Frankenstein Technology: Implications for the Geopolitics of Export Control

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Abstract: Military technologies have always been critical tools in shaping how nation-States interact. Given this, the enactment of export controls has played a fundamental role in the development of geopolitical blocs around the world. Recently, experts have observed a rise in "Frankenstein" weapons, i.e., military technologies reassembled from export-controlled subcomponents, which are available from multiple foreign suppliers. This paper argues that the core contributor to the increase in the creation of Frankenstein weapons has been nation-States favouring unilateralism over multilateralism in enacting their export control laws. This nationalistic approach by numerous (but especially Western) nation-States has created regulatory gaps, in which private players can more readily subvert the policy reasoning for global export control. We identify that Frankenstein weapons are an emerging norm in the current geopolitical context, and we analyse the predominant causes for that emergence, suggesting a need for drastic reframing of export control policy worldwide.

Keywords: *export control; non-proliferation; multilateralism; unilateralism; geopolitics; research security; military technology*

> *"Sin that pays its way can travel freely, and without a passport; whereas Virtue, if a pauper, is stopped at all frontiers"* (Melville 1851, p. 68)

Towards the end of 2022, following its illegal invasion and occupation of Ukraine, Russia began deploying vast numbers of Iranian Shahed-136 loitering munitions (also known as "suicide drones") to attack Ukrainian military sites and defence establishments (Epstein 2022). Analysis of these munitions revealed a troubling fact: 40 out of 52 components in the Shahed-136 were made by Western companies (Bertrand 2023). What was disturbing for investigators was the apparent ease by which the Iranian government was evading United States (US) export controls, frequently referred to as the most draconian regulatory regime of its kind in the world (Walker-Munro 2024). This was not the first time that the alarm bell had sounded on technology evading export controls, particularly those imposed by the US and the European Union (EU). In August 2022, a report by RUSI determined that massive amounts of Russian military technology remained dependent on and were being enabled by Western componentry despite the clear presence of sanctions designed to prevent such exports from occurring (Byrne et al. 2022). In fact, the RUSI report found that:

> …at least 450 different kinds of unique foreign-made components across these 27 systems, the majority of which were manufactured by US companies with a longstanding reputation for designing and building sophisticated microelectronics for the US military. Of these, at least 80 different kinds of components were subject to export controls by the US… (Byrne et al. 2022, p. 5).

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Investigators later found a myriad of Western-sourced componentry in the S8000 Banderol missile, which Russia deployed to strike targets deep in Ukrainian territory (Casimiro 2025; Figure 1). Likewise in Iran, a report (2023, p. 10) identified that Iranian drone programs had "advanced despite export controls and sanctions" and "is relatively mature and well-diversified. Through a combination of domestic production and imports, the [drone technology] program has advanced despite export controls and sanctions".

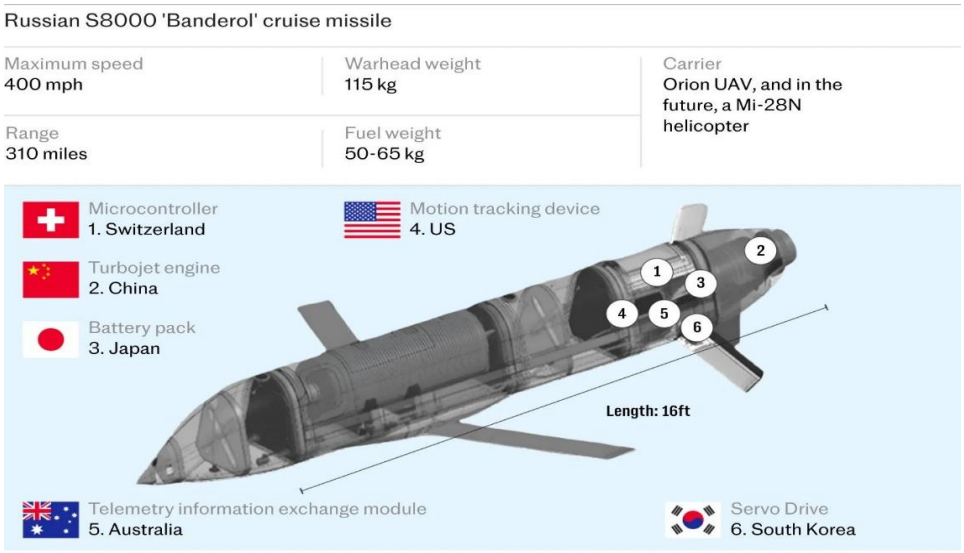


Figure 1. The Russian S8000 Banderol missile, showing summarised components sourced from other countries in violation of export controls (Cleave, 2025).

These incidents highlight the emergence of a new norm some have come to dub "Frankenstein technology", because it involves the incorporation of disparate sources of foreign-owned componentry into military systems in a manner either intended to circumvent export controls, or that results in a practical avoidance of such controls (Syngaivska 2024; Defense Express 2024; Conflict Armament Research 2024; McDonnell 2025; Tillett 2025). Of course, export control avoidance is hardly new – the law has always grappled with contemporary uses of technology (Marchant et al. 2011; Eichler 2019; Kanetake 2021; Ford 2022; O'Shea 2023; Voetelink 2023; Angelo 2025), and nation-States have a military and financial incentive to avoid export controls (Bilousova et al. 2024). However, it is the scale, speed and modularity of contemporary systems that make the phenomenon considerably harder to govern, in addition to the ever-increasing role of a largely uncooperative private industry in defence innovation (Herzog and Kunertova, 2024).

