Technology Diffusion and the International System

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Does world politics affect the diffusion of technology? States overwhelmingly rely on technology invented abroad, and their differential intensity of technology use accounts for much of their differences in economic development. Some international relations scholarship suggests states adopt new technology as they seek to avoid vulnerability to attack or coercion by more developed neighbors. We argue the structure of the international system affects the level of competition among states which in turn affects leaders' willingness to enact policies that speed technology adoption. 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 such systemic change Granger-caused technology adoption, and that policies to promote technology adoption are related to concerns about rising international tensions. A competitive international system is an important incentive for technological change, and may underlie global "technology waves." [150 words]

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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 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 of capitalism involves interaction of the economic sphere with other domains, such as science and technology, and institutions." (Fagerberg and Verspagen 2002, 1293).

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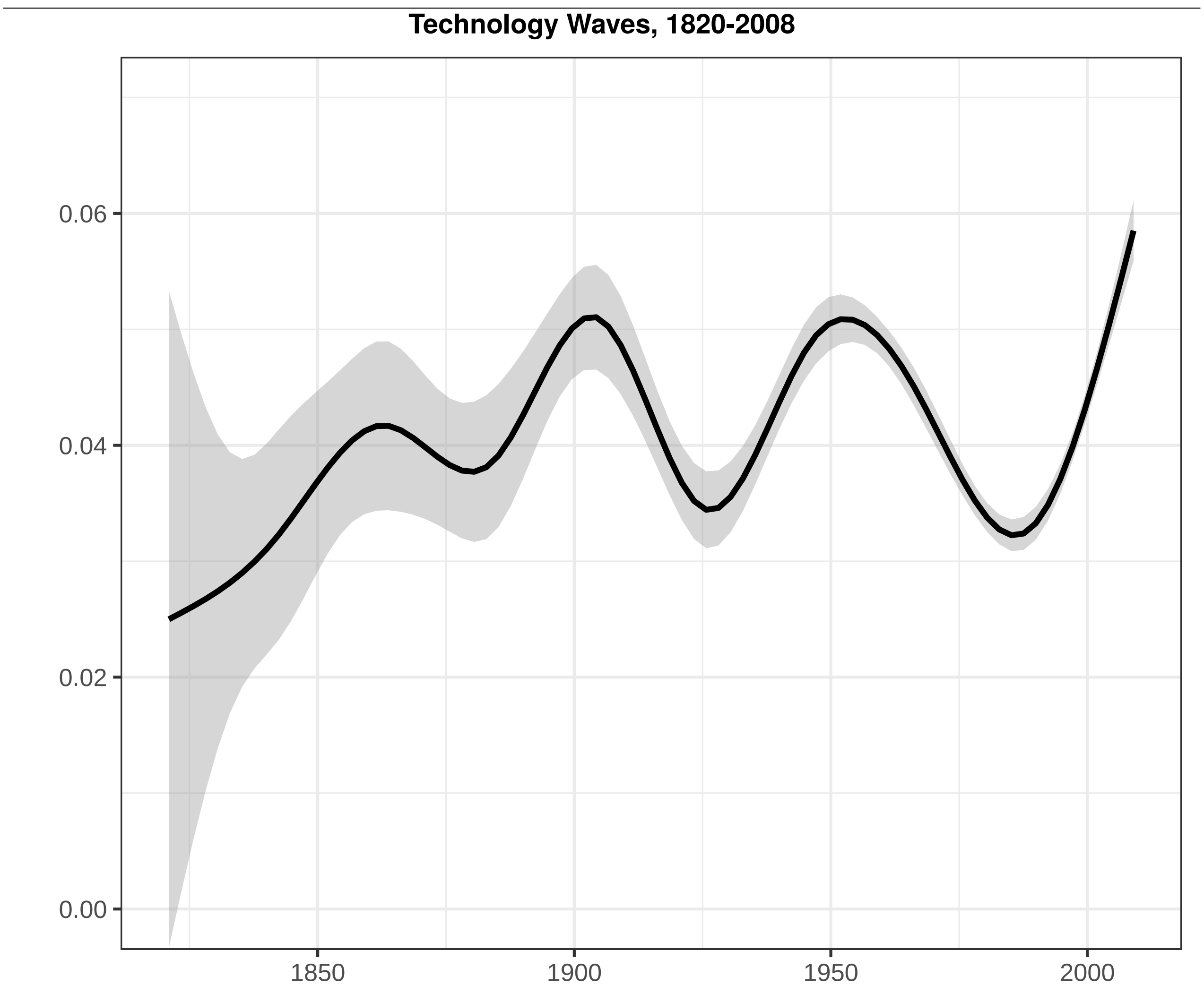
Figure 1 plots the percentage increase in the adoption of twenty of the most important technologies (such as railroads, the telephone and agricultural tractors) over almost 200 years. These especially important technologies form the basis for our analysis. In the words of Blanchard (2009, 213): "Though technological progress is smooth, it is certainly not constant. There are clear technological waves." In this paper, we ask what underlies such waves of technology diffusion?

Scholars in international relations have suggested that international competition, especially short of actual 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 make adjustments

FIGURE 1. Trends in (Δ Log of) Technology Units per Capita of twenty key technologies from Comin et al. (2013) from 1820 to 2009. The plot summarizes more than 90 thousand observations of rates of technology adoption over the past two centuries, with the 95 percent confidence interval in gray.



which increase their productivity and growth. One important such adjustment is the adoption of new technology. We expand this argument to the systemic level: we propose that the level of tensions in the international system influences global technology waves. To test our hypotheses, we expand the most extensive dataset on technology adoption at the country-technology-year level in existence, examining if there are links between technology adoption and international tensions across two centuries, all key technologies, and close to 170 countries for the first time.

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. Adopting new technologies forms an important part of this process. Governments often play a critical role. As we detail below, not only may government initiatives be important in facilitating the adoption of new technology from abroad, but what governments avoid doing is important as well. Elites tend to be favored by current economic arrangements, and thus often see technological change as a threat or cost. For governments to resist calls to protect such established interests through policies, such as tariffs or monopolies, may be just as crucial as their efforts to promote new technologies. Furthermore, competitive pressure from the international system provides incentives for nations to develop their own capabilities as well as those of their allies.

International relations scholarship has expectations about when such pressure on governments is likely to be acute. Specifically, competitive pressures increase when the international system has a less concentrated distribution of capabilities. When there are numerous powerful states, competition is thought to be especially fierce. In such times, 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).[1] 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.[2]

In contrast, when power capabilities are highly concentrated in one or a few states, competitive

[1] 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).

[2] 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.

pressures tend to be lower. Bipolar systems are thought 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.[3] If international relations scholarship is right, there should be more competition at times of more dispersed capabilities, which we believe should induce more adoption of new technology.

This study proceeds with a summary of the literature on technology diffusion, highlighting the importance of technology sourced from abroad, and the key role governments play in helping or hindering adoption of technology. We then develop our theory in more detail and present several hypotheses. The next sections contain details on our data, empirical strategy, and results. A discussion of these results concludes.

INTERNATIONAL TECHNOLOGY DIFFUSION

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 (Keller 2004, 752). Even in OECD countries, the major sources of new technology leading are international (Keller 2001). Foreign sources of technology are estimated to account for around 90 percent or more of technology-based productivity growth for most countries (Keller 2010, 795, see also: Hall and Jones 1999, Easterly and Levine 2001). The pattern of world-wide technological change and levels of productivity are thus largely determined by international technology diffusion.

