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RESEARCH ARTICLE

A theory of international technology regulation

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Abstract

Technology is of increasing importance for international cooperation, yet theory development in rationalist International Relations has not kept pace. I develop a theoretical framework for explaining cooperative outcomes in the international regulation of technology. I propose that uncertainty and the distribution of material capacities create a severe international collective action problem for novel technologies, which precludes robust cooperative outcomes and thus limits joint gains from the appropriation of technological benefits and from the mitigation of technological risks. While the severity of the collective action problem attenuates over time, in principle enabling greater ambition in cooperative outcomes, sociotechnical lock-in reduces the capacities and incentives of state actors to deviate from pre-existing rules. This leads to incremental change whereby rules harden over time but do not change significantly in terms of their regulatory substance. While early regulatory interventions are hampered by collective action problems, late interventions are constrained by lock-in. These temporal dynamics create a tendency towards systemic inefficiency in international technology regulation. I illustrate this argument using the cases of nuclear power and synthetic biology.

Keywords: institutional change; international cooperation; international institutions; path dependence; regime theory; technology

Introduction

Technology poses profound and increasing challenges for international cooperation. Lethal Autonomous Weapons Systems, or 'killer robots', raise complex political challenges for international security as well as international humanitarian law.[1] Transboundary movements of genetically modified organisms, including for agricultural trade, have raised contentious questions of biosafety regulation for more than two decades.[2] Digitalisation has moved into the spotlight of international efforts for pandemic preparedness and response, as access to dematerialised genetic sequence data has become central to the timely development and mass production of vaccines.[3] International climate policy depends on a host of emerging technologies, including large-scale atmospheric carbon

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[1] Ingvild Bode, 'Norm-making and the Global South: Attempts to regulate Lethal Autonomous Weapons Systems', *Global Policy*, 10:3 (2019), pp. 359–64.

[2] Sebastian Oberthür and Thomas Gehring, 'Institutional interaction in global environmental governance: The case of the Cartagena Protocol and the World Trade Organization', *Global Environmental Politics*, 6:2 (2006), pp. 1–31; Mark A. Pollack and Gregory C. Shaffer, *When Cooperation Fails: The International Law and Politics of Genetically Modified Foods* (Oxford: Oxford University Press, 2009).

[3] Dario Piselli, 'International sharing of pathogens and genetic sequence data under a pandemic treaty: What linkages with the Nagoya Protocol and the PIP Framework?', Global Health Centre Policy Brief, (2022).

removals for keeping global warming within safe limits.[4] Nanotechnology, cyberwarfare, satellites, and artificial intelligence are other emerging technologies of growing importance for international politics.[5]

International Relations theory has primarily addressed technology from a constructivist vantage point, often in dialogue with Science and Technology Studies.[6] Engagement from scholars operating within an overall framework of rationalist cooperation theory is limited.[7] For technology as a distinct issue area in world politics, we are missing the middle-range theoretical accounts that have been produced for exploring domain-specific cooperation problems such as climate change, transboundary pollution, or aspects of international trade.[8] Developing such middle-range accounts for technology as a distinct problem of rationalist cooperation theory requires building a bridge between the distinct characteristics that define this specific issue area and higher-order theoretical constructs that have been at the centre of regime theory since the late 1970s. In doing so, I situate myself within a recent wave of rationalist scholarship on international cooperation drawing on insights from historical institutionalism.[9] My theoretical account starts from a puzzle that has long been observed in legal and regulatory scholarship on technology in domestic or regional contexts: that governance responses tend to have insufficient depth when technologies initially emerge; and that they have minimal regulatory impacts once those technologies have consolidated themselves.[10] At the international level, the same pattern can be observed: initial international responses to emerging technologies tend to be tepid, typically taking the form of political declarations, governing body decisions, recommendations, technical guidelines, or other measures with limited degrees of legalisation.[11] While international responses tend to become more robust once technologies mature, they typically merely codify pre-existing rules that have previously emerged at various scales and with various degrees of formality.

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[4] Stuart Haszeldine, Stephanie Flude, Gareth Johnson, and Vivian Scott, 'Negative emissions technologies and carbon capture and storage to achieve the Paris Agreement commitments', *Philosophical Transactions of the Royal Society A*, 376:2119 (2018), p. 20160447.

[5] Robert Falkner and Nico Jaspers, 'Regulating nanotechnologies: Risk, uncertainty and the global governance gap', *Global Environmental Politics*, 12:1 (2012), pp. 30–55; Mette Eilstrup-Sangiovanni, 'Why the world needs an international cyberwar convention', *Philosophy & Technology*, 31:3 (2018), pp. 379–407; Joan Johnson-Freese and Brian Weeden, 'Application of Ostrom's principles for sustainable governance of common-pool resources to near-earth orbit', *Global Policy*, 3:1 (2012), pp. 72–81; Nick Bostrom, *Superintelligence: Paths, Dangers, Strategies* (Oxford: Oxford University Press, 2014); Araz Taeihagh, 'Governance of artificial intelligence', *Policy and Society*, 40:2 (2021), pp. 137–57.

[6] Rolf Lidskog and Göran Sundqvist, 'When does science matter? International Relations meets Science and Technology Studies', *Global Environmental Politics*, 15:1 (2015), pp. 1–20; Daniel McCarthy, 'Technology and "the international" or: How I learned to stop worrying and love determinism', *Millennium: Journal of International Studies*, 41:3 (2013), pp. 470–90; Daniel McCarthy (ed.), *Technology and World Politics: An Introduction* (London: Routledge, 2018).

[7] E.g. Daniel W. Drezner, 'Technological change and international relations', *International Relations*, 33:2 (2019), pp. 286–303; Jane Vaynman and Tristan Volpe, 'Dual use deception: How technology shapes cooperation in international relations', *International Organization*, 77:3 (2023), pp. 599–632; Florian Rabitz, *Transformative Novel Technologies and Global Environmental Governance* (Cambridge: Cambridge University Press, 2023); Jeffrey Ding, 'The rise and fall of technological leadership: General-purpose technology diffusion and economic power transitions', *International Studies Quarterly*, 68:2 (2024), pp. 1–14.

[8] E.g. Nichola Raihani and David Aitken, 'Uncertainty, rationality and cooperation in the context of climate change', *Climatic Change*, 108:1 (2011), pp. 47–55; Carsten Helm, 'International cooperation behind the veil of uncertainty: The case of transboundary acidification', *Environmental and Resource Economics*, 12:2 (1998), pp. 185–201; Pollack and Shaffer, *When Cooperation Fails*.

[9] See Michael Zürn, 'Historical institutionalism and international relations: Strange bedfellows?', in Thomas Rixen, Lora Anne Viola, and Michael Zürn (eds), *Historical Institutionalism & International Relations* (Oxford: Oxford University Press, 2016), pp. 199–228 (pp. 199–200).

[10] David Collingridge, *The Social Control of Technology* (London: Pinter, 1980); Gary Marchant, 'The growing gap between emerging technologies and the law', in Gary Marchant, Braden Allenby and Joseph Herkert (eds), *The Growing Gap between Emerging Technologies and Legal-Ethical Oversight* (Dordrecht: Springer, 2011), pp. 19–34.

[11] Kenneth W. Abbott, Robert O. Keohane, Andrew Moravcsik, Anne-Marie Slaughter, and Duncan Snidal, 'The concept of legalization', *International Organization*, 54:3 (2000), pp. 401–19.

From this starting point, I develop a theoretical account of international technology regulation that revolves around two causal mechanisms. First, I propose that emerging technologies give rise to severe international collective action problems due to uncertainties and strongly asymmetric global distributions of technological capacities (such as material infrastructure or property rights). Both factors attenuate over time, and the severity of the collective action problem accordingly decreases. Second, lock-in effects occur as technologies gradually become consolidated into wider sociotechnical systems, which are broadly characterised by interlinkages between technologies and social structures.[12] As these interlinkages tighten over time, sociotechnical systems become increasingly difficult to change, including through international regulatory intervention. The temporal dynamics of collective action problems and sociotechnical lock-in imply that robust cooperative outcomes lack feasibility at first, and, as they gain in feasibility over time, states increasingly lack capacities and incentives to deviate from the status quo. This creates a tendency towards systemic inefficiency in international technology regulation and calls into question the capacities of the international community to deal with key challenges in 21st-century world politics. As I discuss further in this text, the configuration of these causal mechanisms is virtually unique to technological issue areas and might characterise non-technological issue areas in, at best, an incomplete and unspecific manner.

The second section elaborates on technology and international cooperation. The next section discusses the role of sociotechnical lock-in, whereas the fourth section turns to the drivers of the international collective action problem. The following section uses the cases of synthetic biology and nuclear power to provide empirical illustrations of the theoretical argument. The sixth section concludes.

