Technological Change and the International System

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Does world politics affect the adoption of new technology? States overwhelmingly rely on technology invented abroad, and their differential intensity of technology use accounts for much of their differences in economic development. Much of the literature on technology adoption focuses on domestic conditions. We argue that the structure of the international system is critical. It affects the level of competition among states which in turn affects leaders' willingness to enact policies that speed technology adoption. Countries adopt new technology as they seek to avoid vulnerability to attack or coercion by other countries. By systematically examining states' adoption of technology over the past 200 years, we find that countries adopted new technologies faster when the international system was less concentrated, that changes in systemic concentration have a temporally causal effect on technology adoption, and that government policies to promote technology adoption were related to concerns about rising international competition. A competitive international system is an important incentive for technological change, and may underlie global "technology waves."

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Introduction

During what is known as "long-waves" or "technological revolutions", new technologies have diffused rapidly through the international system, and growth has surged. At other times, adoption of technology has been slow. As researchers studying such patterns stress, these global waves cannot be attributed to economic factors alone: "any 'model' that limits itself to pure economic factors (such as R&D, capital investment or human capital) provides a much too narrow perspective . . . The transformation

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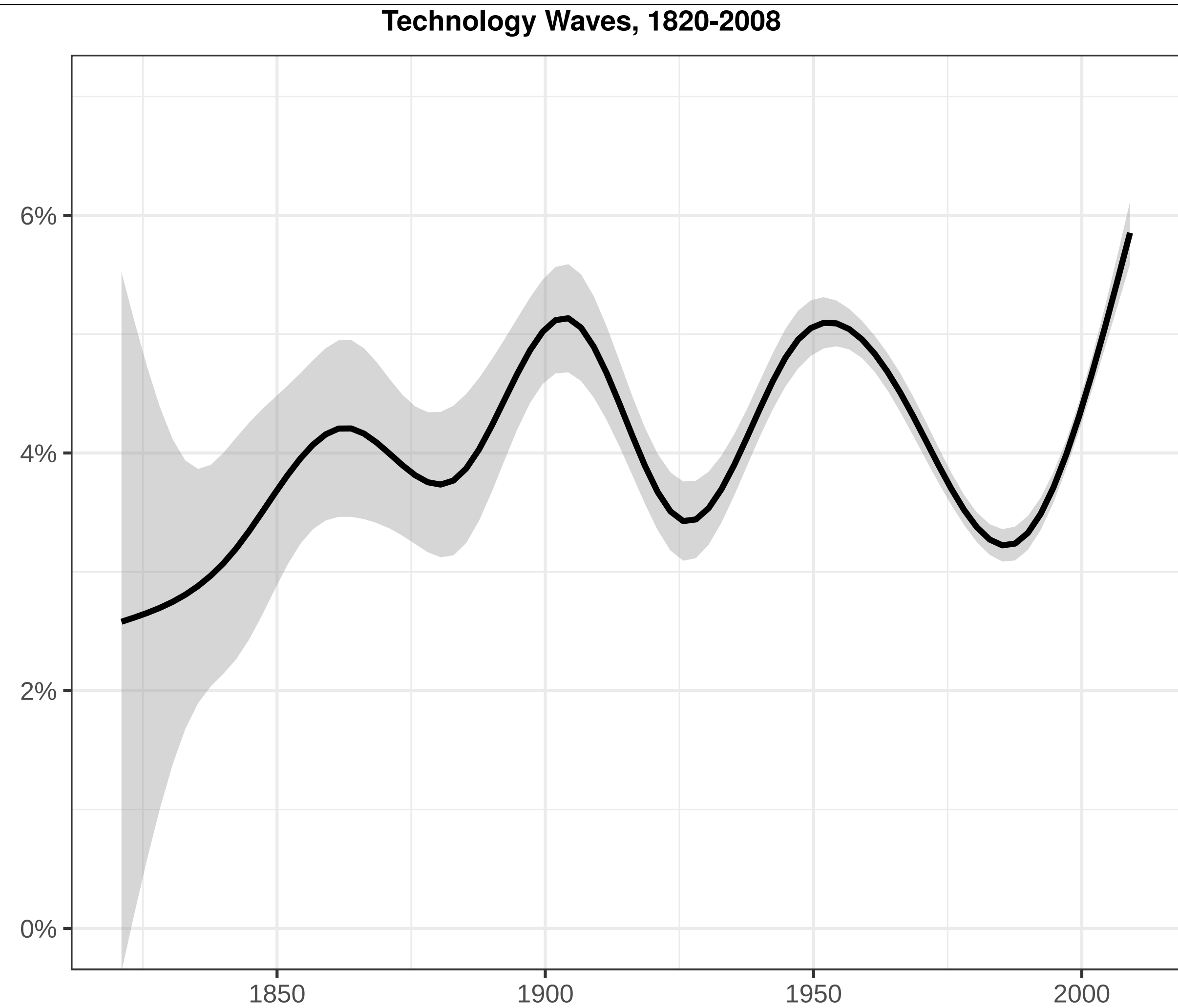
of capitalism involves interaction of the economic sphere with other domains, such as science and technology, and institutions."[1] Examining what facilitates the global spread of technology is therefore important for understanding countries' levels of economic development, their military capabilities, and their state capacity.

Figure 1. Trends in (Δ Log of) Technology Units per Capita of twenty key technologies from Comin et al. (2013) from 1820 to 2009



Details: The plot summarizes more than 90,000 observations of rates of technology adoption for twenty key technologies over the past two centuries. It shows unexplained yearly increase in number of technology units per capita, after controlling for country and technology-specific heterogeneity. The grey area shows the 95 percent confidence interval of the loess regression.

Figure 1 plots the yearly percentage increase in use of twenty of the most important technologies

[1] Fagerberg and Verspagen 2002, 1293.

(such as railroads, the telephone and agricultural tractors) over almost 200 years. These especially important technologies form the basis for our analysis. In the words of Oliver Blanchard: "Though technological progress is smooth, it is certainly not constant. There are clear technological waves.[2]" We do not seek to explain why some technologies diffused faster than others, or why some countries adopted technology at a higher pace. Rather, we want to explain these global waves of technology adoption; why are there periods when many technologies are adopted faster in many countries, at the same time?

Scholars in international relations have suggested that international competition, especially short of violent conflict, may have important positive effects in addition to its obvious costs. In particular, the prospect of competition for survival or predominance may force countries to change policies to increase their growth. As Waltz, among many other scholars of international relations has claimed, the "evolutionary pressure" imposed by an anarchic international system forces states to constantly increase their productivity and military prowess in order to thrive and survive.[3] One important such adjustment is the adoption of new technology. We provide a theory and systematic tests relating the structure of the international system to the speed of technological change.

Our theory argues that (1) external pressures to adopt are not constant over time, (2) that these systemic pressures are related to the distribution of capabilities in the international system, and consequently (3) that systemic shifts can be linked to global "technology waves," i.e., cycles of slow and rapid technology adoption involving many technologies in many countries. We are not the only to argue that external pressures induce changes in economic policy, or that competition in the international system varies with the distribution of capabilities; but we combine the two ideas into a theory of global waves of technology adoption. Empirically, our contribution is to expand the most extensive dataset on technology adoption at the country-technology-year level (adding more than 16,000 observations), and to examine if there are links between technology adoption and the structure of the international system across two centuries, all key technologies, and nearly 160 countries.

This study proceeds with a summary of the literature on technology adoption, differentiating adoption from innovation, highlighting the importance of technology sourced from abroad, and noting

[2]Blanchard 2009, 213
[3]Waltz 1979, 128

the key role governments play in affecting technology adoption. We then develop our systemic theory in more detail and present our hypotheses. The next sections contain details on our data, empirical strategy, and results. A discussion of these results concludes. Our theory shows how the dispersion of power in the international system incentivizes leaders to change policies to make technology adoption more likely. Our data and case study corroborate this causal story, which is a novel international system-based explanation of global technology waves.

Technological Change and Its Enemies

The empirical literature on technology adoption has established four key conclusions about technological change: (1) Most countries most of the time adopt new technologies from abroad; few countries ever innovate. (2) Adoption is costly and disruptive. (3) Because of this fact, most new technologies are resisted by vested interest groups and governments. (4) Governments and their policies are critical factors in slowing or speeding up technology adoption. We discuss these claims below since they are crucial to our theory. In the next section, we bring them together with scholarship in international relations.

Research and development efforts are concentrated in a relatively small number of highly developed countries, which means that most countries most of the time rely on adopting technology from abroad. For instance, the seven largest industrialized countries accounted for about 84% of the world's R&D spending in 1995.[4] Foreign sources of technology are estimated to account for around 90 percent or more of technology-based productivity growth for most countries. For almost all countries almost all the time, the majority of new technology is developed in other countries.[5] The pattern of world-wide technological change is thus largely determined by the adoption of technology from abroad. Our focus is thus on adoption of new technology and not on innovation.

Technology adoption is not costless, easy, or automatic. A range of empirical evidence indicates that international technology transfers carry significant resource costs.[6] Furthermore, it is known that

[4]Keller 2004, 752
[5]Keller 2010, 795, see also: Hall and Jones 1999, Easterly and Levine 2001, Keller 2001.
[6]Mansfield and Romeo 1980; Ramachandran 1993

the market for new technologies is inefficient due to incentives to misrepresent technologies' value.[7]

Most importantly, adopting new technology is disruptive of existing economic arrangements, and has throughout history been resisted by self-interested status quo forces.[8] From ride-hailing services to railroads, existing industries lobby their governments to block adoption. Consumers voice concerns about safety, voters about distributive implications, workers about the loss of jobs. Those who bring new technology to a country must overcome this resistance, and must often do so from a position of weakness. A new technology's benefits may be very uncertain, and newcomers often face the realized capabilities of powerful vested interests.