However, the key contribution to the emergence of Frankenstein military technology ("Frankentech")[3] has been the global move away from multilateral export control regimes and towards unilateralism and plurilateralism, which opens gaps for interpretive dissonance and regulatory arbitrage because proscriptive lists of technologies no longer capture the full range of concerning, impermissible, or unwanted use cases. Disparate nation-State approaches to regulating emerging, critical and disruptive

[3] We define Frankentech herein as "any militarily-relevant system that is composed of discrete sub-technologies, items or fields of knowledge". Those sub-technologies, items or fields of knowledge are either a.) not themselves subject to export controls; or b.) they are, but those controls are applied in ad hoc, inconsistent and/or incoherent ways. As a result, these discrete sub-components may be "reassembled" by a State or non-State Actor to recreate restricted systems, and/or create novel means or methods of warfare from such reassembly. We do exclude from this definition technologies created willingly by the parties to the transactions and in compliance with export controls, i.e., the "hybridized" tank produced by Rheinmetall for service in the Ukrainian theatre (Luyken 2024).

technologies (ECDTs)[4] – i.e., fields like gene editing and synthetic biology, hypersonics, artificial intelligence, quantum computing, and autonomous sensing and navigation – exacerbates this interpretive dissonance by creating more urgent, regular and cyclical challenges to traditional forms of export control enforcement (Brockmann 2019; Dekker & Okano-Heijmans 2020; O'Shea 2023; Nguyen 2024; World Economic Forum 2026). Further, private industry and academia are playing increasingly larger parts in the development of military technologies yet appear less stringent about understanding and complying with either the policy rationales or the empirical reasoning for export controls (O'Shea, 2023; Vaynman and Volpe, 2023; Herzog and Kunertova 2024; Bilousova et al. 2024). In those environments, unilateralism and plurilateralism fuels ambiguity over dual-use and intangibles, the modularity of componentry, and the proper role of the private sector in driving innovation, which in turn results in more regular and more disruptive impacts on export control.
This paper examines the move from multilateralism towards unilateralism as a key functional dependency in Frankentech emergence, using Winston's (2018) theory on norm creation as a conceptual lens. As a proposition, any global norm has both constitutive and constraint functions, establishing classes of behaviour that are globally either acceptable or unacceptable between and within nation-States (Winston 2018, p. 640); it is Winston's (2018, p. 641) hypothesis that norms reflect the statement "given this [problem], my [values] dictate this [behavior]". Because export controls limit nation-States from developing problematic or dangerous military technologies, yet those same nation-States cleave to values invoking military and economic strength and independence, they must adopt behaviours that circumvent those controls. Thus, we argue Frankentech is an emerging (and, we say, novel) global norm of export control avoidance, and one that challenges ordinary mechanisms of nation-State governance (Marchant, 2011; Eichler 2019; Kanetake 2021; Ford 2022; O'Shea 2023; Voetelink 2023; Angelo 2025).

We also suggest some changes to export control regulation which seek to tackle the root cause of this norm emergence – i.e., the push towards unilateral export control measures. What is required is more attention to both supply-side and demand-side regulation. By focusing on supply-side export controls, i.e., both academia and private industry taking a stronger lead in enacting their own guardrails, incentives to avoid or circumvent export controls are either removed or made less relevant (Vaynman and Volpe, 2023). Then, a focus on demand-side export controls could help better define the scope of relevant technologies, integrate deemed exports and research security into control frameworks, and build adaptive governance that addresses the pacing problem (Herzog and Kunertova 2024; OECD 2024).

A push towards export control nationalism: Cold War to now

COCOM and the emergence of multilateralism

A key principle of export control laws has always been that "certain kinds of knowledge posed a danger to the very existence of the [State] if shared too freely" (Daniels and Krige 2022, pp. 5-6). Thus in 1949, the first major international effort to coordinate export controls was established with the Coordinating Committee for Multilateral Export Controls (COCOM). This mechanism united seven

[4] We paraphrase the OECD (2024, p. 9) definition of ECDTs to include a military end-use, such that these technologies are "characterised by rapid development, evolution, novelty and uncertainty in trajectory and impact on the development of conventional (including nuclear) military capabilities".

Western countries – the US, UK, France, Italy, Belgium, Luxembourg and the Netherlands – to restrict exports of military-sensitive goods and technologies to the Eastern Bloc (especially nuclear weapons). COCOM operated through establishing a set of agreed lists of "strategic items", requiring unanimity among its members before exporting those strategic items was allowed (Aeppel 1985; Henshaw 1993). COCOM was the first example of export control multilateralism, i.e., the involvement of numerous parties in an open regime of transnational regulation (Congressional Research Service, 2023). Over the following decades, a broader international framework developed, combining legally binding treaties – such as the Non-Proliferation Treaty (NPT 1970), Biological Weapons Convention (BWC 1975), Chemical Weapons Convention (CWC 1992), and UN Security Council Resolution 1540 (2004) – with politically binding multilateral export control regimes (MECRs) like the Nuclear Suppliers Group (NSG), Australia Group (AG), Missile Technology Control Regime (MTCR), and the Wassenaar Arrangement (Wassenaar). These meetings resulting from the MECRs began to act as a transnational clearinghouse for discussions concerning the emergence of critical technologies that might threaten existing regulations.

