Distance to the Pre-industrial Technological Frontier and Economic Development

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October 2016

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February 19, 2018

Abstract

This research explores the effects of distance to the pre-industrial technological frontiers on comparative economic development in the course of human history. It establishes theoretically and empirically that distance to the frontier had a persistent non-monotonic effect on a country's pre-industrial economic development. In particular, advancing a novel measure of the travel time to the technological frontiers, the analysis establishes a robust persistent U-shaped relation between distance to the frontier and pre-industrial economic development across countries. Moreover, it demonstrates that countries, which throughout the last two millennia were relatively more distant from these frontiers, have higher contemporary levels of innovation and entrepreneurial activity, suggesting that distance from the frontier may have fostered the emergence of a culture conducive to innovation, knowledge creation, and entrepreneurship.

Key Words: Comparative Development, Geographical Distance, Culture and Technology, Innovation, Technological Diffusion and Imitation, Patenting Activity, Entrepreneurship
JEL classification: F15, F43, N70, O10, O31, O33, Z10

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*I wish to thank wish to thank two anonymous referees, an associate editor, the editor, Quamrul Ashraf, Dror Brenner, Carl-Johan Dalgaard, Klaus Desmet, Ruben Durante, Martin Goetz, Peter Howitt, Ross Levine, Glenn Loury, Stelios Michalopoulos, Dan Millimet, Elias Papaioannou, Yona Rubinstein, Dietrich Vollrath, Romain Wacziarg, and David Weil; as well as participants at the Spatial Structures in the Social Sciences Summer School, the EconCon conference at Princeton University, the NBER Macroeconomics and Income Distribution Summer Institute, and Warwick University's Summer School in Economic Growth; and seminar participants at Brown University, El Colegio de México, Southern Methodist University, the World Bank, University of Houston, and Universidad Nacional de Colombia for comments and helpful discussions.

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1 Introduction

The origins of comparative economic development across the world has been one of the most fundamental research agendas in the social sciences. The literature on the subject has focused on deep determinants such as geographical, institutional, cultural and human characteristics (Diamond, 1997; Acemoglu et al., 2001; Guiso et al., 2009; Alesina et al., 2013; Ashraf and Galor, 2013; Galor and Özak, 2016). In particular, given their adverse effect on trade and technological diffusion, geographical isolation and distances to the technological frontier have been widely viewed as fundamental sources of the prevailing inequality among countries (Smith, 1776; Redding and Venables, 2004; Feyrer, 2009; Spolaore and Wacziarg, 2009; Ashraf et al., 2010). This conventional view is based on the fundamental role trade plays in the diffusion of technology and in creating economies of scale in the contemporary era. However, given the limited scope of trade in the pre-industrial era, the conventional channels through which distance could have generated negative effects on productivity, may not have been significant.

This research explores the effects of distance to the pre-industrial technological frontiers on comparative economic development in the course of human history. It proposes that during the pre-industrial era, while a country's remoteness from the frontier diminished imitation, it fostered the emergence of a culture conducive to innovation, knowledge creation and entrepreneurship, which may have persisted into the modern era. The contribution of these cultural values to productivity have counteracted the adverse effect of distance from the frontier via diminished technological diffusion. Thus, the theory proposes that the interaction of these opposing forces resulted in a U-shaped relation between economic development and the distance to the frontier in the pre-industrial era.

In line with the predictions of the theory, the analysis establishes both theoretically and empirically that distance to the frontier had a persistent non-monotonic effect on a country's pre-industrial level of economic development. In particular, advancing a novel measure of the travel time to the technological frontiers, the analysis establishes a robust persistent U-shaped relation between distance to the frontier and pre-industrial economic development across countries. Moreover, it demonstrates that countries, which throughout the last two millennia were relatively more distant from these frontiers, have higher contemporary levels of innovation and entrepreneurial activity, suggesting that distance from the frontier may have fostered the emergence of a culture conducive to innovation, knowledge creation, and entrepreneurship.

The proposed theory suggests that variations across countries in distance to the pre-industrial technological frontier generated differences in incentives for technological imitation, adaptation and innovation, which culminated in differences in innovative and entrepreneurial culture. In particular, since during the pre-industrial era, the usefulness and transferability of technologies decreased with the distance from the technological frontier, distant countries benefitted less from imitation and had to tinker and toil more in order to adapt existing technologies to their own environment. Additionally, geographically distant countries also tended to be culturally different from the frontier, which may have facilitated the application of existing technologies to uses not discovered or intended by the original innovators. Finally, for some countries the process of technological diffusion from the frontier may have been too slow or costly, which may have promoted the generation of native innovations. Thus, these forces diminished the usefulness and availability of foreign technology and increased the incentives for native innovation that distant countries faced. While all countries might have been imitating, adapting and innovating, the degree to which each activity was pursued was affected by their geographical location with respect to the frontier. Moreover, as successive generations faced similar incentives, a process of intergenerational learning-by-doing in the creation of knowledge may have reinforced this pattern of specialization, facilitating the emergence of an innovative and entrepreneurial culture.

The proposed theory generates several testable predictions regarding the effect of distance to the pre-industrial technological frontier on economic development across countries. First, the theory predicts the existence of a U-shaped relation between the distance to the frontier and economic development across countries in the pre-industrial era. Specifically, the theory suggests that during the pre-industrial era, countries located at intermediate distances from the technological frontier were less developed than countries closer to or more distant from it, making these intermediate distances the Least Desirable Distances from the technological frontier. Second, the theory suggests that increases in a country's distance to the frontier (e.g., due to a change in the location of the frontier) should have positively impacted its level of economic development, especially among countries that were distant. Third, the theory predicts that the more time a country was farther than countries located at the bottom of the U-shape, i.e., at the More Desirable Distances, the longer it benefitted from its incentives to imitate, adapt and innovate. Thus, the cumulative time a country spent at these distances (across technological frontiers in the pre-industrial era) should be positively associated with its level of development. Finally, the theory suggests that the more time a country was remote from the frontier, the longer it experienced conditions that may have facilitated the emergence of an innovative and entrepreneurial culture. Thus, the cumulative time a country spent at the More Desirable Distances (across technological frontiers in the pre-industrial era) should be positively associated with its innovative and entrepreneurial activities in the contemporary era.

To explore these predictions empirically, the research introduces a novel measure of the pre-industrial geographic distance between countries and pre-industrial technological frontiers. For each country, this measure estimates the potential minimum travel time to the pre-industrial technological frontiers, accounting for human biological constraints, as well as geographical and technological factors that determined travel time before the widespread use of steam power. This strategy overcomes the potential mismeasurement of distances generated by using geodesic distances (Özak, 2010), for a period when travel time were the most important determinant of transportation costs (O'Rourke and Williamson, 2001). Additionally, it removes the potential concern that travel time to the frontier reflect a country's stage of development, mitigating further possible endogeneity concerns. The research validates these measures by (i) analyzing their association to actual historical travel time; (ii) examining their explanatory power for the location of historical trade routes in the Old World; and (iii) analyzing their association to genetic and cultural distances.

Consistent with the predictions of the theory, the empirical analysis establishes the existence of a robust U-shaped relation between the distance to the technological frontier and pre-industrial economic development across countries. Additionally, it establishes the positive effect of increases in a country's distance to the frontier (due to changes in the location of frontiers) on pre-industrial economic development across countries. Moreover, the analysis establishes that the length of time a country was relatively more distant from the frontiers is positively associated with its economic development as well as its contemporary domestic patenting and entrepreneurial activities.

The analysis establishes these results in various layers: (i) a cross-country analysis of the relation between the distance to the pre-industrial technological frontier and technological sophistication in 1500CE; (ii) a cross-country panel-data analysis of the relation between the distance to the pre-industrial technological frontier and population density in the pre-industrial era; (iii) a cross-country panel-data analysis of the relation between changes in the distance to the pre-industrial technological frontier and changes in population density in the pre-industrial era; (iv) a cross-country panel-data analysis of the cumulative effect of distance from the pre-industrial technological frontier on population density in the pre-industrial era; (v) a cross-country analysis of the relation between the distance to the last pre-industrial technological frontier and contemporary technological sophistication and income per capita; (vi) a cross-country analysis of the cumulative effect of distance from the pre-industrial technological frontier on contemporary income per capita; and (vii) a cross-country analysis of the cumulative effect of distance from the pre-industrial technological frontier on contemporary patenting and entrepreneurial activities.

The analysis accounts for a wide range of potentially confounding geographical factors that might have directly and independently affected a country's economic development (e.g., elevation, area, malaria burden, share of area in tropical, subtropical or temperate zones, caloric suitability, latitude, island and landlocked regions). Moreover, unobserved geographical, cultural, and historical characteristics at the continental, regional or country level may have codetermined a country's level of economic development. Hence, the analysis accounts for these unobserved characteristics by accounting for continental, historical region, and when possible country and period fixed effects. Furthermore, it accounts for other time-varying pre-industrial country characteristics (e.g. change in caloric suitability due to the Columbian Exchange, colonial status, lagged technology levels, the onset of the Neolithic Revolution). Additionally, the analysis accounts for period-region fixed effects and thus for unobserved time-varying regional factors.

The analysis exploits variations in the location of the pre-industrial technological frontier in order to: (i) mitigate potential concerns relating to omitted country characteristics; (ii) analyze the effects of increases in distance to the frontier on a country's development; and (iii) explore the persistent and cumulative effect of distance from the frontier on a country's development. First, changes in the location of the pre-industrial technological frontier permit the analysis to account for country fixed effects, and thus for omitted time-invariant heterogeneity at the country-level. This allows the analysis to differentiate the effect of distance from the frontier from other unchanging characteristics of a country. Moreover, changes in a country's distance to the pre-industrial technological frontier across different time periods are potentially less endogenous when exploring their association with differences in development, especially after accounting for period, region and period-region fixed effects. Second, changes in the location of the pre-industrial technological frontier permit the analysis to explore the effects of increasing distance on development across countries. Thus, allowing alternative tests of the theory. Third, changes in the location of the pre-industrial technological frontier generated variations in the length of time countries were relatively remote from the frontiers. These variations permit the exploration of the cumulative and persistent effect of distance from the frontier on economic development across countries.