This disruptive quality is important because governments are widely seen as key actors in fostering or deterring technology adoption. As Mokyr writes: "... outright resistance is a widely observed historical phenomenon. Precisely because such resistance must work outside the market and the normal economic process, artificial distinctions between the 'economic sphere' and the 'political sphere' for this class of problems are doomed.[9]"

Governments may both facilitate and suppress technology adoption. The promotion of technologies has often been undertaken as projects commissioned by national governments (e.g., railroads), or has necessitated government participation (e.g., air travel). Subsidies are one critical way in which government action can get a new technology "off the ground". More important is often what the government does not do: erect or enforce barriers to technology adoption. Through policies such as restrictions on trade or on imports of certain products, granting of monopolies, setting of prohibitive safety standards, erecting regulatory barriers, or granting existing industries avenues of legal action, governments have many means to limit the adoption of new technology. Scholars note that the "regulatory power" of states can have major effects on innovation and adoption [10]. Even when unable to keep new technology out of a country entirely, such policies may matter enormously for the intensity at which technologies are utilized.

Markets and firms are important actors in technological change, but governments are nevertheless

[7]Often, only the broad outlines of technological knowledge are or can be codified and easily shared. Other times, lack of necessary investment — be it in people or infrastructure — slows adoption.
[8]Mokyr 1998b
[9]Mokyr 1998a, 40
[10]Farrell and Newman 2010; Newman and Posner 2011

crucial. As firms grew in size and capital requirements, government policy became more important for facilitating or deterring investments in new technology. Within Europe, economic development processes differed considerably between countries in both "speed and character" as a the result of government policies. As Gerschenkron noted in his seminal essay: "the state, moved by its military interest, assumed the role of the primary agent propelling the economic progress in the country".[11]

Research attempting to pin down systematic differences in technological adoption rates tends to highlight the importance of domestic politics.[12] In particular, Comin and Hobijn find that domestic institutional characteristics explain much of the variation in countries' adoption of technologies with competing predecessors[13]. They argue that (1) government barriers often hinder adoption of new technologies, and (2) that such barriers are erected when lobbying efforts by vested interests outweigh the benefits of adoption. These effects are large: ". . . the estimated effect of lobbies on technology diffusion represents 50% of the observed variation in technology diffusion".[14]

Indeed, scholars of technological change frequently argue that the main barrier to it lies in entrenched domestic interests and the policies that governments adopt to protect them.[15] As Mokyr notes: "Technological change involves substantial losses sustained by those who own specific assets dedicated to the existing technology...When the new techniques arrive, it is optimal for those groups that stand to lose from technological change to resist them. It is also obvious that they have to use non-market mechanisms to do so."[16] He goes on to show that when these conservative groups capture

[11]Gerschenkron 1962, 17

[12]Olson 1982; Mokyr 1994, and Parente and Prescott 2000 are three prominent examples.

[13]Comin and Hobijn 2004. See also Comin et al. 2006.

[14]Comin and Hobijn 2004, 238. These findings join extant theoretical work wherein authors suggest that the degree to which elites feel their economic interest is under threat determines their responses to technological change (e.g., Acemoglu and Robinson 2000). Political scientists writing on technology adoption have typically focused on the political *consequences* of new technologies. One focus has been on the consequences of new military technologies for international relations, especially the impact of changes in perceptions of offensive or defensive advantage (Jervis 1978, Levy 1984, see also Christensen and Snyder 1990, Tang 2009, Acharya and Ramsay 2013). Other works consider the spread of nuclear weapons technology (for early works, see e.g. Brodie et al. 1946, Oppenheimer Oppenheimer), and other military technology innovations (Horowitz 2012). Considerably less has been written about how international political structures influence technology adoption, though some consider this with regard to specific technological innovations, such as the Internet (Milner 2006), or the degree to which the innovation process can be held secret and gains internalized within non-democratic regimes (Londregan 2015).

[15]Mokyr 1990, 1994, 1998a, 2002, 2010; Landes 1990, 2006; Taylor 2016; Jones 1988; Schmid and Huang 2017

[16]Mokyr (1994, 564). As Mokyr (1998a) notes, while new technology may make things better on average, it almost always makes things worse for someone.

government policy, they can slow or prevent technological change, which thus explains what has become known as Cardwell's Law — "no nation has been very creative for more than an historically short period. Fortunately, as each leader has flagged there has always been, up to now, a nation or nations that take over the torch."[17] Taylor summarizes it thus: "everyone agrees that progress in science and technology is routinely blocked by status quo interest groups."[18]

The second part of Cardwell's Law suggests a puzzle: how does technological change ever take place given these domestic vested interests? The answer for Mokyr and Taylor, alluded to in a general economic productivity context by Waltz[19] and others, is that international factors also matter. A threatening international environment provides a strong incentive for governments to not fall behind — and adopting new technology is one way to do so.

A Counter to Domestic Forces

International relations scholarship tends to assume that variation in economic policies — and thus implicitly policies affecting the adoption of new technology — responds in some fashion to threats from abroad. Important works such by Tilly[20], Kennedy[21] and Waltz[22], for example, assume that international security competition forces new policies upon governments. They claim that military-strategic concerns or "evolutionary pressures" in the struggle for survival in an anarchic system promoted the adoption of new technologies that were militarily relevant ("dual-use"), or suggest that military procurement stimulated nascent industries. Other work argues that differential rates of economic growth (and thus implicitly technology adoption) are a cause for larger global change and conflict.[23]

The importance of international competition is also emphasized in works on economic development generally: "The remarkable development of Western Europe from relative backwardness in the 10th century to world economic hegemony by the 18th century is a story of a gradually evolving belief system in the context of competition among fragmented political/economic units producing economic

[17] Cardwell 1972, 210
[18] Taylor 2016
[19] Waltz 1979
[20] Tilly 1992
[21] Kennedy 1989
[22] Waltz 1979
[23] Gilpin 1981

institutions and political structure that produced modern economic growth."[24]

More recent research has argued for a close link between external threats and new technology adoption. Based on studies of European economic history, Mokyr argues that international competition in fractured political environments can break the iron hand of domestic vested interests. Taylor, while focused on technology innovation rather than adoption, argues that "creative insecurity" generated by a situation where the threats from economic or military forces abroad are greater than the dangers from domestic forces, leads governments to change their policies and institutions in favor of new technologies.[25] He concludes, "competition causes innovation, not [domestic] institutions or policies, and the most compelling form of competition is that which takes place between states in the international arena."[26]

Policymakers explicitly link the need for technology adoption with external pressures. As Joseph Stalin said in 1931: "We are 50 or 100 years behind the advanced countries. We must make good this distance in 10 years. Either we do it, or we shall go under."[27] These leaders seek to balance fierce domestic resistance to change with the pressures of their international context. They recognize that in a more competitive international environment, the risks generated by being technologically backward are greater. Falling behind other countries can endanger the nation's existence, its bargaining position, and its influence. Furthermore, the potential benefits of being more technologically advanced are also greater, allowing the extraction of concessions and resources from other states. Political leaders thus have stronger incentives to push for, facilitate, and/or fund the adoption of new technologies when they perceive the international environment to be more competitive. In sum, as Taylor argues, "creative insecurity" drives states to innovate and adopt new technologies: Threats and challenges to the government and country from the outside must be greater than the costs to the government of overcoming domestic resistance.[28]

But which configuration of the international system promotes technology adoption is not theorized in the literature, nor has anyone attempted to explain global temporal variation in new technology

[24] North 1994, 15
[25] See also Acemoglu and Robinson 2006.
[26] Taylor 2016, 275
[27] As quoted in Engerman 2004, 27.
[28] Taylor 2012, 2016

adoption. These are tasks we undertake below. We link the international system to *global* patterns of technology adoption. We show how pressures from a more or less competitive configuration of capabilities can be linked to global technology waves.[29]

Our theory is consistent with the view that threats from abroad provide an important pressure on governments to adopt policies facilitating technology adoption. This pressure is necessary: such policies are costly and almost always resisted by domestic interests favored by the status quo. But we do not focus on the external environments of particular countries, on how small states with strong neighbors adopt technology faster, or the security implications of adopting specific technologies. Rather, using facts established by economists and ideas incipient in the IR literature, we bring together a systemic theory of *global* technology waves, ones affecting many countries at the same time.

Competition in the international system is always present; we focus on temporal variation in how vigorous that competition is. Our contribution is thus to theorize and show under what conditions the international system matters or more less, in the process providing an explanation for global variation in technology use.[30]

We argue that a competitive configuration of the international system makes the costs of not adopting new technology larger for all countries. If the system is highly competitive, then states have to worry more about their position. When international competition is strong and leaders face threats to their regimes' or state's interests and even survival, they will be more likely to facilitate technological dynamism. When the international system does not threaten leaders as much, their tendency may be to give in to domestic elite pressures for retarding technological change. When the international environment is very competitive, the costs of resisting technological change rise and the benefits of adopting it also rise, making governments more willing to enact policies that foster adoption. It is this temporal and systemic variation in international competition which underlies global technology waves.

Our project thus does not seek to explain why certain countries innovate or adopt technology faster than others. This is an important question that many scholars have endeavored to address. Answers have focused on the nature of the domestic environment, its politics, economics, and social relations.

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[29] These are related to Kondratieff waves (also known as "K-waves") in the sense of being long-term wave-like economic phenomena.

[30] We also bring the first link between the international system and technology adoption using direct measures of technology use.

The wealth of a country, its population size, its military budget, its internal and external conflicts, its regime type, its veto players, its government policies toward technology and innovation, its economic policies toward market failures, its research and development spending, and its educational policies are well-known factors.[31] As Taylor notes, most of these explanations do not hold across time and space, as countries have followed and can follow very different policy paths to reach the technology frontier.[32] Nor do we explain why some technologies diffuse faster than others. Our objective is instead to explain the waves of technology adoption over time across the globe.