Criticisms of MECRs vary but have been consistently made since at least the early 1970s (Beck 2000; Jaffer 2002; Jones 2006; Karapinar 2011; Beck and Jones 2019). One challenge is the practical impossibility of reaching a consensus on listing certain technologies, especially for countries or States that have a monopoly or strategic advantage in said technology (Qureshi 2023). MECRs are also incredibly slow for a digitised, global economy – getting a new technology added to the Wassenaar list can take up to three years (Gehrke and Ringhof 2023, 14; Junusova and Reinsch 2024). Further, degrading geopolitics plays a far more important role than it has in the past. As a founding member of Wassenaar, Russia has successfully vetoed every attempted modification to the dual-use technology list since it unlawfully invaded Ukraine in 2022 (Benson 2024).

"National security": A shift towards unilateralism

Over time, these challenges have weighed heavily on the rules-based global order, and nation-States have increasingly turned to unilateral[5] control measures that also address nationalist priorities. Since the fall of the Berlin Wall and the dissolution of the Soviet Union, nation-States have grown objectively less concerned with WMDs – the *du jour* security threat of the Cold War – and more concerned with protecting their technological edge over geopolitical competitors. Policy shifts in nation-State rhetoric and enactments claim less about being motivated by "global" security (instead protecting domestic, municipal, or sovereign capabilities); alternately, they invoke concepts of "national", "economic" or "industrial" security (Qureshi 2023; Woods 2023; Department of Commerce 2025). Several global examples may be made:

- US export controls were originally enacted to limit conventional and nuclear weapons technology from falling into the hands of the Soviets (Daniels and Krige 2022). However, since 2019 they have become a primary foreign policy instrument to restrict technology transfers to autocratic nations, especially the People's Republic of China (Dekker and Okano-Heijmans 2020; Velliet 2025).

[5] In this context, unilateralism denotes state action undertaken outside established multilateral frameworks, characterised by the absence of coordination with other parties and the lack of a requirement for their consent, often reflecting domestic political priorities.

- The European Union originally enacted a harmonised regulation of export controls across its polity (Kanetake 2021); however, the Netherlands, Spain, Lithuania and Finland have all since passed their own national legislation with distinct differences (European Commission 2024, pp. 7-8).
- UK export controls were originally aligned well with the EU, but since Brexit have increasingly prioritised nationalist technology agendas and goals (Rogowsky 2026).

These "unilateral pushes" (Dekker and Okano-Heijmans 2020, p. 54) complicate the operation of MECRs in several ways. Firstly, they create uncomfortable proximity between notions of economic prosperity and national security (Congressional Research Service 2023). Secondly (unlike in MECRs), States do not need to consult or discuss regulatory impacts when they enact or change unilateralist export control systems. There is a resulting global lack of transparency and consultation on *what* is being included by *which* State, and for *what* reasons. For example, although the EU Dual-Use Regulation encourages Member States to coordinate their national control lists (European Commission 2021, articles 9 and 10), they have shown a clear reluctance to do so (European Commission 2024, pp. 8-9). Thirdly, MECRs have globally created perceptions of double standards, turning many nation-States to unilateralism to avoid being disadvantaged, which in turn incentivizes other States to adopt unilateral measures (Zhou 2025). A fragmented patchwork of unilateral measures mean that the same piece of military technology can be regulated in different ways whether one looks nationally, trans-nationally or internationally. Therefore, MECRs struggle for relevance, being asked to do more work on problems they were never designed to tackle (Ford 2022).

A middle road? The role of plurilateralism

Plurilateralism is used in specialized contexts to describe cooperation within smaller groups, smaller than MECRs but with more than two participants (Congressional Research Service 2023). We thus include here the term "minilateralism", which usually features between three and five nations "that aim to coordinate their strategic agendas and facilitate functional cooperation in particular issue areas" (Koga 2022, p. 28). Plurilateral and minilateral regimes are more closed in nature, comprising participants whose national security and economic interests are closely aligned, like the Quad security partnership (India, US, Japan, and Australia) and the partnership on semiconductors between US, Japan and the Netherlands (Benson and Mouradian 2023; ESU 2024; Nguyen 2025). Pluralist export controls include coordination of EU foreign investment screening as well as "anti-coercion measures" (Petersmann 2022); joint efforts to restrict the export of advanced semiconductor manufacturing equipment to China (Congressional Research Service 2023); AUKUS (Benson and Mouradian 2023; Nguyen 2025); and, most recently, the creation of lists of favoured "partner countries" with harmonized controls (Kanetake 2021; Covington 2024).

Plurilateral responses might seem advantageous on their face. Joyner (2004) suggests that export control laws could be structurally aligned to afford remedies under the World Trade Organisation (WTO). Similarly, Wolf and Weinstein (2022, p. 25) describe opportunities for plurilateral agreements to act as "COCOM's Daughter", requiring "[a] new regime of like-minded techno-democracies…to address traditional non-proliferation issues". The recent US AI Action Plan explicitly called for "promoting plurilateral controls" to avoid exclusive reliance on multilateral treaties (White House 2025).