Technology and international cooperation

Technology is a major factor in world politics. Numerous theoretical accounts have been developed from a largely constructivist outlook, particularly in dialogue with Science and Technology Studies.[13] Yet relatively few attempts have been made to fit technology into a rationalist, cooperation-theoretical framework. Some rationalist scholars have proposed theoretical accounts of technology in its relationship to international political and economic order.[14] Others have focused on specific issues such as dual use or weaponised interdependence in supply chains.[15] Yet what we are missing are theoretical accounts of technology as a distinct issue area in international cooperation. There is a need to develop middle-range rationalist approaches that are both specific enough to account for issue area-specific idiosyncrasies of technology while simultaneously being general enough to allow for insights that are applicable to a wide range of technological categories. This text is an attempt to take a step in that direction. My starting point is that states create and operate international regulatory arrangements to realise cooperative gains from appropriating benefits and mitigating risks associated with different types of technology in diverse transboundary contexts. Satellites for Earth observation can provide public goods in the form of improved natural disaster preparedness.[16] Nuclear energy can create cross-border negative externalities through

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[12] E.g. Frank W. Geels, 'From sectoral systems of innovation to socio-technical systems: Insights about dynamics and change from sociology and institutional theory', *Research Policy*, 33:6–7 (2004), pp. 897–920; Johan Schot and Frank W. Geels, 'Niches in evolutionary theories of technical change', *Journal of Evolutionary Economics*, 17:5 (2007), pp. 605–22; Jochen Markard and Bernhard Truffer, 'Technological innovation systems and the multi-level perspective: Towards an integrated framework', *Research Policy*, 37:4 (2008), pp. 596–615.

[13] Maximilian Mayer, Mariana Carpes, and Ruth Knoblich (eds), *The Global Politics of Science and Technology: An Introduction* (Heidelberg: Springer, 2014); Lidskog and Sundqvist, 'When does science matter?'; McCarthy (ed.), *Technology and World Politics*.

[14] Drezner, 'Technological change and international relations'; Ding, 'The rise and fall of technological leadership'.

[15] Vaynman and Volpe, 'Dual use deception'; Guillaume Beaumier and Madison Cartwright, 'Cross-network weaponization in the semiconductor supply chain', *International Studies Quarterly*, 68:1 (2024), pp. 1–18.

[16] See Johnson-Freese and Weeden, 'Application of Ostrom's principles'.

reactor accidents or from the dumping of nuclear waste.[17] Agricultural biotechnology can perhaps enhance food security, while raising complex questions about biosafety and the integrity of socio-economic structures, particularly in developing countries.[18] On the one hand, the precise transboundary distribution of risks and benefits depends on technological characteristics. Nuclear reactors entail transboundary risks in ways that, say, geothermal energy technology does not. Digital technologies usually create benefits which, in principle, can be freely shared at the international level in a manner that is not possible for physical, rivalrous technological outputs.[19] On the other hand, distributions of costs and benefits are also partially shaped by governance arrangements, at the international level as well as other scales, that may attempt to facilitate the generation of costs or benefits, or to redistribute them between countries.

The extent to which positive- and zero-sum elements are present in the cost–benefit distributions that are associated with a given technology shapes the parameters for effective cooperative outcomes. Where positive-sum elements dominate, cooperation will gravitate towards facilitating or encouraging the development, deployment, or diffusion of technologies that are mutually beneficial. Such positive-sum elements also occur for certain types of technological risks, where all relevant states expect potential harms to exceed the benefits they can draw from a technology, and where international arrangements for risk mitigation can accordingly create joint gains.[20] Conversely, where zero-sum elements dominate, international cooperation revolves around various types of linkage strategies where states trade concessions on functionally unrelated issues in ways that are mutually beneficial.[21] This can enable cooperative outcomes even for technologies that create benefits for some participants but risks for others. Cooperation in the presence of strong zero-sum elements is considerably more challenging to maintain due to the existence of incentives for defection. This, in turn, has knock-on effects for institutional design due to the need to include reporting, monitoring, or enforcement provisions. It should be noted, though, that the existence of positive- and zero-sum elements is typically not as clear-cut as this discussion might suggest. Empirically, most cooperation contexts will consist of a mixture of both, although one or the other is likely to dominate and thus to define the institutional solution space.

In principle, there is a strong theoretical rationale for robust international cooperation on a wide variety of contemporary technological issues. In practice, cooperative action is out of step with technological development. This phenomenon is well known from legal and policy studies of technology regulation at national levels. The term 'pacing problem' describes the inability of institutions to adapt to rapid technological changes.[22] The International Relations literature has prominently addressed this issue in the context of nuclear weapons, the destructive potential of which provides a powerful rationale, or even driving force, for the transformation of an anarchical international system into a world state.[23] A related concept is the dilemma of control initially proposed by Collingridge: 'attempting to control a technology is difficult … because during its early stages, when it can be controlled, not enough can be known about its harmful social consequences to warrant controlling its development; but by the time these consequences are apparent, control has become costly and slow'.[24] Both concepts – the pacing problem and the dilemma of

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[17] Charles Perrow, *Normal Accidents: Living with High Risk Technologies* (Princeton, NJ: Princeton University Press, 1999); William M. Alley and Rosemarie Alley, *Too Hot to Touch: The Problem of High-Level Nuclear Waste* (Cambridge: Cambridge University Press, 2012).

[18] Convention on Biological Diversity (CBD), *Synthetic Biology. CBD Technical Series No. 100* (Montreal: Secretariat of the Convention on Biological Diversity, 2022); see also Pollack and Shaffer, *When Cooperation Fails*.

[19] E.g. Piselli, 'International sharing of pathogens and genetic sequence data under a pandemic treaty'.

[20] See Scott Barrett, *Why Cooperate? The Incentive to Supply Global Public Goods* (Oxford: Oxford University Press, 2007).

[21] Ronald B. Mitchell and Patricia Keilbach, 'Situation structure and institutional design: Reciprocity, coercion, and exchange', *International Organization*, 55:4 (2001), pp. 891–917.

[22] Marchant, 'The growing gap between emerging technologies and the law'.

[23] William E. Scheuerman, *Hans Morgenthau: Realism and Beyond* (Cambridge: Polity Press, 2009); Alexander Wendt, 'Why a world state is inevitable', *European Journal of International Relations*, 9:4 (2003), pp. 491–542.

[24] Collingridge, *The Social Control of Technology*, p. 19.

control – raise important points regarding the temporality of international technology regulation. From a perspective of international cooperation, both describe situations in which potential cooperative gains remain unrealised due to the inability to devise appropriate regulatory solutions. The dilemma of control, furthermore, suggests that such solutions may become more difficult as technologies mature. Lock-in, in other words, may increasingly limit the efficacy of regulatory interventions as time passes.[25]

As I will further unpack in the sections that follow, the central problem of international technology regulation thus lies in its *temporality*: early interventions could, in principle, exert relatively large influence over technologies while lock-in is not yet operational. As I discuss in the fourth section, such early interventions tend to be shallow in nature due to the collective action problems that underpin them. The underlying assumption is that the joint gains which states realise from international cooperation tend to increase as the associated cooperative arrangements become more deeply legalised.[26] The literature discusses exceptions to this rule of thumb in the context of depth–participation trade-offs, as deep legalisation may deter participation and thus reduce cooperative gains. The scope of this trade-off, as well as institutional mechanisms for mitigating its effects, are a matter of debate.[27] In the absence of lock-in, the limitations of early-but-shallow interventions would create a strong rationale for delaying action until the point at which states are able to agree on cooperative arrangements of greater robustness. The presence of lock-in effects, however, implies that such latter arrangements will be increasingly constrained by status quo biases that can limit their regulatory efficacy.[28]

Sociotechnical lock-in

Technology is always embedded within wider social structures that include diverse public and private institutions of a political, legal, or other nature. These ensembles are usually referred to as sociotechnical systems, which are sectors of social activity organised around the 'production, diffusion and use of technology'.[29] Among technological, infrastructural, and other material elements, they also incorporate rules, knowledge, and social practices. Some scholars have alternatively referred to 'techno-institutional complexes', where technologies and institutions 'can become intimately inter-linked, feeding off one another in a self-referential system', which leads to 'persistent incentive structures that strongly influence system evolution and stability'.[30] As with related concepts such as Large Technical Systems,[31] sociotechnical systems are composed of both material and ideational elements.[32] Their precise ontology and the relative importance of these respective

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[25] Gregory C. Unruh, 'Understanding carbon lock-in', *Energy Policy*, 28:12 (2000), pp. 817–30; Gregory Trencher, Adrian Rinscheid, Mert, Duygan, Nhi Truong, and Jusen Asuka, 'Revisiting carbon lock-in in energy systems: Explaining the perpetuation of coal power in Japan', *Energy Research & Social Science*, 69 (2020), p. 101770.

