From the lab to the market: a roadmap to turn quantum science and engineering into a global workforce

Workshop on Quantum Science and Technology
Pontifical Academy of Sciences
https://www.pas.va/en/events/2023/quantum_science.html

Salvador E. Venegas-Andraca
Professor, Tecnologico de Monterrey
Founder and PI, The Unconventional Computing Lab
salvador.venegas-andraca@keble.oxon.org
salvador@venegas-andraca.org
December 2023

Abstract
Quantum Technology is a scientific and engineering field that, due to its pervasiveness and maturity, is now transitioning from the lab to the market. Quantum technology is expected to become a driving force of the global economy. In this paper, we analyse the role of Quantum Initiatives, Education and Technical Training, Technical Norms, Standards, and Tools for production and education, for the advancement of Quantum Technology and its potential use to boost the economic performance of participating societies as well as to decrease the technological and social gaps among nations.

I. Introduction

Cross-pollination between physics and computer science has long been mutually beneficial. For example, R. Landauer used thermodynamics to study the relationship between energy consumption and irreversible computation [1] and C.H. Bennett introduced a reversible version of the Universal Turing Machine [2]. Solid-state physics is the scientific basis of semiconductor-based computer technology [3] and annealing has been used to create a most celebrated stochastic algorithm [4]. Moreover, computer science has been instrumental to advance our understanding of Nature and applied physics [5], being the work of R.P. Feynman along those lines the foundation of quantum computing [6].

Quantum Information Science is a scientific and engineering discipline in which we use quantum mechanics (i.e., the laws of physics that describe the behaviour of objects at atomic scale) combined with computer science, information theory and other fields of science and engineering to collect [*quantum sensors*], generate [*e.g., quantum random number generators*], transmit [*quantum networks*], protect [*quantum cryptography*], compute [*quantum computation*], and store [*quantum memories*] data. Additionally, Quantum Information Science includes the development of classical and quantum algorithms to simulate the behaviour of quantum-mechanical systems.

Based on the scientific discoveries of Quantum Information Science, a large group of universities, research centres and companies have focused on the development of Quantum Technology, being the main goal to identify how to harness quantum-mechanical systems to create products and services that perform better than and/or complement other existing (digital or analogue) technologies, for example faster algorithms, more accurate sensors, and cryptography protocols with higher security levels.

Quantum Technology is expected to coexist with other technologies. For instance, the transmission of both digital and quantum information via the same optical fibre infrastructure [7]. Also, access to existing and future quantum computers is and will be done via digital computers and, most likely, quantum and digital algorithms will work together on solutions that require massive data access and intensive calculations.

The successful deployment and commercialisation of quantum-based products and services will be a complex and long-term endeavour that will require, in addition to continuing efforts on basic and applied scientific research, the development of high-tech tools for engineers and technicians devoted to production, innovative teaching methods, extensive public and private funding, the uninterrupted identification of new applications, industrial standards, novel business models, and new models of value and supply chains (a thorough set of principles for informing stakeholders about the responsible use of quantum computing that could be extended to other quantum technologies can be found in [8]).

Quantum technology is expected to become a driving force of the global economy. At the forefront of basic and applied research as well as at the manufacturing and commercialisation of quantum technology, we find developed nations and large multinational companies that have extensive knowledge and expertise on the creation and advancement of high-tech markets.

To reduce the technological gap among countries and to increase the probability of sharing the benefits of quantum technology worldwide, nations with modest access to expertise and funding must identify how to best use their resources and strengths to create and manage their own quantum technology portfolios (in this endeavour, small- and medium-sized companies, entrepreneurs, and educators will play a crucial role).

In the following sections, I analyse several aspects of the Quantum Technology Ecosystem in order to draft how this new technology can be used to advance the agenda of economic development and, possibly, to decrease the social and technological gaps among nations.

II. The Quantum Technology Market

Quantum technology is indeed unique in several senses. For instance, it allows us to enhance symmetric cryptography protocols by using Nature to create private keys [9,10]. It also provides us with quantum teleportation (a method that has no equivalent in classical physics) to transfer quantum information using quantum and classical channels [11]. Furthermore, quantum computing is a path towards finding new meanings of computation that will likely allow us to accelerate scientific discovery [12].

