Regulatory measures on goods and services in the quantum computing industry

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Abstract

In the last ten years quantum technology has attracted billions of dollars worth of investment. Propelled by the promises of significant speed-ups in calculating chemical interactions, improvements in sensor technology, and obliterating the cryptographic protocols that currently secure our internet communication, dozens of states have launched national training programmes to educate the next cohort of scientists and engineers. These shifts can, of course, reshape the world's military and security landscape. How to manage the approach to the quantum future is now a pressing policy agenda, and the go-to approach has been to apply trade-restrictive measures. In this article we report on the pathways made possible to trade restriction by international trade law and show that through the application of its export licensing scheme, the US has effectively divided the world into four groups, applying pressure on other states to match its export policies. China, which belongs to an unfavourable group, is forced to seek technology sovereignty and has responded with its own export policy and controls on raw materials. We analyse this dynamic in terms of global trade, through the perspective of the international laws written in the General Agreement of Tariffs and Trade (GATT) treaty of the World Trade Organisation (WTO) agreements and conclude by asking whether we are witnessing the last stages of international trade as a rule-based system.

Contents

1 Introduction

We have become accustomed to thinking of the 20th century as one of technological progress: in that time we witnessed the electrification of our cities; the advent of aviation; the discovery of antibiotics and far more. This period also marks the time that the foundations of quantum mechanics were laid, a theory, which on the molecular level, is the chain of understanding that links physics with chemistry and biology. If in the 20th century large milestones were achieved roughly once every generation, then in the 21st century technological progress has become sub-generational. We are now electrifying our cars, customising medication and treatment plans and piloting commercial flights to space. Waiting, on the precipice of a paradigmatic technological revolution is the quantum computer.

Before eulogizing all of the things that a quantum computer can do, it is important to appreciate that there are surprisingly 'basic' things that it can't. For instance, a quantum computer cannot copy information (unlike in the classical world where a photocopier or smartphone suffice),[1,2] nor can it put two arbitrary states in superposition (a particle can be put in superposition with itself, but not with another body).[3] In spite of these obstacles, one of the most remarkable aspects of quantum computation is that in some cases it is able to offer super-linear and even exponential speed-ups for particular problems. This additional power in certain corners of complexity space was not fully appreciated until the 1990s. The quantum computer is also the native system in which to simulate Nature, i.e., to do calculations related to molecular interactions. Despite the fact that only a few dozen algorithms have been provably identified to run faster on a quantum computer[4,5] quantum computing still has the potential to be one of the most transformative technologies of our time, dramatically changing industries ranging from material science and pharmaceuticals to artificial intelligence and cryptography.

Today, the heavy investment in quantum underscores the high stakes involved in maintaining a competitive edge in the industry: governments are increasingly concerned about what this technology can do and who will be the masters of it. In 2021, 17 countries had national programmes for quantum research and development (R&D)[6] and by 2023 global public investment totalled $42 billion with China contributing over $ 15 billion, almost three times as much as the next largest investor Germany ($5.2

[1] "The concept of transition in quantum mechanics". In: *Foundations of Physics* 1.1 (1970), pp. 23–33. DOI: https://doi.org/10.1007/BF00708652.

[2] W. K. Wootters and W. H. Zurek. "A single quantum cannot be cloned". In: *Nature* 299.5886 (1982), pp. 802–803. DOI: 10.1038/299802a0.

[3] U. Alvarez-Rodriguez et al. "The Forbidden Quantum Adder". In: *Scientific Reports* 5.1 (2015), p. 11983. DOI: 10.1038/srep11983.

[4] Ashley Montanaro. "Quantum algorithms: an overview". In: *npj Quantum Information* 2.1 (2016), p. 15023. DOI: 10.1038/npjqi.2015.23.

[5] Aram W. Harrow and Ashley Montanaro. "Quantum computational supremacy". In: *Nature* 549.7671 (2017), pp. 203–209. DOI: 10.1038/nature23458.

[6] Johnny Kung and Muriam Fancy. *A Quantum Revolution: Report on Global Policies for Quantum Technology.* CIFAR. 2021. URL: https://cifar.ca/wp-content/uploads/2021/04/quantum-report-EN-10-accessible.pdf.

billion).[7] Private firms too have been able to raise staggering amounts of venture capital with individual funding rounds reaching hundreds of millions of dollars[8,9] propelling total private investments into the billions.

The industry differs in its development to that of previously nascent technologies. For example in the case of nano-technology,[10] the standards for the sectors (goods, food and drinks, cosmetics and pharmaceuticals) came from the industries themselves. Here, states permitted and even encouraged private firms and public entities to cooperate to advance progress and the technology was essentially left to control itself. This contrasts to the case of quantum computing in that even now, in the early stages of enterprise, states are applying trade restrictive measures to control activity in the industry. The main reasons behind these manoeuvres are: national security concerns; the protection of intellectual property; and the desire to maintain technological leadership.

Trade, as a policy instrument, has long been used as an effective method to substantiate and further state interests, and trade restrictive measures are nothing new in international trade, where traditionally import restriction and export promotion have been the go-to policies. In the field of quantum computing, however, we are witnessing that export restriction is being increasingly applied as another method of trade restriction.

Export restrictive measures such as taxes, quotas, licensing requirements or bans have far-reaching implications for global trade and international collaboration. On the one hand, these measures are argued to be essential for protecting national security interests by preventing the misuse of quantum technologies, while on the other hand they risk fragmenting the global quantum ecosystem, hindering innovation, and creating barriers to cooperation. One of the reasons that these measures can be implemented so quickly and with little consequence is that they are an under-developed branch of international trade law. To implement them, states use the language and the exceptions that are granted to them by the General Agreement of Tariffs and Trade (GATT) and World Trade Organisation (WTO) law to form their policies. In the former, the most important instruments are GATT Art. XX (general exceptions) and GATT Art. XXI (security concerns), thus understanding the relation between these and WTO law is of great importance.

The main actors competing to master quantum technology are the US and China, and both use their available channels to influence other countries. The US does so through its export licensing scheme, arguing that quantum technology is directly related to its security concerns. Only those countries that adopt equivalent trade-restrictive measures to the US are permitted to have access to its quantum computers and related devices. As we will observe, this has the effect of segmenting the world into four trade groups.

China, on the other hand, uses its position as one of the major suppliers of raw materials and rare

[7] McKinsey & Company. *Steady progress in approaching the quantum advantage.* 2024. URL: https://www.mckinsey.com/capabilities/mckinsey-digital/our-insights/steady-progress-in-approaching-the-quantum-advantage#/.

[8] *Alice & Bob Closes €100M Series.* 2025. URL: https://alice-bob.com/newsroom/alice-bob-100m-series-b-fundraising-press-release/.

[9] Rishi Kant. *Quantum computing startup QuEra closes $230 million funding round.* 2025. URL: https://www.reuters.com/technology/quantum-computing-startup-quera-closes-230-million-funding-round-2025-02-11/.

[10] Jordan Paradise. "Regulating Nanomedicine at the Food and Drug Administration". In: *AMA Journal of Ethics* 21.4 (2019), E347–E355. DOI: 10.1001/amajethics.2019.347.

Earth metals to control the commodity market, which is indispensable to the manufacture of quantum hardware. Earlier, this was done through arguing that its export policy is connected to the protection of exhaustible natural resources under the exceptions in GATT Art. XX, but the latest version of Chinese trade law, also refers to national security to control its quantum industry.

This article maps out the current state-of-affairs regarding regulatory measures in the quantum computing industry and how they relate to WTO law; it is structured as follows: Section 2 starts with an introduction to quantum computing and description of the main platforms and machines, as well as the primary points of their components along the supply-chain. In Section 3 we address the export restrictive measures promoted by the US and put them into the WTO law context. Then we shall shortly address how private firms may operate within this dynamic field and finally, as well as how the current trade-restrictive policies may shape quantum computing as an industry. Section 4 proposes some possible scenarios as consequences of the current trade climate and closes with concluding remarks.

2 Technical background

Quantum technologies can be grouped into three broad sectors: quantum computing; quantum sensing; and quantum communication. In this article, our focus is on legislature affecting quantum computers, although much of the law is general enough to apply to the other sectors.