A large literature on diffusion helps us understand how technologies spread. Economists have pointed to many aspects of the domestic environment that support faster diffusion of technologies.[33] In political science, extensive literature has focused more on the diffusion of policy or political norms rather than technology per se.[34] These models usually point to emulation, learning, coercion, and contagion as primary mechanisms leading countries to adopt. Horowitz in his book, *The Diffusion of Military Power*, is one of the few who focus on technological diffusion in particular.[35] As the title makes clear, Horowitz's interest is military power capabilities, and he postulates that the way that these capabilities are adopted by militaries has a major impact on international politics. His adoption-capacity theory focuses on how the financial and organizational intensity of innovations shapes how they are adopted by states and their militaries and then on how they change national military might and strategy and thus world politics. Unlike these studies, our focus is not on how diffusion pressures operate, but rather how competition in the international system provides an incentive to adopt new technology. Diffusion is usually seen as a process generated by neighbors or close competitors; for our theory, it is the overall system that matters. We argue that such systemic competition affects all countries in the system and the adoption of all types of technology.[36] Linking the international system structure to patterns of technology adoption is important not only because of its implications for material welfare,

[31] Taylor 2016; Nelson 1993; Lundvall 2010; Acemoglu et al. 2006; Acemoglu and Robinson 2008; Soskice and Hall 2001; North 1990; Breznitz 2007; Drezner 2001; Mokyr 1990; Rosenberg and Birdzell 1987; Comin and Hobijn 2004; Fagerberg and Srholec 2008; Comin et al. 2013

[32] Taylor 2016, 276

[33] Mansfield 1961; Rogers 2003; Comin and Hobijn 2009b

[34] See e.g. Finnemore and Sikkink (1998); Elkins and Simmons (2005); Simmons and Elkins (2004); Dobbin et al. (2007); Shipan and Volden (2008); Cao (2010); Solingen and Börzel (2014); Risse (2016)

[35] Horowitz (2012). Wan (2014) considers nuclear weapons diffusion.

[36] To show that the effect of the international system cannot be reduced to diffusion from nearby countries, we control for such diffusion explicitly, and find that the pressure of the international system remains important.

but also because of its theoretical importance in international relations.

Theory: International Competition Spurs Technology Adoption

We propose a formal model linking international competition to government choices to foster or hinder technology adoption. This abstract model combines domestic political interaction in which groups can reward or punish politicians for their policies with leaders' concerns about the international system. The model is not explicit about the domestic process of aggregating interests; such domestic political institutions are important but they vary greatly across countries and can have many different effects.[37] However, policies affecting the adoption of new technologies have implications beyond domestic politics. In particular, they make it more (or less) likely that the government can withstand a challenge from other countries in the international system. One contribution of the model is to show that the likelihood of such international challenges exerts a powerful influence on government policy. Another is to show that such challenges are more likely if capabilities are more evenly distributed in the international system.

The model posits a country controlled by a unified government (g), facing firms (f) and consumers (c). The government provides national defense because it values surviving international challenges, and it values receiving contributions from these two domestic groups. Firms want the government to refrain from supporting a new technology and provide national defense so they can survive and prosper. Consumers want the government to provide national defense and support the new technology because this increases their welfare.[38]

1. Firms and consumers simultaneously announce contribution schedules $r_f(s), r_c(s)$, which promise a certain level of contributions for each level of government support for technology adoption $s \in [0, 1]$.[39]

[37]See for example a recent study by Simmons (2016).

[38]Proofs are provided in the appendix.

[39]Contributions may be money, electoral support, endorsements, policy cooperation or other benefits. We also created a more complex model in which contributions to different political factions are possible (thus incorporating the possibility of "negative" contributions from the government's perspective), which is available upon request. We assume that firm and consumer support is bounded and positive; there is a limit to how much support firms or consumers can provide.

2. The government selects policies and thus s, which indicates the amount of support for the new technology. At low levels of support, the government actively blocks adoption of the technology.
3. Firms and consumers contribute the promised levels of support $r_f(s), r_c(s)$ as a function of s, the implemented level of support for technology adoption.
4. Technology adoption level Y is realized, a value strictly increasing in government support s.[40]
5. The country faces an international system of possible adversaries. With probability 1 - p the game ends. With probability p the country finds itself in disagreement with another country and the game enters a "conflict subgame." This other country has capabilities λ, a draw from U$(-\gamma, \gamma)$, the distribution of capabilities in the international system.[41]
6. In the conflict subgame, the country and its adversary simultaneously choose whether to back down (payoff = -1) or escalate. If neither backs down, the disagreement becomes a conflict in which either side has a probability of winning related to its capabilities: $\pi = \Phi(s - \lambda)$, where Φ is a strictly increasing function between 0 and 1, and λ denotes the capabilities of the other country.[42] However, as in Fearon, a conflict entails a cost, here $0 < c < \frac{1}{2}$.[43] The two sides will then only enter a conflict if both have a chance at succeeding great enough to offset its cost.[44]
7. If the government loses the dispute, all agents incur a cost, normalized to 1.

We characterize a subgame perfect equilibrium by first solving for equilibrium in the conflict subgame (steps 5-7) and then using the equilibrium utility from this subgame to characterize equilibrium behavior in the technology adoption game (steps 1-4).

We model the process by which countries enter disputes explicitly. In doing so, we show how system concentration is linked to the likelihood of conflict and how, accounting for the fact that greater capabilities brought on by technology adoption can stave of conflict in the first place, lower system

[40]As we detail in the two preceding sections, government policy (including what a government does not do), is enormously influential in countries' technology adoption. Comin and Hobijn (2004) estimates that such policies can account for 50 percent of the variation in technology adoption.
[41]See below for discussion of other distributions.
[42]We assume $\Phi(.)$ is invertible and twice continuously differentiable.
[43]Fearon (1995). We normalize cost of losing the conflict in this subgame to 1, and assume countries which win receive zero. To guarantee a possibility of conflict we assume that $c < 1/2$. We assume s, λ, and c < 1/2 are common knowledge.
[44]We are agnostic as to whether such a conflict between the two sides entails open warfare or a negotiated solution. Our assumption is only that the chance of succeeding in such a conflict is increasing in the difference between one's capabilities and those of the other side.

concentration is tied to greater support for technology adoption.

We first relate the balance of capabilities to countries' decisions about whether to escalate a disagreement. We define:

$$\Delta \equiv \Phi^{-1}(1-c)$$

Proposition 1. *If* $|s-\lambda| < \Delta$, *the unique equilibrium of the conflict subgame is for both countries to escalate. If* $|s-\lambda| > \Delta$, *the unique equilibrium is for the stronger country to escalate and the weaker to stand down.*

The following Corollary expresses the utility that the government, firms, and consumers realize in the conflict subgame.

Corollary 1. *Equilibrium utility in the conflict subgame is given by*

$$C^*(s,\lambda) = \begin{cases} 0 & \lambda < s-\Delta \\ \Phi(s-\lambda) - 1 - c & s-\Delta < \lambda < s+\Delta \\ -1 & \lambda > s+\Delta \end{cases}$$

We can now use Corollary 1 to derive each domestic actor's expected utility (over adversary capability, λ) in the conflict subgame.[45] In the event that disagreement occurs, expected utility in the conflict sugbame is given by

$$\mathbb{E}[C^*(s,\lambda)] = \int_{s-\Delta}^{s+\Delta} \frac{\Phi(s-\lambda) - 1 - c}{2\gamma} \, d\lambda - (1 - \frac{s+\Delta+\gamma}{2\gamma})$$

$$= \frac{1}{2\gamma}(\int_{s-\Delta}^{s+\Delta} \Phi(s-\lambda)\, d\lambda + s + \Delta(2c-1) - \gamma)$$

$$= \frac{a(s)+b}{2\gamma}$$

[45]Note that we do not characterize utility for $\lambda \in \{s-\Delta, s+\Delta\}$ in Corollary 1. In each case, the conflict subgame has multiple equilibria. Payoffs therefore depend on equilibrium selection. Because λ is uniformly distributed on $[-\gamma,\gamma]$, it is unnecessary to specify payoffs in these two cases to calculate expected utility, as these two cases occur with probability zero.

where $a(s) = \int_{s-\Delta}^{s+\Delta} \Phi(s-\lambda)d\lambda + s$ and $b = \Delta(2c-1) - \gamma$. We now introduce a new quantity $\tau \equiv \frac{p}{\gamma}$ which measures the competitiveness of the international system. Because the country enters into a conflict with probability p, the expected conflict payoff from technology policy s to each domestic actor can be expressed as

$$V(s;\tau) = \frac{\tau}{2}(a(s) + b)$$

Note that $a(s)$ is strictly positive and that b is strictly decreasing in γ. Therefore $V(s;\tau)$ is strictly increasing in τ. It is straightforward to check that $V(s;\tau)$ is also strictly increasing in s:

$$\frac{d}{ds}V(s;\tau) = \frac{\tau}{2}(\frac{d}{ds}a(s)) = \frac{\tau}{2}(\frac{d}{ds}(\int_{s-\Delta}^{s+\Delta} \Phi(s-\lambda)d\lambda) + 1)$$

By Leibniz rule,

$$\frac{d}{ds}(\int_{s-\Delta}^{s+\Delta} \Phi(s-\lambda)d\lambda) = 2c - 1 + \int_{s-\Delta}^{s+\Delta} \frac{\partial}{\partial s}\Phi(s-\lambda)d\lambda$$

Because Φ is strictly increasing in its argument, $\frac{\partial}{\partial s}\Phi(s-\lambda) > 0$ for all λ. Therefore

$$\int_{s-\Delta}^{s+\Delta} \frac{\partial}{\partial s}\Phi(s-\lambda)d\lambda > 0$$

It follows that

$$\frac{d}{ds}V(s;\tau) = \frac{\tau}{2}(2c + \int_{s-\Delta}^{s+\Delta} \frac{\partial}{\partial s}\Phi(s-\lambda)d\lambda) > 0 \tag{1}$$

We now analyze the technology adoption stage. We assume that the government's utility, U_g, is linear in the support from firms and consumers. Given contribution schedules $r_f(s)$ and $r_c(s)$, the government's equilibrium level of technology adoption solves

$$\max_{s\in[0,1]} \quad V(s;\tau) + r_f + r_c$$

Firms value national defense, dislike paying more in contributions, and dislike higher levels of technology adoption. Their utility is given by

$$U_f(s, r_f) = V(s;\tau) - r_f + g_f(s)$$

where $g_f(s)$ denotes firms' utility of technology adoption which is strictly decreasing and twice continuously differentiable in s.

Consumers value national defense, dislike paying more in contributions, and like higher levels of technology adoption. Their utility is given by

$$U_c(s, r_c) = V(s;\tau) - r_c + g_c(s)$$

where $g_c(s)$ denotes consumers' utility of technology adoption which is strictly increasing and twice continuously differentiable in s.