This research is the first attempt to analyze the effects of the geographical distance from the pre-industrial technological frontier on economic development. In doing so, it contributes to various literatures. First, it contributes to the literature on the effects of distance on development (Redding and Venables, 2002; Feyrer, 2009; Spolaore and Wacziarg, 2009; Ashraf et al., 2010; Puga and Trefler, 2010). This literature has focused mainly on the effects of distance on contemporary levels of trade and development across countries. An exception is Ashraf et al. (2010), which examined the impact of a country's prehistoric degree of isolation (i.e., its average isolation level from all locations in a continental mass prior to the advent of seafaring and airborne transportation technologies) on its economic development. Their cross-country analysis finds a positive relation between their measure of prehistoric isolation and population density in the years 1, 1000, 1500CE, and GDP per capita in 2000CE. In contrast, this research explores the effect of distance to the technological frontier during the pre-industrial era (i.e., after the introduction of seafaring technologies) on pre-industrial and contemporary economic development across countries. It is the first to establish the persistent U-shaped relation between distance to the frontier and development. Moreover, it provides evidence for a novel channel through which these pre-industrial distances may have had persistent effects on a country's development. In particular, it presents novel evidence on the persistent effect of pre-industrial distances on contemporary innovative and entrepreneurial activities.

Second, the research contributes to the literature on the determinants of entrepreneurship (Knight, 1921; Schumpeter, 1934; Hwang and Powell, 2005; Guiso et al., 2015), which has stressed the role of personal traits as well as the cultural and institutional environment in the prevalence of an entrepreneurial spirit. In contrast, this paper sheds light on a deep historical determinant of innovative and entrepreneurial activities. Finally, the research sheds additional light on the geographical origins of comparative development (Diamond, 1997; Gallup et al., 1999; Ashraf and Galor, 2013; Galor and Özak, 2016). Specifically, it provides novel evidence of the changing effects of geography in the course of economic development (Andersen, Dalgaard and Selaya, 2016) and suggests a novel geographical determinant of cultural and institutional differences and their persistent effect on economic development (Giuliano et al., 2006; Alesina et al., 2013; Galor and Özak, 2016).

The rest of the paper is structured as follows: section 2 presents anecdotal evidence supporting the proposed theory. Section 3 rationalizes the theory using an overlapping generations model and establishes the existence of a U-shaped relation between distance and economic development. Section 4 presents the data and the empirical strategy. Section 5 presents the empirical analysis for the pre-industrial era. Section 6 analyzes the persistent effect of distance from the frontier on contemporary economic development. Section 7 concludes. All additional supporting material is presented in the Appendix.

2 Anecdotal Evidence

This section presents anecdotal evidence for the pre-industrial era that shows (i) the limited role trade could play in technological diffusion before 1850, (ii) the importance of human mobility in technological diffusion, (iii) the difficulty of technological diffusion across space, (iv) the intertemporal links in the imitation and creation of technology, and (v) examples supporting the theory.

2.1 Importance of Trade

Although trade plays a crucial role in the process of economic development in the modern era, historically its role seems to be more restricted, as high transportation costs during the pre-industrial era limited the amount and type of trade being conducted. For example, Maddison (1995) estimates that by 1820 world trade represented only 1% of world GDP. Clearly, trade in technological goods represented an even smaller share, especially since technologies embodied in goods were difficult to transport, as in the case of heavy machinery (e.g. clocks, steam engines, furnaces). Case in point, during its first 25 years of operation, the Boulton and Watt Co. constructed less than one additional steam engine per year in order to fulfill international orders, which represented 4% of their total sales during the period 1775-1800 (Tann, 1978). These low trade volumes in the pre-industrial era suggest that the indirect gains from trade via learning-by-doing or the direct gains from trade in technology were small before 1850.

Furthermore, many technologies could not be embodied in tradable goods (e.g. canal systems, water mills, three-field rotation system, husbandry rules), or required access to tacit knowledge in order to produce them (Robinson, 1974; Epstein, 2006; Jones, 2009). For example, Boulton and Watt had recurring problems securing the services of engineers or skilled mechanics who could travel and install their steam engines overseas (Tann, 1978). To these impediments one must add any kind of state intervention, which forbade the trade in technologies considered fundamental to national security or for the comparative advantage of the nation (Jeremy, 1977). British laws prohibiting the export of machinery and travel of skilled technicians during the 18th and 19th centuries, as well as the current embargo on the trade in nuclear weapons, technology, and knowledge, are examples of these types of measures.[1]

2.2 Transferability across Space and Time

Under such circumstances, most technologies had to be invented *in situ* or imported, not directly through the goods that embodied them, but indirectly through the people who knew the technology. For instance, Epstein (2006) after establishing that neither texts nor patents played a major role in technological diffusion in premodern times, argues that "[i]n practice, technological transfer could only be successfully achieved through human mobility". Mokyr (1990) highlights the importance of master-and-apprentice and father-and-son dynasties in the diffusion of technology, especially in the machine and engineering sector:

[1] Furthermore, during the pre-industrial era most trade was based on goods that could not be produced locally due to agro-climatic, environmental or geological constraints.

> "From Nuremberg and Augsburg the art of instrumentmaking spread to Louvain in the southern Netherlands and from there to London. The London instrumentmaker Humfray Cole was apprenticed to the Liége craftsman Thomas Gemini. [...] Gemini himself had studied in the south of Germany. [...] Another German instrumentmaker, Nicholas Kratzer, lived in England for many years." (Mokyr, 1990, p. 71,fn. 9)

Similarly, Justus von Liebig, the German chemist whose innovations and book on organic chemistry gave birth to the fertilizer industry, studied in Paris under Joseph Louis Gay-Lussac. In turn von Liebig was the professor of August von Hoffman, who moved temporarily to London in order to head the creation of the Royal College of Chemistry and taught there for about twenty years before returning to Germany, teaching the first generation of professionally trained English chemists. Another example is Leonardo Pisano, more commonly known as Fibonacci, who learned mathematics from the Arabs as a boy during his father's trade missions in North Africa, and later introduced Europe to the use of algebra.[2]

Besides the formal networks of scientists and apprentices, the dispersion of technologies was based also on the work of businessmen, merchants, diplomats, and spies, who many times were sent or travelled by their own initiative to the technological frontier in order to gain access to the most advanced products, ideas, processes, and the skilled workers who knew them (Robinson, 1958, 1974; Mokyr, 1990; Epstein, 2006; Jones, 2009). For example, Robinson (1958) notes that

> "Eighteenth-century industry was conducted in an atmosphere of secrecy. The newspapers of Manchester, Birmingham and other industrial centres, during the seventeen-seventies and 'eighties, contain frequent references to foreign spies who were snooping in factories and warehouses to learn the trade secrets of the area and to entice away the workmen who knew them. Committees were formed to protect these trade secrets by warning the locality about foreigners and by enforcing the various acts against the exportation of tools and the enticing of artisans abroad, so that every manufacturer became spy-conscious and perhaps more deliberately secretive than he already was". (Robinson, 1958, p. 3)

Similarly, in 1789, after a notorious spy was caught exporting drawings, plans and objects of industrial interest, the Birmingham industrialist, Samuel Garbett, complained to Matthew Boulton, Watt's partner, that

> "[o]ur country [UK] is certainly considered as a School of the Arts and that great improvements in Manufacture are originating here. And it seems We are a common plunder for all who will take the trouble of coming here. And our Magazine of Secrets at the Patent Office is exposed to all Foreigners" (Robinson, 1974, p. 91).

These examples highlight the two central dimensions through which technology was accumulated, which are central to the mechanism highlighted in this paper. First, technology moved across space, from advanced to less advanced regions, by means of the people who travelled to the first, learning and copying the technology there, and bringing it back to the latter. Second, across time, between generations of innovators, fathers and sons, masters and apprentices.

[2] This last example exemplifies how trade's effect on the diffusion of innovation could be related more to the transmission of information than to the transmission of goods. Pacey (1990, p. vii) holds a similar view and offers as an example the Indian textile industry, "which had a profound influence in Britain during the Industrial Revolution even though there were few 'transfers' of technology. Just the knowledge that Indians could spin fine cotton yarns, weave delicate fabrics, and dye them with bright and fast colours stimulated British inventors to devise new ways of achieving these same results". Another role trade can play is in creating incentives to adopt certain technologies or to invest in certain types of capital which are conducive to economic development.

Clearly the movement along the first dimension is easier the closer the two regions are geographically or culturally. For example, it was easier for Francis Cabott Lowell to visit the textile mills in Lancashire in 1810 and appropriate the new techniques, which would revolutionize manufacturing in the U.S., than it would have been to do so for the contemporaries of Willem Van Ruysbroeck in 13th-century Mongolia, Marco Polo in 13th-century China, Rabban bar Sauma in 13th-century Europe or Matteo Ricci in 16th-century China.[3]

Additionally, if the technology is not generally applicable across space, or requires modification in order to be useful in different locations and environments, the diffusion across space will be facilitated by the proximity to the frontier, requiring less tinkering and toiling in order to adapt the technology to its new location. For instance, the diffusion of the "new husbandry" in the Middle Ages was slowed by these differences, in part because "[d]ifferent crops have different requirements, and the same crop will use different inputs and technology depending on elevation, rainfall, soil type, and so on" (Mokyr, 1990, p. 32).

Similarly, agricultural techniques, windmills, waterwheels, among other machines, required adaptation in order to work in different locations.[4] Jones (2009) mentions the impressions made by the visit of a skilled Welsh ironmaster to Tarnowitz in 1786 on the Prussian Commissioner for Affairs of War, Taxation, Mining and Factories, who concluded that "some ideas were made active in Silesia, old ones improved, some implemented in part, insofar as the differing location of German industry as compared to that of England permits". Similarly, the diffusion of the Bessemer and Siemens-Martin processes of steel production encountered many problems given that they could only be used with phosphorous-free iron ores, which were not abundant (Mokyr, 1990). Also, Epstein (2006) mentions the problems of applying the structural theory for Gothic churches across regions in Europe, as well as other techniques, noting the difficulty of transferring "recipes", adding that "recipes, as opposed to machines, were hard to transfer, because their result depended critically on a combination of material ingredients, and atmospheric and other conditions that could not be easily controlled for, and thus, easily reproduced" (p.23).