Models of computation

What does it mean to compute? Although this question doesn't garner a consensus among computer scientists or philosophers one can approach an operational understanding through the machine we have the most contact with today — the universal classical computer. The term 'universal' refers to the model of computation and, roughly speaking, is the statement that the latter is able to express and compute any mathematical function and algorithm when given enough time and resources. The invention of the transistor heralded the point at which the theoretical model of classical computation (due to Alan Turing[11]) could become a reality, leading to the von Neumann computer architecture we use today, in which a central processing unit (CPU) performs sequential operations on an encoded stream of information.[12] This computer is essentially an advanced abacus — a counting device that keeps track of all the primitive units – the bits (0s and 1s) – in a calculation. For the classical computer, 'to compute' is therefore similar to 'to count'.

Counting, however, is by no means the only way of calculating something and an abundance of other models for computation exist: these models are frameworks that define the fundamental capabilities of abstract computers with proposals ranging from Cellular Automata, Boltzmann Machines to Neural Networks to name a few.[13,14,15] Quantum computing is yet another such model and is expressed in terms

[11] Alan Turing. "Intelligent Machinery (1948)". In: *The Essential Turing*. Oxford University Press, Sept. 2004. ISBN: 9780198250791. DOI: 10.1093/oso/9780198250791.003.0016.

[12] Ethan Evans Dominic Byrne Matthew Cook. "Quantum Computing for Machine Learning: An Introduction". In: NSWC PCD TR-2023-002 (2023). DOI: https://apps.dtic.mil/sti/trecms/pdf/AD1212942.pdf.

[13] D. C. Mikulecky. "Cellular Automata: A Brief History and Overview". In: *Artificial Life II*. ed. by Christopher G. Langton et al. Addison-Wesley, 1993, pp. 137–144.

[14] Geoffrey E. Hinton and Terrence J. Sejnowski. "Optimal Perception as Determined by Backpropagation". In: *Proceedings of the IEEE Conference on Neural Networks*. IEEE, 1983, pp. 395–403.

[15] Frank Rosenblatt. "The Perceptron: A Probabilistic Model for Information Storage and Organization in the Brain".

of its primitive unit the quantum bit or *qubit* — a two level system with intrinsic quantum properties that are not observed in large, everyday objects. These systems allow for quantum phenomena such as superposition (a description of the state that is neither in one or the other level, but a combination of both) or entanglement (a special relationship between two or more systems which cannot be captured by individual, isolated characterisations). A model of quantum computation is then established on the principal of how qubits can be transformed, how they interact with one another and what outcomes they produce under measurement — a behaviour that is accurately predicted by the underlying governing theory: quantum mechanics.

Once a theoretical model of quantum computation is established one must embark on the task of looking for qubits in physical systems in order to realise the model — in practise these are extremely diverse ranging from manipulated light to very particular states in matter. The qubits required to perform a quantum computation don't come 'for free' — an exquisite amount of control is required to execute transformations and exceptional circumstances must be created in order to maintain their quantum properties: on some platforms the signals sent to different qubits must be synchronised to picosecond (one trillionth of a second) accuracy.[16] Each architecture has its own associated physics and requires extensive knowledge of the specific devices and experiments — the promise of additional power comes with a penalty: the proviso of control.

The only *universal* models of quantum computation in active production today are so-called *gate-based* models. Here, the picture is comparable to the classical case: sequential operations (gates) are performed on qubits (instead of bits) and given enough resources, a combination of gates is able to compute any function and perform any protocol. The 'gap' between quantum and classical computing can then be measured against those functions that can be computed much faster or with far fewer resources than by the classical counterpart. Outside of the realm of universal quantum computing there are also methods which appeal to specific tasks: quantum machine learning[17,18] and quantum annealing for optimisation problems[19] cannot be used to tackle all problems, but that could prove to be practical in handling very particular tasks.

Transformation and read-out

To understand the different stages in quantum computing platforms it is of conceptual importance to split the computation into two parts: the transformation and the measurement. In both classical and quantum machines the fundamental unit of computation is manipulated in each step of a calculation.[20] In a quantum computer, meaningful computations consist of interactions between different qubits, known as *gates*. Any algorithm can be written by composing one and two-qubit gates (1Q, 2Q respectively),

In: *Psychological Review* 65.6 (1958), pp. 386–408. DOI: 10.1037/h0042519.

[16] Richard Versluis and Chad Hagen. "Quantum computers scale up: Constructing a universal quantum computer with a large number of qubits will be hard but not impossible". In: *IEEE Spectrum* 57.4 (2020), pp. 24–29. DOI: 10.1109/MSPEC.2020.9055969.

[17] M. Cerezo et al. "Challenges and opportunities in quantum machine learning". In: *Nature Computational Science* 2.9 (2022), pp. 567–576. DOI: 10.1038/s43588-022-00311-3.

[18] Vedran Dunjko and Peter Wittek. "A non-review of quantum Machine Learning: trends and explorations". In: *Quantum Views* 4 (2020), p. 32. DOI: 10.22331/qv-2020-03-17-32.

[19] Atanu Rajak et al. "Quantum annealing: An overview". In: *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 381.2230 (2023), p. 20210417. DOI: 10.1098/rsta.2021.0417.

[20] we refer here to gate-based models

but with imperfections in implementation, the desired interaction is not always achieved. How well the gate is enacted is known as *gate fidelity* and is a number between 0 and 1 — the higher the fidelity, the more accurate the quantum computer is at performing what it was actually instructed to do. As will be seen in Section 3.1, gate fidelities are already being used as a criterium for regulation.

The second stage of computation comes after the gates have been applied to the qubits: measurement often termed *read-out* is where things differ dramatically to the classical case. On a classical computer reading out the final state of the computer heralds the solution to the problem, and is fixed at the last step of computation, whereas in the quantum case is not. A qubit does not have a fixed description until it is measured — one cannot keep track of the state of a qubit because observing it destroys all of its quantum properties and sabotages the computation: only after all the gates have been performed can one enquire as to the state of the qubits. But quantum mechanics is a fundamentally probabilistic theory, and so, the outcome of this read-out occurs probabilistically meaning that exactly the same conditions and run of the computation produce different outcomes on read-out.

This intrinsic feature of quantum measurement implies two things: first that quantum theory is only repeatable in the statistical sense and second that one run of a quantum computation is typically never enough to infer the answer to the problem at hand; one must initialise the system again and re-run the same computation many thousands of times in order to take statistics on the measurement outcomes and infer the solution to the problem. The art of quantum algorithm design is, then, to come up with a series of steps, which massage the probability distribution over all the outcomes such that at the roll of the quantum die, the desired outcome (the solution to the problem) occurs most often. The hearsay that quantum computers are capable of unimaginable speed and power because they somehow process everything in "parallel" leads often to confusion, since the aim of the game is to land (in a fashion controlled by the algorithm designer) as often as possible on the correct outcome from all of those being held in superposition (parallel).

Error correction

However a qubit is realised, it is extremely fragile and sensitive to its environment, making it unavoidably error-prone. The two main sources of error that can creep into a quantum computation: decoherence and gate imperfections. In the former, any passing particles (be they of light or matter) can upset a qubit's state and unsettle or remove the information contained in it, delicate properties such as entanglement are easily lost as the systems de-cohere in their environment. In the latter, due to limitations in control; the signals that manipulate the qubits are not always implemented perfectly and result in transformations that are different from those desired. Surprisingly, there exist schemes called *error correcting codes* which effectively undo these errors and render the computer *fault-tolerant.* The idea is to arrange qubits in groups of 'physical' qubits (between 100 to 10,000 in size) such that each group behaves in such a way as to protect the information of just one underlying qubit, the error-corrected or *logical* qubit. These ideas have been demonstrated theoretically and in the lab, but today there is not a single commercially available physical system which is error corrected and works with logical qubits; terminology such 'algorithmic' qubit is often used as a marketing term to distract from this fact.