However, plurilateralism works only as a "sideshow" to multilateral arrangements. Both Joyner, and Wolf and Weinstein's models still require consensus, as well as supporting legal infrastructure to support compliance – Joyner's in particular requires adherence to WTO membership, something China has resolutely demonstrated it will not do (Hillman 2023). In a later paper, Wolf (2023, p. 15) himself was quite blunt in saying "I do not think most people… realize how far behind the (well-intentioned and dedicated) allies are to the U.S. system with respect to authorities to impose new controls, resources to conduct policy analyses, and investigative and enforcement capabilities". From the EU perspective, involvement in plurilateral regimes is also likely to be difficult. Where they choose to enact such regimes with non-Union partners, there exist "difficulties of amending national Constitutions, process- rather than rights- based constitutional traditions, power politics and neo-liberal 'business capture' of economic legislation" (Petersmann 2022, p. 20). These various difficulties would make harmonising EU and non-EU export controls through plurilateral mechanisms laborious to achieve.

MECRs fuelling the emergence of Frankentech

This complex architecture forms the foundation of today's international non-proliferation and export control regime, harmonising controls on nuclear, chemical, biological, dual-use technologies,[6] and conventional weapons. Historically, export control regimes focused on preventing non-proliferation of WMDs or diversion of conventional weapons from legitimate sales (Brockmann 2019). Since the early 2000s, export controls have increasingly expanded to include foreign policy concerns related to terrorism, human rights, national and economic security (Cupitt 2021; Qureshi 2023). For example, the EU included terrorism (Colussi 2024) and human rights (Kanetake 2021) as a basis for catch-all clauses in its 2021 Recast Regulation.

The problem

As outlined above, export controls rely on a diverse web of regulation which can operate transnationally but are enacted domestically. In the absence of adherence to the guiding hand of a MECR, nation-States that enact measures unilaterally form openings in global regulation exploitable by private sector actors. These actors are often incentivised to move and operate in domains where restrictions are at their lowest (Brown 2023). Even when coordination or harmonisation measures exist, they are often voluntary in nature: the EU's harmonisation clause has had little effect on "commercially available technologies outside those controlled through the multilateral regimes" (European Commission 2024, p. 6).

Further, MECRs are established and run by large, industrialised, Western democracies in which private sector actors have significant freedom and resources, meaning they can use these freedoms to prioritise their own interests, even if it compromises the security of other nation-States (Hanson 2017, p 187). Comparisons of MECRs to "cartels" – i.e., acting as a collaborative commercial effort to restrict

[6] We use the definition of "dual-use" technology in the European Commission (2021) Regulations: "items, including software and technology, which can be used for both civil and military purposes, and includes items which can be used for the design, development, production or use of nuclear, chemical or biological weapons or their means of delivery, including all items which can be used for both non-explosive uses and assisting in any way in the manufacture of nuclear weapons or other nuclear explosive devices".

competitors' access to specific goods and technologies – have a long history (Victor 1991; Beck and Jones 2019; Michel, Caponetti and Vella 2021). Those criticisms seem valid given that MECRs are increasingly being leveraged to pass restrictions on developing countries (United Nations 2024; Brockmann, Bromley and Maletta 2024), and enlargement of MECR membership usually results in *decreased* sharing of information amongst MECR members because of concerns about interference with economic competitiveness (Brockmann 2019).

In that environment, ECDTs add a further complicating layer. Firstly, ECDTs are incredibly attractive financially for private sector actors, not just in military or defence applications (OECD 2024). Given this, nation-States are themselves incentivised to disagree on the possible implications for national security of ECDTs (Dekker and Okano-Heijmans 2020). For example, encryption (Eichler 2019), cybersurveillance (van Daalen et al. 2021) and weaponised computer programs (Perlroth 2023) are currently proscribed by EU export controls, whilst the US and Israel remain completely silent on such regulation. Even the best multilateral proposals may – through vague or permissive language – permit or encourage disagreements. A recent UN General Assembly resolution called on Member States to "take concrete measures to promote international cooperation on materials, equipment and technology for peaceful purposes, in particular not to maintain any restrictions incompatible with the obligations undertaken" (United Nations, 2024). The terminology in that Resolution makes clear that because peaceful purposes are permitted, "defensive" applications of ECDTs should not be regulated by export control.

Secondly, controls intended to serve as "pre-emptively ring-fencing" technological capabilities (i.e., preventing advances from falling into the wrong hands by controlling the equipment and know-how, as well as the items themselves) can inadvertently hamstring legitimate researchers and laboratories (Nguyen 2025). Quantum technology serves as a useful example of the division between nation-States, where the very definition of precisely what quantum technology is covers a very vast field containing dozens of sub-fields and thousands upon thousands of applications. The fundamental characteristic of quantum technology – i.e., the manipulation of the smallest components of the physical universe – is such that traditional "dual-use" distinctions become completely meaningless. In other words, *every* application of quantum technology could also have a military application, even if States disagree on the nature of that application (Walker-Munro 2025).