Technology adoption is not costless or easy. International technology diffusion (ITD) is either direct (buying access to new technologies) or indirect (employing specialized and advanced intermediate products invented abroad). But the market for new technologies is plagued by problems due to asymmetric information and incentives to misrepresent technologies' value. Firms try to monopolize

[3]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)).

the benefits of a technological advantage by keeping new technology secret. Furthermore, often only the broad outlines of technological knowledge are or can be codified. A range of empirical evidence indicates that international technology transfers carry significant resource costs (Mansfield and Romeo 1980; Ramachandran 1993).

International technology diffusion is crucial because the utilization of technology in large part determines countries' economic fortunes and military prowess. Understanding what facilitates technology diffusion is therefore important to understand the determinants of countries' levels of productivity and technological development. While many things determine the speed and extent of adoption of a particular technology in a particular country, we focus on factors affecting many countries and technologies. We want to explain global technology waves; not why some countries adopt some new technologies faster than others.

Governments are important actors in international technology diffusion. Work attempting to pin down systematic differences in technological adoption often highlighted the importance of domestic politics (Olson 1982; Mokyr 1994, and Parente and Prescott 2000 are three prominent examples). Landes (2006, 10) concludes that domestic institutions constraining political intervention were one important reason why the industrial revolution took place in Europe and not China.

Government may be crucial facilitator or completely block technology adoption. The adoption of some technologies has often been undertaken as projects commissioned by the national government (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, or granting existing industries avenues of legal action, governments have many means to limit the diffusion of technology.

Recent research on the international diffusion of technology has found large effects of governments' action. In particular, Comin and Hobijn (2004) find that domestic institutional characteristics explain much of the variation in countries' adoption of technologies with competing predecessors (i.e., technologies which have vested interests because of a previously adopted alternative — 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. They argue these effects are large: "...the estimated effect of lobbies on technology diffusion represents 50% of the observed variation in technology diffusion" (p. 238).

Scholars of technological change frequently point out that the main barrier to it lies in entrenched domestic interests and the policies that governments adopt to protect them (Mokyr 1990, 1994, 1998, 2002, 2010; Landes 1990, 2006; Taylor 2016; Jones 1988). 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." 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 short period. Fortunately, as each leader has flagged there has always been, up to now, a nation or nations that take over the torch." (Cardwell 1972, 210). Taylor in his recent study of technological change (2016, 11) also notes that "everyone agrees that progress in science and technology is routinely blocked by status quo interest groups."

But the second part of Cardwell's Law suggests another puzzle: how does technological change ever take place given these domestic vested interests? The answer for Mokyr and Taylor is that international factors also matter. For Mokyr, a more competitive international system allows countries to break from the iron hand of domestic forces; and for Taylor, "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. As Taylor (2016, 275) 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."

Our theory is consistent with this view, taking it as a point of departure for a systemic theory of global technology waves. Competition in the international system is always present; what varies is how vigorous that competition is. Our contribution is to show under what conditions the international system matters. We argue that a very competitive configuration of the international system makes the costs of *not* adopting larger. In this way, a threatening international environment acts as an counterweight to domestic vested interests' lobbying to protect and prevent adoption. Our project 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. 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.

Linking the international system structure to patterns of technology diffusion is important not only because of its implications for material welfare, but also because of its theoretical importance in international relations. Though often implicitly, international relations scholarship makes assumptions about how changes in the speed of technology diffusion respond to the configuration of the international system. Most importantly, however, differential rates of adoption are often seen as a cause for larger global change and conflict.

Several important works in international relations, including Tilly (1992), Kennedy (1989) and Waltz (1979), either argue or assume that international security competition forces technological diffusion upon governments. They focus on how military-strategic concerns promoted the adoption of new technologies that were militarily relevant ("dual-use"), or how military procurement stimulated nascent technology industries.

As Gerschenkron writes on Russia in his seminal essay (1962):

> *(1) Basic was the fact that the state, moved by its military interest, assumed the role of the primary agent propelling the economic progress in the country. (2) The fact that economic development thus became a function of military exigencies imparted a peculiarly jerky character to the course of that development; it proceeded fast whenever military necessities were pressing and subsided as the military pressures relaxed. [p. 17]*

The importance of international competition is also emphasized in works on economic development generally. As argued by North (1994) in his Nobel lecture:

> *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. [p. 365]*

We know that in a wider historical perspective, political pluralism has neither been a sufficient or necessary condition for technological dynamism, as Mokyr (1994) stresses. As the following sections will make clear, we also see considerable variation in international technology diffusion over time periods in which there was little change in states' domestic regimes or their borders. In these periods, there was however considerable variation in the configuration of capabilities in the international system.

THEORY: COMPETITION SPURS TECHNOLOGY DIFFUSION

The adoption of new technology is disruptive, and usually resisted. It often requires substantial investment (both public and private), depressing current consumption. Adoption may also require the transfer of considerable resources to trading partners in exchange for technology goods. Vested interests may stand to lose from the introduction of new technologies, or leaders fear the political ramifications of technological change.

Policy-makers seek to balance this resistance to change with the demands of the international context. They recognize that in more competitive international environments, 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. 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." (As quoted in Engerman (2004, 27)). 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.

Central is the fact that new technologies create winners and losers. If the losers can press the government to adopt policies that halt or slow down new technology, then countries fall behind. Domestic distributional battles consume the government and prevent change, as Olson (1982) predicted, and many later have evidenced (Mokyr 1990; Acemoglu and Robinson 2008; Haggard 1990; Doner and Ritchie 2009). When faced with external threats, leaders more become willing to bear the costs of pushing ahead with new technologies. As Taylor concludes (2016, 275), "Without international competition in the form of external threats to a society's economic and military security, national innovation rates tend to slow. External threats matter because they counter the domestic political fights over distribution that kill off incentives and rewards for innovation."

Our theoretical innovation is to argue and specify how (1) this external pressure to adopt is not constant over time, (2) that it is related to the distribution of capabilities in the international system, and consequently (3) that systemic shifts can be linked to global "technology waves" — cycles of slow and rapid technology diffusion in many countries.

Specifically, when capabilities are more evenly distributed, competition in the international system is especially fierce. In such environments, as states find themselves on a more even footing to compete for influence, the form and outcomes of disputes become harder to predict. 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 in the first place. In both cases, a higher number of contenders for international influence increase states' marginal utility of increased technological capabilities.

As with firms in market economies, a larger number of powerful actors have a harder time coordinating against third parties to increase their profits. If power is concentrated in a few countries, vested interests may, for instance, find it easier to coordinate to slow down the pace of technology adoption, securing protection for industries which otherwise might be made obsolete by technological development and imports. 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 case, states can afford to forgo individual benefits from selling technology to maintain their collective technology edge. In both situations, the concentration of power in the system means competitive pressures are diminished.

The induced need for more capabilities, especially the need to be *relatively* capable, is very strong in more competitive environments. An international system with less concentrated power capabilities is more competitive and hence more likely to impel leaders to relinquish policies that limit adoption or use of new technologies and to implement policies that promote such adoption. This has two consequences: during times of low system concentration, new technology is (1) more likely to be utilized more intensely, and (2) adopted at a faster pace.