2.3 The Mechanism and Examples

Thus, distance to the technological frontier decreases the diffusion of technology across space by making it more difficult for people to move between their home location and the frontier, and by limiting the usefulness of the acquired knowledge and technology. At the same time, this lower usefulness

[3]Although the motives behind their voyages varied, and so did the circumstances with which they were received, it is clear that Lowell's endeavor was facilitated by him sharing a common language, customs, and religion with his hosts. On the other hand, the difficulties, the hostility, and general lack of trust with which these emissaries and ambassadors were received, gives an idea of how difficult the situation might have been for foreigners lacking their credentials. Van Ruybroeck, also known as Rubruquis, tells of how, in the beginning of his voyage, his guide distrusted him, and how at their arrival at Kûblâi Khân's court, his guide was well received and offered proper accommodations, while the friar and his companions were given a small hut, and they "were called and closely questioned as to the business which had brought" them there [van Ruysbroek 1900, p. 166-167; Polo 1858, p. 66-7]. Marco Polo notes that the people of Maabar distrust sailors [Polo 1858, p. 263; Beazley 1906, p. 138]. Similarly, Rabban bar Sauma, a Christian envoy of the Mongols, was initially treated as a heretic upon his arrival to Rome (Budge, 1928, pp.56-63).

[4]Bazzi et al. (2016) present evidence that the problem of transferability across space in the agricultural sector is still prevalent in the modern period in developing countries.

demands additional innovative work in order to adapt the technologies to local conditions (Mokyr, 1990; Epstein, 2006; Immelt et al., 2009). So, a greater distance to the frontier decreases the offer of directly applicable technologies, but simultaneously increases the innovative effort of the distant receiving society. Additionally, a larger distance to the frontier, which increases the cultural distance to the frontier, expands the possible new uses of any given technology (Ehret, 2002), resulting in more innovation in distant locations.

Moreover, for far enough locations it might be more economical to create the technology at those locations than to go through the process of imitation and adaptation. Thus, one can expect to observe independent innovation in multiple geographical locations, contrary to the diffusionist view (Blaut, 1987, 2012). In particular, this process can potentially increase the innovativeness of distant economies, allowing them to accumulate skills and technology across time. Since the transmission of skills and technologies within a location is easier than across space, and also more efficient and effective the more experienced the master or elder is (Epstein, 2006), the increased demand for innovative effort in distant locations may be accompanied by an improved intergenerational transmission of skills and technology.

All this is conducive to the independent and persistent creation of technologies and innovativeness in locations distant from the technological frontier. Case in point, the Old and New Worlds were mostly incommunicated between the last ice age and the modern discovery voyages, but in both landmasses people independently discovered agriculture and domestication (Diamond, 1997), the compass (Carlson, 1975), and the number zero (Kaplan, 2000), among others. Similarly, research on African medicine has found that kingdoms, like the Bunyoro-Kitara in Uganda, which were isolated from the rest of the world until around the 18$^{\text{th}}$ century, had discovered the use of the Caesarean section and variolation through inoculation, among other medical technologies (Felkin, 1884; Davies, 1959; Dunn, 1999). Moreover, distant cultures like the kingdoms of Mapungubwe and Great Zimbabwe were some of the most complex societies in Africa (Huffman, 2009). Additionally, ethno-mathematicians have shown that some pre-colonial African and Amerindian cultures had advanced (native) mathematical knowledge in areas like congruences, boolean algebra, fractals, topology, graph theory, etc. (Zaslavsky, 1999; Ascher, 1991, 2002; Bangura and Bangura, 2011; Selin, 2003).[5] Similarly, many ancient Chinese mathematical innovations and results, like solutions to linear, quadratic and cubic equations, Horner's method and Descartes' rule of signs, were much later rediscovered in Europe (Smoryński, 2008; Needham and Wang, 2008; Joseph, 2011).

Further evidence can be found in the improvement of non-native technologies. For example, around the year 1CE African iron-smelting, which had been introduced from the eastern Mediterranean around 500BCE, was technologically superior to European, Middle Eastern, and South Asian smelting techniques (Austen and Headrick, 1983).[6] Analogously, the windmill, which had been invented in central Asia and imported to Europe by its contact with the technologically advanced Islamic world, was

[5] It is interesting to note that some of this knowledge is being currently used to understand modern mathematical problems. For example, the mathematical ideas inherent in the kola designs of the Tamil Nadu in southern India have influenced the development of modern computer science theory (Katz, 2003). See also Selin (1997) and Joseph (2011).

[6] There still exists a debate among archeologists about the possibility of an independent discovery of iron smelting in Sub-saharan Africa (Ehret, 2002), which would provide even stronger support to this paper's theory.

developed and attained its state of perfection in the Netherlands (Mokyr, 1990). These last two examples defy conventional wisdom since it is in locations far away from the technological frontier and from the source of original innovation where these technologies attained their highest expression. Similarly, Great Britain's location made it one of the most distant places relative to the technological frontiers in the Old World until about the 14th century, when the "English had long been known as the perfecters of other people's ideas [...]", to which "[a] Swiss calico painter remarked in 1766 of the English: 'they cannot boast of many inventions, but only of having perfected the inventions of others [...]" (Mokyr 1990, p. 240). Finally, Nicholas (2011), Choi (2011), and Hashino (2012) have recently shown that local innovation played a mayor role in Japan's industrialization process during the 20$^{\text{th}}$ century.

3 A Model of Technology Imitation and Creation

This section introduces a model that generates a U-shaped relation between the distance to the technological frontiers and economic development.[7] The model embeds the main elements of the proposed theory and of the historical evidence in a fairly standard overlapping generations model. The main features of the model are (i) the presence of imitation, adaptation and innovation processes, (ii) the presence of negative spatial spillovers in the process of imitation, and (iii) the presence of positive (sector specific) intertemporal spillovers in the processes of imitation, adaptation and innovation. The presence of negative spatial spillovers in the process of imitation, which captures the loss of functionality of pre-industrial technologies when moved across space, captures the essential force highlighted by conventional wisdom. Without it, there would not exist spatial variations in economic development in the model or economic development would otherwise be positively associated with the distance from the technological frontier. Similarly, the presence of positive intertemporal spillovers due to learning-by-doing or learning-by-watching in the processes of adaptation and innovation, which have characterized these processes during the pre-industrial and contemporary eras, play a fundamental role in the emergence of the U-shape. Without these positive spillovers, although larger distances would generate a reallocation of resources from imitation to innovation, the additional innovation would not be enough to counteract the negative effects of the spatial spillover. On the other hand, if the positive intertemporal spillovers in adaptation and innovation are sufficiently strong, especially stronger than any potential positive intertemporal spillovers in imitation, then a U-shaped relation between the distance to the technological frontier and economic development may exist.

3.1 Setup

The world consists of a set of economies $\mathcal{E} \subseteq \mathbb{R}^n$ and n technological leaders. Assume that all economies in $\mathcal{E}$ are identical except for their geographical distance $\mathbf{d} = (d_1, \ldots, d_n)$ from these leaders, and thus identify each economy with this distance vector $\mathbf{d}$. Each economy $\mathbf{d} \in \mathcal{E}$, is populated by overlapping generations of two-period lived individuals. Population is constant and is normalized so that its size is 1. Each individual is endowed with one unit of time when young and one unit of time when old. For simplicity, assume that young individuals can only engage in activities of imitation or creation of

[7] Appendix C presents all the proofs and intermediate steps.

technology, and do not engage in consumption. On the other hand, old individuals can only engage in production and consumption activities, where their production possibilities are determined by their own technology, which is generated by their decisions when young and the technology inherited from their parents.[8] Under these assumptions the individual's only meaningful economic decision is how to allocate her labor when young between innovation and imitation from the n technological frontiers in order to maximize the growth rate of technology. Thus, to simplify notation, denote by the subscript t all variables corresponding to individuals born in $t-1$ who will be old in period t.

An individual born in period $t-1$ inherits a level of technology A_{t-1} from her parents. She increases her stock of technology, which will be available for production in period t, using two types of intermediate activities. In particular, she produces an intermediate input, $\tilde{I}$, by imitation from the technological frontiers, and a second one, $\tilde{R}$, through independent creation. Her productivity in each activity depends not only on the amount of labor she allocates to it, but also on sector specific intertemporal spillovers due to learning-by-doing or learning-by-watching in imitation and creation of technologies by her ancestors. Importantly, the individual does not take into account the effect of her own allocations on the sector specific productivities of her descendants. In particular, let l_t denote the amount of labor she allocates to independent creation and i_{jt} denote the amount of time she allocates to imitating from frontier j, so that, $\sum_j i_{jt} = 1 - l_t$. Additionally, denote by $\mathbf{l_t} = (l_t, l_{t-1}, \ldots)$ and $\mathbf{i_{jt}} = (i_{jt}, i_{jt-1}, \ldots)$ the history of allocations up to generation t. She produces a quantity $\tilde{R}_t = aS_R l_t^{\alpha} A_{t-1}$ of independent knowledge, where $a > 0$, $\alpha \in (0,1)$ and $S_R = S_R(\mathbf{l_{t-1}})$ captures the positive intertemporal spillovers in innovation. She devotes the rest of her time, $(1-l_t)$, to creating intermediate knowledge through imitation from the frontiers. Assume that the intermediate knowledge from each frontier is generated using similar technologies, namely

$$\tilde{I}_{jt} = b(d_j) S_{Ij} i_{jt}^{\beta} A_{t-1}, \qquad j = 1, \ldots, n \tag{1}$$

where $\beta \in (0,1)$, the function $b : \mathbb{R}_+ \to \mathbb{R}_{++}$ is continuous, decreasing, twice differentiable. $b(d_j)$ captures the negative effect of distance on the productivity of imitation, while $S_{Ij} = S_{Ij}(\mathbf{i_{jt-1}})$ captures the positive intertemporal spillovers in imitation from frontier j. She combines the intermediate knowledge she gained from the frontiers through a constant elasticity of substitution production function to produce her aggregate knowledge from imitation

$$\tilde{I}_t = \left(\sum_{j=1}^{n} \lambda_{2j} \tilde{I}_{jt}^{\rho_2} \right)^{\frac{1}{\rho_2}} \tag{2}$$

where $\sum_{j=1}^{n} \lambda_{2j} = 1$, $\lambda_{2j} \in [0,1]$, $0 < \rho_2 \equiv \frac{\eta_2 - 1}{\eta_2} < 1$, and η_2 is the constant elasticity of substitution of knowledge between any two frontiers. The new knowledge she gains from imitation and independent creation are aggregated through another constant elasticity of substitution production function to

[8] These assumptions are made for convenience and in order to simplify the analysis. Changing them would not alter the main qualitative results since the underlying mechanism does not depend on them. For example, one could allow young individuals to produce and consume, or old individuals to engage in additional research activities, without affecting the main results. Additionally, allowing for endogenous population growth in a Malthusian framework would generate similar results.

produce total new knowledge, which is added to her existing stock of technology. Letting $R_t = \tilde{R}_t/A_{t-1}$ and $I_t = \tilde{I}_t/A_{t-1}$, the growth rate of technology can be written as

$$g_t = \frac{A_t - A_{t-1}}{A_{t-1}} = \Big[\lambda_1 R_t^{\rho_1} + (1-\lambda_1) I_t^{\rho_1}\Big]^{\frac{1}{\rho_1}}, \tag{3}$$

where $\lambda_1 \in (0,1)$, $0 < \rho_1 \equiv \frac{\eta_1 - 1}{\eta_1} < 1$, and η_1 is the constant elasticity of substitution between imitation and creation. Let $u(c_t)$, be the utility an individual born in period $t-1$ derives from consumption, where $u'(c) > 0$, $u''(c) < 0$. She chooses $l_t \in [0,1]$ and $i_{jt} \in [0,1]$ for $j = 1, \ldots, n$, in order to maximize her lifetime expected utility, i.e. she solves the following problem

$$\max_{(l_t,(i_{jt})_{j=1}^n)\in[0,1]^{n+1}} \quad u(c_t) \qquad \text{subject to} \qquad c_t = (1+g_t)A_{t-1}, \; l_t + \sum_{j=1}^{n} i_{jt} = 1, \tag{4}$$

which amounts to maximizing the growth rate g_t.