2.1 Types of quantum computers

The behemoth of quantum computing is maturity and scale. The machines available today are not fault tolerant but nevertheless provide interesting experimental testing grounds, especially in the realm of quantum machine learning. Below, we present an overview of the hardware which is most prominent in the quantum computing industry today. Behind each one is a scientific breakthrough that started the journey — there are at least six Nobel Prizes that can be associated with today's quantum technology and developments are so frequent, that some specifications and announcements become obsolete on the timescale of months. For instance, on exactly the same day in December 2024, Google announced its 105 qubit superconducting chip Willow[21] and the Chinese Academy of Sciences announced a 504 qubit superconducting computer, the Tianyan-504.[22]

Important to note is that every single technology requires cooling, or effective cooling be it at the computation or read-out stage. Absolute zero is at 0 Kelvin (K) and, by the third law of thermodynamics, is a physically unattainable temperature — the closer one wishes to come to absolute zero, the more effort and energy one must put into refrigeration.[23,24,25] These costs are not negligible and it is an open question in the scientific community as to whether the cost of operating a quantum computer for certain algorithms has a good trade-off with the costs of running and cooling and whether (if at all) it is more energy-efficient than a classical machine.

- **Superconducting**. One way to create systems with the property of spin is to take a regular electronic circuit and to add a component made of superconducting material. At temperatures of less than 0.1 K the component, called a Josephson Junction, induces a modification in the energy levels of the circuit in such a way that the lowest two can be interpreted as a qubit. This device can be printed on a small silicon chip, surrounded by cabinet sized cooling systems, which are required for the circuit to become superconducting. The chips are fabricated using lithographic and metallisation processes with the most common fabrication technique for qubits generation being the oxidation of aluminium.[26] Because of their proximity to the classical computing industry especially with respect to the fabrication process and the foundries, some of the world's largest computing companies have opted to develop superconducting quantum computers. Developments in technology, which are primarily focussed on the Josephson devices, are strongly influenced by the fields of material science and nanotechnologies applied to superconductivity.[27]

  Superconducting quantum computers split into two strands: universal gate-based computers and

[21] Hartmut Neven. *Meet Willow, our state-of-the-art quantum chip.* Google Research. 2025. URL: https://blog.google/technology/research/google-willow-quantum-chip/.

[22] Chinese Academy of Sciences. *China Unveils Record-breaking 504-qubit Superconducting Quantum Computer.* Dec. 2024. URL: https://english.cas.cn/newsroom/cas_media/202412/t20241206_893281.shtml.

[23] Lluís Masanes and Jonathan Oppenheim. "A general derivation and quantification of the third law of thermodynamics". In: *Nature Communications* 8.1 (2017), p. 14538. DOI: 10.1038/ncomms14538.

[24] Henrik Wilming and Rodrigo Gallego. "Third Law of Thermodynamics as a Single Inequality". In: *Phys. Rev. X* 7 (4 2017), p. 041033. DOI: 10.1103/PhysRevX.7.041033.

[25] Fabien Clivaz et al. "Unifying Paradigms of Quantum Refrigeration: A Universal and Attainable Bound on Cooling". In: *Phys. Rev. Lett.* 123 (17 2019), p. 170605. DOI: 10.1103/PhysRevLett.123.170605.

[26] Conal E. Murray. "Material matters in superconducting qubits". In: *Materials Science and Engineering: R: Reports* 146 (2021), p. 100646. ISSN: 0927-796X. DOI: 10.1016/j.mser.2021.100646.

[27] Francesco Tafuri. "Introductory Notes on the Josephson Effect: Main Concepts and Phenomenology". In: *Fundamentals and Frontiers of the Josephson Effect.* Ed. by Francesco Tafuri. Cham: Springer International Publishing, 2019, pp. 1–61. ISBN: 978-3-030-20726-7. DOI: 10.1007/978-3-030-20726-7_1.

quantum annealers. For the former, the major hardware developers are: Alice&Bob[28] (France), Anyon (France), Atlantic Quantum (Canada), Chinese Academy of Sciences (PRC), Fujitsu (Japan), Google (US), IBM (US), IQM (Finland), OQC (UK), Rigetti (US). Superconducting annealing quantum computers are produced by D-Wave (Canada/US) and Qilimanjaro (Spain).

- **Trapped ion**. Charged atoms (ions) can be used as qubits because they can be contained in precise locations using electric fields. These so-called traps are created by suspending the ions in a vacuum cavity and although it is not fundamentally necessary, the trap is usually housed in a closed-cycle cryostat at moderate temperatures between $2 - 10$ K.[29] The ions are then cooled even further using using laser light to around 0.001 K in order to minimise their thermal jiggling. Current technology is able to trap ions that are arranged in a line, which is itself confined to a chip, surrounded the laser equipment required in order to interrogate the ionic states and manipulate them. The read-out is also performed by a laser which drives an electronic transition in the ions and releases photons (fluorescence), which are then detected by photomultipliers. Major manufactures are: AQT, (Austria), IonQ (US), and Quantinuum (US).

- **Photonic.** Photonic technologies rely on manipulating light into particular states which then behave with spin properties. Of all the major quantum computing hardware today photonic systems are the the only one whose computation stage operates at room temperature. The read-out stage, however, relies on superconducting nanowire single photon detectors (SNSPDs), which operate at temperatures between $0.8 - 3$K, and consequently must be cooled by cryostat.[30]

  Photonic quantum computers are printed on integrated circuits using a similar manufacturing process to the microprocessors of the classical computing industry, however in contrast to electronics, instead of electrons being conducted around the chip, photons (single elements of light) are guided through the devices. Complementary metal-oxide semiconductor (CMOS) manufacturing makes these circuits extremely cheap and fast to produce. Photons have an almost non-existent interaction among each other, which imposes great challenges in manipulating them and performing gate operations. Different techniques have had to be developed to overcome , including measurement-based quantum computing[31] and more recently fusion quantum computing.[32] Manufacturers include: Jiuzhang QC (PRC), Orca (UK), PsiQuantum (US), Quandela (France), QuiX (Nederlands) and Xanadu (Canada).

- **Neutral Atom.** Qubits can also be created from neutral atoms. These, by definition, have no charge, so they are not affected by electric fields like the ions in the ions traps. Instead, optical tweezers[33] (intense fields of focused laser beams) immobilise neutral atoms in order that one can perform operations on them. This technology has the advantage that it's almost 'wire free'. Compared to superconducting chips, which require more and more physical connections between

[28] This technology is superconducting but generates a different kind of qubit called a *cat* qubit.
[29] Jwo-Sy Chen et al. "Benchmarking a trapped-ion quantum computer with 30 qubits". In: *Quantum* 8 (2024), p. 1516. ISSN: 2521-327X. DOI: 10.22331/q-2024-11-07-1516.
[30] Jacquiline Romero and Gerard Milburn. *Photonic Quantum Computing*. 2024. arXiv: 2404.03367 [quant-ph]. URL: https://arxiv.org/abs/2404.03367.
[31] H. J. Briegel et al. "Measurement-based quantum computation". In: *Nature Physics* 5.1 (2009), pp. 19–26. DOI: 10.1038/nphys1157.
[32] Sara Bartolucci et al. "Fusion-based quantum computation". In: *Nature Communications* 14.1 (2023), p. 912. DOI: 10.1038/s41467-023-36493-1.
[33] A. Ashkin. "Acceleration and Trapping of Particles by Radiation Pressure". In: *Phys. Rev. Lett.* 24 (4 1970), pp. 156–159. DOI: 10.1103/PhysRevLett.24.156.

circuit components as the system grows larger, neutral atoms can be entangled using just laser light. These systems operate at room temperature (i.e., without cooling systems), but the atoms themselves are cooled to below 0.001 K using laser techniques.[34] Major hardware manufacturers are Atom Computing (US), InfleQtion (US), Pasqal (France) and QuEra (US).

- **Other platforms.** The platforms listed above present the most advanced technologies in production to date. Other candidates for quantum computers exist either in the lab or on paper, meaning that they are unlikely to be severely affected by today's trade restrictions. Quantum dots are crystals made up of a few thousand atoms of semiconductor material (at nanometre scale). By controlling the material one can make the dot emit light with qubit properties and are thus named 'spin' qubits. Topological qubits are the theoretical 'holy-grail' of quantum computing, these are naturally error-free systems but occur in highly exotic systems – to date not a single one has ever been realised in experiment.

Unlike the evolution of the classical computing industry in the 1970s and 80s, quantum computing is decidedly not vertically integrated. Few companies producing quantum computers for commercial use are creating their own software or peripherals, simply put because hardly any exist. At present, there are no proper quantum compilers and so algorithms researchers are writing code that goes down to the operation of the hardware itself. For example on IBM quantum computers one can even specify and change the physical pulses of the lasers that illuminate the qubits,[35] which in its absurdity is almost equivalent to controlling the electrical signals in a laptop that turn the transistors on and off.