We focus on *truthful* equilibria in which firms and consumers both make strictly positive contributions in equilibrium.[46] In a truthful equilibrium, consumers and firms use truthful contribution schedules which promise the government the excess of the group's welfare relative to a fixed baseline level. If group $i \in \{f, c\}$ makes a positive contribution both before and after the government changes the level of technology adoption, a truthful contribution schedule for i pays the government exactly the amount that i's welfare changes. Formally, a contribution schedule is truthful if

$$r_i(s) = \max\ \{0, V(s;\tau) + g_i(s) - B_i\}$$

for some fixed level of welfare B_i. Because utility functions for all agents are linear in contributions, the equilibrium level of technology adoption is characterized by Corollary 1 to Proposition 4 in Dixit et al. (1997).

Proposition 2 (Dixit-Grossman-Helpman)**.** *In a truthful equilibrium with strictly positive contributions,*

[46]This is standard in menu-auction models of lobbying. For justification and intuition, see Bernheim and Whinston (1986), Grossman and Helpman (1994), and Dixit et al. (1997).

$r_f(s^*), r_f(s^*) > 0$,

$$s^* = \arg\max_{s \in [0,1]} \; 3V(s;\tau) + g_f(s) + g_c(s) \qquad (2)$$

We further note that in an equilibrium with positive contributions, the government selects an interior level of technology adoption. Consumer welfare, $V(s;\tau) + g_c(s)$, is strictly increasing in s. Therefore its truthful contribution schedule, $r_c(s)$, must be (weakly) increasing in s. Firms therefore cannot offer a positive contribution if $s^* = 1$ as they could strictly improve their utility by offering no contributions for any s. Similarly, because $r_c(s)$ is weakly increasing in s, if the government selects $s = 0$ in an equilibrium in which $r_c(0) > 0$, then it also adopts $s = 0$ if consumers deviate and $r_c(0) = 0$. This deviation strictly benefits consumers: the same level of technology is adopted as in equilibrium but at a lower cost to consumers in terms of contribution.

Remark 1. *In a truthful equilibrium with strictly positive contributions,* $s^* \in (0, 1)$.

Note that the objective function in (2) in Proposition 2 is the sum of differentiable functions and therefore itself differentiable. Because s^* is interior, it follows that s^* satisfies the first order condition:

$$\frac{\partial}{\partial s}[3V(s;\tau) + g_f(s) + g_c(s)] = 0$$

We can now use this condition to examine how s^* responds to changes in the concentration of the international system, τ. Because s^* is a local maximum, the sign of $\frac{\partial s^*}{\partial \tau}$ corresponds to that of

$$\frac{\partial^2}{\partial s \partial \tau}[3V(s;\tau) + g_f(s) + g_c(s)]$$

It follows from (1) that

$$\frac{\partial^2}{\partial s \partial \tau} V(s;\tau) = c + \frac{1}{2}\int_{s-\Delta}^{s+\Delta} \frac{\partial}{\partial s}\Phi(s-\lambda)d\lambda) > 0$$

Proposition 3. *The equilibrium level of government support for technology adoption is increasing in* *the competitiveness of the international system:*

$$\frac{\partial s^*}{\partial \tau} > 0$$

Two complementary effects underlie this relationship. First, as τ increases, the government sees a larger benefit in increasing its ability to withstand an international challenge. Second, these contribution schedules change: as τ increases, the relative contributions of firms and consumers change in the favor of the new technology. Firms see less value in opposing technology adoption, and consumers more.

Our theory centers on τ, the competitiveness of the international system, and specifically, on the *systemic* source of variation in this probability. We propose that this systemic variation — over time, affecting all countries — underlies global technology waves. τ has two components, the probability that a disagreement will arise (p), and distribution of capabilities in the system (γ).

We next analytically link γ to measures of system concentration. Let us, the without loss of generality, let $\theta * n$ denote total capabilities in the international system, where n is the number of countries. We then let λ^* equal $\lambda + \theta$, allowing us to more easily relate capabilities to their expected sum. We can then see that:

$$\lambda^* \sim U(\theta - \gamma, \theta + \gamma) \qquad \Rightarrow \qquad \mathbb{E}(\lambda^*)^2 = \frac{1}{(\theta + \gamma) - (\theta - \gamma)} \int_{[\theta - \gamma, \theta + \gamma]} (\lambda^*)^2 dx = \frac{3\theta^2 + \gamma^2}{3} \tag{3}$$

This makes for the following expectation of the sum of squared proportion of capabilities as a function of γ, denoted HHI (the Herfindahl-Hirschman index):

$$HHI \equiv E(n * \frac{\lambda^*}{n\theta}) = \frac{3\theta^2 + \gamma^2}{3\theta} = \theta + \frac{\gamma^2}{3\theta} \qquad \Rightarrow \qquad \frac{\delta HHI}{\delta \gamma} > 0 \tag{4}$$

Our measure of system concentration (SYSCON - presented in the Data section below), and several others, are monotonically increasing in the sum of the squared proportion of capabilities (HHI):[47] This

[47]While one could specify a new system concentration equal to $1/2\gamma$, we prefer to stick to SYSCON, as using a new metric would disconnect the work from wider scholarship in international relations, which in thousands of papers have favored the use of the system concentration index, and related it to a variety of phenomena of interest.

means there is a positive relationship between γ and system concentration:

$$\frac{\delta \text{SYSCON}}{\delta \gamma} > 0 \tag{5}$$

We thus have multiple effects which all combine to produce a negative relationship between system concentration and technology adoption.

Within the country, we know the government's marginal utility of supporting technology adoption derived from contributions is decreasing in γ, because a high γ means less conflict, which shifts contribution schedules in favor of supporting technology. Looking outward, we know that governments' marginal utility in the conflict game is decreasing in γ. Finally, we straightforwardly assume that government support (s) has a positive effect on realized technology adoption (Y). Both domestically, and in relations with other countries, the government's utility from supporting technology adoption is thus decreasing in γ.

This combines with the positive relationship between γ and our measures of system concentration, shown in Equation 5, to form our main result:

Proposition 4. *Equilibrium government support (s^*) and realized technology adoption (Y) is decreasing in system concentration.*

$$\frac{\delta s^*}{\delta SYSCON} < 0 \qquad \wedge \qquad \frac{\delta Y}{\delta SYSCON} < 0 \tag{6}$$

This suggests our first hypothesis:

Hypothesis 1. *The less concentrated power capabilities are in the international system, the faster the rate of technology adoption at the country-technology-year level.*

We argue this is happening not just in many countries and technologies at the same time, but also when measured at the systemic level (averaged across all countries and technologies).

Hypothesis 2. *The less concentrated power capabilities are in the international system, the faster the* ***global*** *rate of technology adoption.*

Our theory does not specify a channel by which government decisions to facilitate technology adoption may affect system concentration, and we do not wish to exclude the possibility here. We argue that, for most countries in the system in the short term, this relationship is unidirectional and causal: changes in the international system precede and impel changes in government policies.

Hypothesis 3. *In the short term, changes in system concentration Granger-cause changes in technology adoption, and systemic change and technology adoption should in case studies be causally linked as cause and effect.*

While simple, the model and its results are robust to many natural extensions and complications. For instance, a natural concern is that that governments face challenges of varying severity. This may be answered by an interpretation of p as the product of external challenges' severity times their likelihood.[48] Deterrence, possibly by technological sophistication, is incorporated as well. Firm and consumers are common names for groups lobbying for or against policies with economic implications. But some firms may favor the adoption of technology, and some consumers may oppose it. Our model is indifferent to this: one can more precisely specify r_{firm} and $r_{consumers}$ as the net cumulative effort of those against or in favor of government policies in support of the new technology. This is not to say that political institutions cannot impact the magnitude of the effects we identify, a subject we hope future work can explore.

We propose a link between technology adoption and the international system, and contribute an international relations theory which can explain *global technology waves*, specifying when and under what conditions we may see the international adoption of technology accelerate across countries and technologies.[49]

To provide support to the our underlying assumptions and the conclusions arising from them, we in our appendix demonstrate links between conflict and system concentration empirically. We show that lower system concentration is related to more MIDs, more world-wide military spending, and more

[48]For instance, one could define p in any given country and year as follows:

$$p \equiv \sum_{c} Probability\ of\ Challenge_c * Severity\ of\ Challenge_c \tag{7}$$

in which c indexes possible challenges from abroad, and both probability and severity range from zero to one.

[49]The relationship we propose has been investigated among firms. Studies of firms and markets (an imperfect but still useful analogy) find a positive relationship between more competitive industries and technology adoption (for a review, see Holmes and Schmitz (2010)); industries with less concentration of revenues among the top firms adopt new technologies faster.

wars. For readers who remain skeptical about the link between system concentration and conflict, we also demonstrate a link between such direct measures of conflict and technology adoption (itself a novel result - see appendix tables 4 and 5). While our theoretical justification and formal exposition is novel, the suggestions that competitive pressures tend to be lower for most countries in highly concentrated systems have been made before.[50] Some have linked competition to polarity: Bipolar systems in which two states have control over a large share of capabilities are theorized to make predicting how great powers will act easier, as both superpowers tend to intervene on behalf of their allies and have an interest in reducing uncertainty about whether they will do so. The sizable advantage of a few countries makes others less interested in spending resources to catch up.[51]

We present a story that is demand-driven: countries seek more technological prowess when faced with a higher likelihood of a challenge from the international system. A complimentary channel relating system concentration to technology adoption is through supply. As with firms in market economies, a larger number of powerful actors have a harder time coordinating against third parties to maintain dominance and increase their profits. While each actor would like to maintain a technological edge, they also benefit more from selling technology (due to higher demand) in high-competition contexts, and especially if buyers are their adversaries' enemies. In contrast, when power is concentrated in a few countries, vested interests may find it easier to coordinate to slow down the pace of technology adoption, securing protection for industries which otherwise might be made obsolete. A more concentrated system may also make it easier for states or interest groups to collude and restrict technology transfer to other countries; in this environment, states can afford to forgo individual benefits from selling technology to maintain their collective technology edge. For instance, studies show that during the bipolar Cold War era when the system was very concentrated, the US and USSR cooperated to limit the spread of nuclear technology; as nuclear superpowers they were able to collude to prevent its spread.[52]

More competition in the system, in contrast, makes it harder for any state to control the spread of

[50]See e.g. Waltz (1979), Christensen and Snyder (1990), Huth et al. (1992), and Grant (2013).

