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Export Controls as Innovation Marketing? Sociotechnical Imaginaries in the Ringfencing of Quantum Technologies

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Abstract

Why are a host of states, such as the United States, Canada, the United Kingdom, France and the Netherlands, imposing export controls on quantum computers with technical specifications (e.g. 2000 qubits) that are not yet realisable? No full-fledged 'useful' quantum technology (QT) exists yet; instead, the regulatory object of export controls is the network of technological artefacts (equipment, prototype, proof-of-concepts), people and labs (the 'assemblage' of quantum innovation) endeavouring to make quantum a reality. Thus, export controls serve mainly as a tool of knowledge regulation over critical knowledge and R&D exchanges taking place to realise the quantum ambition. This article contends that it is not the material reality of quantum innovation – which is still mired in major engineering challenges – that informs export control efforts surrounding QT, but rather the 'sociotechnical imaginary' of quantum that serves as the 'muse' for law- and policy-makers. Quantum imaginaries are pivotal to understanding the rationales of QT export controls and the narratives in which they are entrenched. It is not necessarily the '2000 qubits' in and of themselves, their technical (non-)feasibility or (non-)realisability, but rather the imaginaries told and believed about their technological possibilities and power that are decisive in the ringfencing performed by export controls on QT.

***Keywords**:* Export controls; quantum technologies; innovation marketing; sociotechnical imaginaries.

Here is the essence of mankind's creative genius: not the edifices of civilization nor the bang-flash weapons which can end it, but the words which fertilize new concepts …
Dan Simmons, *Hyperion*[1]

1. Introduction: Export Controls as a 'Go-to' Legal Instrument to Ringfence Quantum Technologies

The saliency of quantum technologies (QT) cuts across all domains of science, industry and the state. In an era of 'GeoTech Wars', state involvement in quantum innovation to reach 'quantum supremacy' seems like a foregone conclusion.[2] The United States has already 'blacklisted' QT transfers to almost all major Chinese quantum actors.[3] Amidst the sense of urgency for states to ringfence their quantum innovation spaces, in the past years the governments of Spain,[4] France,[5] Denmark,[6] the United

[1] Simmons, Hyperion, 191.
[2] Choi, "Quantum Supremacy."
[3] Additions of Entities to the Entity List, Document no. 89 FR 41886 (Rule of the Bureau of Industry and Security, effective 9 May 2024).
[4] Spanish Order ICT/534/2023 of 26 May 2023.
[5] French Order ECOI2401482A of 2 February 2024
[6] Amendment to the Danish Export Control Act by Act No. 641(11 June 2024).

Kingdom,[7] Canada,[8] Italy,[9] Germany,[10] Finland,[11] Norway,[12] the United States[13] and the Netherlands[14] have announced virtually identical export controls on quantum computers operating with up to 2000 quantum bits ('qubits'). Similar export control restrictions were imposed in South Korea,[15] with further restrictions planned in Japan.[16]

Strangely, the greatest number of qubits ever achieved was 1121 qubits by IBM's Condor quantum processor in December 2023.[17] No quantum players in any of the jurisdictions imposing export controls on quantum computers have come close to surpassing IBM, let alone the ambitious parameter of '2000 qubits'. Are these export controls with hypothetical qubit capacity a deliberate measure of 'innovation marketing' to signal states' quantum ambitions and preparedness to protect any technological breakthroughs that will eventually emerge from their respective ecosystems? Are these measures pre-emptive or premature?

This article interrogates why export controls are imposed on QT, particularly with technical specifications (e.g. 2000 qubits) that are not yet realisable. To answer this question, the article proceeds in three steps: first demystifying the nature of QT and their sociotechnical assemblage (Section 2); second examining current QT export controls (Section 3); and third, presenting three quantum imaginaries that have coproduced narratives, in which QT export controls are grounded (Section 4). The imaginaries and narratives section will further touch upon why the recent wave of export controls has not restricted other QT, such as quantum sensing or quantum communication technologies, but instead only zeroed in on quantum computers, which typically conjure up powerful sociotechnical imaginaries that animate policy action and permeate regulatory choices in the export control space.

The imposition of export controls on emerging and cutting-edge technologies with dual-use potential is by no means unique to quantum innovation. The chase after a technology's potential and the subsequent ringfencing through export controls can be seen in export restrictions on other promising technologies, such as advanced semiconductor chips and manufacturing equipment crucial for developing next generations of AI.[18] This article explores the dynamics of export control law and policy at a specific moment in time when a technology, such as QT, has yet to materialise with any viable (commercial) utility, yet because of its (borderline) fantastical hype inspires regulatory fervour to ringfence access to technology that is still condemned to always be five or ten or even 20 years away.[19]

By adopting the concept of sociotechnical imaginaries to understand the ringfencing performed by export controls on QT, this article contributes to ongoing export control discussions, which until now have been contextualised and historicised by the literature and perspectives of international relations, geopolitics and geoeconomics.[20] Considering the sociotechnical imaginaries shaping export control law-making adds new contours and dimensions to our current understanding of the geopolitics of technology, showing that it is not merely pure power politics (between nations, corporations and scientific institutions) that moves the grand projects of crossing technological frontiers but also the imaginaries of frontier technologies constructed and believed by the actors involved.[21]