The value

"Value" in the context of international norms refers to "the enjoyment or attainment of something 'good' or the avoidance of something 'bad'" (Winston 2018, p. 640). In the context of export controls, the question must be asked about the moral character that controls seek to achieve or avoid, which can be observed in formal texts of MECRs and treaties. For example, the founding documents of Wassenaar make clear that it was "established in order to contribute to regional and international security and stability" (the *good*) whilst also ensuring that "transfers of these items do not contribute to the development or enhancement of military capabilities which undermine these goals, and are not diverted to support such capabilities" (the *bad*). In both cases, the treaty text acknowledges that arms sales and exchanges *will* occur, but seeks to limit those sales and exchanges to the State level and those occurring in good faith.

MECRs also leverage values by appealing to global safety or security. The prohibition of particular kinds of information on proscribed forms of technology or know-how is because they are seen as immoral. For example, the Guidelines of the Nuclear Suppliers Group (NSG) obligates the adoption of "fundamental principles for safeguards and export controls" to ensure nuclear weapons cannot be developed by States that do not already have them.[7] The MTCR (2025) likewise claims it will "limit the risks of proliferation of weapons of mass destruction (i.e. nuclear, chemical and biological weapons)" (the *good*) whilst being "also intended to limit the risk of controlled items and their technology falling into the hands of terrorist groups and individuals" (the *bad*).

However, value-driven regulation can also incentivize private industry actors – and therefore their hosting States – to maintain the protection of their sovereignty, self-determination and national interests, even where those actions might run contrary to the "values" themselves. For example, Winston (2018, p. 641) cites landmines as an example of an international norm which evolved out of a desire to avoid the long legacy of land wars; however, there are nations that continue to use landmines even despite that norm. Conversely, because of the lobbying of US private industry to win the "chip war" with China (Qureshi 2023) and which resulted in prioritising domestic manufacture over global exports, ubiquitous semiconductors in toasters and microwaves are now treated with the same export restrictions as tanks and missiles.

The turn to unilateralism thus reinforces State (i.e., private industry) values over those of the global collective. Goals of national legislation are usually considered "moral" by the State enacting them if they contribute to the achievement of a "desirable" future (Depledge, Santos and Hobson 2025) under which the State's interests are met and respected. The US ITAR (Daniels and Krige 2022), EU's Dual-Use Regulation (European Commission 2021) and Commonwealth export control frameworks in the UK, Canada, Australia and New Zealand (Ghori 2023) make these value propositions explicit. Thus, the State aims to attain a "desirable" future by linking policy to solutions offered by the State's development of science and technology (Hendriks, Karhunmaa and Delvenne 2025). States can thus alter their adherence to the obligations imposed on them by claiming differing moral grounds which align to their own self-interests. This can occur either by unilateral mechanisms imposing less stringent obligations required by MECRs or plurilateral agreements, or by remaining silent about areas in which regulation is resisted.

Export control frameworks (both internationally and domestically), therefore, involve a careful balance of competing values. Usually these are national, economic or personnel security on the one hand, and protection of the freedoms of State sovereignty and free trade on the other. The most common result of this value balance is typified in "dual-use" technologies, which are restricted even if the receiving State lacks the actual infrastructure or know-how needed to weaponize such technology (Kanetake, 2021; Daniels and Krige, 2022). Recipients of military technology are also usually routinely subject to obligations which prohibit them re-exporting armaments to third countries (O'Shea 2023), measures

[7] Interestingly, Annex A to the Guidelines explicitly addresses the possibility of Frankentech, saying "[t]he object of these controls should not be defeated by the transfer of component parts. Each government will take such actions as it can to achieve this aim and will continue to seek a workable definition for component parts, which could be used by all suppliers" (IAEA, 2019).

which have long been considered a violation of sovereignty and self-determination (Voetelink 2023; Shu Shang 2024).

At the same time, export controls can have unintended consequences. Export controls can push nation-States to develop their own sovereign capabilities and supply chains, and move beyond traditional black-market transactions, which are consequentially easy to track (Salisbury, 2025). COCOM banned the sale of typewriters to the Soviet Union from 1949-1971, because they were considered a technology necessary for the Soviet Union to function during the Cold War (even though they had a host of civilian applications, which would have been unduly and unfairly impacted: Kotsioris, 2016). For example, China's response to prohibitions of semiconductor exports from the US was "increased investment in wafer manufacturing and the push to encourage domestic substitution across the entire semiconductor supply chain" (Ding, 2025, p. 127). Rather than preventing China's deployment of chips in advanced military technologies, US export controls may have the opposite effect, leading to a "one world, two systems" environment where both US and Chinese semiconductors compete in the open market (Ding, 2025, p. 141).

The behaviour

Corrective behaviours by States occur because "the problem inhibits the full enjoyment of a value", where a corresponding behaviour addresses the problem (Winston 2018). Where a nation-State wants to obtain a given technology but cannot do so because of export controls ("problem"), the nation-State's need for military superiority, economic security and financial competition ("values") will therefore drive it to pursue a range of behaviours to circumvent that problem ("behaviour"). Export control regimes – enacted transnationally but enforced domestically – that preclude a State's access to a given technology will force corrective behaviours to protect State sovereignty, freedom of knowledge collection and generation, and uphold their national interests (Wolf 2023).