[26] Abbott et al., 'The concept of legalization'.

[27] Thomas Bernauer, Anna Kalbhenn, Vally Koubi, and Gabriele Spilker, 'Is there a "depth versus participation" dilemma in international cooperation?', *The Review of International Organizations*, 8:4 (2013), pp. 477–97; Deborah Farias and Charles Roger, 'Differentiation in environmental treaty making: Measuring provisions and how they reshape the depth-participation dilemma', *Global Environmental Politics*, 23:1 (2022), pp. 117–32.

[28] See James Mahoney, 'Path dependence in historical sociology', *Theory and Society*, 29:4 (2000), pp. 507–48.

[29] Geels, 'From sectoral systems of innovation to socio-technical systems', p. 900; see also Schot and Geels, 'Niches in evolutionary theories of technical change'; Markard and Truffer, 'Technological innovation systems and the multi-level perspective'; Lea Fuenfschilling and Christian Binz, 'Global socio-technical regimes', *Research Policy*, 47:4 (2018), pp. 735–49.

[30] Unruh, 'Understanding carbon lock-in', pp. 825–6.

[31] Bernward Joerges, 'Large technical systems: Concepts and issues', in Renate Mayntz and Thomas P. Hughes (eds), *The Development of Large Technical Systems* (Frankfurt: Campus, 1988), pp. 9–36; Thomas P. Hughes, 'The evolution of large technical systems', in Wiebe E. Bijker, Thomas P. Hughes, and Trevor Pinch (eds), *The Social Construction of Technological Systems* (Cambridge, MA: MIT Press, 2012), pp. 45–76.

[32] Geoffrey L. Herrera, *Technology and International Transformation: The Railroad, the Atom Bomb, and the Politics of Technological Change* (New York: SUNY Press, 2006), pp. 35–6.

elements are a matter of debate.[33] In contrast to concepts such as sectoral innovation and production systems,[34] but similar to the notion of technological systems,[35] sociotechnical systems explicitly include users and uses of technology. Sociotechnical systems are usually analysed at the national scale, which is in line with the focus of this text on distributions of technological capacities between states (see 'Technological capacities' below). Some authors have also proposed locating sociotechnical systems at other scales.[36]

Sociotechnical systems have a propensity to exhibit path dependence. This tendency has also been widely noted in evolutionary economics, with distinct 'technological trajectories' that play out within a given technological paradigm,[37] or as 'natural trajectories' that appear 'almost inevitable'.[38] In contrast to these latter concepts, path dependence in sociotechnical systems can result from both technological and institutional factors.[39] Path dependence is conceptualised in diverse ways[40] and has been making increasing inroads into International Relations scholarship.[41] Path dependence can entail a gradual increase in resistance to exogenous interference because of positive feedback mechanisms.[42] It can also refer to resilient system states that can only be perturbed through strong exogenous shocks, resulting in a stop-and-go pattern of institutional change known as punctuated equilibrium.[43] As such, path dependence in sociotechnical systems is distinct from technological determinism.[44] Instead, a key insight from historical institutionalism is the contingency of initial triggering events that set in motion path-dependent processes: sociotechnical systems tend to have high degrees of plasticity initially but become increasingly difficult to change as time goes by.[45] The result of such path dependence can be *sociotechnical lock-in*: a situation in which technologies and institutions are enmeshed in ways that increase the (economic, political, and other) costs of deviating from established regulatory patterns.[46] This creates a risk of historical inefficiency, where past events stabilise contemporary regulatory arrangements that are inferior, in terms of the benefits they produce, to regulatory alternatives.[47] Historical inefficiency resulting from sociotechnical lock-in has been observed across a variety of domains, notably in the fossil fuel-based global production system that has shown a remarkable degree of resilience in the face of an increasingly overriding urgency to transition towards climate neutrality.[48] The centrality of efficiency for the

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[33] See Geels, 'From sectoral systems of innovation to socio-technical systems', p. 904.

[34] Franco Malerba, 'Sectoral systems of innovation and production', *Research Policy*, 31:2 (2002), pp. 247–64.

[35] Bo Carlsson and Rikard Stankiewicz, 'On the nature, function and composition of technological systems', *Journal of Evolutionary Economics*, 1 (1991), pp. 93–118.

[36] E.g. Fuenfschilling and Binz, 'Global socio-technical regimes'.

[37] Giovanni Dosi, 'Technological paradigms and technological trajectories: A suggested interpretation of the determinants and directions of technical change', *Research Policy*, 11:3 (1982), pp. 147–62.

[38] Richard R. Nelson, *An Evolutionary Theory of Economic Change* (Cambridge, MA: Harvard University Press, 1982), p. 258.

[39] Frank W. Geels and Rene Kemp, 'Dynamics in socio-technical systems: Typology of change processes and contrasting case studies', *Technology in Society*, 29:4 (2007), pp. 441–55 (p. 443).

[40] See Mahoney, 'Path dependence in historical sociology'; Jürgen Beyer, 'The same or not the same: On the variety of mechanisms of path dependence', *International Journal of Humanities and Social Sciences*, 4:3 (2010), pp. 186–96.

[41] See Thomas Rixen and Lora Viola, 'Putting path dependence in its place: Toward a taxonomy of institutional change', *Journal of Theoretical Politics*, 27:2 (2015), pp. 301–23.

[42] Paul Pierson, 'Increasing returns, path dependence, and the study of politics', *American Political Science Review*, 94:2 (2000), pp. 251–67.

[43] See Johannes Gerschewski, 'Explanations of institutional change: Reflecting on a "missing diagonal"', *American Political Science Review*, 115:1 (2021), pp. 218–33.

[44] See McCarthy, 'Technology and 'the international''.

[45] Herrera, *Technology and International Transformation*, p. 36.

[46] See Rose Cairns, 'Climate geoengineering: Issues of path-dependence and socio-technical lock-in', *Wiley Interdisciplinary Reviews: Climate Change*, 5:5 (2014), pp. 649–61 (p. 650).

[47] Glenn R. Carroll and J. Richard Harrison, 'On the historical efficiency of competition between organizational populations', *American Journal of Sociology*, 100:3 (1993), pp. 720–49.

[48] E.g. Unruh, 'Understanding carbon lock-in', Antje Klitkou, Simon Bolwig, Teis Hansen, and Nina Wessberg, 'The role of lock-in mechanisms in transition processes: The case of energy for road transport', *Environmental Innovation and Societal*

concept of path dependence reflects the partial origins of historical institutionalism in economics.[49] It is worth pointing out though that, just like the notion of 'gains' in rationalist cooperation theory, 'efficiency' is here benchmarked against collectively shared goals and understandings that are conventionally defined in reference to material factors.[50]

The literature identifies diverse drivers of path dependence that can result in lock-in effects for technologies,[51] institutions,[52] as well as sociotechnical systems.[53] Klitkou et al. identify factors ranging from economies of scale over network externalities up to institutional learning effects as causes resulting in the lock-in of unsustainable transportation regimes.[54] In their study of coal power in Japan, Trencher et al. argue that carbon lock-in results from a complex interplay of factors that include selective institutional support, social power relations, and the directionality of research policy.[55] Cairns discusses different risks associated with the potential lock-in of large-scale systems for atmospheric carbon dioxide removal.[56] A key insight which thus emerges from the literature is that there is not one single factor driving path dependence in sociotechnical systems and thus potentially giving rise to lock-in effects, but rather complex, interacting, and partially idiosyncratic mechanisms. We can thus identify diverse material, ideational, and mixed drivers of sociotechnical lock-in. While this text adopts a rationalist outlook, this does not preclude non-material factors from playing a constitutive role in the *formation* of interests, based on which states subsequently make strategic decisions regarding the modalities of international cooperation.[57] Such non-material factors may include, for instance, cognitive routines subject to self-reinforcement that introduce a status quo bias into the decision-making of rational actors. However, there is also plausibly an *independent* causal role for non-material factors. Simoens et al., for instance, show how discursive factors can drive sociotechnical lock-in unmediated by interests.[58] For the purposes of this text, though, I focus on lock-in as it relates to rational decision-making based on interests that can be defined by material and non-material factors alike.

