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. We examine this systematically by considering 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 systemic change Granger-caused technology adoption, and that 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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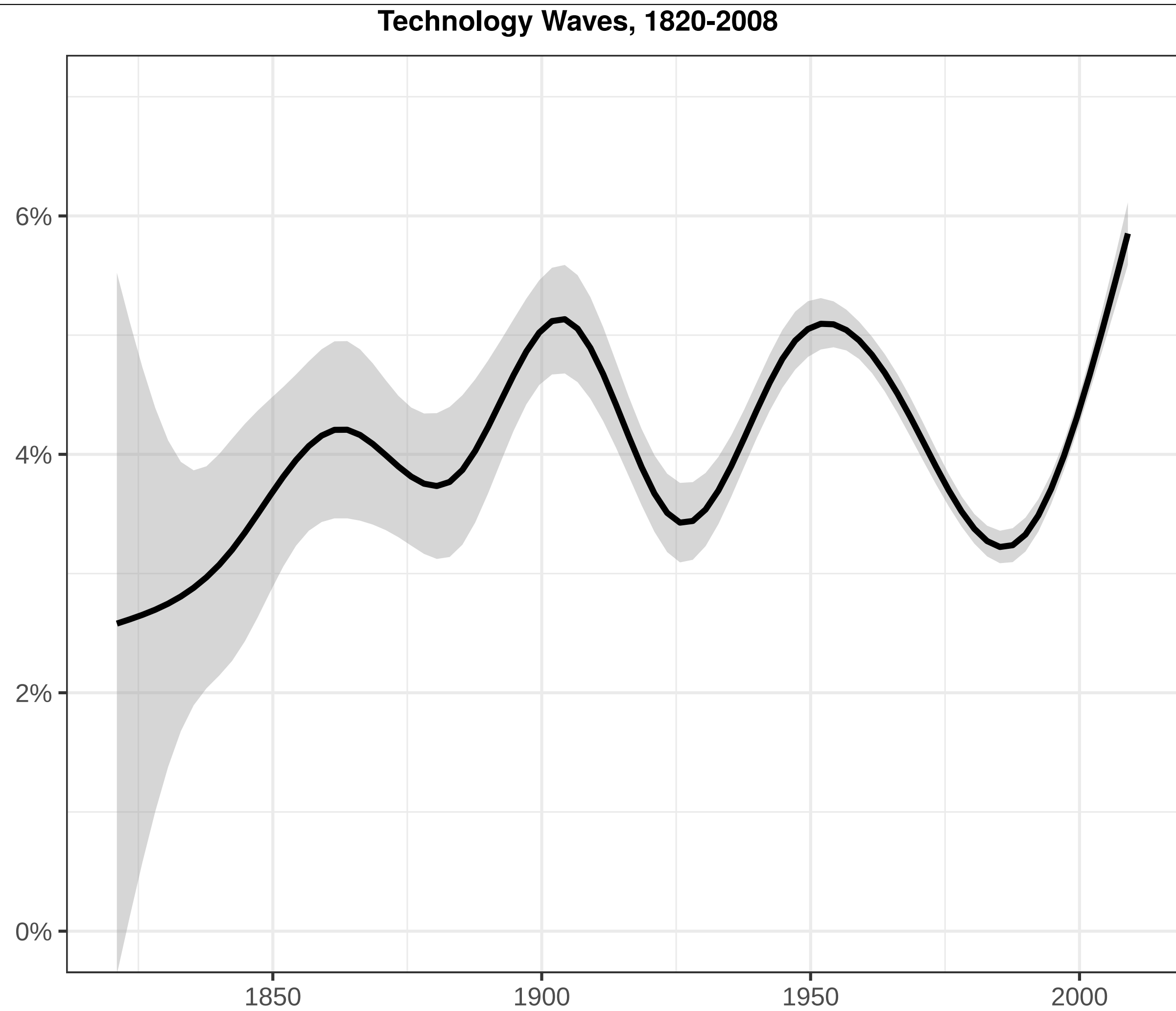
of capitalism involves interaction of the economic sphere with other domains, such as science and technology, and institutions."[1] Examining what facilitates the global spread of technology is therefore important for understanding countries' levels of economic development, their military capabilities, 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 Blanchard (2009, 213): "Though technological progress is smooth, it is certainly not constant. There are clear technological waves." 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 (1979, 128) 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. One important such adjustment is the adoption of new technology. We provide a theory and systematic test 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 wecombine 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 close to 170 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 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.[2] 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.[3] 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.[4] Furthermore, it is known that

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

the market for new technologies is inefficient due to incentives to misrepresent technologies' value.[5]

Most importantly, adopting new technology is disruptive of existing economic arrangements, and has throughout history been resisted by self-interested status quo forces.[6] 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 (1998a, 40) 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."