Today, quantum computers can be tinkered with through cloud computing services by anyone who has the resources, provided they do not come from a forbidden country (see e.g., Item 7 "Prohibited Countries"[36]) with a trip to this playground costing anywhere between \$3000–\$8000 per hour of quantum processing unit (QPU) time. Due to the extremely technical nature of the equipment and the scarcity of the highly trained personnel required to maintain it, hardly any cloud service providers own their own quantum hardware. Most simply re-sell computing time on machines located on premises elsewhere. Exceptions include IBM and Atom Computing, who have their own cloud platform. Some vendors provide purely quantum services, while others offer a blend of quantum and classical computation in a hybrid setting. These include AWS (US), Azure (US), Google Cloud (US), QBraid (US), and QMWare (Germany).

2.2 Essential elements and their supply chain

In this section we detail the essential elements in quantum computers, focussing particularly on chips, coolers and lasers. At present, the industry is far from modular and between the platforms the few truly identical parts.

[34]Karen Wintersperger et al. "Neutral atom quantum computing hardware: performance and end-user perspective". In: *EPJ Quantum Technology* 10.1 (2023), p. 32. DOI: 10.1140/epjqt/s40507-023-00190-1.
[35]IBM. *Fractional gates*. Quantum Documentation. 2024. URL: https://docs.quantum.ibm.com/guides/fractional-gates.
[36]IBM. *Quantum End User Agreement*. 2023. URL: https://quantum.ibm.com/terms.

Chips

The raw materials required to manufacture quantum chips can be divided roughly into two categories: the rare Earth elements (REEs) and other metals (e.g., light, transition, post-transition). Both are an important commodity in the creation of quantum computing hardware, and although the current rate of chip production does little to put pressure on reserves, regulatory measures and geopolitical circumstances will have the effect of redistributing the global supply chain; as the OECD report states supply is "concentrated and demand widespread", making the markets for raw materials highly sensitive to trade and in particular export restrictions, which between 2009–2022 increased five-fold.[37]

The REEs are a group of 17 heavy metals, that, despite their name, are found abundantly in the Earth's crust. They are essential in everyday technologies (such as smartphones and computers) as well as medical equipment (e.g. MRI scanner magnets) and defence communications (satellites and aircraft).[38] The 2024 US Geological Survey (USGS) reported that in 2023 China's rare earth mine production already outstripped its next competitor, the US, by over five times and accounted for 69% of rare earth production worldwide.[39] In 2023, 94% of EU imports of REEs came from China, Malaysia and Russia.[40]

- **Superconducting**. Superconducting quantum chips typically solicit one or more of the metals niobium, tantalum and aluminium in their Josephson junctions. In 2018, under Executive Order 13817, the US Department of the Interior published a list of 35 critical mineral commodities that included niobium and tantalum. The order highlighted that dependency on foreign sources creates a strategic vulnerability for the US economy and military to adverse foreign government action, natural disasters, and other events that can disrupt the supply these minerals.[41] In 2020 tantalum became a "covered material", which prohibits prohibits commercial contracts and subcontracts in its acquisition in any covered country (China, Iran, North Korea, or Russia) and any end-item manufactured using this material from any country in that list.[42]

- **Trapped ion.** The essential element required in the ion-trap chips is typically ytterbium (a heavy REE), but traps can also me made using barium, beryllium, calcium or strontium. USGS highlights that the US imports 95% of its ytterbium – with imports coming primarily from China, Malaysia, Japan and Estonia. China dominates the market for processing heavy REEs, although some facilities exist in the US, India and Japan. Future IonQ systems are planned around barium atoms, a metal, which the US produces domestically.[43]

- **Photonic.** Photonic chips are printed on wafers of silicon; gallium arsenide is a common material for the on-chip laser components and in addition lithium and doped REEs may also be used

[37] OECD. *OECD Inventory of Export Restrictions on Industrial Raw Materials 2024: Monitoring the use of export restrictions amid market and policy tensions.* Paris. 2024. URL: https://doi.org/10.1787/5e46bb20-en.

[38] Eurostat, European Union. *International trade in critical raw materials.* Oct. 2024. URL: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=International_trade_in_critical_raw_materials.

[39] *Mineral Commodity Summaries.* Reston, VA: U.S. Geological Survey, 2024, p. 212. ISBN: 2024. DOI: https://doi.org/10.3133/mcs2024.

[40] Eurostat, European Union, *International trade in critical raw materials*.

[41] Chad A. Friedline. *2020 Minerals Yearbook, Niobium.* U.S. Geological Survey. 2020. DOI: 10.3133/mybvII. URL: https://pubs.usgs.gov/myb/vol1/2020/myb1-2020-niobium.pdf.

[42] Chad A. Friedline. *2020 Minerals Yearbook, Tantalum.* U.S. Geological Survey. 2020. DOI: 10.3133/mybvII. URL: https://pubs.usgs.gov/myb/vol1/2020/myb1-2020-tantalum.pdf.

[43] IonQ. *IonQ Announces Partnership with NKT Photonics for Next-Generation Laser Systems to Power Future Quantum Computers.* 2024. URL: https://investors.ionq.com/news/news-details/2024/IonQ-Announces-Partnership-with-NKT-Photonics-for-Next-Generation-Laser-Systems-to-Power-Future-Quantum-Computers/.

in manufacture. Integrated photonic circuits have the potential not only to be used in quantum computers, but also to replace electronic semiconductor circuits. Keen to pursue this path is China. An article by the Center for Strategic and International Studies (CSIS) reported that Yao Yang (Dean of the National School of Development, China) stated (in response to 2024 US restrictions[44]) that US semiconductor restrictions amounted to the US "shooting themselves in the foot," because photonic chips will eventually make electronic chips obsolete.[45] The same article points out that China's 14th Five-Year Plan[46] places significant emphasis on developing quantum information and quantum technology as well as the development of national laboratories for quantum and photonics.

- **Neutral atom.** Neutral atoms suitable for quantum computing are rubidium, sodium, caesium and strontium, calcium and ytterbium. Sodium and calcium are some of the world's most abundant elements. In 2023, no rubidium was mined in the US and nor were there any stockpiles,[47] major world produces include Canada and Argentina.

Cooling and laser equipment

The dominant international manufacturers of dilution refrigerators, the cooling systems required for superconducting quantum computers are: Blufors (Finland), Oxford Instruments (UK), and Janis Research Company (US). In 2023 China announced a breakthrough in cooling capabilities and by 2024 was able to mass produce the dilution refrigerators ending its reliance on this foreign technology.[48,49,50] Laser equipment is required on every quantum platform and varies between architectures. Semiconductor lasers (also known as diode lasers) are produced worldwide but concentrated in countries with strong associated track records in semiconductors, e.g. US, Japan, China, Germany and South Korea. Trapped ion, photonic and neutral atom quantum computers all rely on diode lasers, whose manufacture requires gallium arsenide or gallium-based compounds. Superconducting quantum computers use microwave lasers (i.e., masers) to end pulsed signals through cables or lines to manipulate the qubits. These are created using microwave signal generators whose essential elements include silicon, gallium and their associated compounds as well as conductive metals.

[44] The US Commerce Department's Bureau of Industry and Security (BIS). *Commerce Strengthens Export Controls to Restrict China's Capability to Produce Advanced Semiconductors for Military Applications.* 2024. URL: https://www.bis.gov/press-release/commerce-strengthens-export-controls-restrict-chinas-capability-produce-advanced.

[45] Matthew Reynolds. *Controlling Light: Is Silicon Photonics an Emerging Front in US-China Tech Competition?* Center for Strategic and International Studies (CSIS). 2024. URL: https://www.csis.org/analysis/controlling-light-silicon-photonics-emerging-front-us-china-tech-competition.

[46] Center for Security and Emerging Technologies. *Outline of the People's Republic of China 14th Five-Year Plan for National Economic and Social Development and Long-Range Objectives for 2035 [Translation].* 2021. URL: https://cset.georgetown.edu/publication/china-14th-five-year-plan/.