[51]There are a number of ways to relate the polarity of the international system, a categorical measure related but different from concentration, to its competitiveness. But even over the two hundred years investigated here, there is little variation in polarity. Classifications of systems by polarity thus may mask considerable variation in the concentration of capabilities over time (for more on the advantages of incorporating information beyond polarity, see Mansfield (1993)).

[52]Kroenig 2010; Colgan and Miller 2019

technology and prevent its diffusion. The concentration of capabilities in the system, as with firms in markets, thus means competitive pressures are diminished. We believe this channel to be important especially for cutting edge technology (such as technology to create machines that create computer chips), and technologies intimately tied to crucial military infrastructure, such as missile guidance systems — where our theory might be less applicable. For most of the time and technologies we investigate, there were however few steps taken to limit technology transfer, and even if they were, they were often overcome. Focusing on the demand side to explain technology adoption broadly is therefore appropriate.

Empirical Analysis

Our focus is on adoption of new technology, not innovation or invention. Analysis of international technology adoption has been approached empirically in one of three ways. The first has been to track cross-country citations in patent applications, while the second and largest tradition has focused on differences in total factor productivity (TFP). Here, the underlying assumption is that the differences between countries' output when holding factor inputs constant is their utilization of technology. Thirdly, and especially recently, researchers have directly tracked both the extent and intensity of technology adoption (e.g., number of radios per capita).

We follow this third path and rely on direct measures of technology use because of its two distinct advantages: wider coverage and higher precision. Whereas the necessary data coverage for TFP calculations is limited and patents are filed in small numbers, direct measures can in principle track all technologies in the countries where their use has a written history. Furthermore, direct measures are more precise because they track technology adoption specifically.

We investigate technology adoption both at the country-technology-year and system-year level. Investigations at the country-technology level allow us to incorporate information about countries and technologies, increasing the amount of information and alternative explanations we can access. Our investigations at the systemic level enable us to explicitly link international system characteristics to global technology waves. We systematically test relationships between the international system and technology adoption for many countries using direct measures of technology, made possible in part by our collection of 16,000 new observations of countries' technology use (detailed below).

In addition to our quantitative analysis, we investigate technology adoption in a qualitative case: Sweden's first railroads. This case helps illustrate our causal mechanism, in which calculations about the structure of the international environment make political leaders initiate policies which either slow down or accelerate the adoption of technology. We show that policymakers were motivated by increasing competition in the international system to change their policies, and that these changes were consequential in bringing about the more rapid adoption of the new technology.

Data

Measuring International Technology Adoption Directly tracking the adoption of technology has been done for a long time, but it is only recently that datasets covering a wide range of countries, years, and technologies have been made available. Comin and Hobijn's CHAT dataset captures both the presence and in many cases the intensity of utilization of many technologies in more than 150 countries since 1800.[53] We followed Comin, et al., in focusing on twenty of these technology types.[54] This dataset lists the number of technology units (e.g., number of television sets, the number of kilometers of railroad, ship tonnage, electricity) used in a given country in a given year.[55]

We expanded this dataset to include new observations from the years since 1990, adding about 16,000 country-technology-year observations. Care was taken to ensure all country-technology data series were matched exactly, which included manually inspecting the join between old and new data for every single country-technology observation series added. In most cases, a similar (but updated) source was used as in the original data set, and the source for every new observation is listed explicitly (available upon request). We follow Comin et al.[56] in our specification of the dependent variable.

Technology Adoption: The yearly change in log number of technology units per capita per year per

[53]Comin and Hobijn 2009a
[54]Comin et al. (2013). The twenty technologies were selected because they were widely used by many countries, and have been seen as crucial or the focus of prior studies of technology. The majority of remaining technology series in the CHAT data set capture the yearly number of medical procedures, or are technologies related to textile production in a smaller number of countries. See Appendix Section 2.
[55]We explore the use of many alternative sets of technologies in the robustness checks below.
[56]Comin et al. 2013

country:

$$\Delta Y_{i,tect,t} \equiv Log\left(\frac{\#\ Tech.\ Units_{i,tech,t}}{Population_{i,t}}\right) - Log\left(\frac{\#\ Tech.\ Units_{i,tech,t-1}}{Population_{i,t-1}}\right)$$

We capture only the adoption of new technologies by censoring observations once a technology becomes outdated, defined as the year the adoption level of the current highest adoption country begins to decline. This ensures that, for example, sending fewer telegrams after the telephone is invented is not seen as adoption failure.

Measuring International System Concentration As is standard, all our measures of systemic concentration are based on the Composite Index of National Capabilities ("CINC", fifth edition[57]). These scores are created by calculating a state's average share of the world total for six types of resources: urban population, total population, military expenditure, military personnel, iron and steel production, and total energy consumption. We use these to construct many different measures of system concentration on a yearly basis, providing us with results insensitive to the way concentration is calculated.[58]

For our analysis, we use the popular "system concentration" score frequently used in studies of international politics, wherein a higher score means capabilities are more concentrated.

System Concentration (Syscon) - Measure from Singer, et al.[59]. This is defined as:

$$\text{SYSCON}_t \equiv \sqrt{\frac{\sum_{i=1}^{n}(\pi_{t,i})^2 - \frac{1}{n}}{1 - \frac{1}{n}}}$$

Where t denotes the year, and $\pi_{t,i}$ is the share of power resources held by state i in year t, there being n states total. More concentration means less competition so we expect a negative relationship with international technology adoption.[60] In our appendix, we show that all our results are robust to several alternative measures of concentration (e.g., the share held by the top 4 states, the number of possible coalitions among great powers).

[57]Singer et al. 1972

[58]We detail a range of such alternative measures in our robustness checks. These include measures which only incorporate the military and population subindicies of CINC scores, and indicies which for any country is based only on capabilities in other countries.

[59]Singer et al. 1972

[60]In line with most recent work (e.g. Bas and Schub 2016), we calculate the index based on the capabilities of all states. Scholars have in some cases restricted their sample to major powers.

Control Variables We include several control variables other studies of technological adoption have identified that might affect a country's adoption of new technology. Civil war is both destructive and reduces the efficacy of government policy, and we thus expect it to reduce technology adoption. Interstate war is also destructive, but may impel the government to mount additional resources to pursue new technology to increase its chance of survival. The effect is thus indeterminate. Finally, regime type has been found to be especially important.[61] Here, regime type may be thought to reflect both the extent to which governments are responsive to firms vs consumers (or those against or in favor of adopting new technology), and these groups' ability to put pressure on the government (i.e. $r_c(.)$, and $r_f(.)$). It is here important to note that in a wider historical perspective, political pluralism and its global spread have been important, but perhaps not a sufficient nor necessary condition for technological dynamism, as Mokyr stresses.[62]

War, Civil War (both lagged 1 year) — Dichotomous variables, from the Correlates of War project.

Polity2 score — A country's Political Regime type that year on the Autocracy-Democracy dimension (-10 to 10 scale with 10 being fully democratic[63])

Our theory suggests that the international system pressures governments, but that this external pressure has both a $systemic$ and $local$ component. We therefore include models in which we control for the latter country-specific (i.e., local) pressure explicitly. We here use data from the Correlates of War project on military spending, great powers, and country capital-to-capital distances. For any country i we consider the change in military expenditure of all countries adjacent to i, plus the change in military expenditure of all great powers, the latter inversely weighted by their distance to country i.

Change in Neighboring Countries Military Spending:

$$\Delta\text{Local Threat}_{i,t} \equiv Log\left(\sum_{j \neq i} Mil.\ exp_{j,t} * \frac{\mathbb{1}\{D_{i,j}=0\ |j \in GP_t\}}{1+Log(1+D_{i,j})} \right) - Log\left(\sum_{j \neq i} Mil.\ exp_{j,t-1} * \frac{\mathbb{1}\{D_{i,j}=0\ |j \in GP_{t-1}\}}{1+Log(1+D_{i,j})} \right)$$

Wherein $Mil.\ exp_{j,t}$ is military expenditure, $D_{i,j}$ a distance matrix, $\mathbb{1}$ the indicator function, and

[61] Comin and Hobijn 2009b; Comin et al. 2013

[62] Mokyr (1994). All relationships also hold unconditionally, i.e. without any of these controls.

[63] Marshall et al. 2012

GP_t the set of countries that are Great Powers in year t.[64]

Our theory postulates that the international system affects technology adoption beyond what can be explained by changes in adoption in other countries; diffusion may operate but systemic pressures for adoption are broader and different in kind. To examine this, we control for spatial diffusion of adoption explicitly.

Spatial Distance to Technology — The number of technology units in all other countries scaled by their distance to the country in question and exclusive of system-wide shifts in technology adoption. This was calculated on a country-technology-year basis:[65]

$$SDT_{i,tech,t} \equiv \sum_{j \neq i} \left(Y_{j,tech,t} * D_{i,j}\right) - \sum_{tech,i} \overline{SDT}_{tech,i,t}$$

Wherein i is a country, $tech$ a technology, and t a year, $D_{i,j}$ a distance matrix (capital in i to capital in j) and $\overline{SDT}_t$ computes the worldwide mean SDT by year. Table 1 provides summary statistics.[66]

Table 1. Summary Statistics (Note: Country-Technology-Year data)

Statistic	N	Mean	St. Dev.	Min	Max
Log (Technology Units Per Capita)	94,815	2.41	3.85	0.00	17.26
Δ Log (Technology Units Per Capita)	94,815	0.04	0.14	−3.69	3.05
Spatial Distance to Technology, 3 Year Lag	93,925	−0.62	0.90	−3.54	2.74
Syscon (Singer 1972)	23,728	0.30	0.04	0.22	0.42
Δ Log (Military Expenditure in Neighboring Countries)	13,783	0.23	2.36	−2.93	21.49
Polity2 Score	15,408	−0.33	7.11	−10.00	10.00
At War in previous year (0, 1)	23,015	0.03	0.18	0.00	1.00
Civil War in previous year (0, 1)	24,353	0.04	0.19	0.00	1.00

Details: N observations at the country-year level, except technology units and SDT variables. SDT observations are restricted to country-technology-years wherein we observe technology use for the country and technology in question (i.e. usable observations).