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. 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.

As firms grow in size and capital requirements, government policy becomes more important for facilitating or deterring investments in new technology. Within Europe, economic development processes have differed considerably between countries, as have the economies which emerged from

[5]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.
[6]Mokyr 1998b

these processes. These differences in both "speed and character" were to some extent the result of government policies. As Gerschenkron (1962, 17) 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."

Research attempting to pin down systematic differences in technological adoption rates tends to highlight the importance of domestic politics.[7] In particular, Comin and Hobijn (2004) find that domestic institutional characteristics explain much of the variation in countries' adoption of technologies with competing predecessors (see also Comin et al. 2006). 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" (238).[8]

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.[9] As Mokyr (1994, 564) 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."[10] He goes on to show that when these conservative groups capture 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

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

[8]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, opp 1953), 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).

[9]Mokyr 1990, 1994, 1998a, 2002, 2010; Landes 1990, 2006; Taylor 2016; Jones 1988

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

short period. Fortunately, as each leader has flagged there has always been, up to now, a nation or nations that take over the torch."[11] Taylor (2016) summarizes it thus: "everyone agrees that progress in science and technology is routinely blocked by status quo interest groups."

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 (1979) 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 as Tilly (1992), Kennedy (1989) and Waltz (1979), 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.[12]

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 institutions and political structure that produced modern economic growth."[13]

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

[11] Cardwell 1972, 210
[12] Gilpin 1981
[13] North 1994, 15

in fractured political environments can break the iron hand of domestic vested interests. Taylor (2016), 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.[14] 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."[15]

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."[16] 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 (2012, 2016) 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.

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 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.[17]

[14]See also Acemoglu and Robinson 2006.
[15]Taylor 2016, 275
[16]As quoted in Engerman 2004, 27.
[17]These are related to Kondratieff waves (also known as "K-waves") in the sense of being long-term wave-like economic phenomena.

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.[18]

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. 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

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

well-known factors.[19] As Taylor (2016, 276) 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. 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.[20] In political science, extensive literature has focused more on the diffusion of policy or political norms rather than technology per se.[21] These models usually point to emulation, learning, coercion, and contagion as primary mechanisms leading countries to adopt. Horowitz (2012) in his book, *The Diffusion of Military Power*, is one of the few who focus on technological diffusion in particular.[22] 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.[23] Linking the international system structure to patterns of technology adoption is important not only because of its implications for material welfare, but also because of its theoretical importance in international relations.

[19] 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

[20] Mansfield 1961; Rogers 2003; Comin and Hobijn 2009a

[21] 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)

[22] Wan (2014) considers nuclear weapons diffusion.

[23] 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.

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. 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. The key contribution of the model is to show that the likelihood of such international challenges — i.e., the competitiveness of the international system — exerts a powerful influence on government policy.

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.[24]

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 $s \in [0, 1]$.[25]
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.[26]

[24]Proofs are provided in the online appendix.

[25]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 possible 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.

[26]As we detail in the two preceding sections, government policy (including what a government does not do), is

5. With probability p, challenges from the international system arise against the government. If there is a challenge, the government survives the challenge with probability $f(s)$, a strictly increasing function in s. The function f captures both the usefulness of the new technology in surviving the international challenge, and the degree to which government policy is effective in facilitating technology adoption.[27]
6. If the government loses the dispute, all agents incur a cost, normalized to 1.

We assume that the government's utility (U_g) is linear in the support from firms and consumers, so that the government's maximization problem is:

$$s^*(r_f(\cdot), r_c(\cdot)) = \arg\max_{s\in[0,1]} \underbrace{r_f(s) + r_c(s)}_{\text{utility from contributions}} - \underbrace{p(1 - f(s))}_{\text{probability of losing a challenge}} \tag{1}$$

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

$$U_f(s, r_f) = -p \cdot (1 - f(s)) - r_f + g_f(s) \tag{2}$$

where $g_f(s)$ denotes firms' utility of technology adoption, which is strictly decreasing in s.

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

$$U_c(s, r_c) = -p \cdot (1 - f(s)) - r_c + g_c(s) \tag{3}$$

where $g_c(s)$ denotes consumers' utility of technology adoption, which is strictly increasing in s.

We assume that firms and consumers use only *truthful* contribution schedules in equilibrium.[28]

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.