[47] U.S. Geological Survey. *Mineral Commodity Summaries 2024.* Reston, VA: U.S. Geological Survey, 2024. ISBN: 978-1-4113-4544-7. DOI: 10.3133/mcs2024.

[48] Li Yan. *China makes breakthrough on dilution refrigerator for quantum computing chips.* 2024. URL: https://www.ecns.cn/news/sci-tech/2024-02-28/detail-ihcychvt6115663.shtml.

[49] Matt Swayne. *Reports: China Mass Producing Dilution Refrigerator Critical to Superconducting Quantum Computing.* 2024. URL: https://thequantuminsider.com/2024/02/28/reports-china-mass-producing-dilution-refrigerator-critical-to-superconducting-quantum-computing/.

[50] CGTN. *China's quantum computer fridge rolls off the production line.* 2023. URL: https://news.cgtn.com/news/2023-10-18/China-s-quantum-computer-fridge-rolls-off-the-production-line-1o0py62e5kA/index.html.

3 Regulatory measures

In this section we detail the interplay of regulatory measures that are starting to dictate the distribution of goods and services in the quantum computing industry. We start with on the local level, with state and unilateral measures, before explaining the global instruments behind them.

3.1 State regulation and unilateral measures

Countries can enact trade restrictions via two possible pathways: (i) they are compelled to impose sanctions and trade embargoes under instruction from the UN according to its Security Council Resolutions, or (ii) they can also choose to impose unilateral trade restrictive measures of their own accord. The first scenario requires a UN Security Council Resolution which passes only in the case that no permanent-member of the Security Council vetoes. Proposed sanctions, for example, against China or Russia are also not conceivable, since these parties would also have to vote and none would ever agree to initiate sanctions against themselves. Thus, path (ii) is the one that occurs in practise.

Since almost all countries are members of the WTO, any unilateral sanctions they impose against other member countries must be permissible under the GATT/WTO law. Here GATT Arts. XX and XXI present the main pathways to deviate from these obligations. Countries that adopt trade restrictive measures use the language of these two articles (security and environment) in their regulation but they need not invoke either article directly. GATT Arts. XX and XXI are only used as a defence if the regulation is questioned by other countries before the Dispute Settlement Body (DSB) of the WTO. With respect to unilateral export restrictive measures, we identify four modes by which states can formulate their policies.

1. **Export Controls and Technology Transfer Restrictions.** Export controls (including taxes, quotas and licensing regimes) are a central aspect of many trade-restrictive policies on quantum computing. The US, China, and the European Union have all instituted regulations that limit the transfer of quantum-related hardware, software, and intellectual property to foreign entities. In the US, quantum computing is regulated under the Export Administration Regulations (EAR), which regulates the export of certain advanced quantum technologies to other countries or entities with ties to foreign governments. In similar spirit the European Union's dual-use export controls cover quantum technologies with potential military applications.

2. **Sanctions and Trade Embargoes.** Broader than export controls are sanctions and trade embargoes, which are an outright ban on export to selected countries. These sanctions often target countries seen as adversaries or those with a history of purported intellectual property theft or cyber espionage. To this day the US has a trade embargo against Iran and Cuba and has specifically targeted Chinese tech firms such as Huawei and ZTE. Such sanctions could also prevent firms from accessing key quantum components, algorithms, and software, disrupting the global flow of technology and expertise.

3. **Restricting Access to Talent and Collaboration.** Highly skilled scientists and engineers are crucial to advancing and operating advanced technologies such as AI and quantum computers. Personnel are often sent together with the hardware and in the case of IonQ Forte Enterprise quantum computer in Switzerland, every single piece of equipment and every staff member came from the US, down to the wires. Cloud services are another example of this phenomenon— as

mentioned in Section 2.1 few providers own the machines they sell time on, because they lack the know-how to maintain the devices. Limiting the movement of skills and knowledge severely hinders progress and scientific exchange. International collaborations are now subject to increasing government scrutiny, be they academic or industrial The US and UK have already introduced policies that limit or carefully monitor the recruitment of foreign scientists and researchers in the quantum domain, based on their nationalities. These disincentives have already impacted the UK, which has seen a drop in the number international student enrolments in higher education (whose high fees typically finance permanent staff), resulting in over one third of universities cutting jobs or freezing hires.[51,52]

4. **Intellectual Property (IP) Protection.** To safeguard their technological advancements, states and corporations are increasingly focused on IP protection. Governments may impose restrictions on the use of quantum patents by foreign entities or limit the ability of foreign companies to file for patents in their jurisdictions. This serves to protect national interests but also restricts access to innovation, creating barriers to collaboration and knowledge sharing.

Although, the measures above can be implemented by almost any state, the most dominant influence exerted over international trade in quantum computing devices and services are the regulations wielded by the US and China.

US Regulation on Advanced Technologies

The US assumes a privileged position in that a large majority of private companies in the quantum industry are based there (see list of manufactures in Section 2.1). The latest Code of Federal Regulations (CFR) Parts 736, 738, 740, 742, 743, 772, and 774 (2024), titled: Commerce Control List Additions and Revisions; Implementation of Controls on Advanced Technologies Consistent With Controls Implemented by International Partners) issued by Bureau of Industry and Security (BIS) had updated the rules regulating trade with Advanced Technologies, hereunder quantum technologies.[53] It states that the BIS:

> *"...is implementing export controls on several semiconductor, quantum, and additive manufacturing items for national security and foreign policy reasons. This rule adds new Export Control Classification Numbers (ECCNs) to the Commerce Control List, revises existing ECCNs, adds a new license exception to authorize exports and re-exports to and by countries that have implemented equivalent technical controls for these newly added items, and adds two new worldwide license requirements to the National Security and Regional Stability controls in the Export Administration Regulations (EAR). These controls are the product of extensive discussions with international partners."*

Thus, this regulation governs export, re-export and transfers (in-country) of components, software and services related to "advanced technologies", which quantum technology falls under, and essentially creates a licensing scheme.

[51] Cathleen O'Grady. "U.K. Visa Changes Imperil Recruitment of Scientific Talent, Policy Experts Warn". In: *Science, Science Insider* (2024). DOI: 10.1126/science.z7uosdf.

[52] UCU Queen Mary University of London. *UK HE Shrinking: Current Redundancy Programmes.* 2024. URL: https://qmucu.org/qmul-transformation/uk-he-shrinking/#current-redundancy-programmes.

[53] Bureau of Industry Department of Commerce and Security. *Commerce Control List Additions and Revisions: Implementation of Controls on Advanced Technologies.* Docket No. 240813–0217, RIN 0694–AJ60. Sept. 2024. URL: https://www.govinfo.gov/content/pkg/FR-2024-09-06/pdf/2024-19633.pdf.

Section 4A906 of the regulation addresses quantum technology and states two criteria as general categorising definitions for quantum computers: first, the number of physical qubits that are connected and fully controllable (starting from 34 qubits and upwards), and second, the average error rate of the controlled NOT (CNOT) gate. Section 4D001 and 4D906 of the regulation cover “software” “specially designed” or modified for the “development” or “production” of commodities controlled by quantum computers and their components and measurement devices. Hence the advanced technologies covered by the regulation range from laser-equipment, to chips and equipment to print them, semiconductor devices, coolers to the personnel having access to them, as well as the software and algorithms needed to operate these devices. Trade of these items requires an export licensing from the relevant US authorities.

The regulation specifically states national security and regional stability as reasons behind the licensing requirement but also specifies exceptions which will be assessed on a case-by-case basis. Through these exceptions, other countries can obtain permission to import US quantum computers and their components. The criteria to obtain such permission is to adopt equivalent export restrictive measures as the US has towards other countries. Thus, through this regulation, the US aims to maintain its technological foothold effectively dividing the world into four groups. Here, where applicable, we adhere to the group names assigned by the BIS (see reference for full list of countries in each case[54]) and note that the following applies to the trade of quantum technologies in particular.

Group A:1 **(Wassenaar Arrangement.)** This group consists of all countries signatory to the Wassenaar Agreement (WA)[55] except for Malta, Russia and Ukraine. In general, a country in this group must apply for a license to import quantum technologies from the US but whether they get the permission to actually do so is treated on case-by-case basis and the outcome is highly unpredictable. With respect to the EU, due to the structure of its treaties, and the fact that quantum technology is under the National Security remit of its member states, the EU Commission does not have the authority to regulate trade in quantum computers on behalf of its member states rendering the trade in quantum computers is under the sovereign right of each member state.