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[7] UK Export Control (Amendment) Regulations 2024 (SI 2024 No. 346)
[8] Canadian Order Amending the Export Control List: SOR/2024-112
[9] Italian Decree of 1 July 2024 establishing the National Control List for dual-use goods and technology not listed in Annex I to Regulation (EU) 2021/821
[10] Amendment to the German Foreign Trade Ordinance, *Federal Law Gazette* 2024, No. 243 (22 July 2024).
[11] Finnish Act on the Export Control of Dual-Use Items (500/2024) (16 August 2024)
[12] Amendment to the Norwegian Export Control Regulations (3 October 2024).
[13] US Bureau of Industry and Security Rule 2024-19633 (89 FR 72926) of 6 September 2024
[14] Regulation of the Netherlands Minister for Foreign Trade and Development Aid of 11 October 2024, nr. BZ2405833.
[15] South Korean Amendment of 24 February 2023 to the Public Notice of Special Measures on Trade to Undertake Obligations for International Peace and Security Maintenance
[16] Furukawa, "Japan Tightens."
[17] Gambetta, "Hardware Software."
[18] See, for instance, Hrynkiv, "Not Trading with the Enemy," 63ff or more popularised accounts in Miller, Chip Wars, 201, 299, 301.
[19] For instance, voiced by Google CEO Sundar Pichai and Microsoft founder Bill Gates. Similarly, when Nvidia CEO Jensen Huang voiced the '20 years' assessment for the development of a useful quantum computer, stocks of publicly listed quantum companies plummeted: see Swayne, "Practical Quantum Computing" and Aaronson, "Quantum Stock Crash." Google and Microsoft are involved in full-stack quantum computing development, while Nvidia is involved in cloud provision for quantum computing services.
[20] Cain, "Computers Cold War," 131–147; Wu, Export Restrictions, 172–178; Zhang, "US–China Trade War," 41–59; Hrynkiv, "Not Trading with the Enemy," 63ff; Paulsen, "Economic Security," 10–11.
[21] Jasanoff, Dreamscapes, 22.

2. Demystifying the 'Frontier-ness' of Quantum Technologies

The hype surrounding QT – especially its poster child, the quantum computer – tends to border on the fantastical. Quantum computers have been hailed as being able to simulate and find new materials and chemical compounds that can help solve climate change and cure cancer.[22] Simultaneously quantum computers are believed to be able to crack all existing encryption, opening the floodgates to cyberattacks that could 'break the internet' ('Q-Day').[23] Quantum sensors could sense objects underground, beyond walls and what is out of vision. They promise perfect transparency of the world, materials, the human body and the Earth.[24] Quantum communication technologies could alter the idea of online communication, provide unhackable communication, bend time and warp reality.[25] This section demystifies these claims to put our feet back on the ground and understand what kind of QT are subject to export controls.

The QT discussed in this article are the so-called 'second-generation' QT – as opposed to first-generation QT premised on the manipulation of the interaction between quantum particles (photons, atoms, electrons)[26] such as nuclear power, semiconductors and lasers.[27] Second-generation QT are premised on the direct manipulation and control of the quantum states of these particles to exploit their quantum mechanical properties.[28]

Fundamental to understanding QT – particularly quantum computers – is its building block, the quantum bit ('qubit'). Qubits are quantum mechanical systems that can be generated by manipulating atoms, ions, electrons, photons, molecules or quasiparticles so they enter into a quantum state. In this state, quantum mechanical properties such as superposition, interference or entanglement can be exploited.[29] There are five major challenges to harnessing the computational and information processing powers from these quantum mechanical properties of qubits:

- *The difficulty in creating conditions for quantum states*. Qubits are fragile. Any interaction between qubits and the outside ('classical') world will make them lose their desired quantum state ('decohere'). Thus, there is a substantial engineering barrier to building the hardware to perfectly isolate qubits from 'noise', which includes light, sound, air, heat, electromagnetic interferences and cosmic rays.[30] The current state of quantum computing is referred to as the noisy intermediate-scale quantum (NISQ) era, in which quantum computers are still prone to noise and thus have no 'quantum advantage' over classical computers.[31]
- *The difficulty in creating 'error free' qubits*. Qubits are also error prone. Thus, a large proportion of qubits must be dedicated to error-correction routines that keep a computation on track. Currently a ratio of about 30–10,000 physical ('redundant') qubits is needed to error-correct for one a logical ('useful') qubit.[32]
- *The difficulty of interacting with qubits*. To harness the computational powers of qubits, we must be able to input commands and controls to 'tell' a qubit what to do. This, however, is greatly complicated because the qubit is prone to decoherence upon interacting with the 'classical' world.[33]
- *The difficulty of scaling up qubits*. Adding more qubits complicates the control over how all qubits may interact with each other.[34] The increased coherence of qubits seems to be only possible at the cost of qubit speed. Protecting a qubit from its noisy surroundings also limits control over it. This is referred to as the qubit speed-coherence dilemma: qubits are either coherent but slow or fast but short-lived.[35]
- *The difficulty in designing quantum algorithms*. Quantum computers are often said to be revolutionary because qubits being in 'superpositions' (instead of binary 0 or 1) can calculate 'all possibilities all at once'. This is a skewed understanding, as we would still need to figure out which one of presumably thousands of millions of possibilities is the correct answer. Thus, quantum algorithms must be designed to properly 'read out' the correct answer – otherwise,

22 TNO, "Future Quantum"; McKinsey, "Quantum Computing."
23 Conover, "Quantum Computers."
24 Ezratty, Understanding Quantum, 781ff.
25 Ezratty, Understanding Quantum, 686ff.
26 Dowling, "Quantum Technology."
27 Krelina, "Quantum Technology."
28 Aspect, "Second Quantum Revolution."
29 Aspect, "Second Quantum Revolution."
30 Brooks, "Quantum Computers."
31 Ezratty, Understanding Quantum, 226.
32 Ezratty, Understanding Quantum, 164.
33 Aaronson, "Quantum Computing."
34 Nature Videos, "Quantum Computers," 0:48.
35 Carballido, "Compromise-Free Scaling."

upon 'reading out' information from a qubit system, one would merely get a random (incorrect) answer from all possible answers.[36]

Consequently, taking these engineering challenges seriously will sober up our evaluation of the hype surrounding QT. The mathematical and quantum mechanical foundations of QT are theoretically sound and have been experimentally proven.[37] As such, QT is not a speculative technology; however, because of these engineering hurdles, the field is still exploratory and uncertain. A *Nature* article puts into perspective: 'Even with 2 million qubits, some quantum chemistry calculations might take a century … breaking state-of-the-art cryptography in 8 hours would require 20 million qubits.'[38]

While there may be hope that QT is already at the cusp of commercialisation, most QT firms are still in the R&D phase, and few have reached the phase of full-fledged commercial scale-up. There is no QT with (commercial) utility. However, there are sites of QT labs, where proofs-of-concept, prototypes and demonstrators are built and reported on in prestigious journals such as *Nature, Science* and *Physical Review Letters*.[39] These quantum R&D artefacts are taken as proxies and reported as 'quantum technologies'. Consequently, the relevant sites to study QT are in fact the 'quantum labs' across all sectors of government, industry and academic R&D.