Of course, States have always sought to circumvent export controls through various means, notably the use of third-party nations or the importation of intangibles (i.e., "brain drain": Kanematsu et al., 2024), which have been a challenge to export controls since they were enacted (Diebold, 1967; Hodkinson, 1988; Krige, 2015; Scott et al. 2020). For example, Soviet intelligence obtained machine tools – clearly restricted under COCOM – in the 1980s from member countries like Japan and Norway (Ottinger 2025), and China obtained restricted space technologies in 1998 by "purchasing" scientists from Loral Space and Communication (O'Shea 2023). More recently, in response to US restrictions on semiconductors, Chinese scientists flew hard drives containing AI models to nearby Malaysia before exporting the produced data back to China (Huang and Lin, 2025). It is unsurprising that this is why many export control frameworks rely on "deemed export" provisions, i.e., the provision of access to a technology to a foreign national is "deemed" to be an export to every country where that foreign national has held residency or citizenship, even if such export does not actually occur (Lundy and Clark, 2023).

What is now clear is that the global push towards unilateralism in export control (and the fragmented and disjointed regulatory framework that such a push has created) has birthed Frankentech as a new norm, because unilateralism permits avoidance behaviour to become industrialised in scope and scale.

Both Russia and China have ramped up purchases of household appliances (i.e., washing machines, cameras, refrigerators, microwaves, and online networking devices) for the "omnibus" or "common" components they contain (Dekker and Okano-Heijmans, 2020; Whalen, 2022; Vaynman and Volpe, 2023; Vakulina, 2024; Conflict Armament Research, 2025). As reports note, although these civilian-grade chips are less durable under high temperatures compared to military-grade ones, they can be adapted by adding heat sinks and insulation seals (Feldstein and Brauer, 2024).

Extensive investigations have also provided detailed information about the use of uncontrolled and commercially available components in missiles and uncrewed aerial vehicles (Conflict Armament Research, 2025). Although Ukraine has benefited significantly from US and EU weapons shipments, it nonetheless had to supplement its surveillance and strike capabilities using commercial drones (Molloy, 2024), and both Iranian and North Korean advances in drone and missile technology have continued despite both export controls and UN Security Council sanctions (Feldstein and Brauer, 2024; Al-Ghusbi and Rousseau, 2025). Nations like Singapore, Vietnam, Cambodia, and China, as well as regions like Hong Kong have also been actively targeted by Iranian and North Korean technology acquisition programs (Conflict Armament Research, 2025). Simply harmonising export controls of intermediaries and third-party countries is unlikely to have any effect, given that they still rely on underfunded national capacity for compliance measurement and acts of enforcement and often actively resist Western-led interventions (Cuomo, 2024; Feldstein and Brauer, 2024).

The future of export control: a return to first principles?

Historically speaking, export controls have posed problems to States wanting to obtain cutting-edge or restricted technologies, but occurred in environments where the global rules-based order largely cooperated with each other on how best to keep the international community secure. The sharp divides between the Allies and Axis nations of World War II might have lasted well into the 1990s (McDonagh 2025, p. 366), but those same nations were able to cooperate in the establishment of binding MECRs such as Wassenaar, the MTCR, the NSG and Australia Group. Now, nationalist imperatives have seen countries prioritise acting in their own interests, even as international collaboration on technology is itself now a global norm (Shih, Zhao and Schwerger, 2025). Yet the emerging forms of avoidant behaviour incorporated in Frankentech are not a transnational border problem, but a betrayal of institutional compliance and access control affecting labs, universities, start-ups and large firms in equal measure. What we argue is needed is a greater scrutiny on both supply- and demand-side regulation that embraces the sharing and understanding of plurilateralism, but does not tie the hands of nation-States to consensus as a condition of enforcement (Vaynman and Volpe, 2023; Herzog and Kunertova 2024; OECD 2024).

Enforcement challenges: an old problem renewed

Even though export controls remain a significant tool of foreign policy, a major vulnerability continues to lie in their legal enforcement (Bilousova, 2024). Often described as the "Achilles heel" of multilateral coordination, enforcement challenges have persisted since the Cold War where COCOM faced "overt non-compliance, differences between individual member nations, the overall secretive regime, and the financial bottom line of tech exporters" (Ottinger, 2025). However, enforcement challenges remain extremely live, especially for the EU Member States, where, despite numerous

efforts to harmonize export controls across the polity (European Commission 2021; European Commission 2024; Colussi 2024), both Commission-level and national statements from countries such as Spain, the Netherlands, Finland, France, Germany, and Italy continue to reinforce a notion that "national controls remain a Member State competence" (Pandiyan and Schild, 2025, pp. 19; Bauer and Bromley, 2019).

Enforcement challenges can manifest across several dimensions. Because very few countries actively enforce re-export controls, this can undermine the collective transnational efforts of MECRs, as one state's prohibition can be easily circumvented if the same item is legally available from other countries not applying similar controls (Benson and Mouradian, 2023; O'Shea, 2023). Re-export controls are usually only enforced at each country's discretion, and often with varying rigor, meaning that a breach of re-export in one country is not the same as a breach in another (Angelo 2025). Second, enforcement becomes technically complex when dealing with intangible transfers, i.e., software or know-how, because it is logistically impossible to stop a scientist or engineer from absconding with what resides in their head.[8] In the Cold War, a defecting scientist might have taken a suitcase full of research notes and prototypes. Now, they only need a USB drive or even just a connection to the Internet to share research information (Daniels and Krige, 2022). Thirdly, ECDTs can enable access and proliferation pathways that simply did not exist prior to the development of the requisite technology. For example, cloud computing services are not universally export-controlled even though they could ostensibly be used to circumvent the US' semiconductor restrictions remotely (Mak, 2025), and intelligence services rue the imminence of "Q-Day", the day that quantum computing renders all existing forms of encryption useless (Montague 2023).