The sociotechnical lock-in that tends to occur once technologies consolidate is also driven by the rules that states initially create during technological emergence: 'soft' governance mechanisms, typically adopted while associated collective action problems (still) present with relatively large degrees of severity (see 'Collective action problems' below), contribute to sociotechnical lock-in by themselves, by constraining subsequent rule development. When states deepen the legalisation of international technology regulation in an issue area, they do not start *de novo* but rather create novel layers of rules on top of any soft governance mechanisms that they adopted initially.[59] The rules through which states attempt to regulate technology, in other words, are endogenous to sociotechnical systems. 'Early' regulatory interventions can thus contribute to subsequent lock-in and thus reduce incentives and capacities for status quo deviation with 'late' interventions.

For purposes of international cooperation, sociotechnical lock-in creates a bias towards cooperative outcomes that present incremental changes to a status quo. Accordingly, lock-in constrains state incentives and capacities to create cooperative outcomes that deviate from extant regulatory

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Transitions, 16 (2015), pp. 22–37; Karen C. Seto, Steven J. Davis, Ronald B. Mitchell, et al., 'Carbon lock-in: Types, causes and policy implications', *Annual Review of Environment and Resources*, 41:1 (2016), pp. 425–52.

[49] Douglass C. North, *Institutions, Institutional Change and Economic Performance* (Cambridge: Cambridge University Press, 1990).

[50] James Fearon and Alexander Wendt, 'Rationalism v. constructivism: A skeptical view', in Walter Carlsnaes, Thomas Risse, and Beth A. Simmons (eds), *Handbook of International Relations* (London: Sage, 2002), pp. 52–72.

[51] Dosi, 'Technological paradigms and technological trajectories'; Nelson, *An Evolutionary Theory of Economic Change*.

[52] Pierson, 'Increasing returns, path dependence, and the study of politics'.

[53] Unruh, 'Understanding carbon lock-in'; Cairns, 'Climate geoengineering'.

[54] Klitkou et al., 'The role of lock-in mechanisms in transition processes'.

[55] Trencher et al., 'Revisiting carbon lock-in in energy systems'.

[56] Cairns, 'Climate geoengineering'.

[57] Fearon and Wendt, 'Rationalism v. constructivism'.

[58] Machteld Simoens, Lea Fuenfschilling, and Sina Leipold, 'Discursive dynamics and lock-ins in socio-technical systems: An overview and a way forward', *Sustainability Science*, 17:5 (2022), pp. 1841–53.

[59] See Jeroen Van der Heijden, 'Institutional layering: A review of the use of the concept', *Politics*, 31:1 (2011), pp. 9–18.

structures, both public and private as well as at different scales and of different degrees of formality, in a sociotechnical system. Lock-in can thus prevent the emergence of alternative forms of international technology regulation even in situations where this could, in principle, increase joint cooperative gains relative to the status quo. By itself, the propensity for sociotechnical lock-in would create a strong rationale for early regulatory action: as states enjoy greater leeway in designing international regulatory instruments during initial technological emergence, early action could allow them to capture cooperative gains that might subsequently become unavailable due to the emergence of lock-in. However, early action is hampered by the severity of the associated collective action problem.

Collective action problems

While lock-in can create inertia in international regulatory choices for technologies that have become institutionally entrenched, problems of collective action primarily create challenges during technological emergence. In this section, I propose two causal mechanisms that initially create high levels of severity in the collective action problem for international technology regulation. This effect tapers off over time, with corresponding improvements in the feasibility of robust cooperative outcomes. With deeper legalisation becoming increasingly viable, states may, in principle, realise increasing amounts of cooperative gains from the appropriation of technological benefits or the mitigation of technological risks.

Technological capacities

'Technological capacities' indicate the respective ability of states to create costs and benefits via technologies under their jurisdiction or control. Technological capacities can entail material factors such as various types of infrastructure.[60] They can also entail immaterial factors such as expert knowledge, property rights, or synergistic social institutions more generally.[61] The degree of asymmetricity in the global distribution of capacities shapes the degree to which states are biased towards either the costs or benefits associated with a given technology. In turn, this means that the collective action problem is increasingly defined by zero-sum elements, as smaller numbers of actors hold greater shares of global capacities.

This phenomenon holds for diverse types of collective action problems. For technologies that can be used to produce global public goods, the core challenge for international cooperation is to ensure adequate levels of supply, as technology owners or operators incur direct costs yet receive only diffuse benefits from the provision of the good themselves. Where global technological capacities are distributed asymmetrically, high-capacity states will be biased towards the costs of providing the associated public good, whereas low-capacity states will be biased towards the benefits of its consumption.[62] The same applies for collective action problems that involve transboundary negative externalities. There, technologies are beneficial for their owners or operators yet impose costs abroad. High-capacity states will be biased towards the benefits of the technology and thus have a policy preference for cooperative arrangements that allow them to continue to externalise the associated costs. Conversely, low-capacity states will be biased towards costs and prefer arrangements that will reduce or eliminate negative externalities. The more uneven the global distribution in the capacities for generating technological benefits or risks, the more regulatory preferences will diverge.

The linkage between capacity distributions and regulatory preferences can be observed in diverse areas of international cooperation on technological matters. Nuclear weapons states tend to oppose international initiatives on nuclear disarmament whereas non-nuclear weapons states tend

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[60] Christian Bueger, Tobias Liebetrau, and Jan Stockbruegger, 'Theorizing infrastructures in global politics', *International Studies Quarterly*, 67:4 (2023), pp. 1–10.

[61] Unruh, 'Understanding carbon lock-in'.

[62] See Barrett, *Why Cooperate?*

to be in favour.[63] States with strong cyberwarfare capacities are less inclined towards international controls than states which lack such capacities.[64] States with advanced space-flight technology prefer international regulations that support their appropriation of the commercial benefits of space exploration; non-spacefaring states prefer regulations that would divert some of those benefits to themselves.[65] Governments with weak domestic agrobiotechnology sectors prefer precautionary international regulation for mitigating biosafety risks, whereas governments with strong domestic sectors prefer facilitative regulation that does not interfere with exports of genetically modified food.[66]

The general phenomenon, whereby asymmetricity drives the severity of the collective action problem, is not exclusive to technological issues in international cooperation. What sets technology apart, first, are the associated temporal dynamics: asymmetricity tends to be large initially and to decrease subsequently. The initial asymmetry for emerging technologies is driven by global differences in innovation capacity and more general factors of socio-economic development.[67] Over time, asymmetricity decreases because of technology transfer, diffusion, or imitation, or due to general catch-up processes in innovation capacities outside of the originator states. Second, the association of capacity distributions with collective action problems is possibly more tenuous for non-technological issues. A long intellectual tradition analyses how, for certain such issues, asymmetrical distributions of capacities, or resources more generally, *facilitate* cooperative outcomes by providing small groups with the leverage to create and maintain multilateral rules that end up benefiting *all* actors in the system.[68] However, the capacity–preference linkage provides a broad-strokes explanation for making sense of cooperative outcomes in international technology regulation, specifically why outcomes with greater degrees of legalisation increase in feasibility over time. Naturally, the exact ways in which this causal mechanism manifests itself empirically will vary from case to case. For present purposes, the initial emergence of concentrated technological capacities and their subsequent geographical diffusion provide a useful framework for explaining shifts in the severity of the collective action problem over time.

Uncertainty

Uncertainty is another causal mechanism that initially creates large degrees of severity in the international collective action problem yet attenuates over time. The concept of uncertainty differs in meaning across intellectual contexts. Large parts of International Relations research have related uncertainty to actor motives and interests.[69] Here, I understand uncertainty in reference to decision environments. Scholars have, for instance, referred to it as 'analytic uncertainty',[70] 'model uncertainty',[71] or uncertainty about the 'state of the world'.[72] Uncertainty has also been conceived as

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[63] Rebecca D. Gibbons, 'The humanitarian turn in nuclear disarmament and the Treaty on the Prohibition of Nuclear Weapons', *The Nonproliferation Review*, 25:1–2 (2018), pp. 11–36.

[64] Eilstrup-Sangiovanni, 'Why the world needs an international cyberwar convention', p. 404.

[65] Rossana Deplano, 'The Artemis Accords: Evolution or revolution in international space law?', *International & Comparative Law Quarterly*, 70:3 (2021), pp. 799–819.

[66] Pollack and Shaffer, *When Cooperation Fails*; Robert Falkner, 'The political economy of "normative power" Europe: EU environmental leadership in international biotechnology regulation', *Journal of European Public Policy*, 14:4 (2007), pp. 507–26.

[67] See Richard R. Nelson and Nathan Rosenberg, 'Technical innovation and national systems', in Richard R. Nelson (ed.), *National Innovation Systems: A Comparative Analysis* (New York: Oxford University Press, 1993), pp. 3–21; Marian Beise, 'Lead markets: Country-specific drivers of the global diffusion of innovations', *Research Policy*, 33:6–7 (2004), pp. 997–1018.