This article borrows the concept of 'sociotechnical assemblage' from Jarrahi and Sawyer, who theorised it within the context of tabletop computing as a 'heterogonous network of people, visions, concepts, technological artifacts, and organizations that come together to enable innovation'.[40]

In this vein, the 'sociotechnical assemblages' of quantum innovation encompass not only the artefacts of proofs-of-concept, prototypes and experimental setups but the entire innovation value chain. This includes the 'value-adding' activities and interactions of physicists, engineers, computer scientists, technologists and technicians across the innovation value chain as well as the material supply chains of highly advanced equipment for quantum labs. Thus, devices such as cryogenics (dilution refrigerator, Helium-3, cryogenic cables), nanofabrication systems (superconducting materials, lithography equipment), photonic sources (lasers, modulators, interferometers), vacuum equipment (vacuum pumps, chambers, isolators), precision electronics (photon detectors, control, measurement equipment) and ion and atom dispensers (strontium, rubidium, iodine are common elements used in quantum labs) could come within the purview of technological ringfencing of quantum innovation.[41] As a result, the 'sociotechnical assemblages' of quantum innovation is a means of understanding what is even there and what is even real about quantum without succumbing to its hyped-up conceptions. To give credence to the material reality of current QT developments, this article concretises the regulatory object of QT export controls as not QT *per se*, but rather the broader 'sociotechnical assemblages' of quantum innovation.

While the regulatory object of QT export controls is the 'sociotechnical assemblages' of quantum innovation, this article contends that these assemblages are not the driving force behind QT export controls. To understand why export controls are imposed early in the R&D phase, when QT is still mired in engineering challenges and prophesied to always be five to ten to 20 years away, this article relies on Jasanoff and Kim's concept of 'sociotechnical imaginaries'. These are 'collectively held and performed visions of desirable futures (or of resistance against the undesirable), and they are also animated by shared understandings of forms of social life and social order attainable through, and supportive of, advances in science and technology'.[42]

Imaginaries surrounding QT, which are fuelled by the hype of utopia (solving climate change and curing cancer) and premonition of dystopia (breaking all public key encryption), link up to the central inquiry of this article about the seemingly 'performative' nature – that is, the 'innovation marketing' aspect of export controls on quantum computers with hypothetical '2000 qubit' capacity that is not yet realisable. As Jasanoff points out, 'The performative dimension of sociotechnical

[36] Aaronson, "Quantum Computing."
[37] Zeilinger, Dance of Photons.
[38] Brooks, "Quantum Computers."
[39] Kim, "Evidence for Utility"; Hamlin, "Extreme Diamond"; Lia, "Satellite-Relayed."
[40] Jarrahi, "Networks of Innovation."
[41] This draws on more extensive supply chain mapping of QT R&D labs conducted as part of the author's empirical research within a PhD project, 'Legal Dynamics in the governance of quantum technologies innovation value chains' at the University of Amsterdam (Netherlands). The technical veracity of the mapping has been externally verified by a quantum technology and supply chain specialist based at the Netherlands Organisation for Applied Scientific Research (TNO), an independent statutory research organisation.
[42] Jasanoff, Dreamscapes, 19.

imaginaries, however, also relates this term to concepts more closely linked to instrumental political action – in other words, to policy as well as politics.'[43]

Quantum imaginaries help to reconcile why current QT export controls set out to regulate quantum computers of their hypothetical '2000 qubit' capacity, which is far removed from the current state of the art. Despite the major engineering challenges of creating (error-free) qubits, interacting with them, scaling them up and designing algorithms to obtain the correct answers from their calculations, quantum imaginaries serve as a muse for the law and policy-making process, which defies the often lustreless and convoluted reality of quantum innovation.

3. The Law of Export Controls on Quantum Technologies

This section presents three ways in which export controls are designed to sink their regulatory hooks into the transfer of QT outside the territory of the regulating state: (1) through restrictions on QT as such; (2) through restrictions on the material supply chains of QT; and (3) through restrictions on the 'intangibles' (software, IP, algorithms) and knowledge exchange in the R&D and production of QT.

3.1 Export Controls on QT as Such[44]

Export controls impose restrictions – for example, a licensing or authorisation requirement – on the transfer of certain technologies outside the territory of the regulating state. These controlled technologies are either military or dual-use technologies. Export controls can set up a list of entities to whom the technology export is restricted, or regulate according to technical specifications of a controlled technology.

In May 2024, the US Export Administration Regulation added 37 Chinese quantum industry and research institutions to its Entity List.[45] These are deemed to be 'acquiring and attempting to acquire US-origin items in support of advancing China's quantum technology capabilities, which has serious ramifications for US national security given the military applications of quantum technologies'.

Spain, France, Denmark, Italy, Germany, Finland and the Netherlands made use of the Article 9 EU Dual-Use Regulation,[46] which allows EU states to prohibit or impose an authorisation requirement on the export of dual-use items not included in the Regulation's Annex I (at the time of writing this Article does not include QT). Between 2023 and 2024, the governments of Spain (May 2023), France (February 2024), the United Kingdom (April 2024), Denmark (June 2024), Canada (June 2024), Germany (July 2024), Italy (July 2024), Finland (August 2024), Norway (October 2024), the United States (September 2024) and the Netherlands (October 2024)[47] have all adopted export restrictions on quantum computers (a QT *as such* – the 'end product') with virtually identical technical specifications:

> Quantum computers and related electronic assemblies and components therefor, as follows:
>
> a) Quantum computers, in accordance with the following requirements:
> 1. Quantum computers supporting *34 or more, but fewer than 100*, fully controlled, connected and working *physical qubits*, and having a C-NOT error of less than or equal to 10^{-4}
> 2. Quantum computers supporting *100 or more, but fewer than 200*, fully controlled, connected and working *physical qubits*, and having a C-NOT error of less than or equal to 10^{-3}
> 3. Quantum computers supporting *200 or more, but fewer than 350*, fully controlled, connected and working *physical qubits*, and having a C-NOT error of less than or equal to $2x10^{-3}$
> 4. Quantum computers supporting *350 or more, but fewer than 500*, fully controlled, connected and working *physical qubits*, and having a C-NOT error of less than or equal to $3x10^{-3}$
> 5. Quantum computers supporting *500 or more, but fewer than 700*, fully controlled, connected and working *physical qubits*, and having a C-NOT error of less than or equal to $4x10^{-3}$
> 6. Quantum computers supporting *700 or more, but fewer than 1100*, fully controlled, connected and working *physical qubits*, and having a C-NOT error of less than or equal to $5x10^{-3}$
> 7. Quantum computers supporting *1100 or more, but fewer than 2000*, fully controlled, connected and working *physical qubits*, and having a C-NOT error of less than or equal to $6x10^{-3}$

[43] Jasanoff, Dreamscapes, 20.
[44] In this analysis, 'QT as such' refers to also QT prototypes, proof-of-concepts and demonstrators.
[45] Additions of Entities to the Entity List, Document no. 89 FR 41886.
[46] Dual-Use Regulation (EU) 2021/821.
[47] See notes 4–14 above.

8. Quantum computers supporting *2000 or more* fully controlled, connected and working *physical qubits* …[48]

These export restrictions define in their accompanying Technical Notes that a 'physical qubit' is 'a two-level quantum system used to represent the elementary unit of quantum logic by means of manipulations and measurements that are not error corrected'.[49] These rules cover different forms of qubit models including 'semiconductor, superconducting, and photonic qubit chips and chip arrays; surface ion trap arrays; other qubit confinement technologies; and coherent interconnects between such items'.[50]

As explained in Section 2, qubits are error prone and thus need to undergo error-correcting routines in order to become a 'logical' ('useful') qubit. 'Logical qubits' are 'physical qubits' that have been 'error corrected'. Therefore, the technical specifications also include a 'C-NOT error' rate, which the rules define as 'the average physical gate error for the nearest-neighbour two- "physical qubit" Controlled-NOT (C-NOT) gates'.[51] Essentially, a C-NOT gate is a two-qubit operation and acts as one of the basic building blocks of a quantum circuit.

Between February and October 2024, when multiple European governments announced these identical export restrictions on quantum computers, the rules were not accompanied by specific scientific or technical explanations of the specific thresholds for the qubit number and C-NOT error rate. For instance, the Dutch Minister for Foreign Trade and Development noted in an Explanation accompanying the new export control rules that quantum computers, being part of the controlled technology, 'make a crucial contribution to certain advanced military applications and thus have a significant impact on national and international security policy'.[52]

The scientific community's reaction was reserved and sceptical. These identical restrictions were deemed as 'mysterious', with concerns expressed about the lack of 'scientific reason' or even lack of 'basis in science' for these restrictions as well as the 'secret international discussions' in which these technical specifications had been negotiated.[53] Quantum computing experts were reportedly 'baffled' by specifications, which were perceived as 'pointless' or making 'no sense'.[54] These 'secret' negotiations refer to confidential talks under the Wassenaar Arrangement, a non-binding multilateral export control regime that allows participating member states to better coordinate export restrictions on military and dual-use technologies.

Then, on 9 September 2024, the US Bureau of Industry and Security handed down an Interim Decision on Commerce Control List Additions and Revisions, which included the restrictions on quantum computers.[55] The Interim Decision explains that the qubit number is a measure of 'engineering advances in component design and system integration that will enable scaling of quantum computers to very large systems',[56] whereas the 'C-NOT error' rate is a 'measure of the quality of the qubit'.[57] These two metrics combined are intended to indicate certain technological advances in the development of quantum computers. As such, the metrics for the qubit number and C-NOT error must be assessed together to form a certain threshold reflecting incremental technological advances. This seems to suggest pre-emptive ringfencing of specific ranges of piecemeal advances in varying degrees of quantum computing performance to 'future-proof' the necessary material (and knowledge) resources, ensuring that such advances in computational power do not fall into the wrong hands.

The Interim Decision does not include explanations for the numerical choice of each of the eight thresholds set out in the export control rules. It explains that the uppermost threshold of 2000 qubits was set because this is the point of 'plateau'. Concretely, the necessary error rate increases with increased qubit count but plateaus around 2000 qubit (with an error rate at 10^{-2}). The lower threshold of 34 qubits was chosen because it 'represents a high level of technological sophistication warranting national security, regional stability, and antiterrorism controls'.[58] Most likely, these rationales would also be applicable to the identical technical specifications adopted by the United States' European counterparts.

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[48] See legislative text of UK, Canada and US export control rules, notes 7, 8, 13 (emphasis added).
[49] For example, US export control rules, note 13 or as also explained above in Section 2.
[50] For example, US export control rules, note 13.
[51] For example, US export control rules, note 13.
[52] Explanation to Regulation of the Netherlands Minister for Foreign Trade and Development Aid of 11 October 2024, nr. BZ2405833.
[53] Sparkes, "Multiple Nations Enact Mysterious Export Controls"; "UK Ban on Quantum Computer Exports."
[54] Sparkes, "UK Ban on Quantum Computer Exports."
[55] US Bureau of Industry and Security (BIS) Rule 2024-19633 (89 FR 72926) of 6 September 2024.
[56] US BIS Rule 2024-19633 (89 FE 72926), 72935
[57] US BIS Rule 2024-19633 (89 FE 72926), 72935
[58] US BIS Rule 2024-19633 (89 FE 72926), 72935.

Crucially, however, the Interim Decision does not make any concrete reference to scientific studies, research or publications that further substantiate and justify the claims made about the upper and lower thresholds – that is, the point of 'plateau' and the minimum 'high level' of 'sophistication' warranting national security protective measures. The decision does not further reference or indicate any scientific expert (bodies) that have been consulted during the drafting of these export restriction s.