What is required to deal with enforcement challenges in Frankentech is therefore a focus on both supply- and demand-side regulation, with an increased level of involvement by private sector actors such as companies and universities. Private sector actors are predominantly the ones making values-based decisions about *who* they work with, on *what* projects or topics, and whether those projects or topics involve or touch upon export-controlled items: as a result, they are not incentivised "to come to firm resolutions of difficult questions" (O'Shea, 2023). Offering "safe harbour" from prosecution or fines may go some way to encouraging definitive answers in permit applications (Gustafsson et al. 2025), as can specifically tailored freedoms like the "fundamental research exemption" well-known to many universities and academics (Alter 2025). Banks and financial institutions could be enrolled to police suspicious arms control transactions in the same way as they are for terrorism and money laundering (Hilgenstock et al. 2025).

The private sector also has a bigger role to play in demand-side regulation. Industry partners may actually be best placed to conduct the monitoring and enforcement roles usually reserved for the government. For example, a key enforcement challenge in semiconductors – the tracking and verification of who is holding what chips – could easily be rectified by industry adopting a serial number standard and then participating in a centralised registry (Ottinger, 2025). Such supply-side regulation would also reduce the burden on detecting and preventing every circumvention attempt at the border (which remains highly resource-intensive), where many countries face technological

[8] Though States have tried: the United States, China and the United Kingdom all attempt to regulate the exchange of intangibles through not only export controls but also visa screening and foreign student regulation (Stewart 2023).

limitations like outdated infrastructure and inadequate communication channels (World Customs Organization, 2023, p. 21). That said, because of the complexity and opacity of global supply chains, suppliers may not always have visibility of who they are providing export-controlled technologies to (Bilousova, 2024). In those cases, governments can better assist private industry by encouraging supply chain visibility on other grounds – such as countering human trafficking or slavery. Laws targeting "know your supplier" processes have been suggested to assist in providing the same transparency needed to properly enforce export controls (Rühmkorf, 2023).

A broader strategic policy for technology?

In that kind of environment, governments of nation-States can more clearly articulate not just which technologies – including the relevant sub-field and sub-sub-fields – are subject to export controls, but more importantly *why* such restrictions are necessary. For instance, governments need to integrate discrete policy rationales that express the "morality" of export control rule, i.e., via linkage to human rights, countering terrorism or military technologies, or constraining illicit use of ECDTs. We echo Ottinger's (2025) words and suggest that "export controls represent just one element of a comprehensive technology strategy – one that must be balanced against both economic interdependence and the reality that innovation often flourishes in response to constraints". By articulating these inherent value propositions in export controls, governments can better incentivize private sector actors to be more willing to comply with restrictions or prohibitions (Zarate 2013). Similarly, well-intentioned policy that is misapplied because of the volatility of domestic politics can still achieve a globally relevant effect, because the private sector actors understand and action the rationale for the policy's existence (Aggarwal and Reddie 2025).

Thus, export controls need to be formulated in a way that is more *embracing* and *reflective* of industry and academia, rather than simply being something they are subjected to. This in turn requires national science and technology policy to be strategically formulated, better integrating notions like deemed exports and research security into control frameworks (Stewart, 2023; Angelo, 2025). In one study, Bilousova et al. (2024, p. 26) suggested that existing MECRs should be better aligned, enforcement properly resourced, and the private sector co-opted as meaningful actors in export controls. Alternately, some have recommended a fifth MECR which would aim to align the export control regimes of Western techno-democracies like the US, UK and Canada that would work to "identify together the commodities, software, technologies, end uses, and end users that warrant control"(Wolf and Weinstein 2022).

The implications for enforcement under either existing or new MECRs remain significant considerations, especially with respect to ECDTs. Nation-States will need to actively consider at what point export controls might become counterproductive, and actually hinder their *own* development of those same technologies. For example, Australian Foreign Minister Penny Wong (2025) recently gave a speech in which she indicated that the country's focus was on developing "a relationship that allows us to cooperate and engage with China, while prosecuting our national interests and building security and prosperity in our region". Aptly, she explicitly described the role of multilateralism as being of critical importance in the Indo-Pacific "because international rules and norms deter conflict, enable free trade, and underpin our security and prosperity" (Wong, 2025). Moves by the US to lead the

Multilateral Action on Sensitive Technologies – otherwise known as the "coalition of caution" (Ford, 2018; Ford, 2020) – appear to be steps in the right direction.