From the individual's point of view, the only difference between frontiers is their distance, so, in order to maximize her lifetime expected utility, her time allocations when young, l_t and $\{i_{jt}\}_{j=1}^n$, have to equalize the marginal product of labor across sectors. Importantly, increasing the distance d_j lowers the marginal product of labor in imitation from frontier j, without affecting the marginal productivity of labor in any other activity. Thus, increases in d_j generate a reallocation from imitation from j to all other activities, including innovation. This reallocation process lies at the heart of the mechanism highlighted in this paper.

Furthermore, the sector specific intertemporal spillovers play an essential role in the effects of this reallocation across sectors in the model. In particular, without them the steady state growth rate of the economy would be a decreasing function of distance. To see this, notice that the growth rate can be rewritten as a strictly concave function of the labor allocation in innovation l_t, so that the optimal growth rate in a steady state is $g(l^*(d), d) \equiv g^*(d)$. Without any sector specific intertemporal spillovers, the envelope theorem implies that $g'^*(d) = g_d < 0$, where g_d is the partial derivative of the growth rate with respect to distance. Thus, without spillovers, the model would predict that distance has a negative monotonic relation with development as in the conventional wisdom. On the other hand, if the sector specific intertemporal spillovers are present, then $g'^*(d) = g_{S_R} + g_{S_I} + g_d \lesseqgtr 0$, where g_{S_R} and g_{S_I} are the effects of the spillovers on the growth rate. This opens up the possibility for the emergence of a U-shape in the steady state, depending on the signs and relative sizes of g_{S_R} and g_{S_I}.

In order to simplify the analysis, assume that the sector specific intertemporal spillovers due to learning-by-doing, $S_R(\mathbf{l_{t-1}})$ and $\{S_{Ij}(\mathbf{i_{jt-1}})\}_{j=1}^n$, are continuous, bounded, differentiable and concave functions of its elements, and satisfy the following property: for any steady state allocations $\mathbf{l} = (l, l, \ldots)$ and $\mathbf{i_j} = (i_j, i_j, \ldots)$, $j = 1, \ldots, n$, $S_R(\mathbf{l}) \propto l^{\alpha'}$ and $S_{Ij}(\mathbf{i_j}) \propto i_j^{\beta'}$, where $\alpha', \beta' \in (0,1]$. I.e., in a steady state the intertemporal sector specific spillovers are proportional to a concave function of the steady state allocation in each sector.[9]

[9] The following functions satisfy these conditions: (i) $S(\mathbf{x_{t-1}}) = x_{t-1}^{\beta'}$, (ii) $S(\mathbf{x_{t-1}}) = \lim_{T\to\infty} \frac{1}{T}\sum_{\tau=0}^{T} x_{t-1-\tau}^{\beta'}$, (iii) $S(\mathbf{x_{t-1}}) = (\lim_{T\to\infty} \frac{1}{T}\sum_{\tau=0}^{T} x_{t-1-\tau})^{\beta'}$, (iv)$S(\mathbf{x_{t-1}}) = \sum_{\tau=0}^{\infty} \delta^\tau x_{t-1-\tau}^{\beta'}$, and (v) $S(\mathbf{x_{t-1}}) = (\sum_{\tau=0}^{\infty} \delta^\tau x_{t-1-\tau})^{\beta'}$. Clearly, these are not the only functions that satisfy these conditions, but they are commonly used in the literature.

The steady state growth rate of economy $\mathbf{d}$ generated by the individual's optimal decisions is given by[10]

$$g^*(\mathbf{d}, \lambda_{\mathbf{2}}) = R^*(\mathbf{d}, \lambda_{\mathbf{2}}) \left[\lambda_1 + (1-\lambda_1)\left(\frac{I}{R}(\mathbf{d}, \lambda_{\mathbf{2}})\right)^{\rho_1}\right]^{\frac{1}{\rho_1}}, \tag{5}$$

where $\lambda_{\mathbf{2}} = (\lambda_{2j})_{j=1}^{n}$, and $R^*(\mathbf{d}, \lambda_{\mathbf{2}})$ and $I/R(\mathbf{d}, \lambda_{\mathbf{2}})$ are the optimal levels of imitation and of the ratio of imitation to creation. Furthermore, the first factor is increasing and the second one is decreasing in all the components of $\mathbf{d}$. This implies, in particular, that increasing the distance to frontier j, d_j, increases the amount of creation while lowering the aggregate amount of imitation. As shown below, this trade-off, which is caused by individual's desire to equalize the marginal product of labor, can generate under some conditions a U-shape in the level of development.

3.2 Steady-State Growth in a World with a Unique Frontier

Clearly, economies that are equidistant from all frontiers, effectively only have one frontier. Thus, individuals in these economies behave as if they lived in a world with a unique frontier. For these economies, $\mathbf{d} = d \cdot \mathbf{e}$ and $g^*(\mathbf{d}, \lambda_{\mathbf{2}}) = G(d)$, where $\mathbf{e}$ is the n dimensional vector of ones, $d \in \mathbb{R}_+$, and $G(d)$ is the steady state growth rate for an economy at distance d in a world with a unique frontier. Assume that

$$(\alpha' + \alpha)\rho_1 < 1, \qquad (\beta' + \beta)\rho_1 < 1, \tag{ES}$$

$$\frac{\rho_1 \beta \left[\frac{\alpha'}{\alpha} - \frac{\beta'}{\beta}\right] x}{\big(1-(\alpha'+\alpha)\rho_1\big)(1-x) + \big(1-(\beta'+\beta)\rho_1\big)x} = 1 \text{ for some } x \in (0,1). \tag{U}$$

Condition (ES) ensures that in a steady state the marginal productivity of labor of young and old individuals is "jointly" decreasing in the production of intermediate products. Condition (U) gives a measure of the strength of intertemporal spillovers across sectors, and imposes limits on the differences in labor productivities across them. Clearly, $\alpha'/\alpha > \beta'/\beta$ is a necessary condition for (U) to hold, which implies intertemporal spillovers are stronger in creation than imitation. Additionally, it implies that if in the production of each intermediate input the same quantities of current and past labor are used, then the marginal rate of technical substitution between current and past labor is larger in I than in R. So, as the distance d increases, the lower productivity of labor in imitation generates a substitution out of imitation and into research. Under these assumptions, in a world with a unique frontier, $G(d)$ is U-shaped with the lowest growth rate attained at the *Least Desirable Distance* $\bar{d} > 0$.[11] Figure 1 depicts the relation between distance d and steady state growth rates in a world with a unique frontier.

[10] See Appendix C for the proof.
[11] See Appendix D for the proof.

Figure 1: The steady state relationship between distance and economic growth in a world with one frontier.

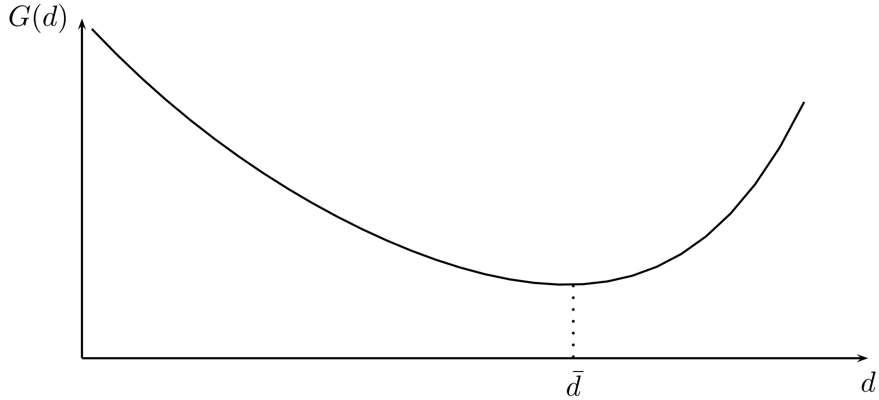
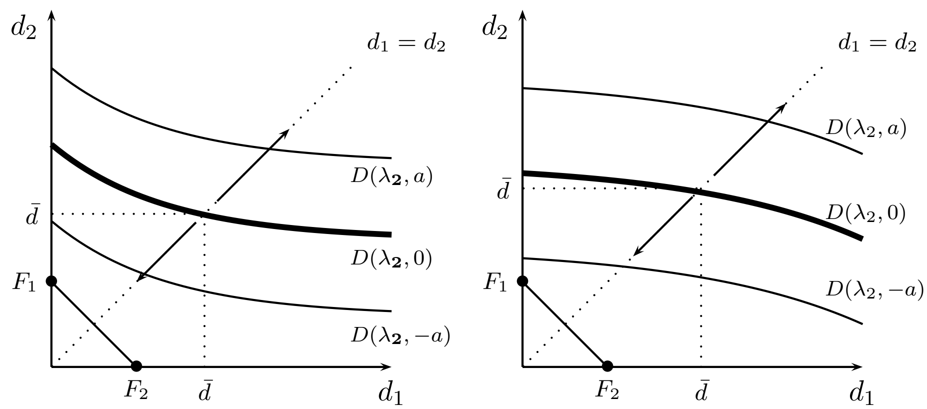


Figure 2: Isogrowth maps in a world with two frontiers.