3.2 Export Controls on the Material Supply Chains of QT

Beyond the restrictions on QT as such, restrictions can also be placed on equipment, devices and component parts of the QT material supply chain. The above-mentioned export restrictions regulate these supply chains, as reflected in the text's inclusion of 'Qubit devices and qubit circuits containing or supporting arrays of physical qubits', 'Quantum control components and quantum measurement devices' and 'Technology for the development or production' of quantum computers and their devices.[59]

Previously, the US Commerce Control List (CCL) had already regulated categories of technologies that are part of the QT supply chain: superconductive materials,[60] lasers and sensors,[61] vacuum equipment,[62] microelectronics,[63] optical components[64] and atom dispensers.[65] Overall, these devices can also be found in any (generic) material sciences or experimental physics labs and are not quantum specific.[66] However, with the new wave of export restrictions on quantum computers, these specific pieces of equipment can be regarded as 'qubit devices', 'qubit control components and quantum measurement devices', enabling technologies 'for the development or production' of quantum computers.

Some export control legislation explicitly restricts vital equipment for the QT supply chain, namely 'cryogenic cooling systems and components … cryogenic wafer probing equipment and advanced materials'.[67] Similarly, Finland has imposed export controls on cryogenics,[68] in which the Finish company Bluefors is an industry leader, supplying to major players such as IBM and burgeoning quantum computing start-ups such as Alice & Bob.[69] Cryogenics have also been included in the US CCL under their Export Administration Regulation. The CCL includes 'Cryogenic refrigeration units'[70] as well as 'Helium refrigeration units'[71] and Helium-3.[72]

3.3 Export Controls on 'Intangibles' and Knowledge Exchange in QT R&D

It has been noted that export controls on the technology as such and their supply chains may not be enough to effectively hamper the indigenisation of controlled technologies in the rival state. For instance, only three weeks after the US blacklisting of Chinese quantum actors, a Chinese research team announced a breakthrough, achieving the largest ever quantum computation with trapped-ion qubits. This breakthrough was achieved under the leadership of a US-trained Chinese scientist, which further fuels fears of technology leakage due to open international scientific collaboration.[73] To effectively prevent such technology leakages, 'intangible' aspects (e.g. intellectual property, expertise and know-how) related to the R&D and manufacturing of a controlled technology must also be stemmed.[74]

Within the US export control regime, Daniels and Krige have (re)considered technology export restrictions as a means of 'knowledge regulation'. Natural persons working in cross-border scientific research would be considered 'data exporters' of not only 'technical data' but also their general expertise, know-how and implicit knowledge gained by virtue of contact with US-based technology holders.[75] In this light, US export control implementation is carried out according to the 'mosaic theory', which assumes that export controls should extend to any kind of 'knowledge' related to the material technological artifact

[59] Sub-sections (b), (c) and (e) in each respective export restrictions discussed.
[60] CCL Index, code 1C005.
[61] Category 6 of the CCL.
[62] CCL Index, code 2B231.
[63] CCL Index, code 3E003.a.
[64] CCL Index, code 6A005.e.2.
[65] Category 6 of the CCL.
[66] Farley, Sandia Report, 3.
[67] For example, UK Amendment SI 2024 No. 346: see entry PL9013 in Schedule 3.
[68] Finnish Act on the Export Control of Dual-Use Items (500/2024) (16 August 2024)
[69] Blufors Homepage, https://bluefors.com; IBM Quantum, "IBM Scientists"; Blufors, "Cat in Fridge?"
[70] See Alphabetical Index to controlled items of the US Commerce Control List, code 0B001.d.7.b.
[71] CCL Index, code 1B231.b.1.
[72] CCL Index, code 3A001.b.1.a.4.
[73] Peng, "US-returned Chinese."
[74] Stewart, "Contribution of Intangible."
[75] Daniels, Krige, Knowledge Regulation, 11–13.

because unrelated and innocuous pieces of information could in combination yield a bigger picture.[76] This is a line of reasoning that the US export control authorities have adopted to characterise any comingling of foreign technical data or knowledge with US-origin data or knowledge as a 'deemed export' under the ambit of US export control administration.[77]

The extension of export controls to regulating any form of knowledge exchange is also reflected in Article 2 (2) of the EU Dual-Use Regulation. In addition to defining '(re)export' as the movement of goods from the Union customs territory into that of third states, it also covers various means of 'knowledge exchange':

> (d). transmission of software or technology by electronic media, including by fax, telephone, electronic mail or any other electronic means to a destination … making available in an electronic form … oral transmission of technology when the technology is described over a voice transmission medium.[78]

The 2009 Dual-Use Regulation excluded from its scope the 'the supply of services or the transmission of technology if that supply or transmission involves cross-border movement of persons'.[79] For instance, this could have excluded any knowledge exchanged between scientists at a conference outside of the European Union. Instead, these cases were covered by Article 1 of the Joint Action CFSP/401/2000 under the term of 'technical assistance', which has now also been incorporated into the scope of Article 1 of the 2021 Dual-Use Recast.[80] Article 8 provides that member states must require authorisation for such providers of 'technical assistance' related to controlled technologies under the Regulation. Article 2(9) defines 'technical assistance' as:

> any technical support related to repairs, development, manufacture, assembly, testing, maintenance, or any other technical service, and may take forms such as instruction, advice, training, transmission of working knowledge or skills or consulting services, including by electronic means as well as by telephone or any other verbal forms of assistance.