This suggests our first two hypotheses:

- *Hypothesis 1: The less concentrated power capabilities are in the international system, the more intensely new technology is adopted and utilized.*

- *Hypothesis 2: Declining systemic concentration should lead to faster technology adoption. Increasing systemic concentration should lead to slower technology adoption.*

We thus propose that periods of more evenly distributed capabilities in the international system should be associated with more rapid technological change.

We furthermore propose that in the short term, this relationship is unidirectional and causal: changes in the international system precede and impel changes in government policies. Importantly, we do not suggest that the effect is one-way over longer periods of time: we indeed propose that the two are related precisely because states see changing their ability to interact with their international environment through technology adoption as a viable strategy. We instead argue that in the short term, countries' technology policies respond to changes in the international system, rather than the other way around.

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

While our theory is motivated by the aforementioned scholarship, the relationship we propose has been extensively investigated among firms. As we argue is the case for the international system, investigations of firms find a positive relationship between more competitive industries and technology adoption (for a review, see Holmes and Schmitz (2010)). While the concentration ratio of an industry is related to the economic incentives for and ease of adopting specific production technologies, investigations of technology broadly, such as ICTs, find that industry concentration is negatively related to adoption (e.g. Arduini and Zanfei (2010)). We are the first to suggest such a link between technology adoption and the international system, and provide the first IR theory of global technology waves, specifying exactly when and under what conditions we may see international diffusion of technology speed up world-wide.

EMPIRICS

International technology diffusion phenomenon has been approached 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. Lastly, and especially recently, researchers have directly tracked both the extent and intensity of technology adoption (e.g., number of radios per capita).

We 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.

This investigation is the first to systematically tests 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.

In addition to our quantitative analysis, we investigate how changes in the international system surrounding the unification of Germany led to increased new technology use. This illustrates our causal mechanism, by which calculations about the structure of the international environment make political leaders initiate policies which either slow down or accelerate the adoption of technology. Relying on primary and secondary documents from the countries in question, 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 new technologies.

Data

Measuring International Technology Diffusion 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 over 100 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. 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.

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

Technology Adoption: The log of the number of technology units per capita per year per country.

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 leader begins to decline. This ensures that, for example, sending fewer telegrams after the telephone is invented is not seen as adoption failure.[4]

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 four different measures of system concentration on a yearly basis, providing us with results insensitive to the way concentration is calculated.

The first measure is the popular "system concentration" score frequently used in studies of international politics, wherein a higher score means capabilities are more concentrated.

[4]In the appendix, we include a figure showing which years different technologies are included in our analysis, and in our robustness checks, we explore different technology types.

System Concentration (Syscon) - Measure from Singer et al. (1972). This is defined as:

$$\text{Concentration}_y = \sqrt{\frac{\sum_{i=1}^{n}(S_{y,i})^2 - \frac{1}{n}}{1 - \frac{1}{n}}} \tag{1}$$

Where y denotes the year, and $S_{y,i}$ is the share of power resources held by state i in year y, there being n states total. More concentration means less competition so we expect a negative relationship with international technology diffusion.[5]

Our next two measures are from the economics literature on competition among firms and industry concentration.

C4, C10 index - Proportion of power resources (CINC) controlled by the top four and top ten countries, respectively. These measures are widely used in industrial economics to assess market concentration.

The final measure looks at the number of great power coalitions possible at any time. It increases as the number of great powers grow or these become more equal in strength, and hence a larger number means less concentration, and thus us to expect more technology diffusion.

Number of Viable Great Power Coalitions - The number of possible great power coalitions which satisfy two criteria: the coalition (1) controls at least 50 percent of great powers' resources (CINC), and (2) no member of the coalition is superfluous to doing so.[6]

Control Variables Other studies of technological diffusion have identified several important factors that might independently affect a country's adoption level. War, both international and civil, is among these because they divert and destroy resources states use to adopt technology. In addition some research claims that domestic politics matters greatly and that regime type is especially important (Comin and Hobijn 2009a; Comin et al. 2013). We therefore include these as known predictors (we explore a range of additional specifications in our robustness checks).

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

[5]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. Our approach is in line with Ray and Singer (1973, 405), who stress that an index should reflect researchers theoretical concerns.

[6]We follow the Correlates of War Project's time-varying categorization of states as major and lesser powers.

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)

In the appendix, we include figures plotting the technology-year and country-year coverage of our analysis. Table 1 provides summary statistics. In online appendix table 40, we provide results using imputed data. Many additional robustness checks are detailed below.

In seeking to explain the pace of technology diffusion, including measures of gross domestic product (on an annual or annual per capita basis) as a predictor would bias our estimates. The reason is that 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 tables with GDP per capita estimates included as a predictor as expected reduces the magnitudes of our effects, but all relationships remain significant and in the expected direction (full results for all four systemic measures reported in online appendix tables 18-19).

Quantitative Estimation Strategy

We investigate technology adoption both at the technology-country-year and systemic level. This allows us to incorporate country-technology information and explicitly link international system characteristics with global technology waves, respectively. All regressions are ordinary least squares.

To test hypothesis 1 at the country-technology-year level, we estimated equations of the form:

$$Y_{c,t,y} = X_{c,y}\beta_1 + Z_y\beta_2 + \alpha_{c,t} + \epsilon_{c,t,y} \quad (2)$$

Where $Y_{c,t,y}$ is technology adoption level per capita at the country-technology-year level, $X_{c,t}$ are country and time varying covariates, Z_y are systemic variables that change over time, $\alpha_{c,t}$ is a full set of country-technology fixed effects, and $\epsilon_{c,t,y}$ is the standard error term.

The coefficients for our systemic variables capture the extent that changes in their level are linked to the level of new technology adoption. The inclusion of country-technology fixed effects means that we account for all time-invariant country-technology effects, while including year since invention captures the general trend of technology use increasing over time.[7]

To test hypothesis 2, we estimated equations of the form:

$$\Delta Y_{c,t,y} = \beta_3 + X_{c,y}\beta_4 + Z_y\beta_5 + \epsilon_{c,t,y} \tag{3}$$

We here see if the rate of change in adoption level can be related to higher or lower system concentration, with our theoretical expectation being that technology use increases faster when system concentration is lower. Since these changes are on a within-country-technology basis and the models include an intercept, we do not include country-technology fixed effects and years since invention as predictors.

We also tested hypothesis 1 and 2 at the systemic level through univariate regressions. We here utilized the 3- and 5-year means of residuals of a linear model in which country and technology as well as a linear time trend are included as predictors to avoid bias from the entry of new series in the data.[8] Using this world-technology measure, we also conducted placebo tests. To make the latter as informative as possible by mimicking our system concentration measures closely, our placebo measures were constructed by splitting our Syscon measure into 10 sections of equal length and then re-combining it arbitrarily. To ensure results were not driven by the selection of one particularly “unlucky" combination, we used a different combination for each placebo test.