(a) Convex $b(d)$ (b) Concave $b(d)$

These figure depict the isogrowth maps in a world with two frontiers. F_1 and F_2 denote the locations of frontiers 1 and 2, which are at a distance d_{12} from each other. Every point (d_1, d_2), which does not belong to the triangle generated by the frontiers and the origin, represents an economy located at a distance d_1 from frontier 1 and d_2 from frontier 2. Every isogrowth curve $D(\lambda_2, a)$ represents the set of economies that have the same growth rate. $D(\lambda_2, 0)$ is the set of economies that have the lowest growth rate. The arrows show the direction of increase in the growth rate.

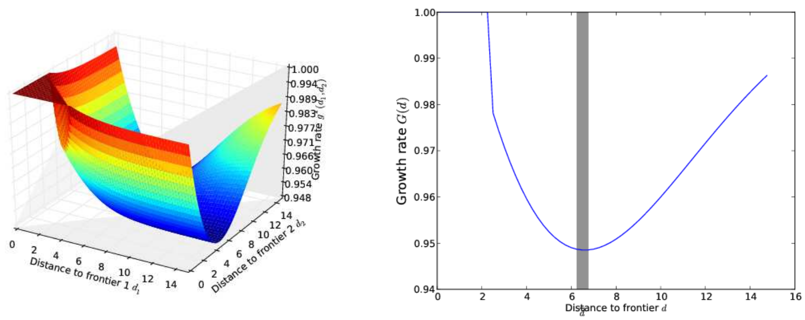
3.3 Steady-State Growth in a World with a Many Frontiers

Since any $d \in \mathbb{R}_+$ can be written as $d = \bar{d}+z$, for some $z \in \mathbb{R}$, the previous result implies that in a world with n frontiers, the growth rate of equidistant economies is given by $g^*\Big((\bar{d}+z)\cdot \mathbf{e}, \boldsymbol{\lambda_2}\Big) = G(\bar{d}+z)$, so that the growth rate for these economies is also U-shaped. Also, since the set of economies $\mathcal{E}$ in the world can be partitioned by the z-isogrowth sets

$$D(\boldsymbol{\lambda_2}, z) = \Big\{\mathbf{d} \in \mathcal{E} \mid g^*(\mathbf{d}, \boldsymbol{\lambda_2}) = G(\bar{d}+z)\Big\}, \tag{6}$$

which is the set of economies that grow at rate $G(\bar{d}+z)$, a similar non-monotonicity holds for all other economies as well (see appendix C). These results imply that the steady state profile of growth rates looks like a valley with the economies belonging to $D(\boldsymbol{\lambda_2}, 0)$ at its bottom. Figure 2 depicts two general isogrowth maps in a world with two frontiers when (a) $b(d)$ is convex or (b) $b(d)$ is concave. Clearly, the shape and direction of the valley will depend on the functional forms and parametrization chosen. For example, for the CES functions above, figure 3 plots the $g(\mathbf{d}, \boldsymbol{\lambda_2})$ and $G(\bar{d} + z)$ functions for an artificial economy in which $b(d) = b_0 e^{-b_1 d}$. The distance $\bar{d}$ is the least desirable distance (LDD) from the technological frontiers and is located where the 45-degree line intersects $D(\boldsymbol{\lambda_2}, 0)$.

Figure 3: Artificial world with two frontiers



(a) Steady state growth rates for all economies.

(b) Steady state growth rates for equidistant economies or a world with only one frontier. Least Desirable Distance $\bar{d}$ in gray.

Notice that the non-monotonicity does not imply that being far from the frontiers *always* increases the growth rate. On the contrary, it only implies that there must exist economies which are farther from the frontiers and have higher growth rates than others which are closer to them. Furthermore, conventional wisdom can be seen as a special case of this theory in which either (i) $\bar{d} = \infty$, so that $D(\boldsymbol{\lambda_2}, z) = \emptyset$ for all $z \geq 0$, or (ii) the observable world is too small, so that $D(\boldsymbol{\lambda_2}, 0)$ is not observable. In either case, any empirical analysis would find a monotonic relation between distance and development.

3.4 Testable Predictions

The previous analysis suggests that if the theory proposed in this paper is valid, then for at least one frontier j the Least Desirable Distance, LDD_j, is positive, statistically significant, and smaller than the maximum distance to frontier j in the sample. In particular, if all frontiers are identical and so the model is fully symmetric, there should exist a U-shaped relation with respect to the distance to each one of them, as depicted in Figure 3(a). Clearly, any asymmetry due to differences in the way frontiers affect imitation, may cause the U-shape with respect to some frontier to not be identifiable.[12]

[12] Symmetry conditions need not hold for all frontiers since imitation from different frontiers can be affected by linguistic, cultural, institutional or geographical differences. In particular, it can be shown that variations in the parameters of the model, e.g. $\boldsymbol{\lambda_2}$ or ρ_2, can disrupt the symmetry of the model and cause estimates not to find a U-shaped effect on development of the distance from certain frontiers. For example, consider the case when $\lambda_{2j} \to 0$ for some j. In this case, the effect of the distance to such a frontier will tend to appear monotonic. Additionally, as suggested in appendix E, even in a symmetric world randomness and sample composition can cause asymmetries in the estimates. Reassuringly, simulations suggest that if the empirical analysis finds at least one frontier with an LDD estimate that satisfies this condition, then with high probability the non-monotonicity exists.

On the other hand, if conventional wisdom holds, then for all frontiers $j = 1, \ldots, n$, the estimated LDD_j lies outside the sample and is statistically insignificant, i.e. $LDD_j = \infty$.

These predictions and Monte Carlo simulations presented in appendix E suggest using the following empirical specification to explore the relation between economic development and the distance to the technological frontier during the pre-industrial era across countries:

$$y_{it} = \beta_0 + \sum_{j=1}^{n} (\beta_{1j} d_{ijt} + \beta_{2j} d_{ijt}^2) + \gamma' x_{it} + \epsilon_{it} \tag{7}$$

where for each country i, y_{it} is its level of economic development in period t, d_{ijt} is its distance to the j-th pre-industrial technological frontier in period t, x_{it} are other covariates in period t, and ϵ_{it} is an error term. The proposed theory implies that for at least one frontier j $\beta_{1j} < 0$, $\beta_{2j} > 0$, and the implied Least Desirable Distance ($LDD_j = -0.5\beta_{1j}/\beta_{2j}$) is positive, statistically significant, and smaller than the maximum distance to frontier j in the sample of countries.

Monte Carlo simulations (appendix E) suggest that this empirical specification tends to over-reject the proposed theory. In particular, using simulations, the analysis finds that in artificial economies in which the theory proposed in this paper is true, the estimation might not be able to capture this non-monotonic relation. Specifically, this test tends to over-reject the null hypothesis of the existence of a non-monotonicity. Thus, the presence of a non-monotonicity in the estimation is strong suggestive evidence that the underlying relation is non-monotonic.

Additionally, a corollary of the theory suggests that countries that are located farther than the Least Desirable Distance (LDD) at the More Desirable Distances (MDD) should be more developed. This in turn implies that if the location of the frontier changes exogenously, the more time an economy spends at the MDD (across technological frontiers), the more developed it should be. Furthermore, the theory suggests that remote economies, which become even more remote after the change in the location of a frontier should get a boost in their economic performance.

4 Data and Empirical Strategy

This section develops the empirical strategy and describes the data used to explore the existence of a U-shaped relation between the pre-industrial distance to the technological frontier and economic development across countries.

4.1 Empirical Strategy

The analysis surmounts significant hurdles in the exploration of the relation between pre-industrial distance to the technological frontier and economic development across countries. First, the results may be biased due to potential measurement error in historical data on economic development. In order to mitigate this concern, the analysis explores the relation using different measures of economic development for the pre-industrial era. In particular, the research explores the relation using the level of technological sophistication in 1500CE and also population density levels for the years 1CE, 1000CE, 1500CE and 1800CE. This allows it to analyze the relation in data constructed from independent sources, over different samples, minimizing the potential effects of mismeasurement and sample selection on the analysis. Additionally, it permits the analysis to exploit cross-country and cross-period variation to explore the non-monotonic effect of distance to the frontier.

Second, the results may be biased by omitted geographical, institutional, cultural, or human characteristics of countries that might have determined their economic development and are correlated with their pre-industrial distance to the technological frontier. This research employs various strategies to mitigate this potential concern. In particular, the analysis accounts for a large set of possible confounding geographical characteristics (e.g., elevation, area, malaria burden, share of area in tropical, subtropical or temperate zones, average caloric suitability, latitude and its square, being an island or landlocked). Moreover, it accounts for continental fixed effects and thus for any unobserved time-invariant heterogeneity at the continental level. In addition, it accounts for common history fixed effects controlling for any unobserved time-invariant heterogeneity due to common historical experience across countries within a region. Additionally, when possible it accounts for country fixed effects and thus for unobserved time-invariant country-specific factors. Furthermore, it accounts for other time-varying country characteristics (e.g. change in caloric suitability due to the Columbian Exchange, colonial status, lagged technology levels), as well as period-region fixed effects and thus for unobserved time-varying regional factors.

Third, the analysis further mitigates the potential concern that the results may partially reflect the effect of omitted geographical, institutional, cultural, or human characteristics, by exploiting the variation in the location of the western technological frontier in the Old World. In particular, changes in the location of the technological frontier permit the research to account for country fixed effects and thus for time-invariant characteristics of a country. Moreover, it is plausible that the change in a country's distance to the frontier may be exogenous to its characteristics, especially once region-period fixed effects are accounted for. If this were the case, the first difference estimator of equation (7) would be unbiased.

Fourth, variations in the location of the western frontier permit the analysis to mitigate various potential concerns by exploring the effects of changes in the distance to the frontier on changes in population densities across countries. In particular, as mentioned above, differences across periods in equation (7) account for omitted time-invariant determinants of population density across countries. Additionally, analyzing changes across different periods mitigates the potential concern that a particular period or technological frontier drives the results. Another potential concern is that the results may not reflect the effect of being far from the frontier, but of countries that were distant from the frontier in one period and became closer to it in another period. Exploration of the differential effect of larger distances (to the technological frontiers) on population density in countries located far from the technological frontiers mitigates this concern.

Fifth, the analysis exploits the variation in the location of the western frontier in order to explore the cumulative and persistent effect of the distance to the pre-industrial frontier on development across countries. In particular, the theory suggests that the more time a country was farther than the LDD, the longer it benefitted from its incentives to imitate, adapt and innovate. Thus, the cumulative time a country spent at the MDD (across technological frontiers in the pre-industrial era) should be positively associated with its level of development.