[68] Duncan Snidal, 'The limits of hegemonic stability theory', *International Organization*, 39:4 (1985), pp. 579–614.

[69] See Brian C. Rathbun, 'Uncertain about uncertainty: Understanding the multiple meanings of a crucial concept in International Relations theory', *International Studies Quarterly*, 51:3 (2007), pp. 533–57.

[70] Keisuke Iida, 'Analytic uncertainty and international cooperation: Theory and application to international economic policy coordination', *International Studies Quarterly*, 37:4 (1993), pp. 431–57.

[71] Helm, 'International cooperation behind the veil of uncertainty'.

[72] Barbara Koremenos, Charles Lipson, and Duncan Snidal, 'The rational design of international institutions', *International Organization*, 55:4 (2001), pp. 761–99.

'random exogenous factors' that can change the availability and distribution of cooperative gains in unexpected ways.[73] Uncertainty acts as a constraint on the ability of boundedly rational actors to approximate the pay-offs that are associated with different decision alternatives due to a limited understanding of the characteristics of a given policy problem.[74] As an information deficit, uncertainty drives divergence in the expectations of state actors and can lead to differences in their assessments of the cost–benefit distributions associated with a given technology. This is a problem that has been noted, for instance, in the case of international monetary policy coordination, where governments tend to operate on different theoretical models of the functioning of the world economy.[75] As uncertainty can be asymmetrical, different state actors may have access to different types of information. This, in turn, drives differences in state assessments of the cost–benefit distributions associated with different technological choices. While orthodox rationalist approaches rely on the role of such private information to account for uncertainty and differences in state assessments,[76] other scholarship stresses how uncertainty and learning can be integrated 'without violating the rationalist core of these approaches'.[77]

Most rationalist scholars consider uncertainty as detrimental to international cooperation.[78] Barrett and Dannenberg argue that uncertainty about fat-tail climate risks leads to unfavourable cooperation structures.[79] Helm argues that uncertainty exacerbates the implications of divergent regulatory preferences by providing states with a pretence for defection.[80] Dimitrov suggests that uncertainty about the consequences of environmental problems impedes international cooperation.[81] Iida notes how uncertainty 'can undermine Pareto-improving coordination'.[82] Analysing the global politics of nanotechnology, Falkner and Jaspers find that uncertainty 'is one of the factors that stands in the way of a broader political consensus on how to create global governance structures'.[83] The emerging literature on the global governance of artificial intelligence (AI) identifies uncertainty as a major barrier for robust international cooperation, for instance because the limited contemporary understanding of complex machine-learning algorithms limits the pursuit of transparency and accountability in AI governance.[84]

The severity of the collective action problem in international technology regulation accordingly scales with the degree of uncertainty over scientific, technical, and economic aspects of a given technological issue. At the scientific level, uncertainty can relate to fundamental cause–effect relationships, including with regards to technological impacts, including risks. This level of uncertainty relates to the underpinning causal 'model' that decision-makers use for informing their cooperative choices, as authors have noted for other contexts of international cooperation.[85] At the technical level, uncertainty can attach to questions of material implementation. At the economic level,

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[73] Alexander Thompson, 'Rational design in motion: Uncertainty and flexibility in the global climate regime', *European Journal of International Relations*, 16:2 (2010), pp. 269–96 (p. 272).

[74] Radoslav S. Dimitrov, 'Knowledge, power and interests in environmental regime formation', *International Studies Quarterly*, 47:1 (2003), pp. 123–50.

[75] Jeffrey A. Frankel and Katharine E. Rockett, 'International macroeconomic policy coordination when policymakers do not agree on the true model', *American Economic Review*, 78:3 (1988), pp. 318–40.

[76] See James Fearon, 'Rationalist explanations for war', *International Organization*, 49:3 (1995), pp. 379–414 (p. 392).

[77] Andreas Hasenclever, Peter Mayer, and Volker Rittberger, 'Integrating theories of international regimes', *Review of International Studies*, 26:1 (2000), pp. 3–33 (p. 26).

[78] Iida, 'Analytic uncertainty and international cooperation'; Koremenos et al., 'The rational design of international institutions'.

[79] Scott Barrett and Astrid Dannenberg, 'Climate negotiations under scientific uncertainty', *Proceedings of the National Academy of Sciences*, 109:43 (2012), pp. 17372–6.

[80] Helm, 'International cooperation behind the veil of uncertainty'.

[81] Dimitrov, 'Knowledge, power and interests in environmental regime formation'.

[82] Iida, 'Analytic uncertainty and international cooperation', p. 444.

[83] Falkner and Jaspers, 'Regulating nanotechnologies'.

[84] Taeihagh, 'Governance of artificial intelligence'.

[85] Helm, 'International cooperation behind the veil of uncertainty'; Frankel and Rockett, 'International macroeconomic policy coordination'.

uncertainty can exist regarding the competitiveness and commercial feasibility of a given technology. For emerging technologies, uncertainty tends to be high across these dimensions: important causal properties may be insufficiently understood, questions of technical implementation may be unresolved, and economic prospects may be unclear.[86]

As technologies mature and become consolidated in wider sociotechnical systems, uncertainty tends to decrease: at the scientific level due to methodological advances and improved data availability; at the technical level due to process innovation and learning effects; and at the economic level due to the better understanding of market actors as they can observe commercial performance over longer periods of time. Uncertainty should thus see continuous decrease over time, which in turn implies that the collective action problem ameliorates. As with global distributions of technological capacities discussed in the previous subsection, the severity of the collective action problem is accordingly high for emerging technologies but decreases as they mature and consolidate. The role which uncertainty plays for the temporality of the collective action problem makes technology a distinct object of international cooperation, although with parallels to environmental issues where initial uncertainty as an impediment to cooperation should similarly decrease over time.[87]

Empirical illustrations

This section provides an empirical illustration of the theoretical argument through case studies of synthetic biology and nuclear power. The case studies assess the respective role of collective action problems and sociotechnical lock-in, making the case that, in the absence of either type of constraint, regulatory interventions that unlock greater cooperative gains would have been possible. This requires the incorporation of counterfactual reasoning.[88] Synthetic biology and nuclear power respectively constitute typical cases: the former is an example of a new technology subject to considerable uncertainty and strong asymmetricity in the global distribution of technological capacities. ‘Early’ international regulatory intervention in synthetic biology has led to shallow legalisation despite a counterfactual where deeper legalisation would enable more benefits associated with synthetic biology to be captured and more risks to be mitigated. The latter case deals with a mature technology that has, over time, become embedded in a sociotechnical system. While the collective action problem associated with nuclear power has arguably become less severe over the decades due to decreasing uncertainty and asymmetricity in capacity distributions, sociotechnical lock-in has created a status quo bias for international regulatory interventions. The shift towards deeper legalisation in international nuclear safety thus codifies and incrementally builds upon pre-existing soft rules, with the consequence that risk mitigation is lower than in the counterfactual where rule development is unconstrained by lock-in.

Synthetic biology

Synthetic biology refers to a range of recent developments in biotechnology that, in the broadest sense, revolve around the targeted design or re-engineering of life. Synthetic biology includes diverse applications such as genome synthesis from anorganic components; the use of standardised biological building blocks for the construction of cells and biological circuits; or novel biocontrol agents intended for rapid and large-scale genetic engineering of entire species or ecosystems.[89] Synthetic biology is gradually increasing in technological readiness, while some of its more extravagant ideas, such as the reversal of cell rotation to make humans immune to all existing pathogens,

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[86] See Daniele Rotolo, Diana Hicks, and Ben R. Martin, ‘What is an emerging technology?’, *Research Policy*, 44:10 (2015), pp. 1827–43.

[87] See Dimitrov, ‘Knowledge, power and interests in environmental regime formation’.

[88] James D. Fearon, ‘Counterfactuals and hypothesis testing in political science’, *World Politics*, 43:2 (1991), pp. 169–95; Richard N. Lebow, *Forbidden Fruit: Counterfactuals and International Relations* (Princeton, NJ: Princeton University Press, 2010).