Article 2(10) widely defines the scope of 'technical assistance', which encompasses transfers from natural or legal person or partnership 'from' or 'resident' or 'established' in the EU 'into' or 'within' the territory of a third state or 'to a resident of a third state temporarily present' in the EU customs territory. This last case covers instances of third-country citizens following courses at universities, research centres or participating in industry research and development programs in the EU. Previously, such cases were neither covered by Article 7 of the 2009 Dual-Use Regulation nor Article 1 Joint Action CFSP/401/2000.[81]

Given that the main challenge of QT is one of acquisition and bringing together of engineering ingenuity from a collectively skilled workforce, export controls critically serve as a tool of knowledge regulation. This could have major implications for open international academic and scientific exchange in QT, with institutions, entities, individuals, scientists, engineers and technicians from foreign (non-US/non-EU) states constituting a sizeable part of the pool of talent in the high-tech sector. The US Bureau of Industry and Security observed in its Interim Decision to impose export restrictions on quantum computing:

> Quantum computing research and development is substantially a *global endeavor*, with major innovation occurring in academic labs, small companies, large companies, and national laboratories distributed throughout the world. Key foundational concepts, capabilities, and discoveries from one side of the globe are often borrowed, improved, and/or incorporated to advance efforts on the other side of the world … At the same time, there is a global shortage of quantum computing expertise, with demand currently outstripping supply. This has led to *a substantial world-wide competition to attract the top talent. Academia and industry have described the talent bottleneck as one of the largest impediments to acceleration.*
>
> The domestic development of quantum information science and technology (QIST) experts, including in quantum computing, is insufficient to fill the United States' QIST strategic goals. The United States will continue to rely on foreign talent to fill critical workforce gaps. Currently, much of the QIST talent developed in the U.S. are foreign persons. Foreign persons are subject to visa requirements as administered by the Department of State. More than half of QIST-related degrees conferred in the U.S. are awarded to temporary U.S. residents.[82]

Given that certain parameters are still technically unrealised and currently unrealisable, there is no 'real' quantum device that can demonstrate such hypothetical performance. However, what are real and can be ringfenced are the 'knowledge'

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[76] Daniels, Krige, Knowledge Regulation, 3.
[77] "Hydrocarbon Research Inc., et al: Consent Denial and Probation Order," 12487.
[78] Article 2 (2) Dual-Use Regulation (emphasis added).
[79] Article 7 Dual-Use Regulation.
[80] Article 1 Dual-Use Regulation.
[81] Michel, "European Union Dual-Use," 21–22.
[82] See US Bureau of Industry and Security Rule 2024-19633 (89 FR 72926) of 6 September 2024, 72929.

communities of quantum scientists in university and company (start-up) R&D labs working on realising such ambitious hypothetical parameters such as 2000 qubits.

Export control regulating knowledge exchange over a controlled technology does not merely give effect to those provisions restricting the controlled technology as such (Section 3.1) and their material supply chains of enabling technologies (Section 3.2). If current export controls are to be enforced as knowledge-regulation tools, they could indeed sink their regulatory teeth into the people – that is, ‘knowledge’ that make the ‘sociotechnical assemblage’ of quantum innovation possible. As discussed in Section 2, this assemblage does not just encompass the material artefacts and resources of quantum innovation but the activities and interactions of physicists, engineers, computer scientists, technologists and technicians which make this endeavour to innovate possible.

Following this logic, the non-existence of a quantum computer with ‘hypothetical’ not yet realisable ‘2000 qubit’ capacity is immaterial for the *raison d’être* of export controls. What is relevant is the existence of communities of scientists, engineers and innovators within sociotechnical assemblages of quantum innovation, striving for the elusive ‘2000 qubit’ – of which there are currently plenty for export control ringfencing to sink their teeth into.

4. The Narratives Underlying the Ringfencing of Quantum Technologies

Export controls on quantum computers with hypothetical ‘2000 qubit’ capacity are rooted in different narratives co-produced with three specific sociotechnical imaginaries of quantum computers. These narratives around quantum imaginaries have fed into the export controls’ different rationales for ringfencing. This section discusses the imaginary of (1) the universal quantum computer (UQC) within the (quantum) ‘sovereignty’ narrative; (2) the cryptographically relevant quantum computer (CRQC) within the ‘security’ narrative; and (3) the fault-tolerant quantum computer (FTQC) within the ‘Sputnik’ narrative.

4.1 The Sovereignty Narrative

The cutting-edge and transformative nature of QT has become the driving force behind export controls’ ringfencing rationale to promote and protect a state’s ‘sovereignty’ over innovation resources vital to states’ technological base.[83] For the EU, ‘technological sovereignty’ means to ‘[avoid] situations where the EU is reliant on a sole, or limited number of, third country suppliers for technologies which are critical to startups and to the EU’s economic and societal wellbeing’.[84] This reflects the effort to protect material and human resources vital for maintaining the ‘technological lead time’, which is taken as a proxy for both ‘technological predominance’ and ‘technological sovereignty’ – a rationale particularly evident in US export controls.[85]

Within the context of QT, the term ‘quantum sovereignty’[86] has emerged. It similarly implores the need for Europe’s self-sufficiency and mastery of quantum capabilities at various stages of the supply chain and levels of the technology stack, which is expected to impact a broad range of sectors such as aerospace, defence, pharma, material sciences and finance. This has manifested in R&D and industry investments into quantum projects such as the EU’s European Quantum Communication Infrastructure Initiative,[87] the ‘Quantum Valley’ R&D ecosystem[88] and the recently proposed EU ‘Quantum Chips Act’.[89] Similar investments into the quantum industry are also seen in the Division B funding under the US CHIPS and Science Act.[90] Quantum imaginaries are strong drivers of the ‘quantum sovereignty’ narrative, which is contingent on policy makers’ perception of the promises, potentials and prospects of QT. Quantum imaginaries relate to the (un)desirable futures attached to the possession, lack of or belated possession of quantum capabilities. A powerful imaginary which encapsulates the cutting-edge and transformative nature of QT is that of the universal quantum computer (UQC).[91] Also referred to as a general-purpose quantum computer, the UQC is believed to be capable of executing all quantum algorithms, despite their creation still being one of the main challenges in quantum computing. The possibilities provided by a UQC have been touted as being a game-changer across all fields such as automotive, logistics, finance, pharma and chemicals,[92] as well as paving the way for all types of ‘quantum use case’ supporting the Sustainable Development Goals and bridging the digital divide.[93]

[83] European Parliamentary Research Service, “Key Enabling Technologies.”
[84] EIC, “Statement on Technological Sovereignty,” 6.
[85] Krige, “Change and Continuity.”
[86] BCQ, “Quantum: Tech Race.”
[87] “EuroQCI.”
[88] Quantum Flagship, “New Roadmap.”
[89] Matthews, “Commissioner Designate Virkkunen.”
[90] quantum|gov, “Quantum.”
[91] Ezratty, Understanding Quantum, 225
[92] TNO, “Quantum Computing.”
[93] OQI, “Accelerating Applications.”