Finally, the results may reflect the European expansion in the post-1500CE era or other time-varying characteristics of a country. The analysis mitigates this potential concern by using various strategies. In particular, it restricts the analysis to the Old World, where European population replacement was less prevalent. Additionally, it establishes that the results hold for the pre-colonial period, before European expansion. Furthermore, it accounts for time-varying characteristics of a country (years since the Neolithic Revolution, lagged technological sophistication) as well as other changes generated in the Old World during the colonial period (e.g. changes in colonial status, changes in caloric suitability). In addition, it accounts for the interaction between region and period fixed effects, which control for the effects of time-varying region-specific unobserved heterogeneity, and thus partially account for the potential effects of European expansion and other omitted time-varying characteristics of a country.

4.2 Independent Variable: An Economic Measure of Pre-industrial Distance[13]

This section introduces a novel cross-country measure of the pre-industrial distance to the technological frontier in the pre-industrial era, which is the main independent variable employed in the analysis. This distance is based on a novel measure of geographical distance during pre-industrial times: the Human Mobility Index with Seafaring (HMISea). The HMISea measures the time required to cross any square kilometer on land and on some seas accounting for human biological constraints, as well as geographical and technological factors that determined travel time before the widespread use of steam power. Based on HMISea, the analysis estimates distances as the potential minimum travel time between locations (measured in weeks of travel). This strategy overcomes the potential mismeasurement of distances generated by using geodesic distances (Özak, 2010), for a period when travel time were the most important determinant of transportation costs (O'Rourke and Williamson, 2001).

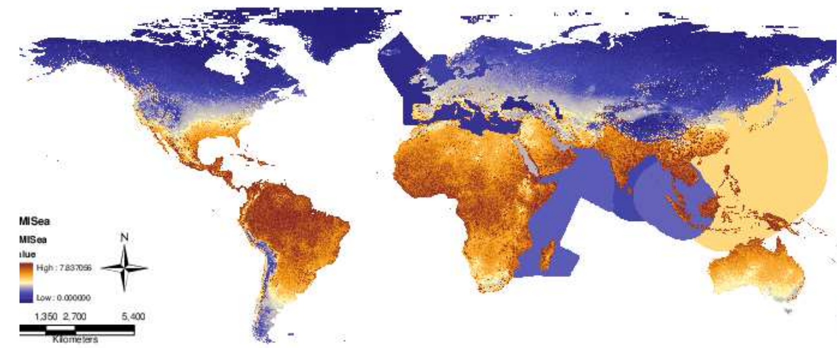
The estimated time required to cross each square kilometer on land is based on data on the maximal sustainable speeds of dismounted infantry movement under different climatic, topographical, and terrain conditions (Hayes, 1994). In particular, Hayes (1994) estimates the maximal sustainable speeds of dismounted infantry movement under different temperature, relative humidity, slope, and terrain conditions. Hayes focused on the levels of metabolic rates and speeds that can be sustained for long periods of time without causing a soldier to become a victim of heat-exhaustion.

Based on this data, the analysis estimates the relation between the maximum sustainable travel speeds and these conditions using Ordinary Least Squares (OLS). Given these OLS coefficients, the analysis proxies the time required to cross any square kilometer on land, given the average geographical conditions prevalent in it. Additionally, it complements this Human Mobility Index (HMI) by estimating the time required to cross any square kilometer on seas in the Old World, by constructing average times for each sea from primary and secondary historical sources (see appendix A for a more

[13] Given space limitations, a more complete presentation of the material covered in this section is given in Appendix A. The interested reader can find additional material regarding the construction and testing of the measure there. See also Özak (2010).

complete description). Figure 4 depicts the resulting HMISea cost surface.

Figure 4: Human Mobility Index with Seafaring (HMISea) cost surface.



The figure depicts the number of hours required to cross each square kilometer on land and on seas in the Old World. Low values in dark lila, high values in dark brown, intermediate values in intermediate tones. See text or Özak (2010) for construction.

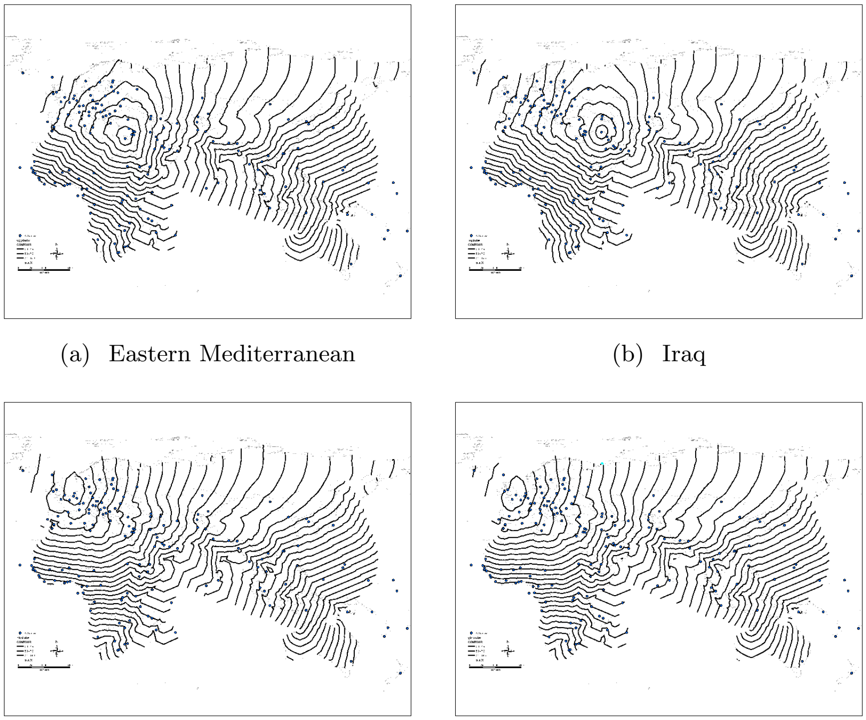
In order to validate this index, Appendix A applies the HMISea measure to estimate distances during the pre-industrial era (see also Özak, 2010). In particular, it estimates the total time required to travel along the optimal paths that connect all modern day capitals and the average optimal time required to travel to each capital from all locations on a contiguous continental mass. Using these estimates, the analysis validates the measures by comparing them with data on ancient trade routes (Ciolek, 2004). As established in Appendix A, the optimal paths among capitals predict the locations of ancient trade routes in the Old World (500BCE-1900CE). Additionally, it explores the relation between these historical migratory distances and genetic, religious, and linguistic distances (Fearon, 2003; Mecham et al., 2006; Spolaore and Wacziarg, 2009). Reassuringly, the optimal time required to travel among regions is strongly positively associated with these cultural distances.[14] Finally, using data on the historical speed of diffusion of news to Venice between the 16^{th} and 18^{th} century from a sample of cities (Braudel, 1972), the analysis establishes that HMISea travel time to Venice approximate these historical data. These results suggest that HMISea based migratory routes are good proxies for the minimum total travel time between the capital of each technological frontier in the pre-industrial era and the capitals of countries in the Old World.

Economic historians suggest that during the pre-industrial, the eastern technological frontier in the Old World era was located in China. On the other hand, the historical record suggests that the western technological frontier changed location during this era from the Eastern Mediterranean (≈1CE), to Iraq (≈1000CE), to the Low Countries (≈1500CE), and to the UK (≈1750CE) (Abu-Lughod, 1989; Maddison, 1995; Mokyr, 1990; Pomeranz, 2000; Maddison, 2003; Findlay and O'Rourke, 2007; Davids, 2008; Blaut, 2012). For each contemporary country the analysis estimates the HMISea migratory distance to all technological frontiers. Figure 5 depicts the travel time to each western pre-

[14]Further supportive evidence of the validity of this method has been provided elsewhere. In particular, as predicted by the Out-of Africa Theory of the dispersion of modern humans, estimated HMI and HMISea migratory distances to East Africa have been shown to have a high explanatory power for the level of expected heterozygocity both at the ethnic and country levels (Ashraf and Galor, 2013; Depetris-Chauvin and Özak, 2015b). Similarly, differences in other cultural values have been linked to these estimated migratory distances (Spolaore and Wacziarg, 2014; Becker et al., 2014; Depetris-Chauvin and Özak, 2015b).

industrial technological frontier in the Old World. In particular, for each western frontier it depicts the iso-chronic lines generated by the HMISea measure, where each line corresponds to half a week of continuous uninterrupted travel.

Figure 5: Potential Travel Time to Western Pre-industrial Technological Frontiers (Old World)



(a) Eastern Mediterranean

(b) Iraq

(c) Netherlands

(d) UK

Note: Each panel depicts iso-chronic lines of travel time to a western pre-industrial technological frontier in the Old World. Each iso-chronic line represents half a week of continuous travel time along the optimal path to the frontier.

4.3 Dependent Variables and Additional Controls

In order to implement the empirical strategy, the analysis employs as independent variables various country-level measures of economic development for the pre-industrial era as well as measures of innovativeness and development during the contemporary era. First, the analysis employs an index of countries' technological sophistication in 1500CE and 2000CE (Comin et al., 2010), which documents around each era whether a certain set of technologies was used or known by the residents of the region where a contemporary country is located. Second, the analysis employs a measure of population density for each contemporary country in 1CE, 1000CE, 15000CE and 1820CE (McEvedy and Jones, 1978). Third, in order to explore the persistence of the effect into the modern era, the analysis uses countries' average level of GDP per capita, patents per capita and new firms per 1,000 people during the 2000-2015 period from the World Bank's Development Indicators.

The distance from the technological frontier is correlated with other geographical characteristics of a country that may have affected its development. Hence, the analysis accounts for the potential confounding effects of a range of geographical factors such as absolute latitude, area, average elevation, mean distance to nearest waterway, malaria risk, caloric agricultural suitability, climatic volatility and correlation, share of area within 100kms of sea, length of coastline, tropical, subtropical and temperate zones, as well as islands and landlocked regions. Furthermore, the analysis accounts for continental as well as historical region fixed effects, controlling for unobserved continent-specific geographical and historical characteristics that may have affected a country's economic development.

The onset of agriculture has been associated with a technological head-start that persisted during the Malthusian era (Diamond, 1997; Ashraf and Galor, 2011). Thus, the empirical analysis considers the confounding effect of the advent of sedentary agriculture, as captured by the years elapsed since the onset of the Neolithic Revolution (Putterman, 2008), on countries' economic development.