[89] See CBD, *Synthetic Biology*, CBD Technical Series No. 100, (2022).

remain extraordinarily speculative.[90] Nonetheless, interest in synthetic biology has been increasing markedly over the past decade due to its potential commercial applications or its potential role for public health, climate, and the environment, but also its dual-use aspects.[91]

Synthetic biology products are only gradually becoming commercialised, and the research and development (R&D) landscape remains fragmented. Interest from legacy industries, such as pharmaceuticals or agrobiotechnology, primarily centres on areas of synthetic biology that overlap with more conventional genetic technologies, notably with genome-editing techniques such as CRISPR.[92] There is thus no coherent advocacy coalition that would attempt to ensure a favourable regulatory environment for the technological field as such. Similarly, governments and international organisations are still struggling with the political and legal implications of synthetic biology and, while recognising its potential as well as potential risks across various issue areas, have not created linkages to core policy interests.[93] In other words, synthetic biology is an emerging technology characterised by a high degree of plasticity and ambiguity,[94] with no indications of sociotechnical lock-in as of present. At the same time, its risks and opportunities in principle present a theoretical rationale for robust international action to facilitate technology diffusion and adoption and to ensure effective assessment and management of transboundary risks.

International cooperative arrangements for synthetic biology that have emerged in recent years share low degrees of legalisation. The World Health Organization has issued non-binding guidelines regarding genetically modified mosquitoes applicable to some specific applications in synthetic biology targeted at the genetic control of disease vectors. The Review Conferences of the Biological Weapons Convention have been exploring various dual-use aspects of synthetic biology without producing specific prescriptions yet.[95] Under the Convention on Biological Diversity and its Cartagena Protocol on Biosafety, a range of non-binding governing body decisions have engaged with certain environmental applications of synthetic biology, yet in a manner that mostly reiterates existing legal commitments as well as the general applicability of the precautionary approach.[96]

The shallowness of existing governance responses to synthetic biology is disproportionate to the scope and magnitude of its potential positive and negative impacts. International biosafety rules are increasingly out of step with technological developments in the agricultural sector, such as the adoption of so-called New Genomic Techniques for plant breeding, or the development of RNA interference methods for inducing pathogen resistance.[97] The same applies for novel biological agents that are being developed against disease vectors, plant pests, and invasive species.[98] The potential contributions of synthetic biology to environmental conservation and sustainable use remain, for the most part, unexplored at the international level.[99] Dedicated international mechanisms for technology transfer and capacity-building in the field of synthetic biology remain virtually non-existent. This is the case also for international standards for risk assessment or

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[90] George Church and Ed Regis, *Regenesis: How Synthetic Biology Will Reinvent Nature and Ourselves* (New York: Basic Books, 2014).

[91] See Bruce L. Webber, S. Raghu, and Owain R. Edwards, 'Is CRISPR-based gene drive a biocontrol silver bullet or global conservation threat?', *Proceedings of the National Academy of Sciences*, 112:34 (2015), pp. 10565–7; Jonathan Symons, Thomas A. Dixon, Jacqueline Dalziell, et al., 'Engineering biology and climate change mitigation: Policy considerations', *Nature Communications*, 15:2669 (2024), pp. 1–9.

[92] See Finja Bohle, Robin Schneider, Juliane Mundorf, et al., 'Where does the EU-path on NTGs lead us?', *Frontiers in Genome Editing*, 6 (2024), available at: {https://doi.org/10.20944/preprints202311.1897.v1}.

[93] Jesse L. Reynolds, 'Governing new biotechnologies for biodiversity conservation: Gene drives, international law, and emerging politics', *Global Environmental Politics*, 20:3 (2020), pp. 28–48; CBD, *Synthetic Biology: Decision 15/31 of the Conference of the Parties to the Convention on Biological Diversity*, CBD/COP/DEC/15/31, (2022).

[94] Rotolo et al., 'What is an emerging technology?'.

[95] See Tao Sun, Jie Song, Meng Wang, Chao Zhao, and Weiwen Zhang, 'Challenges and recent progress in the governance of biosecurity risks in the era of synthetic biology', *Journal of Biosafety and Biosecurity*, 4:1 (2022), pp. 59–67.

[96] Reynolds, *Governing New Biotechnologies for Biodiversity Conservation*; CBD, *Synthetic Biology*, Decision 15/31.

[97] Bohle et al., 'Where does the EU-path on NTGs lead us?'.

[98] Reynolds, *Governing New Biotechnologies for Biodiversity Conservation*.

[99] See CBD, *Synthetic Biology*, Decision 15/31; Symons et al., 'Engineering biology and climate change mitigation'.

environmental impact assessment. In biosecurity, potential uses of synthetic biology for hostile purposes have brought back into focus the absence of an international verification regime under the Biological Weapons Convention. The increasing commercial and scientific use of digitalised genetic sequence data raises complex legal and regulatory questions that have so far been left unanswered under governance systems from the Convention on Biological Diversity to international intellectual property rights agreements.[100]

My framework suggests that this disparity between technological development and institutional responses results from a severe international collective action problem, which is in turn driven by uncertainty and asymmetrical capacity distributions. In the uncertainty dimension, stakeholders struggle with defining synthetic biology and differentiating it from conventional, established approaches in genetic engineering.[101] For many applications of synthetic biology that are presently under development, impacts, risks, and benefits are extraordinarily difficult to predict. The commercial value of synthetic biology is potentially vast but remains abstract for the time being. These uncertainties complicate international collective action by precluding the formation of precise policy preferences linked to core state interests. The same applies to capacity distributions: Synthetic biology R&D is presently dominated by institutions in a handful of industrialised countries as well as China.[102] In the international discussions on the regulation of synthetic biology, this has led to a situation in which low-capacity countries emphasise the need for either technology transfer and benefit-sharing or the mitigation of transboundary technological risks. Conversely, the United States in particular has shunned international regulatory solutions that would negatively impact the intellectual property of domestic industries or subject synthetic biology to onerous procedures for risk assessment and management.[103]

Taken together, the case of synthetic biology highlights how uncertainty and asymmetricity in the distribution of technological capacities are driving a collective action problem that leads to cooperative outcomes which are shallower than the theoretical availability of joint gains in the issue area would indicate. Various conceptual and empirical analyses suggest that cooperative gains might be greater in a counterfactual scenario characterised by deep legalisation. On the one hand, robust international legal measures to enhance responsible innovation, technology transfer, knowledge-sharing, and capacity-building could allow a broader range of countries and regions to derive benefits from synthetic biology.[104] On the other hand, measures for risk assessment, risk management, liability and redress, as well as domestic capacity-building in developing countries, could allow for greater preparedness and response in dealing with the potential harmful impacts of synthetic biology in a transboundary context.[105] The factual state of weak international cooperation on synthetic biology, however, implies that some benefits remain unrealised and risks unmitigated. At the same time, the weak international rules that are being put into place in the present are likely to feed into sociotechnical lock-in in the future, contributing to a status quo bias in which preexisting rules might gradually harden yet without substantial changes in their content. This pattern is precisely what my second empirical example highlights.

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[100] Piselli, 'International sharing of pathogens and genetic sequence data under a pandemic treaty'.

[101] Philip Shapira, Seokbeom Kwon, and Jan Youtie, 'Tracking the emergence of synthetic biology', *Scientometrics*, 112 (2017), pp. 1439–69; CBD, *Synthetic Biology. CBD Technical Series No. 100*.

[102] Shapira et al., 'Tracking the emergence of synthetic biology'; Florian Rabitz, 'The organizational structure of global gene drive research', *Global Environmental Change*, 84 (2024), pp. 1–12.

[103] See Reynolds, 'Governing new biotechnologies for biodiversity conservation'.

[104] See Jack Stilgoe, Richard Owen, and Phil Macnaghten, 'Developing a framework for responsible innovation', *Research Policy*, 42:9 (2013), pp. 1568–80; Nimisha Pandey, Heleen de Coninck, and Ambuj D. Sagar, 'Beyond technology transfer: Innovation cooperation to advance sustainable development in developing countries', *Wiley Interdisciplinary Reviews: Energy and Environment*, 11:2 (2022), pp. 1–25.

[105] Aarti Gupta and Robert Falkner, 'The influence of the Cartagena Protocol on Biosafety: Comparing Mexico, China and South Africa', *Global Environmental Politics*, 6:4 (2006), pp. 23–55; Falkner and Jaspers, 'Regulating nanotechnologies'.