Nevertheless, the evolution of quantum technology towards the inception and development of high-tech markets and the creation of wealth has many properties in common with other technologies. For instance, the maturity level is a crucial factor for any technology to estimate its likelihood of success and time-to-market. Furthermore, the identification, characterisation, and nurturing of the enterprises that will become providers in the supply and value chains of large companies is a key element in the transition of any technology from the lab to the market.

From the lab to the market: a roadmap to turn quantum science and engineering into a global workforce

The growth of quantum technology markets should follow a *glocal* approach, that is, to define and pursue global goals while, simultaneously, countries, regions, companies, and individuals identify how to best contribute with their capacities and interests to the advancement of quantum technology and the development of themselves and their own local markets. For example, a key motivation for the development of quantum gravimeters in Mexico [13] is the country's interest in studying and developing accurate models of earthquakes and volcano eruptions. So, a local need combined with human talent and (even modest) financial resources can become an opportunity to enter global markets.

In the remainder of this section, I address some aspects of the quantum technology market that would significantly contribute to its flourishing and its potential use to increase the economic performance of participating societies as well as to decrease the technological and social gaps among nations.

II.I National/Regional/Industry Initiatives

The sustained growth of technology markets requires the development and deployment of solid strategies that, based on available financial resources, human talent, and identified market niches, allow countries, regions or industrial organisations to become part of the corresponding supply chains and markets.

Over the last few years, several countries have published their National Quantum Strategies (for example, [14-17]. Additionally, the European Union also has a Quantum Strategy [18]), being those nations amongst the early developers of the scientific foundations of quantum information science and the manufacturing of quantum technology products.

The significant potential impact of quantum technologies on economic growth and societal transformation makes us wonder whether it would be reasonable to expect both developed and developing countries to generate Quantum Initiatives. The history of other technologies like Artificial Intelligence and Cybersecurity may shed some light on this matter: societies that focus on efficient use of their resources to enter and benefit from tech markets also tend to create strategies that are typically presented in national or regional initiatives. Sometimes, those initiatives are drafts or just a collection of academic and industrial goals. Some other times, these efforts are formal initiatives sanctioned by governments. What really matters here is the existence of guidelines, a compass that helps a country align interests and resources.

So, the question should be posed as follows: *when and how should a country choose to define a strategy to enter the quantum market?*

Indeed, in this analysis we must consider two factors, among others: a) the maturity of quantum technology, and b) the available resources of each nation *versus* pressing and urgent needs like fighting extreme poverty.

Let us start with factor b): available resources in countries with limited access to capital and/or human talent. To prosper, a country with modest resources needs to find ways to maximise profit out of its capacities and (potential) strengths. Since becoming active players of technology value chains and markets has extensively proved to be a profitable activity [e.g., 19-21], it makes economic sense to invest in human capital and infrastructure to create and commercialise technology.

Now we could ask: which fields of quantum technology should a country invest its resources in? A possible answer would be: at the intersection of the country's scientific and industrial strengths, the timelines of the quantum technologies in which those strengths could have a positive impact within sensible timeframes, and the identification of *glocal* markets that could be of potential interest. In this analysis, factor a) comes as an essential input: depending on the roadmaps of each quantum technology, the timeframes that governments have to present results, and available human and financial resources, a country can choose the markets that would make most sense to enter.

Time is of the essence on this matter. Sometimes, societies organise faster at a regional level or as groups of interest (for instance, software companies interested in exploring new paths on quantum software). Again, what matters on this regard is to identify how to enter the quantum technology markets. In all cases, the tools of business strategy (like SWOT analysis [22] and the Theory of Constraints [23-25], for instance) would be instrumental.

II.II Education

The advancement of quantum technology as an industry (and, consequently, as fertile soil for creating jobs) will likely require efforts at a global scale [15,26,27]. This is particularly true for education and technical training due to two reasons:

a) The diversity of academic backgrounds, professional interests, and learning styles of potential students.
b) There is a deficit of experts (professors, instructors) available to deliver courses on quantum science and quantum technology.

For quantum technology to flourish, we must educate and provide expedite technical and business training to a massive number of people around the world under the following constraints: limited resources, complex course portfolios and target populations with diverse needs and interests. The quantum workforce will be heterogeneous in several senses, including

- Young students reading for degrees in science and engineering who choose to pursue a career in quantum science and technology (BSc, MSc, PhD degrees).
- Seasoned scientists or engineers who are considering a career switch. They may (or may not) have prior formal training on quantum mechanics and/or computer science.
- Professionals and students coming from fields like economics, business, and politics, who need to understand selected aspects of quantum science and technology in order to legislate, create business opportunities, etc.
- Entrepreneurs.