Another option could be to heighten the surveillance of controlled technologies as they move through international supply chains. Studies have already demonstrated that the "anonymous" production of certain components like semiconductors and optical sensors have led to nation-States being able to subvert or divert legitimate trade to fuel their weapons or military research (Dekker and Okano-Heijmans, 2020; Vaynman and Volpe, 2023; Conflict Armament Research, 2025). This could be combatted by nation-States taking steps domestically to better track what it has produced, and where those supplies have gone. Grunewald and Aird (2023, p. 59-61) for example suggest that the export, import and re-export of semiconductors should be tracked at each stage on a global "AI chip registry". This would enable governments and businesses to know the location of semiconductor holdings at any given time, as well as the ability to spot concerning trends, spikes or slumps. Fist, Helm and Schneider (2023) alternately suggest that manufacturing nation-States (like Japan, China, Taiwan, and the US) should randomly audit manufacturers as a way of incentivizing knowledge of the whereabouts of their products. However, there is no doubt that industry would lament the additional regulation and government interventions. Further, both a global register and auditing programs might remain vulnerable to falsified or missing data. Despite those likely limitations, such schemes may have significant merit. Regulators will know where exports are concentrated and have more relevant information for both traditional enforcement and forecasting of future areas of risk.

Beyond traditional controls: Addressing the omnibus/common technology loophole

Finally, export controls need to recognize the growing dilemma presented by omnibus or common technologies. In that space, focus on "dual use" as a discriminator is no longer fit-for-purpose. Technologies that have no military use may still have military *value*, because the components in them can be reassembled into Frankentech. Further, although MECRs might have a future in the export control regime, some elements of a new approach will be necessary so States can share information with each other whilst respecting their sovereignty and economic competitiveness (Dekker and Okano-Heijmans, 2020).

To prove that argument, one need look no further than the originating process for all export control – COCOM. That framework was established under the most premium conditions of success. In 1949, the international stage had only two superpowers. that possessed divergent ideologies and market practices, and were operating in a market of recovery from global war. They were then joined by every other nation-State who obligingly fell into place philosophically, politically, strategically and diplomatically. Despite all of those successful pre-conditions, COCOM *still* struggled to achieve its policy objectives, and today's geopolitics are a far cry from the two-superpower dynamic of 1949. Not only are advanced technological sub-components found in everyday common household objects like "smart" watches, fridges and clocks, but technological advantage is no longer in the hands of a single actor. Global trade networks are simultaneously more expansive but more brittle, adaptable yet prone to structural shocks. Export controls will not be the silver bullet in a future economy driven by investment in ECDTs and where military, intelligence and security technologies are completely indistinguishable from civilian technologies.

Taken together, the foreign direct investment screening framework provides a useful illustration of how such a regime might function, exemplified by the Committee on Foreign Investment in the United States (CFIUS). Like export control regimes, CFIUS balances "promoting an open investment environment and protecting our nation's security" (Tarbert, 2020). Its expanded jurisdiction allows it to review transactions involving access to critical technologies, infrastructure, or sensitive personal data, alongside enhanced notification requirements for "covered transactions" (Tarbert, 2020). Although formally origin-agnostic, CFIUS may consider whether a transaction involves a "country of special concern" pursuing strategic acquisition of critical technologies affecting U.S. national security (Tarbert, 2020: 1509). It thus operates as a values-led regulatory mechanism, recognizing the interdependence of U.S. security and that of its closest allies (Tarbert, 2020: 1519). An export control regime of this kind should apply a similar national security-oriented, values-based metric to ECDTs and other forms of technology. It should be informed by the surveillance of market conditions and trends in the field, as well as the actions of allies and counterparts. Such a regime is far more likely to be able to complement the existing regime of MECRs without unnecessarily duplicating the efforts of those bodies. Furthermore, these bodies or committees could have a powerful signalling effect that discourage private sector actors from "gaming" export control systems (O'Shea, 2023).

Concluding thoughts

Frankentech is a novel challenge to the global export control regime. As a problem of international regulatory law, it serves merely to surface longstanding structural, ideological and resourcing problems that have realistically existed since at least the 1940s. However, as we have argued, Frankentech is also a new norm in geopolitics. Frankentech does not require us to throw out existing export controls – that would likely lead to a massively destabilized global economy and the loss of progress of nearly 80 years of progress towards non-proliferation. Instead, we need to recognize that MECRs and their corollary infrastructure are being used in ways they were never meant to, and so domestic structures need to be reconfigured to supplement and support transnational export control and agency rather than undermining it. Cold War era MECRs still have their place, but cannot hope to apply their glacial, consensus-based, "two-superpower" controls to the contemporary fragmented, volatile and unpredictable geopolitical landscape. This, in turn, requires building a "coalition of the cautious" (Ford, 2018), whilst its members are competing in the race towards technological supremacy.

One scholar has suggested that the words of Abraham Lincoln are an appropriate summation of geopolitical policy on export control: "if we desire to secure peace, one of the most powerful instruments of our rising prosperity [is to ensure] that we are at all times ready for War" (Tarbert, 2020, p. 1524). In other words, the circumvention of export controls is achieved far too easily by nation-States with the willingness to do so. Export control in the era of fragmented and shifting alliances and fierce geopolitical contest does not require that we aim for a world where military technology is perfectly regulated – that goal simply moves too fast for the law to pin it down with any accuracy. Instead, regimes will need to confront the movements of human capital (and, thus, the export of intangibles) as well as the categories of technologies which, in the State's proprietary or economic interests, it wishes to maintain its advantages. In turn, that requires recognition of Frankentech as a new norm in global export control, and the immediate and rapid tailoring of solutions to counter it. Increasingly, export control will need to recognize that the secrets of the newest technology can be

found even in the unlikeliest of places – even if that place is a humble household toaster.

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