Exempt. **(No license required.)** This is a subgroup of Group A:1. Any signatory of the WA who applies the same policies in its trade of quantum computers as the US is exempt from the US licensing requirement and is regarded as a close ally. This group includes: Spain, the United Kingdom, the Netherlands, Canada (which all have export bans on quantum computers with 34 or more qubits). Currently, countries, such as Germany, France and Switzerland, are assessing whether they should adopt the same policies.

Group B. **(Other.)** Almost all other countries belong to Group B. These countries are eligible to apply for an export license from the US, but in practise it is extremely difficult to obtain one, with the regulation stating “presumption of denial” from the outset.

Banned. **(Group E, China and Russia.)** The final group consists of China, Russia, North Korea, Iran, Syria and Cuba and other sanctioned states. These countries are excluded from trading

[54] Bureau of Industry Department of Commerce and Security. *15 CFR Parts 736, 738, 740, 742, 743, 772, and 774*. Docket No. 240813-0217, RIN 0694-AJ60. 2025. URL: https://www.bis.gov/ear/title-15/subtitle-b/chapter-vii/subchapter-c/part-740/supplement-no-1-part-740-country-groups.

[55] The WA is a voluntary export control regime whose 42 members exchange information on transfers of weapons and dual-use goods and technologies.

with the US and Groups A:1 and the 'Exempt'.

In its report *Quantum Technologies and Value Chains,* the European Policy centre placed significant emphasis on semiconductor chips and The European Chips Act (2023)[56] which may be, in part, due to the lack of clarity in the latter legislation. As we saw in Section 2.1, pure quantum chips do not rely on semiconductor materials (there are few electrons in any quantum chips), but the control systems in conjunction with the QPU will be based on regular classical circuits containing semiconducting materials — these are devices that support and enable the quantum components. In the future, quantum computing will be at the scale where directives concerning classical chips will become relevant due to the vast amounts of post-processing required on the classical output data.

Indeed, CFR regulations also cover chips from classical computing and AI (bearing in mind that these are not the same as quantum chips). On 13.01.25 the BIS updated its regulation on the export of AI chips to other countries. Accordingly, Regulation 15 CFR Parts 732, 734, 740, 742, 744, 748, 750, 762, 772, and 774 (2025) titled: "Framework for Artificial Intelligence Diffusion",[57] puts AI chips under the umbrella of National Security and subject them to the export licensing schemes. The regulation exempts some countries from the licensing requirement[58] permitting companies operating therein the opportunity to apply for authorization to build data centers overseas in countries other than China and those countries under US arms embargoes.[59] Most other countries (and therefore companies) must apply for an export licence. Obtaining a license is subject to quotas and computing power thresholds (one can receive up to 50,000 so-called "advanced computing chips," with the possibility to double that cap to 100,000 if they sign technology security agreements with the US. End-users headquartered in (or whose ultimate parent company is headquartered in) China or any other US arms-embargoed country remain effectively barred from receiving advanced chips.

All CFR regulations mentioned are dynamic, referring to the fact that the US has retained its right to add components and services to their general export licensing terms, to re-assign countries to different groups (as we shall see below) and/or add additional procedural requirements for applying for export licensing, as seen fit. With respect to the expert workforce (eligible to work in the US or for US firms abroad) the US regulation on Advanced Technologies acknowledges the shortage of these individuals (both domestically and in allied countries). The requirement to work, however, emphasises the latest nationality and place of residence of individuals and particular example is made of those with Russian, or Iranian citizenship, who would have to go through a complex approval process in order to get the permission to work or gain access to US technologies.

[56] European Union. *Regulation (EU) 2023/1781 of the European Parliament and of the Council of 13 September 2023 establishing a framework of measures for strengthening Europe's semiconductor ecosystem and amending Regulation (EU) 2021/694 (Chips Act).* 2023. URL: http://data.europa.eu/eli/reg/2023/1781/oj.

[57] Bureau of Industry Department of Commerce and Security. *Framework for Artificial Intelligence Diffusion.* Docket No. 250107–0007, RIN 0694–AJ90. Federal Register. Jan. 2025. URL: https://www.govinfo.gov/content/pkg/FR-2025-01-15/pdf/2025-00636.pdf.

[58] Australia, Belgium, Canada, Denmark, Finland, France, Germany, Ireland, Italy, Japan, the Netherlands, New Zealand, Norway, Republic of Korea, Spain, Sweden, Taiwan, and UK.

[59] Afghanistan, Belarus, Burma, Cambodia, Central African Republic, China, Democratic Republic of the Congo, Cuba, Cyprus, Eritrea, Haiti, Iran, Iraq, North Korea, Libya, Lebanon, Russia, Somalia, Republic of South Sudan, Republic of the Sudan, Syria, Venezuela, and Zimbabwe.

PRC Export Control Law 2020, 2025

A great deal is unknown about the Chinese quantum ecosystem, especially with respect to private firms. Alibaba (the e-Commerce conglomerate) and Baidu (the largest Chinese search engine and AI company) both closed down their quantum research divisions in 2023, 2024 respectively, but despite the ostensible lack of participation in the private sector China is still able to hold sway over the quantum technology markets. In short, China's policy in this regard aims to invest heavily in its own quantum and chip-making industries and R&D. This policy can be interpreted in two ways: first, this can be regarded both as a response to other countries' policies against China, for example as a response to the Japanese ban on export of chip-making equipments to China which was implemented in 2023,[60] and second as a traditional Chinese strategy in international trade which aims at making China self-sufficient as an industrial power-house and in particular in advanced technologies.

Since China controls the lion's share of the metals required to build computer chips and other advanced computing devices, she can use her position to control the export of these materials to other countries. Traditionally this has been done through the use of export bans, quotas, minimum export prices, export licensing, and authorized export companies. Through these measures, China could also influence the market prices of these commodities. Until 2020, Chinese export regulations were fragmented making it difficult for trade to manoeuvre; since then she has compiled her measures into a single and comprehensive framework culminating in the enactment of the Export Control Law (ECL).[61]

This legislation not only aimed to protect China's position within the advanced technologies supply chain but was also a direct acknowledgement of DSB rulings: China lost several cases before the DSB and responded by aligning its regulations to the WTO rulings. These explicitly stated that the reasons for export restrictive measures should comply with GATT/WTO law and be stated directly in the regulations. Consequently, the ECL cites "environmental concerns" and preservation of exhaustible natural resources in its preamble. To further comply with the ruling, China removed some of its export restrictive measures and now only operates with export quotas and export licensing. Recently and as a direct response to the latest US measures against China (which in reality bans export of any advanced technological devices and services to China due to national security concerns), China has also cited national security as a reason for its export restrictions, in contrast with earlier appeals to the environment.

ECL (2020) establishes a list of technologies and products which are subject to licensing requirement. This list, which currently consists of 700 titles, includes dual-use, military and nuclear items, as well as products and services related to AI technologies (which also covers quantum technologies). Export of these products and services are either banned or require licensing agreements. Like the US regulations, this list can also be expanded to include other titles. This was for example done as tit-for-tat action against the US additional tariffs on imports from China.[62] The latest list for the ban on the export of

[60] Gregory C. Allen, Emily Benson, and Margot Putnam. *Japan and the Netherlands Announce Plans for New Export Controls on Semiconductor Equipment.* Center for Strategic and International Studies (CSIS). 2023. URL: https://www.csis.org/analysis/japan-and-netherlands-announce-plans-new-export-controls-semiconductor-equipment.

[61] Standing Committee of the National People's Congress. *Export Control Law of the People's Republic of China.* Effective December 1, 2020. 2020. URL: https://english.www.gov.cn/archive/whitepaper/202112/29/content_WS61cc01b8c6d09c94e48a2df0.html.

[62] Eversheds Sutherland. *U.S. and China Tighten Respective Export Restrictions on Advanced Technology and Critical Minerals.* Eversheds Sutherland. 2023. URL: https://www.eversheds-sutherland.com/en/united-states/insights/us-and-china-tighten-respective-export-restrictions-on-advanced-technology-and-critical-minerals.

metal covers: tungsten, tellurium, bismuth, molybdenum, indium, gallium and germanium, as well as antimony and "antimony-related" items.