Good news is that this is a scenario faced by several other technologies in the recent past and today. For example, the solar energy industry:

- For more than three decades, several universities and research centres around the world have offered undergraduate and graduate courses on the fundamental science and engineering of solar systems (e.g., [28]).
- In addition to that, civil society organisations (e.g., [29]) offer technical courses on solar water heating and photovoltaics to mature students who are pursuing a career switch.
- Furthermore, there is an abundant offer of graduate and continuing education courses on the management and business aspects of solar/renewable energy (e.g., [30]).

The physics of solar energy is mainly thermodynamics, electromagnetism, and quantum mechanics. Thanks to the translation of physical principles and laws into engineering rules and technical standard practices (e.g., measuring Voltage-Current output of solar cells without explaining the photoelectric effect or the electromagnetic derivation of Kirchhoff's circuit laws), it has been possible to create a course portfolio aimed at various engineering degrees and training certificates for technicians. This is still a pending task in quantum technology courses: building language bridges that allow us to translate concepts and calculations of quantum mechanics and quantum information science into engineering rules and technical standard practices.

Training full- or part-time professionals who are considering a career switch or career move imposes a severe constraint: available time to attend lectures and to study. In addition to existing online, in-company and intensive courses, a key step will be to foster the use of AI technology in novel online courses fully running on mobile devices that detects the level of expertise of the user and, based on that, selects exercises and learning materials.

As for selected topics of quantum technology for professionals with non-technical backgrounds and interests within the domain of business or politics, it is crucial to create content that supports decision-making processes. This is particularly important in countries and regions in which quantum technology markets, policies, and regulations are in an early stage of development. For the sake of communication agility, content should be produced in the native languages of the countries that such content will be consumed (this is in contrast to technical content that is usually produced and consumed in English.)

Finally, and this is particularly important to entrepreneurs as well as small- and medium-sized companies working on countries with nascent economic activities in high-tech markets, crash courses and continuous follow-up on the legal, financial, and intellectual property facets of entrepreneurship and tech businesses are pivotal. For instance, proper training on Intellectual Property would enable a small company to make sensible decisions regarding the financial health of the organisation and the legal paths that could protect them from legal action and potential takeovers from larger, more powerful companies.

II.III Considerations on Standards and Tools

Technical Norms and Standards

Technical norms and international standards are essential elements of robust engineering practices. Together with mathematics and physics, norms and standards constitute a common language among engineers and technicians to build large and functional projects.

As for quantum technology, the temporal pertinence of developing technical norms and standards depends on the technological maturity of each subfield. For example, it may be too early to write standards for quantum computer technology (although some efforts are currently being carried out [31]) but certainly not for quantum key distribution [32,33] and quantum communications [34].

Both norms and standards tend to be the result of collective efforts but stakeholders must ensure that their views are considered by having an active participation in their technical communities. This fact becomes increasingly important in a multilateral world in which an ample number of organisations and individuals may and will participate, with expedite access to digital channels, in the making of (possibly *de facto*) norms and standards that are sanctioned by their own communities instead of established organisations.

To illustrate this last point, let us review the case of C and Python, two most famous computer programming languages.

- C has several standards, being the most popular the versions released by ANSI [35] and ISO/IEC [36]. ANSI, ISO and IEC are large organisations that have worldwide impact on thousands of (profit and non-profit) companies and other stakeholders.

- The reference implementation of Python, a language which is written in C largely following [35], evolves via the Python Enhancement Proposal (PEP) Process. A PEP is a procedure followed to propose new features and design changes in Python. PEPs are analysed by the Python community and are accepted or rejected by the Steering Council which is composed by five people.

So, standards are made and released following different methods, e.g., via meta-organisations or self-organisation.