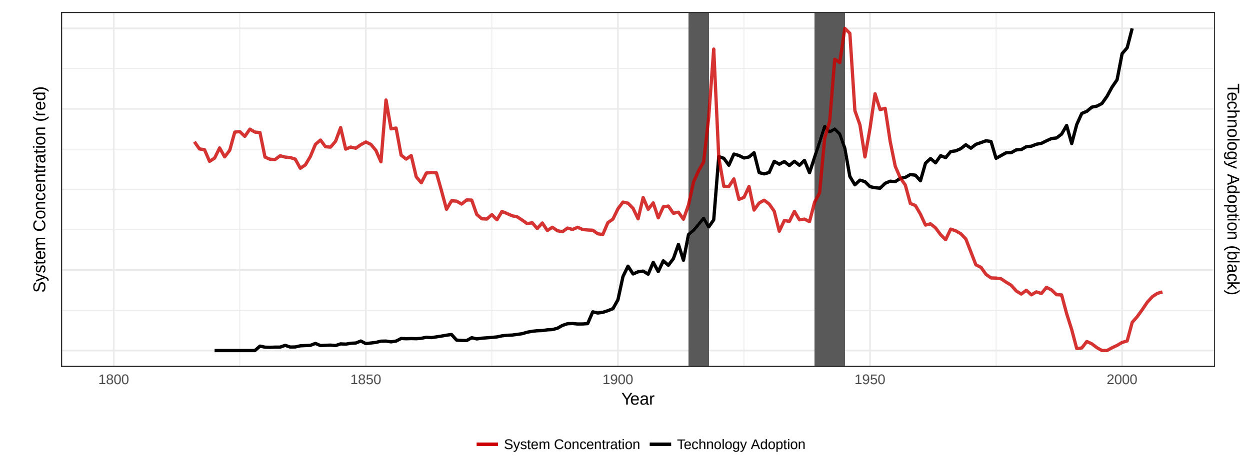
We finally tested if there exists a temporal relationship in line with hypothesis 3 by conducting a series of Granger Causality tests. We here again constructed a yearly series of technology adoption across all countries and technologies.[9] We then constructed an alternative set of system concentration 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. We then tested if in either set: (a) technology adoption

[7]In combination with country-technology fixed effects this is mathematically equivalent to a linear time trend.

[8]In columns three and five, we additionally include Polity2, war and civil war as known predictors. Results were stronger if we did not demean by country and technology nor include a linear time trend.

[9]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.

FIGURE 2. System Concentration and trends in per capita Technology Adoption Level over time. Measures have been rescaled to be between zero and one.



was Granger-caused by changes in the international system and/or (b) Granger-caused changes in the international system.[10] We did this both with and without covariates, and with a variety of year lags.

TABLE 1. Summary Statistics

Statistic	N	Mean	St. Dev.	Min	Max
Log (Technology Units Per Capita)	99,236	2.304	3.794	0.000	17.255
Syscon (Singer 1972)	24,725	0.294	0.041	0.222	0.413
Number of Viable Great Power Coalitions	24,725	7.041	4.972	1	16
C10 (Concentration Index)	24,725	0.761	0.121	0.576	0.930
C4 (Concentration Index)	24,725	0.548	0.083	0.398	0.733
Polity2 Score	16,825	−0.597	7.066	−10	10
At War in previous year (0, 1)	23,631	0.032	0.175	0	1
Civil War in previous year (0, 1)	23,631	0.039	0.193	0	1

Note: N refers to observations at the country-year level for all except technology units.

RESULTS

In figures 2-4, we plot country-demeaned global technology adoption levels and various measures of system concentration over time. These suggest the plausibility of an inverse link between concentration and technology adoption.

[10]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 3. Proportion of resources (CINC) held by the top 10 states and trends in per capita Technology Adoption Level.

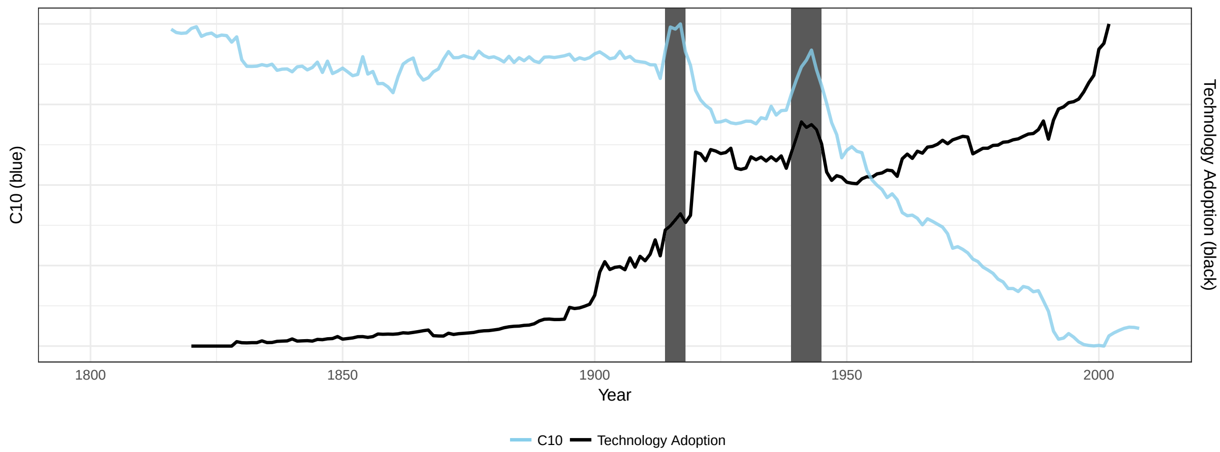


FIGURE 4. Viable Great Power coalitions and trends in per capita Technology Adoption Level. Note the spikes immediately preceding the two world wars (16 possible coalitions), and following the end of the Cold War.

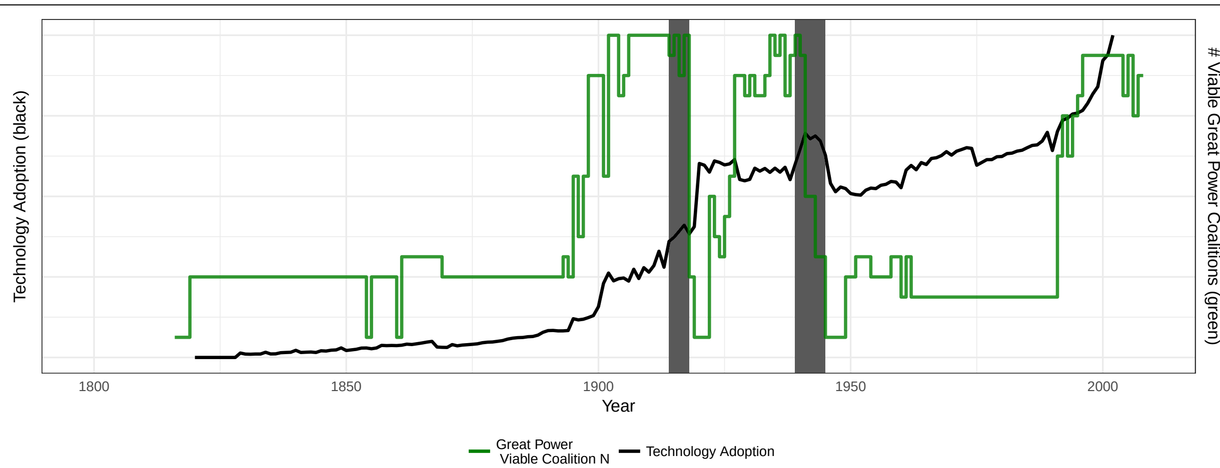


TABLE 2. Intensity of Technology Adoption and Systemic Factors (1820-2008)