The analysis also considers the confounding effect of a country's distance to other potential sources of economic development. In particular, it accounts for the effects of distance from a country to the closest pre-industrial trade route, which may reflect a country's ability to trade goods or information during this era. Additionally, it accounts for the effects of countries' distance to local technological frontiers as well as their distance to East Africa, which may independently have affected a country's development (Ashraf and Galor, 2013; Depetris-Chauvin and Özak, 2015a). Also, the empirical analysis accounts for the effect of the Columbian Exchange during the post-1500CE era. Specifically, it accounts for the effect of changes in caloric suitability (Galor and Özak, 2016) as well as colonial status, legal origin and religious composition on economic development across countries. Appendix B provides the description, source and summary statistics of all variables used in the analysis.

5 Distance to the Pre-industrial Technological Frontier and Pre-industrial Development

This section analyses the relation between the pre-industrial distance to the technological frontiers in the Old World and economic development across countries.[15] In particular, the predictions of the theory and Monte Carlo simulations (section 3 and 4.1, Appendix E) suggest that the theory can be tested using variations of the following empirical specification

$$y_{it} = \beta_0 + \sum_{j=1}^{n}(\beta_{1j}d_{ijt} + \beta_{2j}d_{ijt}^2) + \sum_{j}\gamma_{0j}x_{it} + \sum_{c}\gamma_{ci}\delta_c + \sum_{t}\gamma_t\delta_t + \sum_{ct}\gamma_{ct}\delta_{ci}\delta_t + \epsilon_{it} \tag{8}$$

where y_{it} is a measure of its economic development in period t for country i, d_{ijt} is the number of weeks of travel from country i to the j-th pre-industrial technological frontier in period t, x_{it} are additional characteristics of country i in period t (including geography), $\{\delta_{ci}\}$ are a complete set of continental/regional/historical/country fixed effects, $\{\delta_t\}$ are a complete set of period fixed effects,

[15] As explained in section 4.1, the analysis excludes the New World and Oceania in order to overcome various concerns. In particular, since the development process in both the New World and Oceania was strongly affected by other forces during the pre-1500 and post-1500 eras, their exclusion overcomes potential concerns due to, e.g., the potential confounding effects of population replacement and colonization, as well as the extinction of great mammals. Additionally, the lack of interaction between the Old and New World raises methodological issues regarding the estimation of distances. Reassuringly, Appendix F establishes the robustness of the inclusion of these regions into the analysis. In particular, it establishes the presence of a non-monotonicity when the New World has its own technological frontiers or when distances between the Old and New World are assumed to be larger than within each region.

and ϵ_{it} is an error term.[16] The theory predicts that $\beta_{1j} < 0$, $\beta_{2j} > 0$, and the implied Least Desirable Distance ($LDD_j = -0.5\beta_{1j}/\beta_{2j}$) is positive, finite and statistically significant for at least one frontier j.[17]

5.1 Historical Evidence I: Technological Sophistication (Cross-Country Analysis)

This section explores the relation between a country's level of technological sophistication in 1500CE and the distance to the technological frontiers in the Old World during that period, namely the Netherlands and China. The technology indices for the year 1500 proxy a country's stock of technology and innovativeness.[18] Thus, the dependent variable in these regressions measures the relevant channel through which remoteness affects economic development according to the proposed theory.

Table 1 explores the existence of a non-monotonic relation between the pre-industrial distance to the technological frontier and technological sophistication across countries. In particular, it uses ordinary least-squares (OLS) regressions to analyze the empirical association between a country's pre-industrial distance to the western technological frontier, the square of this distance and a country's technological sophistication in 1500CE. Column (1) shows the unconditional relation between the distance to the western technological frontier in the Old World and technological sophistication. In particular, the estimated Least Desirable Distance (LDD) is statistically and economically significant, and is located at 8.3 weeks. The estimates suggest that an economy located 1-standard deviation (SD) away from the LDD has a technological sophistication 19% higher than at the LDD.

Column (2) accounts for the confounding effect of a country's geographical characteristics. In particular, it accounts for a country's latitude and its square, pre-1500CE caloric suitability, percentage of land area in tropics and subtropics, mean elevation above sea level, land area, malaria burden, and dummies for being landlocked or an island. Reassuringly, the estimated LDD remains statistically and economically significant. The estimated location of the LDD is 5.4 weeks and implies that an economy located 1-SD away from the LDD has a technological sophistication 44% higher than at the LDD.

Columns (3) and (4) consider the confounding effects of the advent of sedentary agriculture and of unobserved time-invariant omitted variables at the continental level on technological sophistication across countries. In particular, column (3) accounts for the years elapsed since the a country experienced the onset of the Neolithic Revolution, which previous research has suggested had a positive impact on its economic development (Diamond, 1997). Additionally, column (4) accounts for continen-

[16] The analysis includes the largest set of countries in the Old World for which all the data in the most general specification being studied is available. Appendix B contains the descriptive statistics for all the samples and variables used in the analysis.

[17] Appendix E explores the performance of this empirical specification using Monte Carlo simulations. In particular, it explores whether the null-hypothesis that $\beta_{2j} = 0$ for all frontiers j is rejected in favor of the alternative hypothesis that $\beta_{2j} \neq 0$ for some frontier j and its LDD_j is finite and smaller than the sample maximum. In these simulations the null-hypothesis was not rejected whenever it was assumed that the null-hypothesis was true. On the contrary, the null hypothesis was only rejected if the alternative hypothesis was assumed to hold. Moreover, even when the alternative hypothesis was true, the null-hypothesis was not always rejected. These findings suggest that rejection of the null-hypothesis in this specification provides strong support for the proposed theory.

[18] These measures were constructed independently of historical or contemporaneous income levels, covering a wide range of sectors, technologies, and countries. Thus, these measures try to prevent biases caused by a country's development. Still, they may be subject to Eurocentric biases due to the choice of technologies and knowledge on which they focus (Selin, 1997; Blaut, 2012).

Table 1: Distance from the Pre-industrial Frontier and Technological Sophistication in 1500 CE

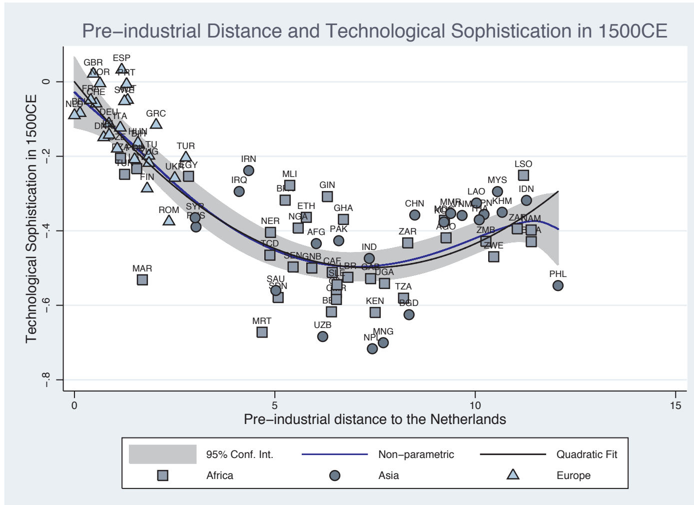
	Technological Sophistication in 1500CE							
	Unadjusted						Migration Adjusted	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Pre-industrial distance to NLD	-0.15***	-0.10***	-0.10***	-0.10***	-0.13***	-0.13***	-0.13***	-0.13***
	(0.02)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)
Sq. Pre-industrial distance to NLD	0.01***	0.01***	0.01***	0.01**	0.01***	0.01***	0.01***	0.01***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Pre-industrial distance to CHN					-0.03***	-0.04	-0.03***	-0.04
					(0.01)	(0.04)	(0.01)	(0.04)
Sq. Pre-industrial distance to CHN						0.00		0.00
						(0.00)		(0.00)
LDD NLD	8.25***	5.37***	5.63***	6.42***	7.66***	7.73***	7.28***	7.41***
	(0.89)	(0.50)	(0.36)	(1.25)	(1.26)	(1.62)	(1.13)	(1.52)
LDD CHN						124.61		61.21
						(1456.00)		(325.44)
Geographical Controls	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time Since Neolithic Revolution	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Continental FE	No	No	No	Yes	Yes	Yes	Yes	Yes
AET		1.87	2.15	3.51	13.05	14.95	10.24	12.88
δ		1.35	1.37	1.26	1.08	1.07	1.10	1.08
β^*		3.97	4.78	5.86	7.51	7.59	7.09	7.26
R^2	0.48	0.83	0.87	0.88	0.89	0.89	0.89	0.89
Adjusted-R^2	0.46	0.80	0.85	0.85	0.86	0.86	0.86	0.86
Observations	84	84	84	84	84	84	84	84

Notes: This table establishes the statistically and economically significant U-shaped relation between the distance to the frontier and technological sophistication in 1500CE across countries. Estimation by OLS. It additionally shows the Altonji et al. (2005) AET ratio as extended by Bellows and Miguel (2009). It also shows the δ and $\beta^*(1,1)$ statistics suggested by Oster (2014). All statistics suggest that the results are not driven by unobservables. Pre-industrial distance to Netherlands/China is the minimum total travel time (in weeks) along the optimal path between a country's capital and the Netherlands/China (see text for construction). Additional controls include latitude and latitude squared of the country's capital, Pre-1500CE caloric suitability, percentage of land area in tropics and subtropics, mean elevation above sea level, land area, island and landlocked dummies, and malaria (falciparum) burden. Least desirable distance (LDD) is the number of weeks that minimizes the quadratic relation with respect to the pre-industrial distance. It is equal to $-\beta_{Distance}/(2\cdot\beta_{Sq.Distance})$. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests.

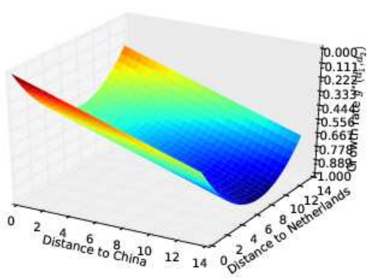
tal fixed effects and therefore for any unobserved time-invariant omitted variable at the continental level. The estimated LDD remains statistically significant at the 1% and implies an economically significant effect of the distance to the technological frontier. In particular, after accounting for a country's geography, the advent of the Neolithic Revolution, and continental fixed effects, the estimated LDD is 6.4 weeks and implies that an economy located 1-SD away from the LDD has a technological sophistication 31% higher than at the LDD.