[27]Such a challenge may come from one country, many countries, or a non-state actor. It may for instance take the form of military invasion (e.g., the Second Schleswig War), or a severe economic "attack" (e.g., the American oil embargo on Japan in 1941).

[28]This is a standard assumption in models of lobbying. For justification and intuition behind this assumption, see Dixit et al. (1997), and Grossman and Helpman (1994).

These are schedules that promise to the government for any s the excess of the group's welfare at s relative to some base level of welfare. Formally, for $i \in \{f, c\}$, the schedule $r_i(s)$ must satisfy:

$$\max\{0, -p * (1 - f(s)) + g_i(s) - B_i\} \tag{4}$$

for some base level of welfare B_i. We also straightforwardly assume that the functions $g_f(s)$, $g_c(s)$ and $f(s)$ are all twice continuously differentiable.

The following proposition then essentially follows from Corollary 1 to Proposition 4 of Dixit et al. (1997):

Proposition 1 (Dixit-Grossman-Helpman)**.** *The equilibrium level of government support for technology adoption (s^*) is given by:*

$$s^* = \arg\max_{s \in [0,1]} -3p \cdot (1 - f(s)) + g_f(s) + g_c(s) \tag{5}$$

The preceding proposition implies the following comparative static on p:

Proposition 2. *The equilibrium level of government support for technology adoption (s^*) is increasing in the probability of an international challenge p:*

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

Two complementary effects underlie this relationship. First, as p increases, the government sees a larger benefit in increasing its ability to withstand an international challenge. Second, these contribution schedules change: as p 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.

We next decompose the competitiveness of a country's international environment, p, into a function of both *local* and *systemic* components:

$$p_{i,t} \equiv p(systemic_t, local_{i,t}) \tag{6}$$

Where i indexes country and t indexes time. For instance, large increases in military spending by a country's neighbors may make its environment more threatening. This would be captured in $local_{i,t}$, and vary by country. A country's international environment may also be made more or less competitive by the distribution of capabilities or resources among all countries. Such pressure would be captured through the systemic component ($systemic_t$) and not vary by country, but rather affect all countries at the same time.

In combination with Proposition 2, we state our main result:

Proposition 3 (Systemic Competitiveness and Technology Adoption)**.** *Equilibrium level of technology adoption is increasing in the international system's competitiveness:*

$$\frac{\delta Y_{i,t}}{\delta systemic_t} > 0 \tag{7}$$

While simple, this 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.[29] Deterrence, possibly by technological sophistication, is incorporated as well: if an outside actor is deterred from challenging the government, the model counts this as a challenge "survived". 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. To incorporate this complication, one 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.

Our theory centers on p, the likelihood that the government is challenged by external actors or pressures, and specifically, on the *systemic* source of variation in this probability. We propose that this systemic variation — over time, affecting all countries — underlie global technology waves.

We argue that such systemic competitive pressures increase when the distribution of capabilities

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

$$p \equiv \sum_c \textit{Probability of Challenge}_c * \textit{Severity of Challenge}_c \tag{8}$$

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

relevant for competition in the international system are spread among many countries. Rather than derive this formally, we here build on a large literature in international relations which has studied systemic concentration and developed measures of such concentration to do so. We also provide a section in the Online Appendix demonstrating this empirically.[30]

A more diffuse distribution of capabilities makes the outcome and participants in any conflict are harder to predict, as intervention may come from more sources (and there is a higher number of possible coalitions on either side).[31] Furthermore, in such conditions leaders are much less able to predict the form these disputes will take, and powerful states find it harder to coordinate on policies to limit the influence of the less powerful.[32] This increased unpredictability is not limited to just outcome uncertainty — that capabilities are evenly distributed between two states in a dispute — but extends to who may consequentially join a coalition, or see themselves as able to challenge a competitor to begin with.

In contrast, when power capabilities are highly concentrated, competitive pressures tend to be lower. Bipolar systems 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. Furthermore, the sizable advantage of these few countries makes others less interested in spending resources to catch up. A hegemonic structure is even more likely to reduce pressure on other states to compete and adopt new technologies.[33]

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

[30]There are several possible systemic characteristics ($systemic_t$) which may be related to the likelihood of a challenge from abroad. We test many of these — including measures of (militarized) international disputes — in the online appendix, where we demonstrate both the validity of the competitiveness-technology link and reliability of the relationship between system concentration and competitiveness.

[31]The link between distribution of capabilities and uncertainty is highlighted in many studies, e.g. Waltz (1979), Christensen and Snyder (1990), Huth et al. (1992), and Grant (2013).