In seeking to explain the pace of technology adoption, including measures of gross domestic product (on an annual or annual per capita basis) as a predictor would bias our estimates. This is because

[64] In our main specification (Column 1 of Table 2), we provide models without this predictor to avoid concerns that it might interact with measures of concentration. The measure also makes our analysis slightly more sensitive to missing data (as missing military spending data in one country affects the local threat score of all neighboring countries).

[65] As in Comin et al. (2013). If not demeaned by year, it would by construction eliminate any temporal systemic variation in adoption rates.

[66] In the appendix, we provide results using imputed data. Many other robustness checks are detailed below.

the inclusion of productivity measures in the conditioning set would be asking how fast technology was adopted but in ways not reflected in productivity, which is not our objective here. While general economic development as measured by GDP can be an asset in international competition, and one consequence of facilitating technology adoption can be economic development, our outcome of interest is technology adoption, not these related concepts. Replicating our country-technology models with GDP per capita included as a predictor as expected slightly reduces the magnitudes of our effects (and sample size), but all relationships remain statistically significant and in the expected direction.[67] In our robustness checks, we estimate models with imputed data, add additional controls, and experiment with a large number of different subsamples — of technologies, countries, and years. Results are in all cases robust.

Quantitative Estimation Strategy

All regressions are ordinary least squares, and all models compare changes within a technology and country over time.

To test hypothesis 1, we estimated equations of the form:

$$\Delta Y_{i,tech,t} = \beta_0 + Z_t\alpha_1 + X_{i,t}\beta_1 + Q_{i,tech,t}\beta_2 + \epsilon_{i,tech,t} \tag{8}$$

Where $\Delta Y_{i,tech,t}$ is change in the natural log of technology adoption level per capita at the country-technology-year level, $X_{i,t}$ are country and time varying covariates, $Q_{i,tech,t}$ is our country, technology and time varying variables, Z_t is our systemic variable which changes over time, and $\epsilon_{i,tech,t}$ is the standard error term. β_0 is an intercept, capturing technology use generally increasing over time.

Recalling our model above, our theoretical expectation is that the coefficient α_1 is negative (i.e., more system concentration means less systemic competition). Our quantitative estimates thus link directly to our formal model, assuming linearity in the proposed monotonic relationships underlying Proposition 6. The terms $X_{i,t}\beta_1$ and $Q_{i,tech,t}\beta_2$ captures both local sources of variation in p and proxies for $g_c(.)$, $g_f(.)$, $r_c(.)$ and $r_f(.)$.

[67]Whenever these are reported, we use GDP per capita estimates from Bolt et al. (2018).

Our outcome of interest, faster technology adoption in many countries, is measured on a within-country-technology basis. Testing our theory at the country-technology-year level rather than system-year level means we are able to control for country-specific effects, and retain information from our broad sample of technologies.[68]

We next perform tests at the systemic level. We here aggregate the rate of change for all technologies in all countries in a given year (moving from over 80,000 to just 188 observations — one for each year). In addition to testing the aggregate relationships, we report models in which we include an additional control for political change in the period: World average Polity2 scores.

$$\overline{\Delta Y_t} = \eta_0 + Z_t\eta_1 + \overline{X_t}\eta_2 + \overline{\epsilon_t}^t \tag{9}$$

Wherein η denotes coefficients, $\overline{(.)}$ the yearly mean and other terms are as previously.[69] We also tested the relationship using two alternative measures of system concentration, described in Appendix Table 2.

We finally tested if there exists a temporal relationship in line with hypothesis 3 by conducting a series of Granger Causality tests. We here again constructed a yearly series of technology adoption across all countries and technologies.[70] We then constructed an alternative set of system concentration and world technology adoption per capita time series, accounting for the effects of war, civil war, and Polity2 (regime) score by summing the residuals of a regression of these variables on Syscon and technology adoption per capita respectively.[71] We then tested if in either set: (a) technology adoption was Granger-caused by changes in the international system and/or (b) Granger-caused changes in the international system.[72] We did this with and without incorporating covariates, and with a variety of

[68]It is possible to run such regressions on the country-year level, but that would require aggregation of adoption rates of many different technologies for the country and year in question, which would lose information and thus mask important variation.

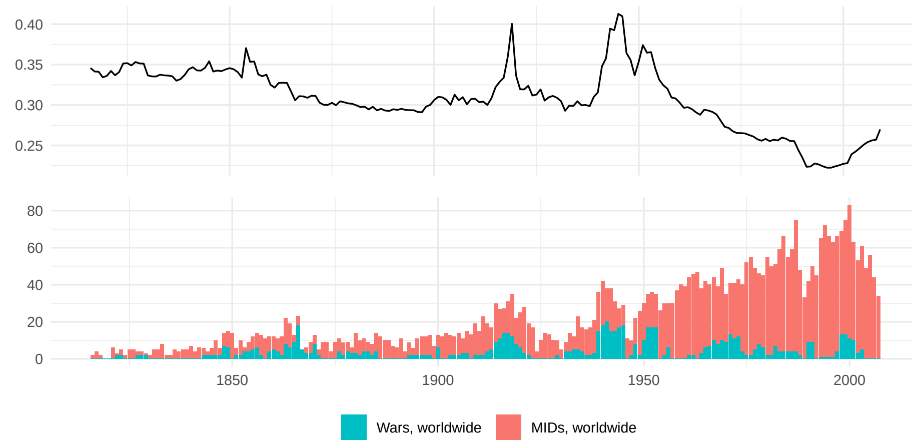
[69]$Q_{i,tech,t}$ is a relative term on a within-year basis, and thus across countries has a yearly mean of 0 for all technologies. Note that the summary statistics above summarizes SDT observations for country-technology-years in which technology adoption rate was observed, and is hence slightly different from zero.

[70]When technologies were censored or series had missing data we used lagged value on a within-country-technology basis as the source for our technology adoption sum per year. This ensured that this missingness had no contribution to variation in the world-wide measure and thus could not drive our results.

[71]Spatial Distance to Technology does not vary when aggregated over all countries and technologies.

[72]Specifically, we used the approach suggested in Toda and Yamamoto (1995), wherein the maximum order of integration was established using both Augmented Dickey–Fuller and Kwiatkowski-Phillips-Schmidt-Shin tests.

Figure 2. System Concentration and Interstate Conflict, 1816-2008



Details: SYSCON (top) and number of states involved in militarized interstate disputes (MIDs) and wars (bottom), from 1816 to 2008. As seen, the two appear negatively related, note that the larger spikes in system concentration appear after peaks in MIDs and wars. We argue that low system concentration is associated with a more competitive international system and hence more disputes. In the appendix, we support this claim statistically, and show that our results are robust to using several alternative measures of the competitiveness of the international system.

year lags.

Results

We first plot system concentration and trends in interstate conflict over time, seen in Figure 2. This illustrates how our systemic concentration measure has changed over time. We clearly see an inverse relationship between violent manifestations of international competition and system concentration, a relationship we evidence quantitatively in the appendix on validity of system concentration as a measure of international competition.

We next present the results of our country-technology-year analysis in Table 2. We find clear links between lower concentration and faster adoption of technology. For both the intensity of new technology use and pace of new technology adoption, there is an inverse and statistically significant relationship between our measure of system concentration and technology adoption.

In line with our expectations, we also find that neighborhood threats tend to be positively related to technology adoption, that civil war is negatively related, while the relationship between interstate war and technology adoption is less clear. As we expect, there is also a link between changes in domestic political institutions and technology adoption, with evidence that as a country becomes more democratic it adopts new technologies faster and more intensely (consonant with changes in $r_f(.)$, $r_g(.)$, $g_c(.)$, and $g_f(.)$ — that is, with consumer and firm's utility from technology and influence over government policy). Spatial distance to technology has a clear negative relationship, which we hypothesize is linked to $g_f(.)$: the benefit of pressuring the government to repress the technology is lower if its use is accelerating in neighboring countries (who may decide to export the technology and thus undercut the government's efforts).

The magnitude of these effects is very large. In Figure 3 we plot the different expected changes in log number of technology units per capita for different levels (-1 standard deviation, mean, +1 standard deviation) of our predictors (means of 5,000 simulations each, with 95% range of observations indicated by bars).[73] The effect of a one-standard-deviation downward shift from the mean of Syscon (i.e. from 0.28 to 0.24) is large: this would in expectation increase technology adoption rate from 4.26 to 5.6 percent per year (≈31 percent faster adoption). Note that this is the expected *average* increase across all new technologies and countries for which we have data, and not just the sum in percentage points. In Figure 3, we also show the means and expected changes for one-standard-deviation change in our other independent variables. The systemic effect is larger than that of political regime change, civil war, and interstate war.

In Table 3, we examine our argument at the systemic level. We move from over 80,000 country-technology-years to just 188 system-years. We again find clear relationships ($p < 0.001$) between our various measures of international system concentration and technology waves, with and without controls. In models without other predictors, our measures of system concentration can account for

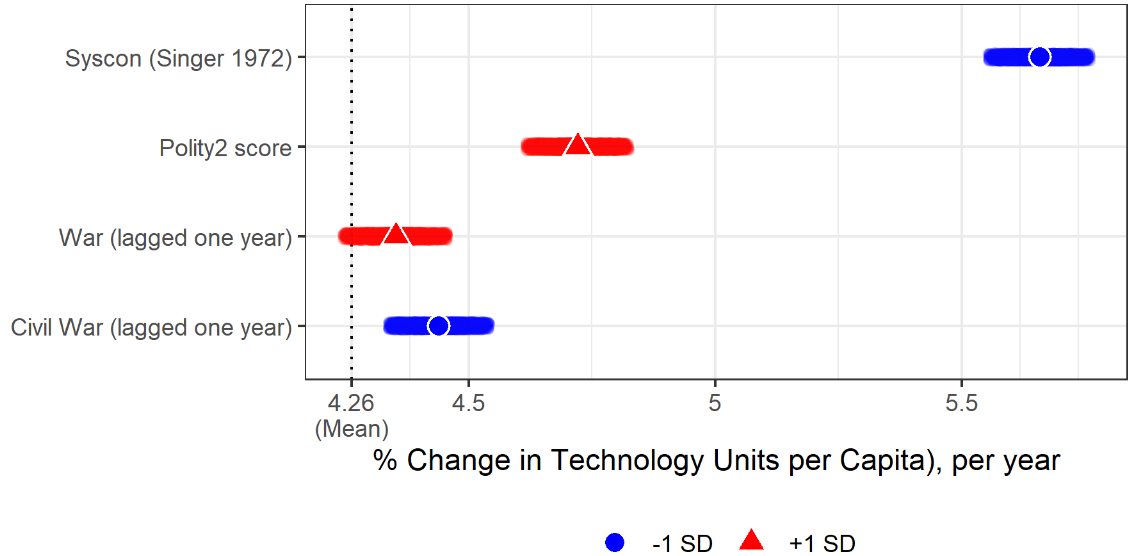
[73]We follow the approach suggested in King et al. 2000.