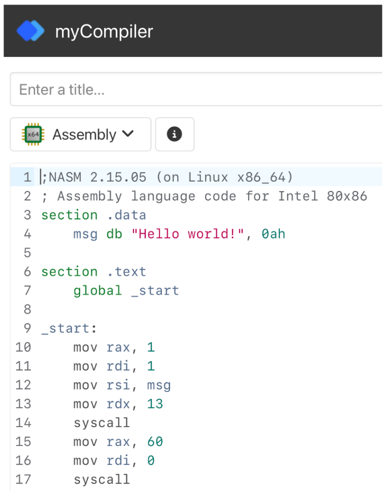
Tools

The success of Information Technology has largely relied on the tools that have been developed to use digital systems in our lives. In particular, advanced programming language environments as well as specialised software platforms (e.g., simulation of manufacturing plants, software for *in silico* analysis of biological systems, and rapid prototyping environments, among many other applications) have been essential to build the Perceived Usefulness of Information Technology.

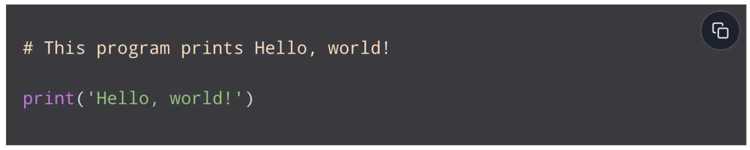
A similar path is likely to be followed by quantum technology: we need advanced tools to increase our productivity (for instance, to design quantum algorithms as well as to assess configurations of quantum sensors and quantum networks.)

To illustrate the importance of building advanced tools to create technology, we present in Fig. (1) three different ways to produce **Hello World**. Exhibit a) shows the assembly language code (80x86), b) presents the Python 3.x code, and c) the same message in Minecraft. The cost of writing assembly code for large projects would be prohibitive, this is why languages like C, C++, and Python were built. Exhibit c) is an example of *Gamification*, a relatively new trend in teaching computer science that aims at engaging students with visual learning styles.

Standard tools to develop quantum algorithms are visual representations of quantum circuits (e.g., [37]) and QASM (Quantum Assembly Language) [38] which are powerful platforms that will likely be the basis of further developments. Moreover, several additional efforts have been made along these lines [39-41] and we need to keep pushing in this direction. The design of these tools would benefit from a multidisciplinary approach that ensures considering the learning styles of the workforce as well as novel methods of working and learning.



a) Hello world in Assembly language code for 80x86. My Compiler (IDE online)



b) Hello world in Python 3.x Programiz (IDE online)

c) Hello world in Minecraft [Gamification] Te@ch with ICT

Fig. (1)

III. Conclusions

Quantum Science and Quantum Technology are decisively transitioning from the lab to the market. The successful deployment and commercialisation of quantum technologies will be a complex and long-term endeavour that will have some unique features as well as several properties in common with the commercial evolution of other technologies.

To shape the future of quantum technologies, we can make use of best practices built for other technologies (e.g., standards and technical norms) as well as to explore new paths in which our creativity will be paramount (e.g., AI-assisted novel educational tools). Quantum technology markets (as well as other technologies like Machine Learning and Cybersecurity) may become outstanding opportunities for countries with limited access to funding and expertise to overcome their current constraints towards becoming full members of the knowledge society. This could be a via regia towards decreasing the technology gap between nations while simultaneously increasing their internal capacity to build wealth.

Acknowledgements

The author would like to thank Luis Alberto Muñoz-Ubando (Tecnologico de Monterrey, Escuela de Ingenieria y Ciencias), Alfonso Avila Robinson (Tecnologico de Monterrey, EGADE Business School), Diego Santiago Alarcon (University of South Florida), Hector Mejia Diaz (Tecnologico de Monterrey, Escuela de Ingenieria y Ciencias), Ahmed A. Abd El-Latif (Prince Sultan University) and Víctor Gutiérrez-Martínez (CEO, Plenumsoft) for their insightful comments and numerous conversations we have held on the subjects of high-tech business and economic development.