[32]Bas and Schub (2016, online appendix) show this empirically: more evenly matched sides are associated with conflicts having higher fatalities and a greater number of warring states.

[33]There are a number of ways to relate the polarity of the international system to its competitiveness. But even over the two hundred years investigated here, there is little variation in polarity. As we show below, classifications of systems by polarity mask considerable variation in the concentration of capabilities over time (for more on the advantages of incorporating information beyond polarity, see Mansfield (1993)).

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. More competition in the system in contrast makes it harder for any state to control the spread of technology and prevent its diffusion. The concentration of capabilities in the system, as with firms in markets, thus means competitive pressures are diminished.

In sum, we have reason to believe that system concentration of capabilities ($SYSCON$) is negatively related to system competition.

$$\frac{\delta systemic_t}{\delta SYSCON_t} < 0 \tag{9}$$

Coupled with Proposition 3, Equation 9 theoretically links system concentration with levels of technology adoption.

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.*

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.[34]

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 technology-country-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

[34]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.

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 (2009) captures both the presence and in many cases the intensity of utilization of many technologies in more than 150 countries since 1800. We followed Comin et al. (2013), in focusing on twenty of these technology types, which are listed in the appendix.[35] 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.[36]

We expanded this dataset to include new observations from the years since 1990, adding about 16,000 technology-country-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. (2013) in our specification of the dependent variable.

[35] 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.

[36] We explore the use of many alternative sets of technologies in the robustness checks below.

Technology Adoption: The yearly change in log number of technology units per capita per year per 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.[37]

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, Singer et al. 1972). 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.[38]

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. (1972). 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.[39] In our online 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

[37]In Appendix Figure A.1, we show which years different technologies are included in our analysis.

[38]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.

[39]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.

possible coalitions among great powers).

Control Variables We include several control variables other studies of technological adoption have identified several important factors 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.[40] 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 (1994) stresses.[41]

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, from Marshall et al. 2012)

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

[40] Comin and Hobijn 2009a; Comin et al. 2013

[41] All relationships also hold unconditionally, i.e. without any of these controls.

GP_t the set of countries that are Great Powers in year t.[42]

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 (as in Comin et al. 2013):[43]

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

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. In the appendix, we include figures plotting the technology-year and country-year coverage of our analysis. Table 1 provides summary statistics.[44]

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 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 models with GDP per capita or world GDP estimates included as predictors as expected slightly reduces the magnitudes of our effects (and sample size), but all relationships remain statistically significant and in the expected direction. Whenever these are reported, we use GDP per capita estimates from Bolt et al. (2018), and World GDP estimates from Delong (2014).[45] In our robustness checks, we estimate models with imputed data, add

[42]In our main specification (column 1, Table 1) 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).
[43]If not demeaned by year, it would by construction eliminate any temporal systemic variation in adoption rates.
[44]In the online appendix, we provide results using imputed data. Many other robustness checks are detailed below.
[45]Non-random missingness for many countries makes it necessary to use a separate source for world GDP estimates

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:

$$\Delta Y_{i,tech,t} = \beta_0 + Z_t\alpha_1 + X_{i,t}\beta_1 + Q_{i,tech,t}\beta_2 + \epsilon_{i,tech,t} \tag{10}$$

Where $\Delta Y_{i,tech,t}$ is change in 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 from systemic change to higher p, from higher p to higher s^*, and from higher s^* to higher Y through equations 6, 7, and Proposition 2. The terms $X_{i,t}\beta_1$ and $Q_{i,tech,t}\beta_2$ similarly capture both local sources of variation in p (i.e., $local_{i,t}$) and proxies for $g_c(.)$, $g_f(.)$, $r_c(.)$ and $r_f(.)$.

Our outcome of interest, faster technology adoption in many countries, is measured on a within-country-technology basis. Testing our theory at the country-year-technology 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.[46]

We next perform tests at the systemic level. We here aggregate the rate of change for all technologies

rather than summing country-level estimates. For world GDP, the Delong's "preferred projection" was used and yearly values were interpolated whenever necessary.

[46]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.

in all countries in a given year (moving from almost 90,000 to just 190 observations — one for each year). In addition to testing the aggregate relationships, we report models in which we include two additional controls for political and economic change in the period: World average Polity2 scores and World GDP.

$$\overline{\Delta Y_t} = \gamma_0 + Z_t\gamma_1 + \overline{X_t}\gamma_2 + \overline{\epsilon_t}^t \tag{11}$$

Wherein γ denote coefficients, $\overline{(.)}$ the yearly mean and other terms are as previously.[47] We also tested the relationship using two alternative measures of system concentration, described in Table 3.