Table 2. Country-Year-Technology Tests: Technology Adoption and Systemic Factors (1820-2008)

	Dependent variable:		
	Change in Technology Adoption Level		
	(1)	(2)	(3)
Syscon (Singer 1972)	-0.336***	-0.334***	-0.333***
	(0.029)	(0.029)	(0.029)
Change in Neighboring Countries' Military Spending		0.001***	0.001***
		(0.000)	(0.000)
Log (GDP pc)			-0.001
			(0.001)
Spatial Distance to Technology Adoption, lagged	-0.041***	-0.042***	-0.042***
	(0.002)	(0.002)	(0.002)
Polity2 score	0.001***	0.001***	0.001***
	(0.000)	(0.000)	(0.000)
War (lagged one year)	0.004	0.004*	0.005*
	(0.003)	(0.003)	(0.003)
Civil War (lagged one year)	-0.007**	-0.008**	-0.008**
	(0.003)	(0.003)	(0.004)
Constant	0.108***	0.107***	0.115***
	(0.008)	(0.008)	(0.014)
Observations	82567	80591	77589
R^2	0.089	0.092	0.095
Adjusted R^2	0.089	0.092	0.095
Residual Std. Error	0.129	0.129	0.128

Note: *p<0.1; **p<0.05; ***p<0.01
(Country-Technology-Clustered Standard Errors in Parentheses)

Figure 3. Substantive Effects - The International System and Technology Adoption



Details: The plot shows the effect of one-standard-deviation shifts of our predictors on yearly increases in technology units per capita, utilizing the model shown in Table 2 column 1. Effect estimates based on 20,000 simulations, mean of which are indicated by points and 95% range of observations by bars. Baseline change per year is indicated by the dotted line. Among these variables, changes in system concentration has by far the largest effect: going from the mean to one standard deviation below takes yearly increases in technology units per capita from about 4.26 to 5.6 percent (difference significant at the $p < 0.001$ percent level).

between roughly 50 and 20 percent of the variation in the world-wide pace of technology adoption.

We next find that changes in system concentration Granger-cause changes in technology adoption. Granger Causality indicates whether previous values of one variable are useful in predicting values of the second variable, once the previous values of the second variable (its "history") is taken into consideration. While one cannot establish causality in the sense of causes and effects by this technique, we show that changes in system concentration are related at statistically significant levels to *later* changes in technology adoption, while the converse is not true.

As seen in Table 4, we can reject the null hypothesis of no temporal relation in all tests of System Concentration → Technology Adoption, while we fail to reject this hypothesis for any of our tests of Technology Adoption → System Concentration.[74] We emphasize that these tests are only evidence of a temporal relation, and that the two phenomena are likely inter-related in the long run. Nevertheless, these tests strongly suggest that in the short or medium term, changes in the international system Granger-cause states to respond by adopting new technology.

[74]Detailed results can be found in Appendix Table 12.

Table 3. Systemic Tests: World-Wide Technology Adoption and System Concentration

	Dependent variable:	
	Δ Log (Tech. Adoption per capita), World-wide	
	(1)	(2)
Syscon	-0.352***	-0.225***
	(0.049)	(0.034)
Polity2		0.005***
(World average)		(0.000)
Constant	0.132***	0.098***
	(0.016)	(0.011)
Observations	188	188
R^2	0.396	0.643
Adjusted R^2	0.393	0.639
Residual Std. Error	0.018	0.014
F Statistic	51.52***	101.02***
Note:		*p<0.1; **p<0.05; ***p<0.01 (Robust Standard Errors in Parenthesis)

Table 4. Granger Causation: World-Wide Technology Adoption and System Concentration

	System → Tech. Adoption	Tech. Adoption → System	System → Tech. Adoption†	Tech. Adoption† → System
Lag 1	Yes***	No	Yes***	No
Lags 1-2	Yes***	No	Yes***	No
Lags 1-3	Yes***	No	Yes***	No
Lags 1-4	Yes***	No	Yes***	No

†*Accounting for the effects of war, civil war (both lagged one year), and polity2 via linear model.*
*p<0.1; **p<0.05; ***p<0.01

A relationship and temporal association between international system characteristics and global technology waves is thus evidenced, as is a link between characteristics of the international system and direct measures of technology use. In our robustness checks and illustrative case study below, we detail evidence suggesting a causal relationship between the two.

Robustness Checks, Alternative Samples, and Technology Types

We conduct a large number of checks to assess the robustness of these findings, which we summarize here. Full tables and replication code for all work is provided in the appendix or upon request.

We first replicated our results across subsets of time, technologies, and countries. We investigated our relationship during the years 1900-2000 (N = 68,615), on only minor powers (N = 75,374), and only major powers (N = 7,193). We considered only European countries (N = 25,421), and only non-European countries (N = 57,146, all in Appendix Table 6). We tested our theory on many technology samples, by turns excluding railroad network and passengers, other transportation technologies, communication technologies, and industry-related technologies. In other models, we normalized measures of adoption across technologies (making their standard deviation equal). In all cases, results remained robust.

To alleviate concerns about coverage and non-random patterns in missingness, we replicated our analysis with imputed data (Appendix Table 6, column 1). We also replicated our analysis with additional controls: a binary democracy variable[75], population[76], and indicators for the Cold War or the five-year interval after a world war (Appendix Table 7)). We used the threat measure suggested by Leeds & Savun[77], which uses information about foreign policy similarity in addition to capabilities. In all aforementioned cases, measures of system concentration remain negatively related to technology adoption at statistically significant levels ($p < 0.01$).

Our theory relating changes in the international system to policies boosting technology adoption is conditioned on such technology being useful for withstanding a challenge from abroad. This implies that the effects should be magnified if technologies for which this is not the case are dropped from the

[75]Boix et al. 2013
[76]Bolt et al. 2018
[77]Leeds and Savun 2007

analysis. Our sample of many different technologies allows us to test this explicitly. We assume that two technologies among the twenty — TVs and ATMs — are less likely to confer an advantage in the event of an international challenge (compared to trucks, railroads, and electricity production facilities). In line with our expectations, the relationship between system concentration and change in technology adoption increases in magnitude by about 20 percent if these two technologies are dropped from the analysis (see Appendix Table 6).

While the invention of the technologies we investigate were quite evenly spread in time, we also tested if measures of system concentration remained robust predictors of technology adoption if we controlled for the pace of invention of technology. We replicated the specifications in Table 3 adding yearly or five-year average inventions per year as a control. We did this with two samples of inventions: the twenty technologies considered in the main analysis and a larger group of 104 important civil and military technologies (Appendix Table 8). In all cases, results remained robust.[78]

We next interacted our "SYSCON" measure with our diffusion measure, indicating the spatial distance to technology adoption levels. We find that states became more responsive to the technology adoption of their neighbors when the system was less concentrated (both unconditional effects, including SYSCON, remained statistically significant at the $p < 0.001$ level).

We have focused on the adoption of new technologies: increase in their use. A related but different concept is the intensity of their use. We replicated both our systemic and country-technology-year analysis, using intensity of use rather than the rate of change as our dependent variable, in all cases including a full set of country-technology fixed effects to account for country-technology fit. In every case, we find that lower system concentration is related to more technology use.

This theory is predicated on the claim that low system concentration brings more international competition. Beyond the evidence provided in this paper, we include a separate section in the appendix where we investigate this claim quantitatively for the case of violent international competition (using data on militarized disputes, wars, and military spending). We find strong evidence that low system concentration indeed is linked to higher levels of competition (Appendix Table 4).

Measures of concentration are sometimes argued to be overly sensitive to how they are specified.

[78]Future research might consider if invention can be related to systemic concentration. For the twenty technologies considered here, we did not find this to be the case.

We therefore include a separate section in the Appendix in which we test the reliability of our claims using alternative measures of concentration, which are insensitive to the number of countries, and to capabilities of the top 4 countries (Appendix Tables 1 and 2). Results are robust. We also replicated our tables with measures of concentration constructed using CINC scores which did not include iron and steel production or total energy consumption as components (*i.e.*, we calculated states' average share of the world total for urban population, total population, military expenditure, and military personnel). Results were unchanged in direction, slightly larger in magnitude, and remained statistically significant at the $p < 0.01$ level (Appendix Table 3). We estimated models in which system concentration for country *i* was calculated using data on all countries except *i* (Appendix Table 3). Results were unchanged.

We argue that states adopt technology in more competitive environments to limit their vulnerability to coercion or attack. We argue that states respond to such more competitive environments with policies that go beyond military spending. We therefore ran systemic regressions with the log of world-wide military spending as an additional control (Appendix Table 8). We found that even if we control for military spending at the country level, there remains an independent effect of international system concentration on technology adoption.

We explore the extent to which the impact of system concentration is distributed over time. Appendix Table 9 shows models with a lagged dependent variable, in which system concentration remains a strong predictor.

