellowships to students in academic institutions, as well as establish partnerships for graduate students to develop research projects in industry. FAPESP should advertise the possibilities for (generous) Young Investigator Awards in major international scientific journals on a regular basis.

# 7 Endorsers

During the preparation of this document, we already obtained endorsements of three kinds of players: a range of interested industrial partners, a list of worldwide scientific leaders who could become members of an advisory/evaluation board, and São Paulo State researchers. We list below the industrial partners and scientific leaders contacted so far.

## 7.1 Interested Industrial Partners

- IBM
- Microsoft
- Petrobras
- Wernher von Braun
- Agrorobotica
- Thorlabs
- QCSC - Quantum Computing São Carlos (Startup)
- Embrapa

## 7.2 Worldwide Scientific Leaders

- Andrew White (The University of Queensland, Australia)
- Artur Ekert (University of Oxford, UK)
- Fernando Brandão (Caltech, USA)
- Kai Bongs (University of Birmingham, UK)
- Luiz Davidovich (Universidade Federal do Rio de Janeiro)
- Peter Zoller (University of Innsbruck, Austria)
- Rainer Blatt (University of Innsbruck, Austria)
- Wolfgang Schleich (University of Ulm, Germany)

# 8 Bibliography


Acín, Antonio, Immanuel Bloch, Harry Buhrman, Tommaso Calarco, Christopher Eichler, Jens Eisert, Daniel Esteve, et al. 2018. “The Quantum Technologies Roadmap: A European Community View.” New Journal of Physics **20** (8): 080201. https://doi.org/10.1088/1367-2630/aad1ea.

Amaral, Barbara, and Marcelo Terra Cunha. 2018. On Graph Approaches to Contextuality and Their Role in Quantum Theory. SpringerBriefs in Mathematics. Springer International Publishing. https://doi.org/10.1007/978-3-319-93827-1.

Arute, Frank, Kunal Arya, Ryan Babbush, Dave Bacon, Joseph C. Bardin, Rami Barends, Rupak Biswas, et al. 2019. “Quantum Supremacy Using a Programmable Superconducting Processor.” Nature **574** (7779): 505–10. https://doi.org/10.1038/s41586-019-1666-5.

Fuchs, Christopher A. 2009. “Coming of Age with Quantum Information.” Cambridge University Press. https://doi.org/10.1017/cbo9780511762789.

Liao, Sheng-Kai, Wen-Qi Cai, Johannes Handsteiner, Bo Liu, Juan Yin, Liang Zhang, Dominik Rauch, et al. 2018. “Satellite-Relayed Intercontinental Quantum Network.” Physical Review Letters **120** (3). https://doi.org/10.1103/physrevlett.120.030501.

Qiu, Jane. 2014. “Quantum Communications Leap out of the Lab.” Nature **508** (7497): 441–42. https://doi.org/10.1038/508441a.

Vermaas, Pieter E. 2017. “The Societal Impact of the Emerging Quantum Technologies: A Renewed Urgency to Make Quantum Theory Understandable.” Ethics and Information Technology 19 (4): 241–46. https://doi.org/10.1007/s10676-017-9429-1.

Zhang, G., Haw, J. Y., Cai, H., Xu, F., Assad, S. M., Fitzsimons, J. F., Zhou, X., Zhang, Y., Yu, S., Wu, J., Ser, W., Kwek, L. C., & Liu, A. Q. 2019. An integrated silicon photonic chip platform for continuous-variable quantum key distribution. Nature Photonics, **13**(12), 839–842. https://doi.org/10.1038/s41566-019-0504-5