We finally tested if there exists a temporal relationship in line with hypothesis 4 by conducting a series of Granger Causality tests. We here again constructed a yearly series of technology adoption across all countries and technologies.[48] 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.[49] 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.[50] We did this with and without incorporating covariates, and with a variety of 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 online appendix on validity of system concentration as a

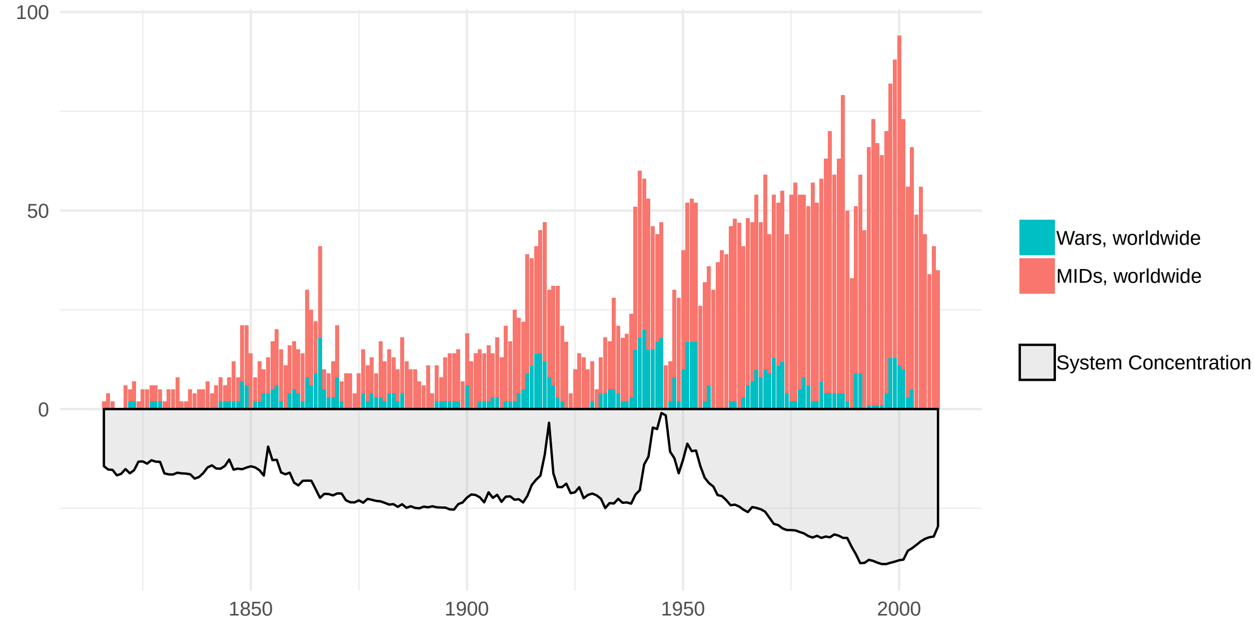
[47] $Q_{i,tech,t}$ is a relative term on a within-year basis, and thus across countries has a yearly mean of 0 for all technologies. Note that the summary statistics below summarizes SDT observations for country-technology-years in which technology adoption rate was observed, and is hence slightly different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

[48] 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.

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

[50] 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: System Concentration (bottom) and number of states involved in militarized interstate disputes (MIDs) and wars (top), from 1816 to 2008. We argue that low system concentration is associated with a more competitive international system and hence more disputes. In the online 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.

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

Statistic	N	Mean	St. Dev.	Min	Max
Log (Technology Units Per Capita)	99,236	2.30	3.79	0.00	17.26
Δ Log (Technology Units Per Capita)	94,989	0.04	0.14	−3.69	3.61
Spatial Distance to Technology, 3 Year Lag	97,722	−0.19	0.69	−2.94	2.60
Syscon (Singer 1972)	24,725	0.29	0.04	0.22	0.41
Δ Log (Military Expenditure in Neighboring Countries)	13,967	0.22	2.35	−6.56	21.49
Polity2 Score	16,825	−0.60	7.07	−10.00	10.00
At War in previous year (0, 1)	23,631	0.03	0.18	0.00	1.00
Civil War in previous year (0, 1)	23,631	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).

measure of international competition.