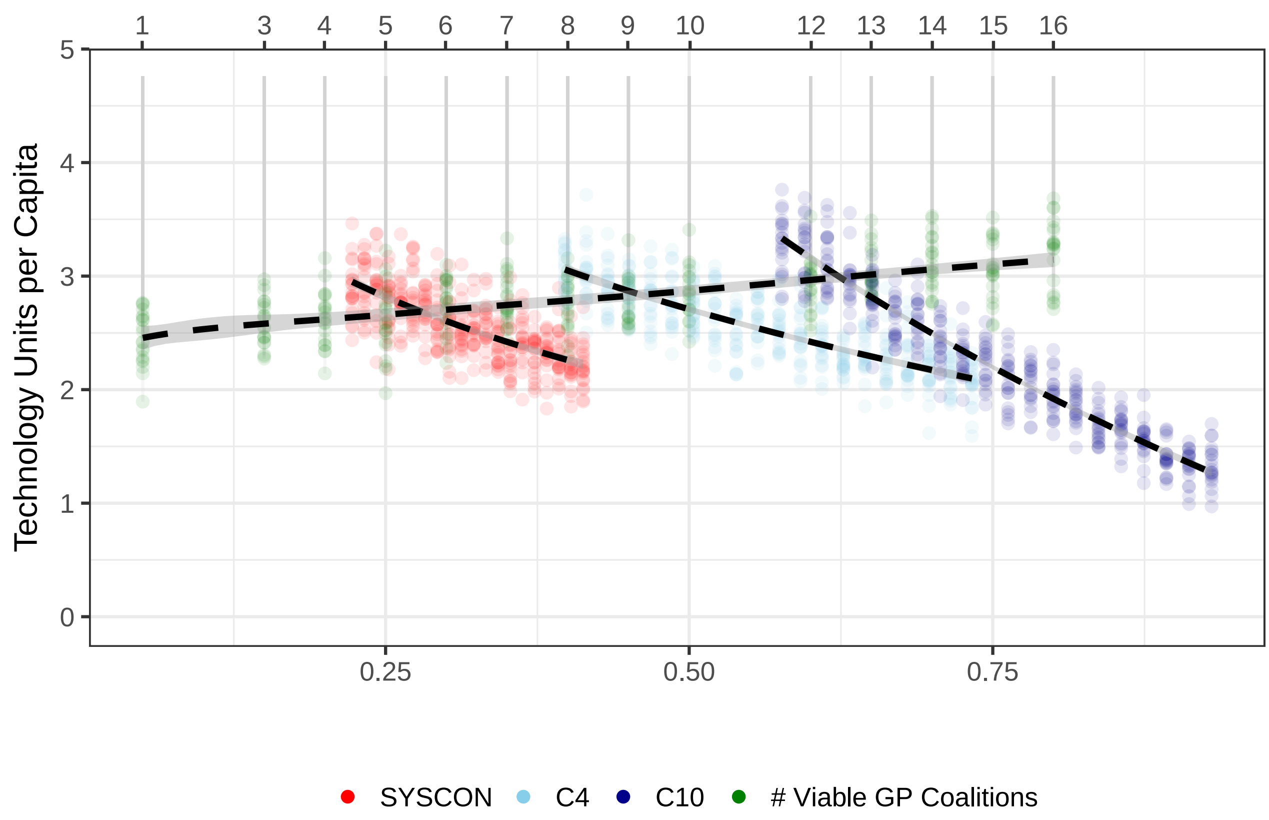
	Dependent variable:			
	Technology Adoption Level			
	(1)	(2)	(3)	(4)
Syscon (Singer 1972)	−0.990**			
	(0.482)			
Viable Great Power Coalitions		0.015***		
		(0.003)		
C4			−0.860***	
			(0.326)	
C10				−1.990***
				(0.468)
Polity2 score	0.007***	0.003	0.007**	0.007***
	(0.003)	(0.003)	(0.003)	(0.003)
War (lagged one year)	−0.064**	−0.076***	−0.060**	−0.046*
	(0.027)	(0.027)	(0.027)	(0.026)
Civil War (lagged one year)	−0.077***	−0.073**	−0.079***	−0.088***
	(0.030)	(0.030)	(0.029)	(0.030)
Years since invention	0.021***	0.022***	0.020***	0.016***
	(0.001)	(0.001)	(0.001)	(0.002)
Constant	−0.648*	−1.033***	−0.348	1.305**
	(0.339)	(0.208)	(0.395)	(0.611)
Country-Technology FE	Yes	Yes	Yes	Yes
Observations	90,268	90,268	90,268	90,268
R^2	0.960	0.960	0.960	0.960
Adjusted R^2	0.958	0.959	0.958	0.959
Residual Std. Error (df = 87806)	0.776	0.773	0.776	0.774
F Statistic (df = 2461; 87806)	846.499***	852.549***	847.171***	850.521***

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

TABLE 3. Rate of Change in Technology Adoption and Systemic Factors (1820-2008)

	Dependent variable:			
	Change in Technology Adoption Level			
	(1)	(2)	(3)	(4)
Syscon (Singer 1972)	-0.381^{***}			
	(0.028)			
Viable Great Power Coalitions		0.004^{***}		
		(0.0002)		
C4			-0.234^{***}	
			(0.016)	
C10				-0.179^{***}
				(0.012)
Polity2 score	0.001^{***}	0.0001	0.0005^{***}	0.001^{***}
	(0.0002)	(0.0002)	(0.0001)	(0.0001)
War (lagged one year)	0.001	-0.007^{**}	0.001	−0.001
	(0.003)	(0.003)	(0.003)	(0.003)
Civil War (lagged one year)	-0.011^{***}	-0.007^{*}	-0.012^{***}	-0.012^{***}
	(0.004)	(0.004)	(0.004)	(0.004)
Constant	0.145^{***}	0.015^{***}	0.158^{***}	0.164^{***}
	(0.008)	(0.001)	(0.009)	(0.009)
Observations	86,803	86,803	86,803	86,803
R^2	0.014	0.020	0.018	0.018
Adjusted R^2	0.014	0.020	0.018	0.018
Residual Std. Error (df = 86798)	0.134	0.133	0.134	0.134
F Statistic (df = 4; 86798)	312.283^{***}	446.290^{***}	403.288^{***}	393.975^{***}
Note:	*p<0.1; **p<0.05; ***p<0.01			
	(Country-Technology-Clustered Standard Errors in Parenthesis)			

FIGURE 5. Substantive Effects I - The International System and Technology Adoption