References

[1] Irreversibility and heat generation in the computing process. R. Landauer, IBM J. Res. Dev. 5(3), 183–191 (1961).
[2] Logical reversibility of computation. C.H. Bennett. IBM J. Res. Dev. 17(6),525–532(1973).
[3] The Physics of Semiconductors. Marius Grundmann, Springer International Publishing (2021).
[4] Optimization by simulated annealing. S. Kirkpatrick, C.D. Gelatt, Jr., and M.P. Vecchi. Science 220(4598), 671–680 (1983).
[5] Computational Physics: Problem Solving with Python (3rd Ed). R.H. Landau, M.J. Páez, and C.C. Bordeianu. Wiley (2015).
[6] Simulating Physics with Computers. R.P. Feynman. International Journal of Theoretical Physics 21, 467–488 (1982).
[7] Quantum technologies in the telecommunications industry. V. Martin, J.P. Brito, C. Escribano, et al. EPJ Quantum Technol. 8, 19 (2021).
[8] Quantum Computing Governance Principles. The World Economic Forum (2022).
[9] Quantum cryptography: Public key distribution and coin tossing. C. H. Bennett and G. Brassard. In Proceedings of IEEE International Conference on Computers, Systems and Signal Processing, 175, 8 (1984).
[10] Quantum cryptography based on Bell's theorem. A.K. Ekert. Physical Review Letters 67 (6), 661–663 (1991).
[11] Teleporting an unknown quantum state via dual classical and Einstein-Podolsky-Rosen channels. C.H. Bennett et al. Physical Review Letters 70, 1895–1899 (1993).
[12] Molecular design with automated quantum computing-based deep learning and optimization. A. Ajagekar and F. You. npj Computational Materials 9, 143 (2023).
[13] Mexican Initiative on Quantum Technologies. Quantum Information Division of the Mexican Society of Physics (2023).
[14] USA National Quantum Strategy. National Science and Technology Council and Executive Office of the President of the United States (2018).
[15] UK National Quantum Strategy. Department for Science, Innovation and Technology (2023).
[16] Strategy of Quantum Future Industry Development. Secretariat of Science, Technology and Innovation Policy, Cabinet Office, Japan (2023).
[17] Quantum Spain. Ministry of Economic Affairs and Digital Transformation of the Spanish Government (2022).
[18] Quantum Technologies Flagship. European Commission, The European Union (2018).
[19] Science and technology in economic development. H.M. Phillips. International Social Science Journal, XVIII, 3, p. 325-344 (1966).
[20] The Role of Science, Technology and Innovation Policies in the Industrialization of Developing Countries. Lessons from East Asian countries. D.U. Park et al. United Nations Industrial Development Organisation and the Science and Technology Policy Institute of the Republic of Korea (2021).
[21] Direction of innovation in developing countries and its driving forces. X. Fu and L. Shi. Economic Research Working Paper No. 69, World Intellectual Property Organisation (2022).
[22] Harvard Business Essentials. Strategy. Harvard Business School Press (2005).
[23] The Goal: A Process of Ongoing Improvement. E.M. Goldratt. North River Press (1986).
[24] It's not Luck. E.M. Goldratt. North River Press (1994).
[25] Essays on the Theory of Constraints. E.M. Goldratt. North River Press (1998).

[26] Australia National Quantum Strategy. Department of Industry, Science and Resources, Australian Government (2023).
[27] Quantum Economy Blueprint. The World Economic Forum (2024).
[28] The MIT Energy Initiative. Massachusetts Institute of Technology (2006).
[29] Photovoltaics: Design and Installation Manual. Solar Energy International (2004).
[30] Renewable and Sustainable Energy Programs (MBA and Specialisation Programs). The University of Colorado Boulder (2023).
[31] P3120 Standard for Quantum Computing Architecture. The IEEE Standards Association (2023).
[32] ISO/IEC 23837-1:2023(en) Information security — Security requirements, test and evaluation methods for quantum key distribution — Part 1: Requirements. The International Organization for Standardization and The International Electrotechnical Commission (2023).
[33] ISO/IEC 23837-2:2023(en) Information security — Security requirements, test and evaluation methods for quantum key distribution — Part 2: Evaluation and testing methods. The International Organization for Standardization and The International Electrotechnical Commission (2023).
[34] Quantum standards. The NPL Quantum Programme, The National Physical Laboratory, UK (2023).
[35] C89/C90 (ANSI C). American National Standards Institute (1989-1990).
[36] ISO/IEC 9899:2018. C Programming Language Standard. The International Organization for Standardization and The International Electrotechnical Commission (2018).
[37] Qiskit Textbook. IBM Quantum Learning (2023).
[38] OpenQASM 3: A Broader and Deeper Quantum Assembly Language. A. Cross et al. ACM Transactions on Quantum Computing Vol. 3(3), article no. 12, pp 1–50 (2022).
[39] Amazon Braket (2023).
[40] Pennylane. Xanadu (2023).
[41] Quantum Benchmarking Project. DARPA, US Government (2023).