Nuclear power

Nuclear power first emerged in the United States during the 1950s amid widespread enthusiasm regarding its supposed ability to deliver electricity that would famously be 'too cheap to meter'.[106] During the 1950s, the United States, the United Kingdom, France, and the Soviet Union deployed the first pressurised water reactors, followed by demonstration projects in numerous industrialised countries during the 1960s, many of which failed to take off.[107] From the late 1960s, nuclear power spread beyond the advanced economies, including to India, Pakistan, South Korea, and Brazil. The total geographical diffusion of nuclear power remained limited, though, with only a handful of countries relying heavily on the technology in their domestic energy systems, notably Canada, France, Japan, the Soviet Union and Russia, South Korea, and Ukraine, as well as the United States. As of 2024, nuclear reactors are operating in 32 countries, with half of the global fleet located in China, France, and the United States.[108] Fifty-seven additional reactors are presently under construction, including by novel entrants such as Bangladesh, Iran, and Turkey.[109]

Primarily because of technology transfer, the global distribution of nuclear power generation capacities has thus become less asymmetrical over time, in principle translating into a less severe international collective action problem. The second driver of severity, uncertainty, has been undergoing changes as well. Permanent storage came to be recognised as a major technical and regulatory challenge, as initial proposals for disposal, including by launching nuclear waste into the Sun, turned out to lack feasibility.[110] Limitations in economic feasibility similarly became clearer over time, as nuclear power turned out to lack competitiveness relative to other energy sources.[111] Finally, notwithstanding considerable progress in reactor design, the inability to eliminate residual accident risks through technical means is now widely understood as a key barrier for the social and political acceptance of nuclear power.[112] In line with my theoretical framework, these and similar reductions in scientific, technical, and economic uncertainty should have ameliorated the collective action problem over time by providing states with a more robust informational basis on which to make decisions about the need for, and modalities of, international cooperation.

Consistent with this gradual decrease in the severity of the collective action problem, the international nuclear safety regime has increased considerably in rule density and legalisation over the decades.[113] Pre-Chernobyl, this included non-binding nuclear safety instruments such as the International Atomic Energy Agency's (IAEA) 1978 Nuclear Safety Standards or various decisions by the Council of the European Atomic Energy Community (EURATOM).[114] It also included several binding instruments: the 1960 Paris Convention on Third Party Liability in the Field of Nuclear Energy, the 1963 Vienna Convention on Civil Liability for Nuclear Damage, a 1963 agreement on emergency assistance between the IAEA and Denmark, Finland, Sweden, and Norway, as well as the 1980 Convention on the Physical Protection of Nuclear Material. The 1986 Chernobyl catastrophe accelerated this trend towards greater rule density and legalisation: two

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[106] See Steven M. Cohn, *Too Cheap to Meter: An Economic and Philosophical Analysis of the Nuclear Dream* (New York: SUNY Press, 1997).

[107] Sonja D. Schmid, *Producing Power: The Pre-Chernobyl History of the Soviet Nuclear Industry* (Cambridge, MA: MIT Press, 2015); Arne Kaijser, Markku Lehtonen, Jan-Henrik Meyer, and Mar Rubio-Varas, 'Introduction: Nuclear energy and society in postwar Europe', in Arne Kaijser, Markku Lehtonen, Jan-Henrik Meyer, and Mar Rubio-Varas (eds), *Engaging the Atom: The History of Nuclear Energy and Society in Europe from the 1950s to the Present* (Morgantown: West Virginia University Press, 2021), pp. 1–24.

[108] IAEA, *World Statistics: Power Reactor Information System* (2024), https://pris.iaea.org.

[109] IAEA, *World Statistics*; see also Robert J. Budnitz, H. Holger Rogner, and Adnan Shihab-Eldin, 'Expansion of nuclear power technology to new countries: SMRs, safety culture issues and the need for an improved international safety regime', *Energy Policy*, 119 (2018), pp. 535–44.

[110] Alley and Alley, *Too Hot to Touch*, p. 23.

[111] Lucas W. Davis, 'Prospects for nuclear power', *Journal of Economic Perspectives*, 26:1 (2012), pp. 49–66.

[112] See Perrow, *Normal Accidents*.

[113] Vanda Lamm, 'Reflections on the development of international nuclear law', *Nuclear Law Bulletin*, 99 (2017), pp. 31–44.

[114] See Mohamed Elbaradei, Edwin Nwogugu, and John Rames, 'International law and nuclear energy: Overview of the legal framework', *IAEA Bulletin*, 37:3 (1995), pp. 16–25.

additional international agreements, respectively on the early notification of nuclear accidents and on international assistance for disaster response, were adopted within a year. A 1988 protocol linked together the previously separate liability regimes of the 1960 Paris Convention and the 1963 Vienna Convention. The nuclear safety regime evolved further with the 1994 Convention on Nuclear Safety, the Convention on Supplementary Compensation for Nuclear Damage, and the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management (both 1997).

While the international nuclear safety regime has thus hardened considerably over time, sociotechnical lock-in created a bias towards incremental rule development. Hultman points out how nuclear technology is embedded 'in a large-scale industrial engineering complex, with strong links to militaries, national funding agencies, and universities'.[115] The creation of international institutions for the promotion and facilitation of nuclear energy, such as EURATOM and the IAEA, is another indicator of sociotechnical lock-in, as is the rise in global nuclear power production since the 1950s until it levelled off around the turn of the millennium. Notwithstanding widespread societal opposition to nuclear energy, it has remained part of the global energy policy agenda in the past two decades due to its linkages with energy security and decarbonisation.[116]

My theoretical framework proposes that sociotechnical lock-in has created a bias towards incrementalism so that the international nuclear safety regime has hardened over time yet without fundamental changes in regulatory substance.[117] Notably, sociotechnical lock-in appears to have remained operational even in the face of the Chernobyl catastrophe, an exogenous shock of a magnitude that, in other issue areas, has typically been associated with considerable institutional adjustment processes.[118] The persistence of incremental change across such an exogenous shock thus testifies to the existence of sociotechnical lock-in. The 1987 conventions on notification and assistance, 'concerned merely with the aftermath of nuclear accidents, not with their prevention',[119] provided a deeper legalisation of extant, non-binding rules and practices.[120] The same applies to the 1994 Convention on Nuclear Safety, which translated 'non-binding, technical provisions into legally binding standards',[121] as well as to the 1997 Joint Convention. Previously, the 1980 Convention on the Physical Protection of Nuclear Materials had already legalised IAEA soft law that had existed since the 1970s.[122] Thus, throughout the 1980s and 1990s, we can witness a process of gradual hardening in the international nuclear safety regime, as previous soft law arrangements were formally becoming more deeply legalised while retaining their substantive content.

There is robust evidence that the incremental evolution and legalisation of the nuclear safety regime has left crucial governance issues unresolved. Questions about transparency and notification requirements in the international nuclear safety regime have persisted from Chernobyl in 1986 to Fukushima in 2011 and beyond.[123] The Article 6 provisions on the decommissioning of unsafe reactors under the Convention on Nuclear Safety lack specificity and legal obligation. Further, the

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[115] Nathan E. Hultman, 'The political economy of nuclear energy', *Wiley Interdisciplinary Reviews: Climate Change*, 2:3 (2011), pp. 397–411 (p. 397).

[116] Hultman, 'The political economy of nuclear energy'.

[117] See Lamm, 'Reflections on the development of international nuclear law'.

[118] E.g. Jeff D. Colgan, Robert O. Keohane, and Thijs van de Graaf, 'Punctuated equilibrium in the energy regime complex', *The Review of International Organizations*, 7 (2012), pp. 117–43.

[119] Menno T. Kamminga, 'The IAEA Convention on Nuclear Safety', *International & Comparative Law Quarterly*, 44:4 (1995), pp. 872–82 (p. 873).

[120] Selma Kus, 'International nuclear law in the 25 years between Chernobyl and Fukushima and beyond', *Nuclear Law Bulletin*, 87 (2011), pp. 7–26 (p. 9).

[121] Kus, 'International nuclear law', p. 9; see also Aleksandra Čavoški, 'Revisiting the Convention on Nuclear Safety: Lessons learned from the Fukushima accident', *Asian Journal of International Law*, 3:2 (2013), pp. 365–91 (p. 368); Kamminga, 'The IAEA Convention on Nuclear Safety', p. 881.

[122] Lamm, 'Reflections on the development of international nuclear law', p. 41.

[123] Kamminga, 'The IAEA Convention on Nuclear Safety', p. 877; Kus, 'International nuclear law'.

Convention provides only weak rules on reporting, review, and compliance.[124] Taebi and Mayer identify monitoring and verification as a crucial sticking point in the nuclear safety regime more broadly.[125] Kamminga notes that these deficiencies are the direct consequence of core elements of the international nuclear safety regime having been moulded on the policy preferences of the nuclear industry.[126] The counterfactual case is that, in the absence of sociotechnical lock-in, states would have created superior institutional arrangements for mitigating the risks associated with nuclear power, as well as for harnessing potential benefits. A common theme in the literature is that more effective international nuclear safety governance would require stronger oversight mechanisms, with Čavoški noting that, for the Convention on Nuclear Safety, 'a stronger monitoring regime would seem indispensable in preventing another Fukushima'.[127] Authors also note that an effective nuclear safety regime may require centralisation of regulatory authority at the international level, which would present a rupture with the state-centric model of nuclear safety regulation as it has emerged during the second half of the 20th century.[128] Sociotechnical lock-in as a constraint on rule development offers a powerful explanation for the relative weakness of international rules on nuclear safety.