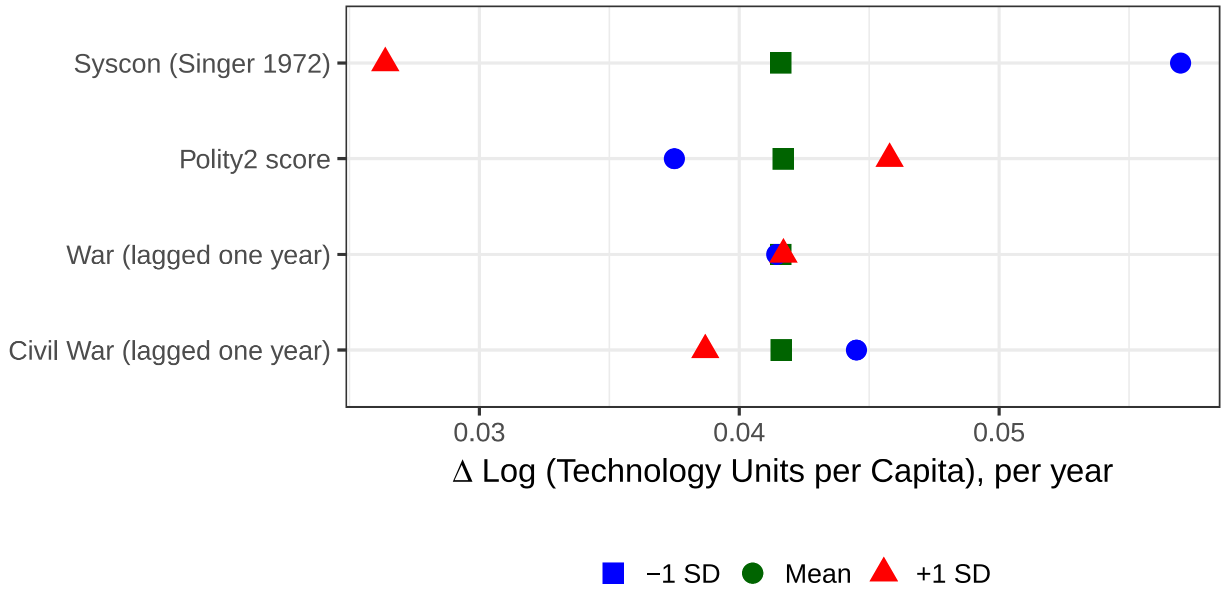


Testing these relationships in table 2 and 3, we find clear links between lower concentration and faster and more intensive use of technology. For both the intensity of new technology use and pace of new technology adoption, there is an inverse and statistically significant relationship between our four measures of system concentration and technology adoption.

In line with our expectations, we also find that civil war tends to have a negative effect on technology adoption, while the relationship between interstate war and technology adoption is less clear. There seems to be some 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.

The magnitude of these effects is very large. In Figure 5, we simulate and then plot the expected level of technology adoption per capita for different values of our systemic variables (following the approach in King et al. 2000). The scale on the bottom horizontal axis is for the three concentration indexes, while the top horizontal axis represents the number of viable coalitions. The range of the

FIGURE 6. Substantive Effects II - The International System and Technology Adoption



systemic variables is in all cases equal to that observed in the data. The points represent expected values of technology units per capita for a given level of our independent variables based on simulations.

In Figure 6 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 200 simulations each). 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 5.7 percent per year (≈40 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 6, 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.

For perspective, consider how a change in the international system can be related to world levels of technology adoption. A one standard deviation downward shift in system concentration in 1960 is related to an expected additional 60 thousand railroad kilometers, 8 million telephones, 9 million radios, *and* 6 million cars in operation: a clear technology wave.

In table 4, we examine our argument at the systemic level. The table summarizes the results of twenty univariate regressions linking our system concentration measures and one placebo system trend to global trends in technology adoption. In all but one case, lower concentration measures are statistically significant predictors of faster technology adoption at the systemic level, whereas in no case is this true for our placebo measures.

We 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,

TABLE 4. Systemic Tests: World-Wide Technology Adoption and System Concentration

	Δ Log (Tech. Adoption p.c.), World-wide			
	Next 3 years	w/ covariates†	Next 5 years	w/ covariates†
System Concentration	−0.14* (-0.32, 0.03)	−0.13* (-0.26, 0.004)	−0.22* (-0.51, 0.03)	−0.22* (-0.46, 0.008)
Viable Great Power Coalitions	0.002*** (0.001, 0.003)	0.001** (0, 0.002)	0.003** (0.001, 0.005)	0.002*** (0.001, 0.003)
C4	−0.10*** (-0.18, -0.02)	−0.08*** (-0.16, -0.02)	−0.16*** (-0.3, -0.02)	0.17*** (-0.28, -0.04)
C10	−0.05* (-0.1, 0.01)	−0.07*** (-0.1, -0.02)	−0.07 (-0.17, 0.02)	−0.09*** (-0.18, -0.02)
Placebo system trends	0.02 (-0.01, 0.05)	0.02 (-0.02, 0.05)	0.007 (-0.08, 0.10)	0.003 (-0.02, 0.09)
N	186	186	184	184

This table summarizes the results of 20 univariate regressions at the world level, with DV indicated by column and IV by row. Statistical significance and 95 confidence interval (in parentheses) as obtained by bootstrap (B = 1000).

†*Accounting for the effects of war, civil war (both lagged one year), and polity2 via linear model before collapsing change in technology adoption to the system-year level.*

*p<0.1; **p<0.05; ***p<0.01

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 5, 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 above for the first time. In our event study below, we investigate and provide evidence of a causal relationship between the two.

Robustness Checks and Interaction Effects

We conduct a large number of checks to assess the robustness of these findings, which we summarize here.[11]

To see if the relationships established in table 2 and 3 are driven by general productivity trends, we estimate our models with GDP per capita included as a known predictor (online appendix, table

[11]Full tables and replication code for all work is provided in the online appendix (o.a.)

TABLE 5. 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

18-19). This shows that even conditioning on general productivity levels, states adoption of technology can be linked to the international system. We construct a measure of countries' spatial distance to technology use in other countries on a within-technology basis, adding this as a control to consider if these systemic trends are driven by emulation (o.a. table 4-7). We add separate intercepts by technology type (using both our own classification and the classes suggested in Comin et al. (2013) - Industry, Communications, and Transport, o.a. table 53-56). To further alleviate concerns about different technologies, we also provide these latter and our main specification models with normalized measures of adoption in which all technologies' adoption levels have a standard deviation equal to 1 (o.a. table 57-60).

To alleviate concerns about coverage and non-random patterns in missingness, we also replicate our analysis with imputed data (o.a. table 40-41). We also replicated our analysis with a binary democracy variable rather than Polity2 (from Boix, Miller and Rosato, 2009, o.a. table 73-74).

In all aforementioned cases, all measures of system concentration remain negatively related to technology adoption at statistically significant levels ($p < 0.01$), and in all but the imputed data case, the number of viable coalitions is positively and statistically significantly related to more technology adoption.

Other evidence further alleviates our concern about a spurious link between the international system and technology waves. Using countries' spatial distance to (other countries') technology adoption, we not only find that low system concentration continues to be a significant predictor of technology adoption once but that there tends to be a significant interaction effect: low system concentration makes states respond stronger to other countries' adoption (o.a. table 51-52).

We also leverage our different technology types to shed light on the system competitiveness-technology link. Specifically, not all technologies are equally beneficial to states ability to compete in the international system and thus likely to be adopted at a faster rate when system concentration is low. We expect one of our technologies to be an outlier: televisions per capita. Not only do we find that dropping observations of this technology increases the magnitude of our effects, but we find there is a negative interaction effect, whereby states *slow down* their adoption of televisions when system competitiveness is high (o.a. table 10-11, 62-63).

We also replicated our tables with measures of concentration and viable coalitions 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 43-44). Results were also unchanged when we estimated our models using only observations from the 20th century (o.a. table 76-77). We also estimated models in which system concentration for country *i* was calculated using data on all countries except *i*, o.a. table 43-44). Results were here too unchanged.

We also considered alternative measures of system characteristics thought to relate to competition. We calculated the world-wide number of wars, militarized interstate disputes (MIDs) with fatalities, and proportion of countries in MIDs (o.a. tables 8-9). While these are unable to capture systemic characteristics related to level of competitiveness generally, they are useful as direct measures of the manifested level of violent international competition. We find that both new technology use and pace of adoption is positively related to more conflictual systems.