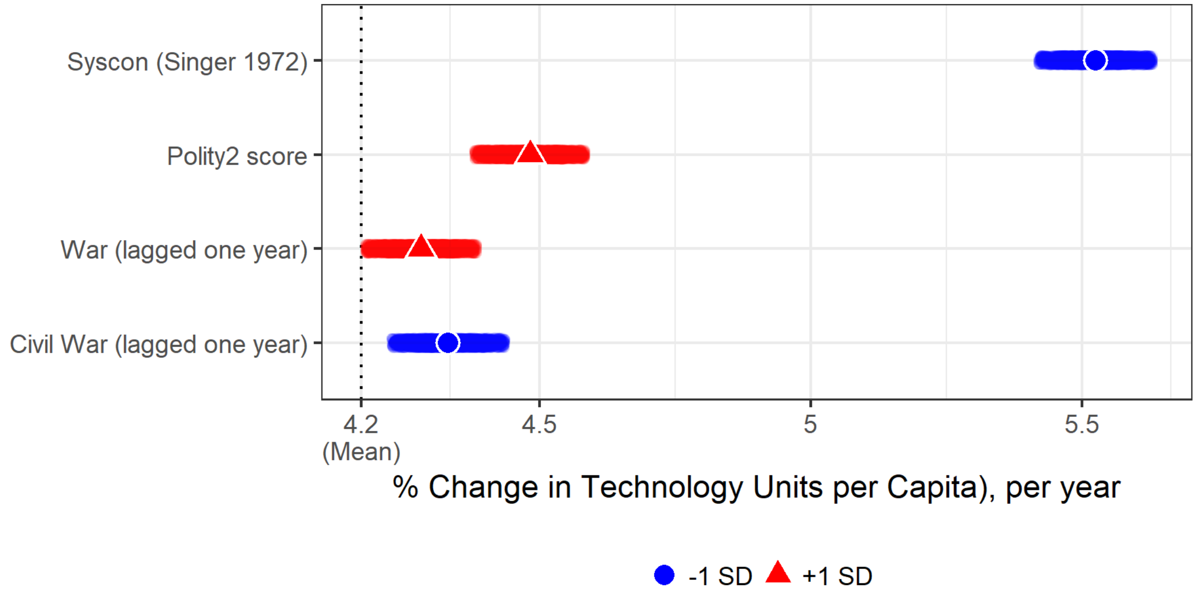
Table 2. Country-Year-Technology Tests: Technology Adoption and Systemic Factors (1820-2008)

	Dependent variable:			
	Change in Technology Adoption Level			
	(1)	(2)	(3)	(4)
Syscon (Singer 1972)	−0.339***		−0.331***	−0.338***
	(0.027)		(0.028)	(0.029)
Change in Neighboring Countries' Military Spending		0.002***	0.001***	0.001***
		(0.0002)	(0.0002)	(0.0002)
Log (GDP pc)				−0.003**
				(0.001)
Spatial Distance to Technology Adoption, lagged	−0.050***	−0.051***	−0.050***	−0.051***
	(0.002)	(0.002)	(0.002)	(0.002)
Polity2 score	0.0004***	0.001***	0.0004***	0.001***
	(0.0001)	(0.0001)	(0.0001)	(0.0002)
War (lagged one year)	0.005**	−0.004	0.005**	0.006**
	(0.003)	(0.003)	(0.003)	(0.003)
Civil War (lagged one year)	−0.006*	−0.001	−0.006*	−0.008**
	(0.003)	(0.003)	(0.003)	(0.004)
Constant	0.123***	0.031***	0.121***	0.146***
	(0.008)	(0.001)	(0.008)	(0.014)
Observations	86,165	84,231	84,231	80,814
R^2	0.075	0.068	0.077	0.079
Adjusted R^2	0.075	0.068	0.077	0.079
Residual Std. Error	0.130	0.131	0.131	0.130
DF	86159	84225	84224	80806

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

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

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



Details: The plot show 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 40,000 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 4.2 to 5.5 percent (difference significant at the $p < 0.001$ percent level).

relationship between our three measures 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).[51] The effect of a one-standard-deviation downward shift from the mean of Syscon (i.e. from 0.29 to 0.25) is large: this would in expectation increase technology adoption rate from 4.1 to 5.55 percent per year (≈35 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.

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

	Dependent variable:	
	Δ Log (Tech. Adoption per capita), World-wide	
	(1)	(2)
Syscon	−0.381***	−0.080***
	(0.047)	(0.029)
Polity2 (World average)		0.004***
		(0.0004)
GDP (World, logged)		0.006***
		(0.001)
Constant	0.138***	0.008
	(0.015)	(0.011)
Observations	190	190
R^2	0.433	0.760
Adjusted R^2	0.430	0.756
Residual Std. Error	0.016	0.011
F Statistic	143.333***	195.934***
Note:	*p<0.1; **p<0.05; ***p<0.01 (Robust Standard Errors in Parenthesis)	

In Table 3, we examine our argument at the systemic level. We move from over 85,000 country-

[51] We following the approach suggested in King et al. 2000.