The imaginary of a UQC goes hand in hand with the sovereignty narrative because of the universalising and totalising 'grand' visions evoked by both concepts. The potential of having state-of-the-art computational resources that could supercharge and unlock all innovation potentials across industries fires up the desire of states to claim technological sovereignty. Despite such quantum export controls' protectionist spirit undermining states' free trade commitments under the Global Agreement on Tariffs and Trade (GATT),[94] the imaginary of the UQC's boundless potential animates policy action to ringfence the necessary innovation resources to elevate states' respective industrial and technological bases such that a state can stake a claim to being technologically 'sovereign' – whether that means 'independent', 'competitive' or 'predominant'.

4.2 The Security Narrative

A common understanding of the rationale behind export controls relates to their national (military) security implications. In this context, QT, as the controlled technology, is viewed as both a security asset and a liability. Export controls are imposed on advanced technologies because of their presumed dual-use nature (for military and/or civilian applications) to protect national security and international peace and security by preventing the non-proliferation and transfer of such dual-use technologies in weapons and arms systems.

Indeed, quantum sensing and quantum communication technologies have been a fixture of defence technology strategies[95] of all leading 'quantum' state players and NATO.[96] Quantum sensors' ability to produce precise information about an electric signal and magnetic anomalies, and for inertial navigation, could have important applications such as anti-drone surveillance radar, anti-stealth technology, detection of submarines or underwater mines and surveillance technology. Quantum communication technologies are envisioned to facilitate secure information exchange between quantum computers with the help of quantum key-distribution via a quantum network that uses optical fibre or free-space channels. Importantly, quantum communication could offer secure communication alternatives in the advent of a quantum computer capable of breaking current standard encryption protocols.

Given the major military, information and cybersecurity implications of both quantum sensing and communication technologies, it is peculiar that these technologies have not been featured in recent QT export control. The discussed export controls have lengthy technical specifications for quantum computers but make no mention of quantum sensing or communication technologies. This is particularly questionable given that quantum sensors have been assessed with a higher technological maturity than quantum computers.[97] Further, experts are working on quantum communication network solutions that could provide secure digital infrastructure that is resilient against potential cyberattacks by quantum computers.[98] Why, then, are only quantum computers such a prominent feature in export control legislation?

It is worth considering that quantum sensors and quantum communication technologies may already be covered by technical specifications provided in states' export control lists, which adopt and are aligned with the specifications in the Dual-Use List under the Wassenaar Arrangement. For instance, Category 5 of the Dual-Use List covers Telecommunications and Information Security, while Category 6 covers Lasers and Sensors. However, recent export restrictions on quantum computers have been added under Category 3 and 4 cover Electronics and Computers respectively.[99] Had regulators intended to include new and more specific export restrictions for quantum sensors or communication technologies under specific categories of their export control lists, such an inclusion could have been coupled and rolled out with restrictions on quantum computers.

The non-inclusion of quantum sensors and communication technology in recent export restrictions and the single-minded focus on quantum computers could be explained by the powerful imaginaries or imagined threat conjured up by a quantum computer. A quantum computer that is able to break current encryption protocols – a cryptographically relevant quantum computer (CRQC) – if realisable, could constitute a major security threat. However, breaking state-of-the-art cryptography would require 20 million qubits and could take up to eight hours,[100] which is still five orders of magnitude away from the current state-of-the-art quantum computer with around 1000 qubits. Given the major engineering challenges in QT, a threat of a CRQC is not non-

[94] See discussions by international trade scholars – for example, Rajput, "Restricting International Trade," 603; Whang, "Undermining the Consensus," 579; Wu, *Export Restrictions,* 172–78; Hrynkiv, "Legal and Policy," 169; Paulsen, "Economic Security," 10–11.
[95] Congressional Research Service, "Defense Primer"; Krelina, "Quantum Technology," 11, 15, 37.
[96] NATO, "Summary."
[97] Krelina, "Quantum Technology."
[98] National Security Agency, "Quantum Key Distribution."
[99] See, for instance, the export control classification code of '4A906 Quantum computers and related ''electronic assemblies'' and ''components'' therefor.' The first 4 of the code indicates Category 4.
[100] Brooks, "Quantum Computers."

existent, but it is not imminent. To fully appraise the cybersecurity threat of a CRQC, two factors need to be borne in mind. There is the threat of 'harvest now, decrypt later', in which state or other actors gather troves of encrypted data, which they hope can be decrypted with a CRQC in the future.[101] This is particularly relevant for certain data, which are 'crown jewels' (e.g. state secrets, military sensitive data) and thus will still be high-value data in the not-so-distant future. However, states are now also shifting towards adopting 'post-quantum cryptography' protocols that are developed to be safe against CRQC attacks. Post-quantum cryptography algorithms have been placed on many export control lists.[102]

The complex on-the-ground reality of assessing the CRQC risks does not directly drive the security narrative for ringfencing quantum computers. Instead, it is the imaginary of the CRQC with its spectre of 'Q-Day' that fuels the policy urgency to protect our digital society from CRQC malicious attacks. The CRQC imaginary seems to have animated a Hobbesian-like reflex of the state, as a sovereign, to protect the interests of society at large by guarding us from threats of CRQC-wielding 'barbarians at the gate', who threaten the cybersecurity architecture of our digital society.