Conclusions

I have developed a cooperation-theoretical account of international technology regulation centered on collective action problems and sociotechnical lock-in. I have suggested that uncertainty and asymmetricity in technological capacity distributions drive high degrees of severity in the international collective action problem for novel technologies, complicating the realisation of cooperative gains through negotiated agreements with suitable depth of legalisation. I have argued that both drivers attenuate over time so that the collective problem becomes less severe, and more robust forms of international cooperation become politically feasible. As I have pointed out, however, sociotechnical lock-in can reduce the incentives and capacities for regulatory status quo deviation: while less severe collective action problems enable deeper legalisation, cooperative outcomes will tend to build incrementally on pre-existing rules. This leads to a hardening of governance arrangements over time yet without substantive changes in regulatory content. This can lead to situations in which cooperative outcomes are historically inefficient in the sense that sociotechnical lock-in prevents the realisation of superior alternatives.

To be sure, phenomena such as lock-in, uncertainty, and asymmetrical capacities are not unique to technological issue areas. In one way or another, they likely characterise most issue areas of global governance as such. What sets technology apart is a matter of degree rather than categorical differences: uncertainty is a defining aspect of technological development yet gradually attenuates as more information becomes available. The only other issue area where we would expect to see gradual reductions from initially high levels of uncertainty is in global environmental politics. Yet even there, we might expect considerably larger variation in the types and degrees of uncertainty than is the case for technological issues.[129] The same specificity applies to the temporal dynamics of asymmetricity in capacity distributions. Numerous non-technological issue areas are characterised by strongly asymmetric distributions in whatever types of material and non-material resources constitute state power and interests.[130] Yet technology diffusion, through a variety of

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[124] Kus, 'International nuclear law'; Čavoški, 'Revisiting the Convention on Nuclear Safety'; Budnitz et al., 'Expansion of nuclear power technology to new countries', p. 541.

[125] Behnam Taebi and Maximilian Mayer, 'By accident or by design? Pushing global governance of nuclear safety', *Progress in Nuclear Energy*, 99 (2017), pp. 19–25.

[126] Kamminga, 'The IAEA Convention on Nuclear Safety'.

[127] Čavoški, 'Revisiting the Convention on Nuclear Safety', p. 391.

[128] Budnitz et al., 'Expansion of nuclear power technology to new countries'.

[129] See Dimitrov, 'Knowledge, power and interests in environmental regime formation'.

[130] E.g. Snidal, 'The limits of hegemonic stability theory'.

mechanisms that range from intentional transfer to diffuse catch-up and imitation processes, creates a unique tendency for technological issue areas in world politics to gradually shift towards lower degrees of asymmetricity, with consequences for international collective action that I have lined out in 'Collective action problems' above. Lock-in, finally, is a phenomenon that similarly occurs in non-technological issue areas yet is particularly pronounced in technological ones. The reason is the tendency for technology and social institutions to form interlocking structures that are highly resilient to outside attempts at change, as noted in the broad literature on sociotechnical systems.[131] While the argument developed in this text might, in one way or another, be applied to other issue areas as well, we should expect the specific causal mechanisms discussed here to be uniquely efficacious for technological issue areas in world politics.

Thus, while contemporary global governance does not have a particularly impressive overall track record in resolving challenges in world politics, technology might well stand out in terms of the intrinsic political difficulties which it poses. Above, I have briefly highlighted the deficiencies of contemporary governance arrangements for capturing the benefits and mitigating the risks associated with the revolution in the global life sciences that is synthetic biology. I have also discussed how sociotechnical lock-in may hamper the development of more effective international structures for nuclear safety. For AI, as one of the most pressing contemporary issues in world politics as such, my theoretical framework highlights the challenges of collective action resulting from deep uncertainties over a wide array of risks and benefits, as well as from the geographical concentration of AI research as a driver of diverging regulatory preferences. The same applies to adjacent areas such as robotics and Lethal Autonomous Weapons Systems. Conversely, Negative Emissions Technologies for the removal of atmospheric carbon dioxide showcase strong indicators of sociotechnical lock-in, narrowing the scope for effective governance solutions for scaling up deployment in line with international temperature targets and for mitigating associated social and environmental risks.[132]

The systemic inefficiency of international technology regulation creates structural barriers towards effective international solutions for pressing contemporary technological issues. This does not imply that regulatory action is destined for universal failure. Cross-case variation can result from differences in technological attributes or from differences in institutional design, in addition to a wide range of other factors. While technology may show a general tendency towards regulatory inefficiency at the international level, this challenge is bound to be more accentuated for some technologies than it is for others.

Yet in parallel to the effects of capacity distributions and uncertainty (here assumed as tending towards invariance), additional mechanisms might operate with significant cross-case variation, thus allowing greater differentiation. At an intermediate level of abstraction, one differentiating feature that I have briefly mentioned in passing but without systematic follow-up is the type of good that a technology produces or represents in itself. Where providers cannot effectively prevent others from consuming these goods, the resulting free-rider problem complicates cooperation by creating additional, costly, and likely contentious requirements for effective institutional design. The collective action problem is accordingly less severe when goods are excludable, just as its severity is greater for rivalrous goods than for non-rivalrous ones. These and other features can lead to differentiating effects at the level of technologies, leading to some variation in the extent to which the tendency towards systemic inefficiency manifests itself on a case-by-case basis. Just as with technological problem structure, institutional design might partially offset the consequences of systemic inefficiency, with some designs more suitable for some problem structures than for others.[133] For instance, states might be able to achieve ambitious outcomes even where large degrees of asymmetry in the global distribution of technological capacities drives substantial divergence in

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[131] Unruh, 'Explaining carbon lock-in'; Seto et al., 'Carbon lock-in'; Simoens et al., 'Discursive dynamics and lock-ins in socio-technical systems'.

[132] Cairns, 'Climate geoengineering'.

[133] Ronald B. Mitchell, 'Problem structure, institutional design and the relative effectiveness of international environmental agreements', *Global Environmental Politics*, 6:3 (2006), pp. 72–89.

regulatory preferences: this is the case where suitable issue linkages allow states to realise net gains from cooperation by simultaneously making concessions on unrelated issues that are more beneficial for their negotiation partners than they are costly to themselves. Whether such linkages are available can depend on numerous factors, including the idiosyncratic attributes of a given negotiation system. While far from a universal solution, issue linkages are thus one institutional design feature that may, in some contexts, allow for more efficient outcomes than the structural features of capacity distributions and uncertainty would initially suggest. With institutional design becoming more demanding, though, the complexity of bargaining situations increases as well, which can create challenges of its own.[134]

Not every novel technology is a problem for international cooperation in the same way as the examples just listed. Inventions such as, say, 3D-printing or biological computer chips have transboundary implications which are diffuse at best. Not every piece of technology is a problem of international cooperation. At the same time, it is worth pondering whether it is worthwhile to consider 'technology' as a distinct object of theoretical interest for scholarship on international cooperation and regime theory. For the most part, this scholarship considers 'technologies' merely as appendices to other policy domains. Agricultural biotechnology might form part of analyses of institutions and cooperation in the domain of food security or international trade. Blockchain might figure in the analysis of international finance. Cyberwarfare has implications for international security. While there is nothing necessarily wrong with this, it is worth considering whether there is also a theoretical utility in considering technology as an overarching governance problem with cross-domain implications. Nuclear technology might be an issue of energy policy, and synthetic biology one of biosafety governance. But perhaps both raise larger issues that transcend their respective policy silos and are thus of broader interest for questions of international cooperation as such.

Considering the dominance of constructivist approaches in this research field, it may thus be worthwhile for rationalist scholarship to pay greater attention to technology as an issue area in international cooperation. This may require further work for specifying the distinguishing characteristics of that issue area, in terms of sociotechnical lock-in, technological capacities, and uncertainty, but also beyond. The advantage of a broader rationalist inquiry into international technology regulation is that it could bring to bear a diverse conceptual arsenal, for instance on institutional design, compliance, and effectiveness, on a broad class of contemporary world political challenges, in a manner that accounts for the idiosyncrasies of that issue area and allows for systematic comparisons between cooperation problems and institutional responses in different technological domains.

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[134] Mitchell, 'Problem structure, institutional design and the relative effectiveness of international environmental agreements'; Bernauer et al., 'Is there a "depth versus participation" dilemma in international cooperation?'.

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