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

technology-years to just 190 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 between 60 and 20 percent of the variation in the world-wide pace of technology adoption.

We next find that changes in system concentration Granger-causes 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. 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.

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 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 online appendix (henceforth "o.a."), 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 = 74,606), on only minor powers (N = 80,454), and only major powers (N = 7,148). We considered only European countries (N = 27,509), and only non-European countries (N = 61,340, all in o.a. Table 4). 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 (o.a. Table 4, column 1). We replicated our analysis with additional controls: a binary democracy variable (from Boix et al. (2013)), population (logged, from Bolt et al. 2018), and indicators for the Cold War or the five-year interval after a world war (o.a. Table 5)). We used the threat measure suggested in Leeds and Savun (2007), 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 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 (available upon request).

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 (o.a. Table 2.5). We estimated models in which system concentration for country *i* was calculated using data on all countries except *i* (o.a. Table 2.4). Results were unchanged.

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 all six 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 (o.a. Table 6). In all cases, results remained robust.[52]

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 - o.a. Table 7).

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 all the aforementioned regressions, including the robustness tests, using intensity of use rather than 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 bringing more international competition. Beyond the evidence provided in this paper, we include a separate section in the online 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

[52] 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.

system concentration indeed is linked to higher levels of competition (o.a. Table 3.1-3.2).

Measures of concentration are sometimes argued to be overly sensitive to how they are specified. We therefore include a separate section in the o.a. 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 rather than top 10 countries (o.a. Table 2.1-2.3). Results are robust.

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 (o.a. Table 6). 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.

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.

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 made evident by the Crimean War ($systemic_t$), and 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 (1960, 267) 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."

By 1853, representatives in the Swedish Riksdag had debated and rejected proposals for state 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.[53] As Modig (1993, 56) 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." Previous government investments in infrastructure (such as the Gota Canal) had been expensive and unprofitable.

But the Crimean War, which broke out in October of that year, dominated parliamentary sessions which began in late November, and "the relations of Sweden with foreign powers again came to the foreground."[54] Swedish worries were not about direct attacks on Sweden as part of the conflict, but rather the indirect consequences and opportunities surrounding a war between Britain and Russia more than a thousand miles away.[55] The Riksdag decided to allocate funds for railroads within weeks. The decision was framed by its proponents in explicitly geopolitical terms. Andersson-Skog (1993, 38, our translation) states it thus: "that defense interests contributed to the decision to establish [railroad] trunk lines is clear beyond any doubt.[56] "Authoritarian powers" to plan and lead construction of the lines were given to Nils Ericson, a colonel in the Navy Mechanical Corps.[57]

The Crimean War erupted as the distribution of capabilities was becoming more equal. From 1845 to 1853, international system concentration fell by 0.33 standard deviations, hitting its lowest point since the 1830s. It would continue falling, and Swedish expenditure on railroads keep rising, throughout the 1860s and early 70s. In the first half of the 1870s, almost 15 percent of all government revenue was spent on building railroads (Holgersson and Nicander 1968, 8).

In Sweden, this state intervention was essential to the establishment of a railroad network, highlighting the importance government action can have for technology adoption. Despite the fact that railroads would cut freight rates by more than half, and travel speeds by nine-tenths, [58] it was only when the state decided to invest that the country's first railroads were built in the latter half of the 1850s. As later investigations attest: "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

[53] Oredsson 1969, 52-56
[54] Cronholm 1902, 280
[55] Elgström and Jerneck 1997, 219
[56] See also Oredsson 1969, 47-71.
[57] Berger and Enflo 2017, 8
[58] Sjoberg 1956

railway companies issued abroad."[59]

The importance of the international system at this juncture endures in the geography of modern Sweden. All main trunk rail lines were placed inland, with separate radial lines providing connections to coastal cities. This economically inefficient setup was intended, as the planners made clear in the 1850s, to make the country less susceptible to raids or attacks by sea. The government responded to the possibility of such challenges as the international system grew more competitive by promoting new technology.