3.2 General Agreement on Tariffs and Trade (GATT/WTO)

One of the main objectives (and one of the main achievements) of GATT/WTO is and has been to minimize trade barriers as well as to provide a harmonized and predictable trading environment for countries and private companies alike. Traditionally, trade barriers have been imposed as *import* restrictive measures such as tariffs and quotas and historically, the WTO has been the forum for states to negotiate their trade relations with the aim of translating various import restrictions into tariffs and then reducing these tariffs as much as possible. Since tariffs are imposed on imports, export barriers have not been on top of the GATT/WTO agenda and therefore it has remained largely a rather gray area in international trade.

Trade has been a corner stone of states' foreign policy, and thus affects and is affected by other policies, such as environment, development and security; with these links in the back of their minds, states have been interested in maintaining a degree of flexibility and sovereignty when formulating their foreign policy and specifically their trade policies. GATT/WTO completely acknowledges this concern and has included "flexibility" in its treaties in form of exceptions which allows states to deviate from their general GATT/WTO obligations in order to achieve their goals. The main GATT/WTO provisions addressing these exceptions are GATT Art. XX "General Exceptions" and GATT Art. XXI "Security Exceptions". However, by becoming member of the WTO, states have also agreed to be subject to litigation by other member-states in the WTO's Dispute Settlement Body (DSB), who has the mandate to review any complaints and state regulation in question that is covered by the GATT/WTO rules. Through its rulings, the DSB provides clues of how GATT/WTO rules should be understood, interpreted and ultimately applied. In the following, we will go through the existing case-law on these provisions and see how they relate to the export restrictive measures on the current quantum technology regulations.

3.2.1 GATT Art. XX: General Exceptions

Known as the General Exceptions, Art. XX permits members to adopt measures that would otherwise violate GATT rules, provided they are necessary to achieve certain policy objectives, such as protecting public health; conserving natural resources; or upholding public morals. As such, Art. XX provides flexibility for members to pursue legitimate policy goals, and its application has been the subject of extensive legal interpretation and debate, particularly regarding the balance between trade liberalization and domestic regulatory autonomy related to environment.

Legal Framework and Key Concepts in the case law

The article consists of a *chapeau* (introductory clause) and a list of ten specific exceptions. The chapeau sets out the conditions under which the article may be invoked as a defence; the invoking country has the burden of proof to justify that the measure in question satisfies *both* the following requirements:

1. **Chapeau requirements:** The measure must satisfy the conditions set out in the chapeau, meaning it must not be applied in a manner that constitutes "arbitrary or unjustifiable discrimination" or a "disguised restriction on international trade".

2. **Substantive requirements:** The measure must fall within one of the specific exceptions listed in

Art. XX (a)–(j). For example, a measure must be "necessary" to protect public health or "related to" the conservation of exhaustible natural resources.

The key concepts in interpretation can be identified as the following:

- **Necessity Test:** For exceptions such as Art. XX (b) and XX (d), the measure must be "necessary" to achieve the stated objective. WTO panels and the Appellate Body have interpreted "necessity" to require that the measure be the least trade-restrictive option reasonably available to achieve the desired goal.
- **Relating to Conservation:** Under Art. XX (g), measures must be "related to" the conservation of exhaustible natural resources. This standard is generally considered less stringent than the "necessity" test, requiring only a reasonable connection between the measure and the conservation objective.

Art. XX has been subject of many cases before the DSB, such as the *US — Gasoline*[63,64] and more recently *China — Rare Earth*[65,66,67] cases. The latter cases (all treated as one) in particular are of great relevance to the CFR Advanced Technologies legislation, as REEs are essential for to industry and China is the main supplier. These cases were initiated in 2012 by the US and EU along with other countries. The complaining countries claimed that China was violating her GATT/WTO obligations by its export restrictive measures through imposition of export duties, export quotas, and limitations on which entities can export certain metals. In response, China invoked GATT Art. XX (g) "Measures relating to the conservation of exhaustible natural resources".

In its review of the *China — Rare Metal* cases, the panel found that China was not able to demonstrate that her measures satisfy the chapeau requirements since they favoured domestic industries and thus were disguised restrictive on international trade. Upon appeal, the Appellate Body agreed with the panel's findings. And in a contested finding, the Appellate Body also ruled that GATT Art. XX (g). is not applicable as defence in the case of China, due to the terms of accession protocol of China to the WTO. Furthermore, the Appellate Body also ruled that the Chinese law did not sufficiently stated environmental concerns as a reason behind the restrictions. This final part of the ruling in essence means that the language of a regulation must directly state why the regulation is in place and justifies why it is necessary to have such regulation. Arguably, this has subsequently influenced the way countries formulate their export-restrictive measures and how they justify them. As we shall see shortly, it is much easier to invoke "security concerns" under GATT Art. XXI than the general exceptions under Art. XX.

3.2.2 GATT Art. XXI: Security Exceptions

Art. XXI stands out as a critical yet controversial provision. While it provides nations with the flexibility to address national security concerns, the broad and ambiguous language of the article has sparked debate

[63] World Trade Organization. *Dispute Settlement: DS2, United States — Standards for Reformulated and Conventional Gasoline*. 1996. URL: https://www.wto.org/english/tratop_e/dispu_e/cases_e/ds2_e.htm.

[64] World Trade Organization. *Dispute Settlement: DS4, United States — Standards for Reformulated and Conventional Gasoline*. 1997. URL: https://www.wto.org/english/tratop_e/dispu_e/cases_e/ds4_e.htm.

[65] World Trade Organization. *Dispute Settlement: DS431, China — Measures Related to the Exportation of Rare Earths, Tungsten, and Molybdenum*. 2014. URL: https://www.wto.org/english/tratop_e/dispu_e/cases_e/ds431_e.htm.

[66] World Trade Organization. *Dispute Settlement: DS432, China — Measures Related to the Exportation of Rare Earths, Tungsten, and Molybdenum*. 2014. URL: https://www.wto.org/english/tratop_e/dispu_e/cases_e/ds432_e.htm.

[67] World Trade Organization. *Dispute Settlement: DS433, China — Measures Related to the Exportation of Rare Earths, Tungsten, and Molybdenum*. 2014. URL: https://www.wto.org/english/tratop_e/dispu_e/cases_e/ds433_e.htm.

over its potential misuse and its implications for the multilateral trading system; it consists of three main provisions:

- Article XXI (a): Permits a member to withhold information that it considers contrary to its essential security interests.
- Article XXI (b): Allows a member to take any action it deems necessary for the protection of its essential security interests, including actions related to fissionable materials, arms trafficking, or actions taken in times of war or other emergencies in international relations.
- Article XXI (c): Enables a member to take action in pursuance of its obligations under the United Nations Charter for the maintenance of international peace and security.

Historically, Art. XXI has been invoked sparingly, often in response to geopolitical tensions. For example, during the Cold War, the US invoked Art. XXI to justify its export ban against countries such as Cuba and Nicaragua, citing national security concerns. More recently, the clause has been invoked in disputes involving the United Arab Emirates and Qatar (which was settled amicably before a ruling was issued)[68] and in *Russia — Traffic in Transit*.[69] This case was brought before the DSB in 2016 by Ukraine, who claimed that Russia's multiple restrictions on traffic in transit from Ukraine through the Russian Federation to third countries violated Russia's GATT obligations under Art. V (freedom of transit), Art. X (publication and administration of trade regulations) and her accession protocol. In response, Russia invoked GATT Art. XXI (b) and argued that the measures under review were necessary for the protection of its essential security interests, and therefore that the panel lacked jurisdiction to address the matter any further.

In its ruling, the panel first decided that it did indeed have the jurisdiction to review aspects of a member's invocation of Art. XXI (b) and that the article was not entirely "self-judging" (i.e., that it cannot be invoked without justification). Second, the panel ruled that although the use of the specific language "which it considers" meant that it is for a member itself to decide on the "necessity" of its actions for the protection of its essential security interests, the action should be taken "in good faith", timely and as a response to an emergency in international relations. Thus Russian measures were justified and were covered by Art. XXI (b).