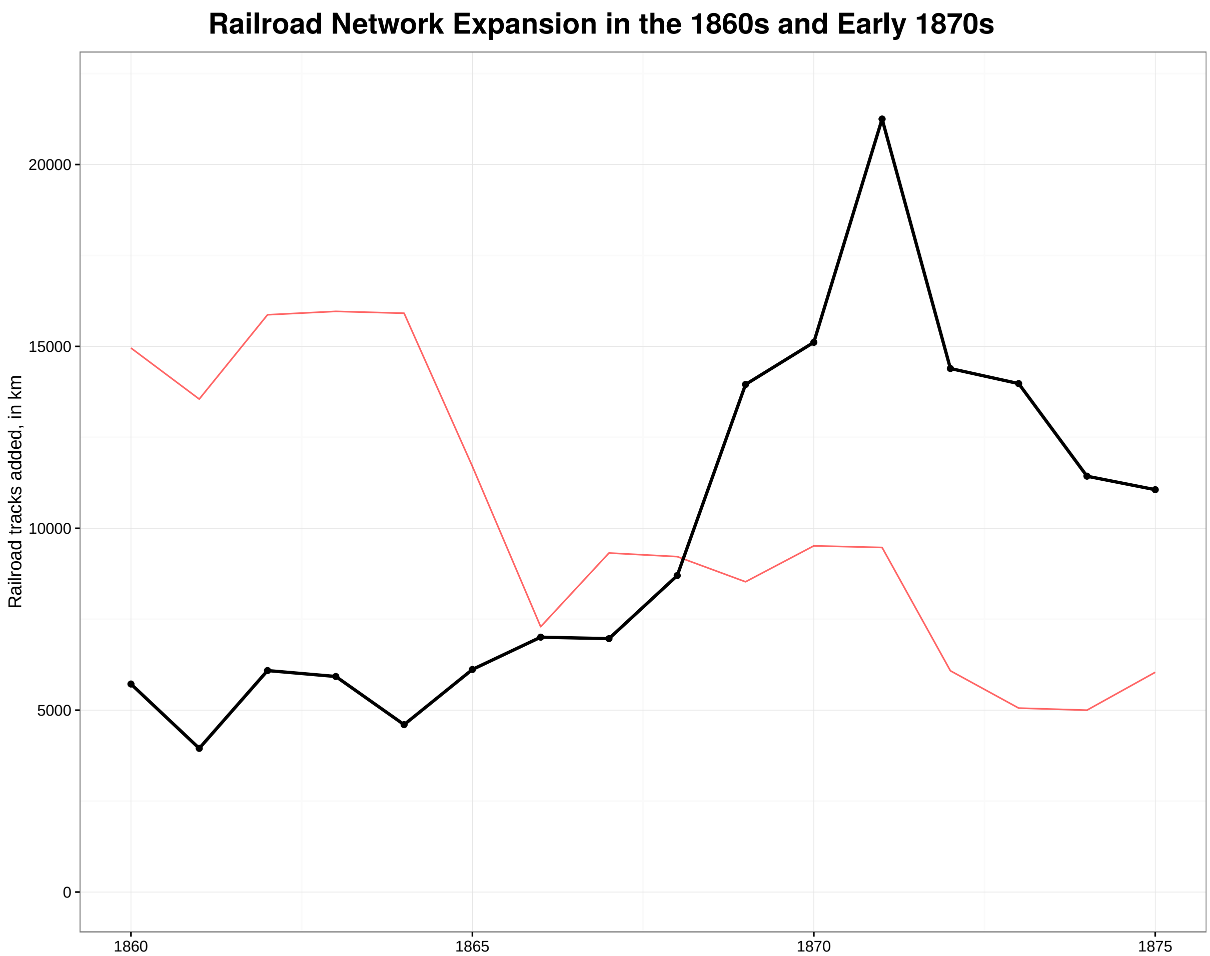
These estimations suggest robust links between international system concentration and the pace of international technology diffusion. As our Granger causality tests show, there is also evidence of a temporal relationship, wherein changes in international system characteristics precede changes in world-wide technology adoption.

We next investigate if changes in the international environment can be causally linked to new government policies facilitating technology adoption.

Event Study: The Technological Revolution

In this section, we examine our claims about systemic competition and technology adoption by considering the period surrounding the unification of Germany and the Franco-Prussian War. We focus on this period because it is one in which systemic competition increased as new powers arose. We do not provide a comprehensive treatment of these phenomena or the technological revolution, but briefly introduce the latter and assess the motivations of some policymakers in this period as they decided whether to implement policies which would facilitate the adoption of new technology.

FIGURE 7. Global railroad network expansion per year in black, and system concentration in red (smoothed and rescaled for exposition). The pace of railroad network expansion tripled in the period 1860-1870.



The late 1860s or 1870 is usually cited as the start of the “Second Industrial Revolution" (Geddes 1915, Landes 1969), sometimes called the “Technological Revolution". In the words of Mokyr (1998, 2):

> *The second Industrial Revolution turned the large technological system from an exception to a commonplace. Systems required a great deal of coordination that free markets did not always find easy to supply, and hence governments or other leading institutions ended up stepping in to determine railroad gauges, electricity voltages, the layout of typewriter keyboards, rules of the road, and other forms of standardization.*

As Mokyr emphasizes, technological change in this period cannot be ascribed to the sudden availability of new technology, information about its usefulness, or private financing. Rather, it was related to actions taken by government actors who coordinated and facilitated the adoption of existing technology systems. Governments at this time incurred massive costs investing in technologies such as the telegraph, steamships, and railroads. An account of this global technology wave must explain this change in states’ behavior.

Investigating the government’s role in bringing railroads to Denmark and Sweden, we find that the timing of policies cannot be ascribed to the potential economic or military benefit being recognized (in both cases known earlier), or that government efforts simply provided support to the private sector. Rather, changes towards a more competitive international system *caused* governments to initiate these policies because they thought they would strengthen their position. They believed that these policies were important in accelerating their nation’s adoption of the technology, which would help them in this more competitive international environment. Finally, pressures from the international system also led them to continue and expand these policies once implemented.

In Denmark, the potential of railroads for defense use had been discussed within parliament and the military general staff since at least the mid 1830s (see e.g. Stiernholm 1854). Negotiations with private entrepreneurs throughout the 1850s resulted in a 1859 agreement in which the state was only willing to supply an interest rate guarantee for a single line.[12] This can be contrasted with the 1860s, when the

[12]When parliament supplied an interest guarantee for an extension of the Copenhagen-Roskilde line to Korsor in 1852, it was not without controversy: a 16-page dissent argued that even though railroads could have military and

government acted decisively and invested massive amounts of its own money to expand Denmark's railroads, with total network length increasing from 131 km in 1860 to 1477 km in 1875. Why this sudden shift in policy?

Analyzing the 1861 decision to fund the Funen railroad, Fransen (2015, 14) writes:

> *The schemes [for a Funen railroad] presented in the beginning of the 1850s were deemed too expensive by politicians, who were wary of binding themselves to a proposal.* ***But as the international tensions in Europe grew****, and the English-oriented factions strengthened,* ***the pressure to commit to a project increased****.* [Our translation and emphasis.]

As Mokyr highlights, the role of the state in facilitating the spread of technology systems was crucial. In Sweden, railroads would cut freight rates by more than half, and travel speeds by nine tenths (Sjoberg 1956). Yet attempts to bring railroads to Sweden by mobilizing private capital 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 (Oredsson 1969, 52-56). 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 railway companies issued abroad" (Kildebrand 1978, 606).