In fact, interest in quantum computing grew in 1994 after mathematician Peter Shor devised his eponymous Shor's algorithm, a quantum algorithm for exponentially fast factoring of large primes (of more than 100 digits) – a crucial step in cracking public encryption protocols.[103] Shor himself recounted that he had initially described his work as 'solving discrete logarithms' – without mentioning factoring, quantum computing or cryptography. However, like the 'children's game of Telephone', his work was reported as a solution for 'factoring' large numbers – that is, with application for cryptography – which eventually caught the attention of NSA officials.[104]

Shor's algorithm has consequently added to the perception of what threats are posed by a CRQC that hypothetically has qubits stable and powerful enough to run Shor's algorithm. The diffusion of Shor's algorithm as scientific knowledge across communities, according to Latour, can be attributed to the production of inscriptions that simplify and 'flatten' the world, and their subsequent distribution by 'centers of calculation' that enable these representations (Shor's algorithm as representing CRQC – that is, cybersecurity, risks) to draw together actors and actions far outside (cryptography and NSA communities) the initial loci of production (solving discrete logarithms).[105] Without the diffusion of Shor's algorithm, the CRQC imaginary would not exist in its current form. The anxiety that a CRQC could execute Shor's algorithm remains a powerful fixture in the narrative of quantum computers, and QT more broadly, as security threats, which underlies the ringfencing rationale of export controls on these devices.

4.3 The 'Sputnik' Narrative

Moving away from UQC and CRQC imaginaries, the fault tolerant quantum computer (FTQC) is a quantum computer with relatively 'error free' and 'coherent' qubit states, and is thus considered one of the most realistic but still moderately ambitious milestones for the quantum computing field.[106] The goal of building a FTQC has fed into the rationale of ringfencing quantum innovation to guard those resources in order for a state to become 'the first' in the race to demonstrate large scale 'quantum coherence' – the key engineering challenge in quantum computing representing the field's 'Sputnik moment'.

The 'Sputnik moment' rhetoric has often been invoked to describe quantum R&D efforts.[107] Thinking beyond the superficial meaning of this turn of phrase referring to a disruptive technology entering the world stage, the launch of the Sputnik was in a fact a technological demonstration – a prototype put together to demonstrate the ability to launch objects into space.[108] In the same vein, any resulting FTQC would also be a protype demonstrating the successful implementation of error-correction routines for logical (error-free and useful) qubits. The Sputnik mission *per se* did not have any immediate military-defence, commercial or economic 'utility'. Its significance was rather the demonstration of a state's scientific technological and engineering power – or, more romantically put, 'human ingenuity' – making the potential of space travel more real. The Sputnik moment refers to a technological achievement that unlocks myriad possible futures in terms of military, geopolitical, industrial, economic and scientific ambition and powers.

[101] Noone, "Are Harvest Now, Decrypt Later Cyberattacks."
[102] Such as in Annex I, EU Dual-Use Regulation, Dual-Use List, Wassenaar Arrangement (5.A.2.c) US CCL (5A002.c), Export control lists of Japan, South Korea and Australia.
[103] Aaronson, "Quantum Computing."
[104] Shor, "Shor's Algorithm," 2:28.
[105] Jasanoff, Dreamscapes, 17 citing Latour, "Drawing Things Together," 30.
[106] Quantum Flagship's Strategic Research Agenda aims to build a FTQC by 2027–2030; France's national QC Programme, "PROQCIMA," aims to build two FTQC prototypes by 2032 and 2035; IBM's Quantum Development & Innovation Roadmap aims to build a FTQC by 2029.
[107] Leclerc, "Quantum Sputnik Moment"; Stamper-Kurn et al, "Topical: Quantum Technologies."
[108] Harford, Reconsidering Sputnik, 22ff.

In this light the FTQC imaginary represents an engineering triumph, a first-of-its-kind quantum computer. The successful construction of a FTQC would be a breakthrough feat of demonstrating quantum coherence, essentially defying the laws of quantum mechanics. Achieving the FTQC milestone could make imaginaries of more ambitious quantum computers such as the CRQC or UQC a more possible reality. Fostering, safeguarding and controlling the entire sociotechnical assemblage of quantum innovation that goes into building a FTQC lends meaning to a state's identity, value and ambition of being 'the first' in achieving quantum fault-tolerance.

The innovative capabilities and potentials surrounding the imaginary of a FTQC become the leitmotif of state's technology strategy.[109] Particularly in the European Union, policy-makers have recognised that Europe has lost out in the semiconductor industry market share and thus also the attendant export control race. Thus, there has been increased emphasis for the European Union and its member states to facilitate 'first movers' in quantum,[110] which makes the FTQC imaginary all the more powerful in these discourses.

While it may be easy to impose export controls on any prized QT, such as quantum computers, the performative nature of policy posturing only goes so far. Export controls should be critically considered upon a transparent basis upon which technical considerations for export control parameters have been decided. Thus far, explanations have only made vague references to the cutting-edge or dual-use nature of QT and have yet to garner wide (public) support from the scientific community. Restrictions on cross-border R&D and knowledge exchange must be considered in terms of how these could backfire on R&D efforts to foster a quantum innovation ecosystem worth protecting before a too-high export control fence is constructed. This could result in an innovation culture fractured along geopolitical fault lines, thus keeping out material and knowledge exchange that may be vital to achieving the quantum 'Sputnik moment'.

5. Conclusion: Is it the Qubits or the Story We Tell About Them That Matter?

Given that no full-fledged 'useful' QT exist, export controls become tools of knowledge regulation. They sink their regulatory teeth into the 'sociotechnical assemblage' of quantum innovation to ringfence the site where critical knowledge and R&D exchanges are at work to overcome the major engineering challenges standing between quantum ambition and reality.

Regardless of whether QT export controls are fit for purpose or whether their parameters make technical sense or are adequate for effective enforcement, the mere invocation of export controls lends the state an air of regulatory authority over prized QT. A state attempting to ringfence the assemblage of quantum innovation has its policies, ambitions and identity tied up in all possible imaginaries of QT, specifically those conjured up by quantum computers.

The technical (non)feasibility or (non)realisability of '2000 qubits' is secondary. What is decisive for understanding the export controls' performance of ringfencing is the imaginaries that inspire visions of power and possibilities of '2000 qubits'. Export controls offer the veneer of control over QT. Even if states cannot ringfence the amorphous assemblage of quantum innovation, export controls provide a conduit through which states can ultimately stake claims to potential futures represented by all possible quantum imaginaries.

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[109] Pfotenhauer, Jasanoff, "Panacea or Diagnosis?" 783, 784.
[110] Haeck, "Europe is Ring-fencing."

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