This decision marked a significant step in clarifying the scope of Art. XXI and establishing a framework for its review. Despite this ruling, questions remain about the extent to which the WTO can or should adjudicate disputes on national security. As such, it can be argued that although the WTO is ill-equipped to address such politically sensitive issues, the panel's ruling de facto asks for a more robust framework to prevent abuse of the security exception.

As we have shown above, all of the current regulations covering quantum industry state National Security as their justifying principle. Thus based on the ruling of *Russia — Traffic in Transit*, although states can use "National Security" as an argument, they have to show that the situation is in fact an emergency and the restrictive measures are taken in good faith and are appropriate response to that emergency. Of course, whether it is the case or not depends on a DSB ruling, which currently is unlikely

[68] World Trade Organization. *Dispute Settlement: DS576, Qatar — Certain Measures Concerning Goods from the United Arab Emirates.* World Trade Organization. 2019. URL: https://www.wto.org/english/tratop_e/dispu_e/cases_e/ds576_e.htm.

[69] World Trade Organization. *Dispute Settlement: DS512, Russia — Measures Concerning Traffic in Transit.* 2017. URL: https://www.wto.org/english/tratop_e/dispu_e/cases_e/ds512_e.htm.

to happen. This is mainly due to three issues. Firstly, China, US or the EU must initiate a case against the others, knowing that since one of the parties to such case will loose, any ruling will also apply to their own regulations and thus has to be changed. Secondly, by inviting the DSB to interpret GATT Art. XXI, they open the door to potentially more formal reviewing principles on what national security is, what is an emergency and how to assess "good faith". This brings us to the reason, why states have been reluctant to bring a case based on this provision. Thirdly, since the DSB's Appellate Body who has the authority to review the panel's rulings has not been functional the last 5 years,[70] although the fact that any panel's ruling that may deal with any WTO provision can still be appealed, due to the not-functioning of the Appellate Body, these appeals will be set on stand-by. Thus any further reviewing of Art. XXI by the DSB is not feasible at the current moment and most likely will not happen in foreseeable future.

3.3 Private regulation

Private companies are, of course, vested in protecting their own progresses. In order to do so, they have two options: (a) through patents and IP and (b) through secretive research. One problem with the first is that shorter-term patents (those which apply for 10 years), may run out before some quantum technology becomes usable in 20–30 years, thus rendering the protection that IP laws provide in such a scenario of limited value. Furthermore, in the industrial world, patent-theft is not an unfamiliar phenomenon and therefore companies may wish to protect their research and progress by not disclosing it in the first place.

While states are concerned about security and maintaining their technological progress, at least in the US and the European countries, most achievements are mainly accomplished by private companies that have different concerns. Their agenda is: to materialize their findings and advances; to be able to produce value for money from their investments; to be able to collaborate with other entities (for example by having access to parts and devices); and finally monetize from their investments (for example by providing devices or services to the public). All of these require a high degree of predictability and certainty in the field in which they operate, a predictable legal framework and a stable market.

Herein lies the problem: the ever-changing (both in scope and in depth) legal requirements set by the states do not promote stability and predictability. This is particularly obvious in the case of countries in Group B with respect to the US regulation, who must apply for export licences. Further to this, the firms also have to ensure that their products and services are not re-exported, re-located or can be accessed by individual from the 'Banned' group . The only tool in this regard is through a very detailed contract formulation that specifies what their products or services can be used for and by whom. The other option for firms to navigate this bureaucratic sea is to restrict their market to operate in those countries who have adopted similar legal frameworks, which in practise means finding trusted partners. In such scenarios, the market tends to go through a 'specialization' of tasks and services, which are placed in authorized countries and performed by authorized partners. The most reliable way to ensure the closeness of the operation is by establishing 'out-posts' of personnel in various countries to make sure that no information is accessed by third parties, and that no abuse of devices or otherwise prohibited actions involving their products and services occurs.

Access to authorized and expert personnel presents another hurdle to private companies. Since

[70]The US has been the blocking appointment of Appellate Body members since 2020 and thus the Appellate Body has not been able to form to address appeals.

training local experts takes anywhere between 7–10 years companies are naturally interested in having access to foreign specialists. Given the spirited nature of regulation changes and updates, one cannot rule out that additional criteria relating to workforce regulation will not be exercised.

4 Conclusion

The allure of capturing quantum technology entangled with national security fears has resulted in state intervention policies that limit trade with other countries. In a recent shift, export, rather than the historically customary import restrictions, are being increasingly exercised, the former being the most popular restriction in 2022.[71] Export restrictive measures are almost always enforced as unilateral policies, but since international trade is a legal apparatus, these must be framed in terms of the language of GATT/WTO law, which provides the necessary exceptions.

Traditionally, trade exceptions were sought by appealing to GATT Art. XX, which inter alia deals with preserving exhaustible natural resources. But since the WTO jurisprudence is rather extensive in this field and the chapeau requirements in Art. XX are often hard to fulfil, the newest export restrictive measures utilize GATT Art. XXI, which deals with national security. Here the WTO system is much less developed and grants states a much larger playing field in using this article. If such a trend continues, it may significantly shake the international trading system.

In these evolving circumstances, the US and China are looking to create a strategic rivalry. To this end they have two options: (a) to establish alliances with like-minded countries or (b) to pursue their strategies unilaterally. Through its export licensing regime, the US has opted for the first. China, which appears as the target of other countries' policies has no option but to adopt (b), comfortably allocating enough resources to establish its own development, independent of other countries. The result of this may be that the development of quantum technology in the US-lead group may evolve to an industry that is not dissimilar to the airplane industry, where various countries specialize in producing component parts and thus become dependent on each others' progress. On the other hand, the unique case of China as a solitary actor may result in the development of a concurring platform and a unique style of quantum technology.

The positioning of the EU member states with respect to the US licensing scheme (either in Group A:1 or 'Exempt') warrants observation. The European Policy Centre, in its Recommendation 9 advised to, "build strategic technological leverage towards the US" and in Recommendation 10 to "reform Europe's export control framework".[72] Heeding these directives would require a significant overhaul of current EU laws, which put national security measures under the remit of individual states; reforming and creating a unified export framework would therefore require huge commitment, investment and time.

As seen from the lists of vendors, quantum technologies are, for the most part, being developed by private companies, and in practise it is they who are the ones who trade, cooperate and ensure that

[71] OECD, *OECD Inventory of Export Restrictions on Industrial Raw Materials 2024: Monitoring the use of export restrictions amid market and policy tensions*.

[72] Georg E. Riekeles. *Quantum technologies and value chains: Why and how Europe must act now: A test case for the EU's technological competitiveness and industrial policies.* Europe's Political Economy Programme, European Policy Centre. 2023. URL: https://epc.eu/en/Publications/Quantum-technologies-and-value-chains-Why-and-how-Europe-must-act-now~4f3940.

the rules are followed. This brings one to the question of how risk-avert companies are. Will they be willing to collaborate with entities in other countries who may not follow the US' licensing requirements? Will they risk cooperating with companies that may not provide access to individuals from 'contentious' backgrounds, simply due to their nationality?

In 2004, after some seasoned decades in the classical computing industry, IBM sold off its PC business to Lenovo, China for $ 1.75 bn, a storyline which is inconceivable in the current climate. Will firms risk to obtain patent and thereby publicize their technological achievements or will they opt for secretive R&D? Will prohibitive bans lead to knowledge clusters, or conversely to an anti-concentrations of skills, stunting the development of quantum technology? Will quantum hardware evolve around the types of materials available on the markets or strive to follow the path prescribed by science? The tit-for-tat that has emerged between US and China may lead one to fear that if these actions continue, the coming measures may cover areas that have nothing to do with quantum technology at all.

We have seen from several DSB cases that rulings demonstrate that the WTO procedural mechanism is functional. However it is feasible in the current situation, and indeed one may envisage a scenario, where a trade case is brought before the DSB; in the event of a ruling, the losing party (or both parties) may initiate an appeal, but since the WTO's Appellate Body has been non-functional since 2020, the appeal would be set on stand-by with no resolution in sight. This has the effect of politicizing security in international trade — a path that countries have conventionally tried to avoid and have only taken as the absolute last resort in order to deviate from the general rules and their obligations. On this unsecure and dynamic background, coupled with more frequent citations of national security concerns, we could be witnessing the last stages of international trade as a rule-based system.