In Sweden the 1860s would be the core of a "first wave" of railroad expansion, with another burst of state construction from 1871 onward (Berger and Enflo 2017). Events such as the 1848 Prussian excursion into Denmark and the Crimean War had changed the context for Swedish foreign policy, and "during the [parliamentary session] of 1853 and 1854 the relations of Sweden with foreign powers again came to the foreground" (Cronholm 1902, 280). It was during this session that initial allocations toward railroad construction were made (at this point debated for nearly a quarter-century), by its proponents framed in explicitly geo-political terms. Andersson-Skog (p. 38 1993, our translation) states it thus: "that defense interests contributed to the decision to establish [railroad] trunk lines is clear beyond any doubt." (See also Oredsson 1969, 47, 71).

economic use, the suggested project was too expensive by far, had problematic distributional implications, and was not right for Denmark which it argued should rely "on sail and steamship" (see Danmarks Rigsdag, 617-633).

Swedish government capital outlay was massive. By 1868, the state had provided 83.4 million kronor (compared to private investment of 30.5 million), by 1880: 185 million, and 61 million kronor worth of railroad products had been imported from abroad. For context, *total* government revenues in 1860 was 36 million kronor.

The increased government efforts to facilitate the adoption of railroads was a broad trend, not restricted to these countries but was related to increasing international competition (see Figure 7). As summarized by railroad historian Oredsson (1969, 28, our translation):

> *In the history of the 19th century, 1870 was in many ways a crucial year. The foreign-policy climate had hardened after the Franco-Prussian war. The great powers sought allies, armaments reached unprecedented levels, and nationalist ideas supplanted the cosmopolitan ideas of the early 1800s... The trend in the 1870s towards state lines and increased state intervention in railroads must be seen in the context of the broader political developments in an industrializing world.*

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.

Pursuing a two-pronged research strategy serves to alleviate concerns with either approach in isolation. Our large-N analysis indicates a relationship between technology diffusion 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. We next investigate and find that changes in the international system in the latter half of the 19th century indeed led to policies which shaped states' adoption of technologies.

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 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. It is hard to think of such variables.

It is difficult to cleanly 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, robustness checks with country-specific concentration scores (excluding the contribution of their own capabilities), and case study can provide clarification about causal relationships in the short and medium term, in which the competitiveness of the international environment drives adoption decisions.

We consider one case in which the international system changed (1860s), and link this change to decisions to pursue policies seen as integral to the this “technology wave." Future work ought to consider the technology waves of the 1890s, 1960s and 1990s, and establish whether policies pursued at these times similarly were linked to concerns about a more competitive international environment. These concerns could be linked to the distribution of capabilities, or to changes in strategy or doctrine that changed levels of competitiveness in the system (e.g., in Germany following Bismarck and Moltke the Elder's retirement, or the "new look" of the Kennedy administration, and China's realignment during the Cold War).

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." Systematizing ideas from IR scholars, we claim 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 diffusion 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 when the international system changed in the 1860s and 1870s, 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. They also further evidence how important government policy can lead to technology adoption.

We thus contribute to the study of IR 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. We are the first to do so for many countries and using direct measures of technology use. 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. Our study demonstrates novel and robust relationships which are large in magnitude.

Third, while some scholars view a more concentrated international system–one of bipolarity (Waltz 1979) or hegemony (Kindleberger 1973) –as most desirable, we show that a more diffuse system may lead to better outcomes with regards 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, and we 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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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. ***Details:*** **Blue indicates observation (that is, at least one country) in technology-year, with darker blue indicating more observations (multiple countries).**

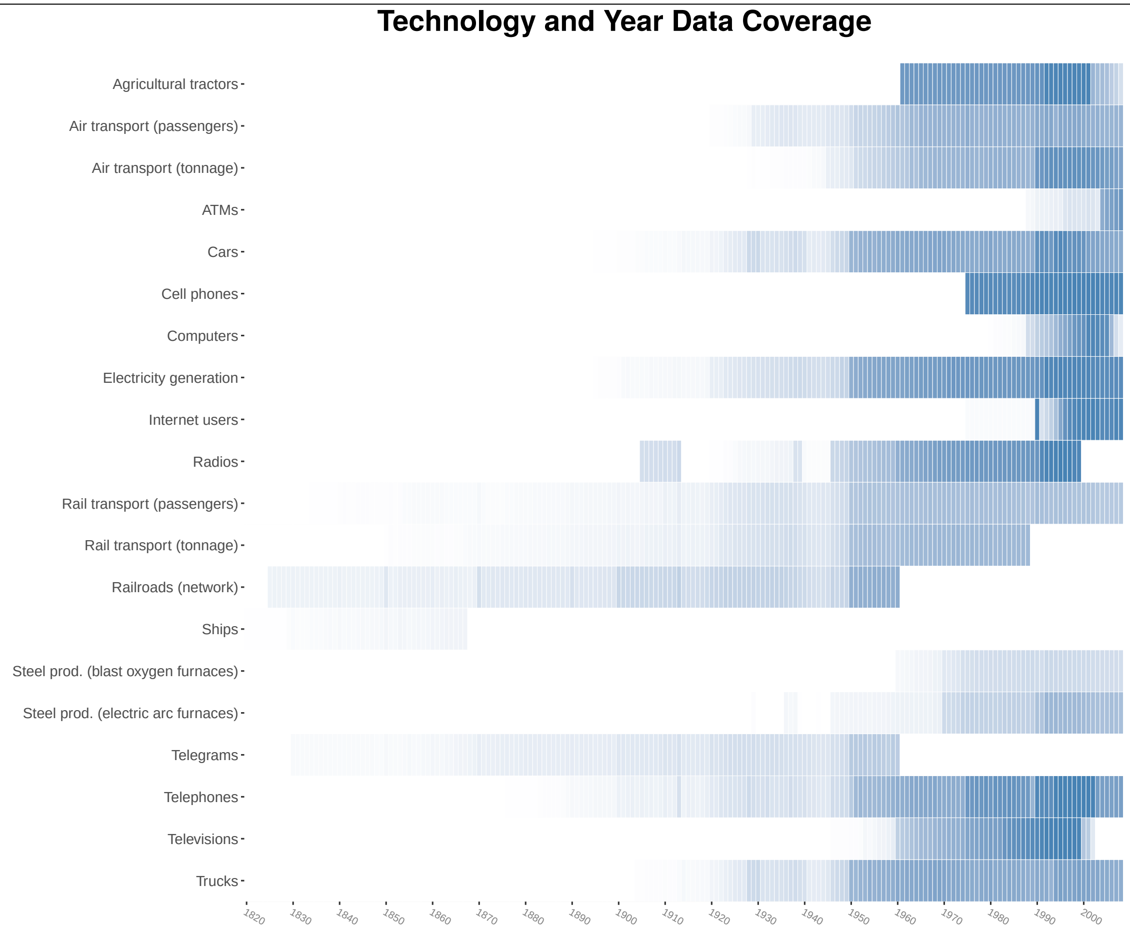

FIGURE A.2. ***Details:*** **Blue indicates observation (that is, data on all model variables and at least one technology) in country-year, with darker blue indicating more observations (multiple technologies). Gray cells are years before the country became an independent state. There are more observations 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.**