These estimations suggest robust links between international system concentration and the pace of international technology adoption. As our Granger causality tests show, there is also evidence of a temporal relationship, wherein changes in international system characteristics precede changes in world-wide technology adoption. International system concentration and global technology waves are broad concepts, and untangling causal relations between them - however important these might be - will always be fraught with difficulty, which we recognize. To complement our Granger causality tests, we therefore employed two other tools: The internal instruments approach of Generalized Methods of Moments estimators (GMM) and Error Correction Models (ECM). Both approaches, summarized in Appendix Tables 10 and 11, respectively, support our claim that more system concentration has a negative effect on technology adoption. Specifically, the effect of system concentration retains its sign and statistical significance using the internal instruments of the GMM estimator across nearly all models at the country-technology-year level and in each case at the systemic level, addressing concerns about potential endogeneity.

Error correction models suggest that non-transitory changes in system concentration have a long-run effect on the steady state of technology adoption from both the country-technology and systemic perspectives. To elaborate, given a sustained negative change to system concentration (*i.e.* the system becomes more competitive), we expect that this would cause an upwards change in the equilibrium value of technology adoption, which it would converge to over the subsequent periods. Given the statistically significant coefficient estimates of long run effects and speed of adjustment to equilibrium, this suggests that our results are not a product of the spurious long-run correlation issues endemic to time series analysis with unit root variables. At the systemic level, we also find (in addition to the extended effects of persistent changes to system concentration) a short-run, albeit quickly dissipating, effect on technology adoption in the presence of transitory shocks to concentration.[79]

Illustrative Case Study: Swedish Government Establishes Railroads

In this section we provide a concrete example of the theoretical argument. We argue that changes in Swedish government policy (s^*) toward a major new technology, railroads, can be traced to changes in the international system, namely the Crimean War which caused a ($systemic_t$ reduction in system concentration). We show that these changes in government policy were instrumental to the establishment of a railroad network in the country (Y). The Crimean War marked the breakdown of order in Europe, and states saw themselves as much less secure than previously. As Craig puts it, this "conflict marks a significant turning point in European history. Behind it lay forty years of peace; before it stretched fifteen years in which four wars were fought by the great powers of Europe, with the result that the territorial arrangements of the Continent were completely transformed."[80]

By 1853, representatives in the Swedish Riksdag had debated and rejected proposals for state

[79] We thank a helpful reviewer for suggesting these auxiliary tests.
[80] Craig 1960, 267

funding for railroads for a more than a quarter-century. Attempts to bring railroads to Sweden by mobilizing private capital had all failed, most notably those by Count Adolph Eugene von Rosen in 1845 and 1847-48, who in both cases obtained a royal permission to do so.[81] As Modig writes: "It was by no means predetermined that the railroad system in Sweden should be erected and organised by public means and under public direction."[82] Previous government investments in infrastructure (such as the Gota Canal) had been expensive and unprofitable. Opponents of railroad funding remained active, citing, among other things, the possibility that it would spread cholera.[83] Large landowners, who feared the political ramifications of industrialization brought about by railroads, would continue to try to oppose their construction for decades to come.[84]

But the Crimean War, which broke out in October of 1853, dominated parliamentary sessions which began in late November, and "the relations of Sweden with foreign powers again came to the foreground."[85] From 1845 to 1853, international system concentration fell by 1/3 standard deviations, hitting its lowest point since the 1830s, and the more even distribution of capabilities in the system was becoming obvious.[86] Previously dominant, Britain and France looked at the growing power of Russia and Prussia with concern, where both military expenditures and economic prowess were on a clear upward trajectory. In Stockholm, worries were not initially about direct attacks on Sweden as part of the conflict, but rather the indirect consequences of a war between Britain, France, the Ottoman Empire, and Russia more than a thousand miles away.[87]

The decision for large public investments in railroads was soon made and framed by its proponents in explicitly geopolitical terms. In his speech to the Swedish Estates Assembly, Johan August Gripenstedt, who would later oversee the financing of railroads as minister of finance (1856-1866), compared railroads to defense fortifications and argued they were "so important and have so profound effects, that they cannot by separated from the state".[88] This shift in policy was not due to a discovery of

[81] Oredsson 1969, 52-56
[82] Modig 1993, 56
[83] Riksdagen 1854, 183
[84] Tyrefors et al. (2017). See also Schmid and Huang (2017), who document the importance of domestic opponents to railroad construction in the China and Japan around the same time.
[85] Cronholm 1902, 280
[86] A trend, though punctuated by a post-war spike, which would continue for the next three decades.
[87] Elgström and Jerneck 1997, 219
[88] Gripenstedt (1871, 152-153), our translation.

railroads' military use (for e.g. troop movements), which had been known for some time.[89] Instead, it was because defense had taken on a new urgency. Andersson-Skog states it thus: "that defense interests contributed to the decision to establish [railroad] trunk lines is clear beyond any doubt."[90] "Authoritarian powers" to plan and lead construction of the lines were given to government actors, mainly Nils Ericson, a colonel in the Navy Mechanical Corps, with the lines to be drawn up with careful consideration to defense needs.[91][92]

In Sweden, this state intervention was essential to the establishment of a railroad network, highlighting the importance of government policy for technology adoption. Despite the fact that railroads would cut freight rates by more than half, and travel speeds by nine-tenths, it was only when the state decided to invest that the country's first railroads were built in the latter half of the 1850s.[93] As system concentration continued to fall throughout the 1860s and early 70s, Swedish expenditure on railroads kept rising: In the first half of the 1870s, almost 15 percent of all government revenue was spent on building railroads[94]. While governments often are important for what they do not do — e.g., setting up barriers to new technology — the Swedish example also shows they can be important in acting to promote technology adoption. As one investigation attests: "It was essential, therefore, that the government should not only build the strategic main lines of the system but also help by guaranteeing the loans which the private railway companies issued abroad."[95]

Discussion

We find that a more competitive international system, as measured by the concentration of resources and as described in the historical record, can be linked to a broad-ranging acceleration of technology adoption. Our large-N analysis indicates a relationship between technology adoption and the structure of the international system. We argue that in the short and medium term, states respond to changes

[89] In neighbouring Denmark, reports on the usefulness of railroads in military operations had been circulating for two decades (see Stiernholm 1834). In Sweden's parliamentary debates of 1853-1854, speakers asserted it as obvious, and the point was not contested.
[90] Andersson-Skog (1993, 38, our translation). See also Oredsson 1969, 47-71.
[91] Berger and Enflo 2017, 8
[92] Welin 1906, 63
[93] Sjoberg 1956
[94] Holgersson and Nicander 1968, 8
[95] Kildebrand 1978, 606

in the international system. Using Granger causality tests, we find that there is a unidirectional temporal relationship in line with our expectations. Our regression specifications are by design sparse. In dealing with this long time-frame, there is a sharp trade-off between adding covariates and maintaining good data coverage. More importantly, our estimation strategy relies on tracking changes on a within-country-technology basis. This means that country-specific confounding variables would need to be time-varying within the diffusion paths of particular technologies within particular countries, and at the same time correlated with our measures of system characteristics. A battery of robustness checks seek to alleviate concerns about such variables. At the systemic level, we test a range of potential systemic confounders, still finding our relationship of interest to be robust. We also provide an historical example of how changes in the international system in the latter half of the 19th century led to policies which shaped states' adoption of technologies.

It is difficult to separate capabilities from states' use of technology. Any reasonable measure of concentration of capabilities must rely on a conceptualization of capabilities that captures states' resources; and these resources cannot be entirely divorced from the use of technology. We hope our Granger causality tests and other tools we employ to this question (GMMs and Error Correction Models), robustness checks with country-specific concentration scores (excluding the contribution of their own capabilities), various subsamples and alternative concentration measures, as well as an historical example can provide multiple sources of support for this relationship in the short and medium term, in which the competitiveness of the international environment drives adoption decisions.

The way we have measured technology has been limited to its physical manifestations. We have not looked at innovations in, for instance, management practices, education, or the spread of new ideas. While restricting the scope of our investigation has been necessary, we think there is fertile ground for further research on the relationships between competition in the international system and other spheres of knowledge. It is interesting that the Renaissance started in the context of intense competition between city-states in Northern Italy (where Leonardo da Vinci for a time advised Cesare Borgia), and what is often named as the most innovative period in Chinese culture and history (475–221 BC) is known as the "Warring States period."

Conclusion

Global waves of technological change seem to occur in the international system, and we have sought to understand what drives these "revolutions." Our theory claims that when international system capabilities becomes less concentrated and the system therefore more competitive, governments feel compelled to strengthen their position. They become more likely to change policies that might have constrained their adoption of new technologies or even to enact new policies that promote such adoption. Competitive pressures in the international system thus generate critical incentives in the face of powerful domestic resistance to new technology. We argue that systemic change may lead to waves of technology adoption in many countries. We develop these claims into a series of hypotheses which we then test.

We examine our proposed relationships using many different sources. Our quantitative evidence spans nearly two centuries, twenty technologies, and almost one hundred and seventy countries. We show that during times when the international system was less concentrated, international technology adoption was faster, accounting for all time-invariant country-technology effects. These models show statistically significant and sizable correlations. But we need finer data to show the relationship between government choices about technology and system change. Presenting a specific instance of international system change, we link changes in government policies to concerns about a more competitive international environment. This helps to demonstrate the microfoundations for our claims about systemic pressures and provides further evidence how important government policy can augment technology adoption.

We thus contribute to the study of international relations and technological change in several ways. First, we show that technology adoption by countries, which is a major factor fostering economic growth, relies to some extent on pressures from the international system. It is not just domestic politics that matters. International pressures on leaders can induce them to override domestic demands for preventing technological change and protecting entrenched interests. Indeed, such international pressure may be the most important influence propelling leaders to allow new technologies. Second, we theorize and provide evidence that specific international system characteristics can be related to global technology waves. Third, while some scholars view a more concentrated international system–one of bipolarity[96] or hegemony[97] –as most desirable, we show that a more diffuse system may lead to better outcomes with respect to technological change.

Our evidence may also be useful in thinking about how the distribution of capabilities in the international system changes. We argue that competitiveness in the international system makes policymakers more likely to facilitate the adoption of new technology. We also know that these technologies may both disrupt existing economic arrangements and be very costly in the immediate term. Over the long term, however, such costly initial investments may lay the foundations for higher than otherwise technological development and economic growth.

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[96]Waltz 1979
[97]Kindleberger 1973

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