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 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

[59]Kildebrand 1978, 606

Granger causality tests, robustness checks with country-specific concentration scores (excluding the contribution of their own capabilities), and 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 a hundred and sixty-six 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[60] or hegemony[61] –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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[60]Waltz 1979

[61]Kindleberger 1973

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Appendix:

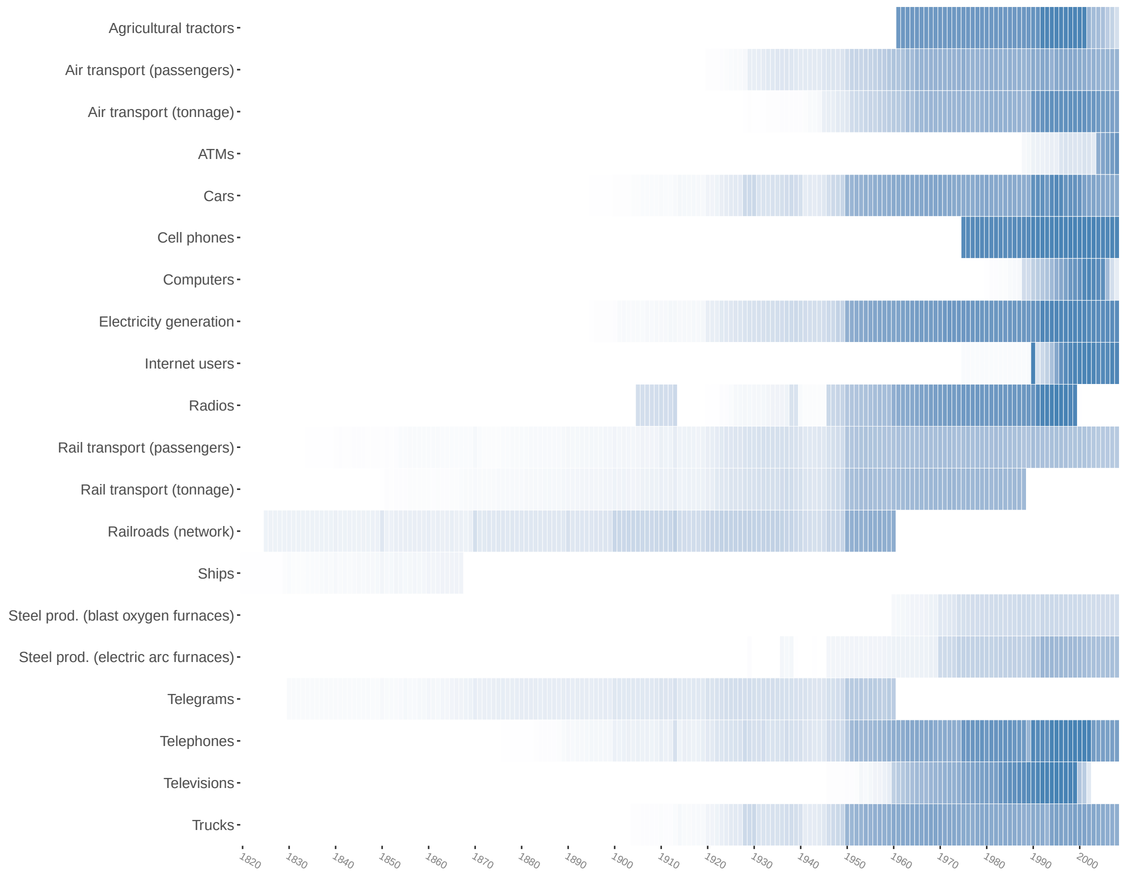
List of Technologies

1. Agricultural Tractors
2. ATMs
3. Aviation Passengers * kilometer
4. Aviation Tons * kilometer
5. Cars
6. Cellphones
7. Commercial Trucks
8. Communication Radios
9. Computers
10. Electricity production
11. Internet users
12. Rail Passengers * kilometers
13. Rail Tons * kilometers
14. Ships
15. Steel Tons from Blast Oxygen
16. Steel Tons from Electric-arc
17. Telegrams
18. Telephones
19. Transportation Rail Line kilometers
20. Televisions

Note: Technologies are measured in number of units, while technology adoption (which we use in our models) are the log of these numbers scaled by population. Our dataset extends the series recorded in Comin and Hobijn (2009b), and follow its definitions.

Data (Detail):

Figure A.1. Technology and Year Data Coverage



Details: Blue indicates observation (that is, at least one country) in technology-year, with darker blue indicating more observations (multiple countries).

Figure A.2. ***Details:*** **Blue indicates observation (that is, data on all model variables and at least one technology) in country-year, with darker blue indicating more observations (multiple technologies). Gray cells are years before the country became an independent state. There are more observations in later years, but this is partly a reflection of new technology being invented and captured in the data, and the emergence of new countries. Our analysis has at least one technology observation in 79.6 percent of possible country-years.**

Country and Year Data Coverage