Furthermore, columns (5) and (6) account for countries' distance to the eastern technological frontier in the Old World. If conventional wisdom were valid, then accounting for the distance to China should eliminate the non-monotonicity with respect to the distance to the western technological frontier (see Appendix E). Reassuringly, the U-shape remains statistically and economically significant. Finally, columns (7) and (8) use an alternative measure of technological sophistication that corrects for possible migration in the pre-1500 era. Reassuringly, the results remain qualitatively similar, with the estimated LDD at 7.3 weeks, which implies that an economy located 1-SD away from the LDD has a technological sophistication 24% higher than at the LDD.

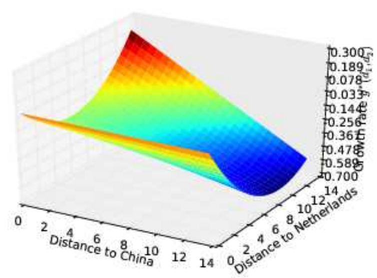
Figure 6: Distance from the Pre-industrial Frontier and Technological Sophistication in 1500 CE



(a) Technological Sophistication (conditional association based on column 7 of Table 1)



(b) Growth valley based on column 7 of table 1.



(c) Growth valley (interaction).

These findings suggests that after accounting for a country's geography, onset of the Neolithic Revolution and continental fixed effects there exists a U-shaped effect of the pre-industrial distance to the technological frontier on economic development. A potential concern with these results is that omitted factors might bias the results. In order to explore this issue, Table 1 additionally analyzes the potential bias generated by omitted variables. In particular, using statistics on selection on observables and unobservables (Altonji et al., 2005; Oster, 2014), it establishes that the degree of omitted variable bias is low and is unlikely to explain the magnitude of the estimated LDD. In fact, omitted factors would need to be 1-13 times more strongly and positively correlated with distance from the frontier, in order to account for the estimated LDD. This suggests that the estimated LDD is not downward biased, which would be a concern for the proposed U-shaped relation. Furthermore, the bias-corrected LDD (Oster, 2014), which assumes that the unobservables are as strongly correlated with distance as the set of observables that are accounted for columns (2)-(8), remains strictly positive, smaller than the sample maximum, and economically significant. These results suggest that it is unlikely that omitted country characteristics are significantly biasing the results.

Figures 6(a) and 6(b) depict the conditional relation between a country's technological sophistication and its distance from the frontier based on column (5) in Table 1. The figures show that the estimates generate a U-shape and a valley as predicted by the theory. Importantly, as shown in Figure 6(a), the semi-parametric regression and the fitted quadratic relation are almost identical, suggesting that the quadratic functional form is a good approximation to the non-monotonicity. A potential concern with these estimates is that the location of the LDD with respect to the Netherlands might depend on the distance from China. Reassuringly, as depicted in Figure 6(c), allowing for this interaction in the specification of column (5) does not affect the results qualitatively.

Table 2: Distance from the Pre-industrial Frontier and Technological Sophistication in 1500 CE
Robustness to Sector Specific Measures

	Technological Sophistication in 1500CE						
	(Agr)	(Comm)	(Trans)	(Mil)	(Ind)	(Av.)	(Av.M.)
Pre-industrial distance to NLD	-0.14***	-0.06	-0.13***	-0.21***	-0.12*	-0.13***	-0.13***
	(0.05)	(0.05)	(0.04)	(0.07)	(0.06)	(0.03)	(0.03)
Sq. Pre-industrial distance to NLD	0.01**	0.00	0.01**	0.01**	0.01**	0.01***	0.01***
	(0.00)	(0.00)	(0.00)	(0.01)	(0.00)	(0.00)	(0.00)
Pre-industrial distance to CHN	-0.03	-0.02	-0.05***	-0.05**	-0.03**	-0.03***	-0.03***
	(0.02)	(0.02)	(0.01)	(0.02)	(0.01)	(0.01)	(0.01)
LDD NLD	8.87***	8.83*	8.32***	7.60***	5.90***	7.66***	7.28***
	(2.21)	(4.82)	(1.90)	(1.82)	(1.02)	(1.26)	(1.13)
Continental FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Geographical Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time Since Neolithic Revolution	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Adjusted-R^2	0.64	0.80	0.74	0.69	0.67	0.86	0.86
Observations	84	84	84	84	84	84	84

Notes: This table establishes the statistically and economically significant U-shaped relation between the distance to the frontier and sectorial technological sophistication in 1500CE across countries. Each column analyzes a specific sector: agriculture (Agr.), communications (Comm.), transportation (Trans.), military (Mil.), industry (Ind.), average (Av.) and migration adjusted average (Av.M.) across sectors. All columns include the same set of controls as column (5) in Table 1. Least desirable distance (LDD) is the number of weeks that minimizes the quadratic relation with respect to the pre-industrial distance. It is equal to $-\beta_{Distance}/(2 \cdot \beta_{Sq.Distance})$. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests.

Another potential concern is that these results may reflect the aggregation of the sophistication measure across sectors. In order to mitigate this concern, Table 2 replicates the analysis for individual sectors. Reassuringly, as established in Table 2, the results remain qualitatively similar and suggest that the U-shape is not generated by aggregation and on the contrary holds for all sectors.

5.2 Robustness to Alternative Theories

This section explores the robustness of the results to alternative theories of development, omitted variables and mismeasurement. In particular, if the distance from the technological frontier correlates with other cultural, historical or institutional characteristics of a country, the estimated U-shaped relation may reflect alternative mechanisms or theories. Table 3 explores the confounding effects of lagged technological sophistication, European colonization, pre-industrial trade, local technological frontiers, and population diversity. For comparability, column (1) replicates the specification in column (5) of Table 1.

A potential concern with the previous findings is that the U-shape may reflect the effect of a country's lagged technology level. In particular, if conventional theory holds, then countries that are far from the frontier would be technologically backward and would benefit more from the advantages of backwardness (Gerschenkron, 1962). Specifically, countries that were lagging technologically should be distant and have larger productivity and technological gains as they imitate from the technological frontier. Thus, according to this alternative theory, lagged levels of technology should be positively correlated with technological sophistication in 1500CE. Moreover, accounting for a country's past technology level should eliminate the non-monotonicity. Reassuringly, as established in column (2), accounting for the potential advantages of backwardness, as reflected by a country's lagged technological sophistication level, does not alter the results.

Another potential concern is that the results reflect the effect of the European expansion of the 16th century. In particular, if regions far from the technological frontier were colonized by (more developed) Europeans, who brought their technology, human capital, institutions, and culture, then regions far from the frontier would be more developed, but the cause would not be the one suggested by the theory. The analysis mitigates this potential concern in two ways. First, and importantly, technological sophistication in 1500CE is measured *before* the large technological transfers generated by European conquest (Comin et al., 2010). Thus, the positive effects of remoteness should not reflect the dispersion of Europeans, but conditions *preceding* it. Moreover, as established in column (3), accounting for countries' post-1500CE colonial history, by controlling for a dummy that is equal to 1 if post-1500CE a country will be colonized by an European power (including Turkey) and 0 otherwise, does not qualitatively alter the results. Thus, the results do not seem to be driven by unobservable time-invariant country characteristics that might jointly determine development around 1500CE and future colonization.

A further potential concern is that the results may reflect the potential beneficial effects of trade. In particular, if countries that are far from the frontier are close to major pre-industrial trade, pilgrimage, or other routes through which information and goods were transported, then the conventional positive effects of trade may be reflected in the U-shape. In particular, regions far from the frontier would be developed due to trade and information flows arriving through these routes, and not the channel suggested by the theory. In order to explore this issue, the analysis accounts for a country's pre-industrial distance to the location of pre-industrial trade, pilgrimage, banking and mail routes (Ciolek, 2004). Reassuringly, as established in column (4) accounting for the pre-industrial distance to these networks does not alter the results.

Another potential concern is that the distance to the global technological frontiers is not as relevant for imitation and innovation as the distance to some local technological frontier. In particular, if the distance from the global technological frontier is negatively correlated with the distance to a local

Table 3: Distance from the Pre-industrial Frontier and Technological Sophistication in 1500 CE
Robustness to Alternative Theories

	Technological Sophistication in 1500CE						
	Base	Back	Colony	Trade	Local	OOA	All
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Pre-industrial distance to NLD	-0.13***	-0.13***	-0.14***	-0.13***	-0.14***	-0.14***	-0.15***
	(0.03)	(0.04)	(0.03)	(0.04)	(0.03)	(0.03)	(0.04)
Sq. Pre-industrial distance to NLD	0.01***	0.01***	0.01***	0.01***	0.01***	0.01**	0.01**
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Pre-industrial distance to CHN	-0.04***	-0.03**	-0.04***	-0.04***	-0.04***	-0.05***	-0.06***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.02)
Lagged technological sophistication		0.05					0.07
		(0.11)					(0.10)
European colony			-0.06				-0.08
			(0.06)				(0.07)
Pre-industrial distance to major trade routes				-0.00			0.02
				(0.03)			(0.04)
Pre-industrial distance to local frontier					0.01		0.01
					(0.02)		(0.02)
Pre-industrial distance to East Africa						0.01	0.02
						(0.01)	(0.01)
LDD NLD	7.77***	7.57***	7.83***	7.69***	7.84***	8.69***	9.83***
	(1.27)	(1.37)	(1.26)	(1.33)	(1.34)	(2.10)	(2.96)
Continental FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Geographical Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time Since Neolithic Revolution	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Adjusted-R^2	0.87	0.86	0.87	0.86	0.86	0.86	0.86
Observations	82	82	82	82	82	82	82

Notes: This table establishes the robustness of the U-shaped relation between the distance to the frontier and technological sophistication in 1500CE across countries to accounting for lagged technology levels, European colonization, trade, local technological frontiers, and the Out-of-Africa hypothesis. Estimation by OLS. See table 1 for list of additional controls. Least desirable distance (LDD) is the number of weeks that minimizes the quadratic relation with respect to the pre-industrial distance to the Netherlands. It is equal to $-\beta_{Distance}/(2 \cdot \beta_{Sq.Distance})$. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests.

technological frontier, then countries far from the global frontier would be close to their local frontier. Thus, if conventional theory were true, they would be developed, but not through the channel suggested by the theory. The analysis mitigates this potential concern by accounting for a country's pre-industrial distance to the local technological frontiers identified by Ashraf and Galor (2013). Specifically, column (5) shows that accounting for a country's pre-industrial distance to its local technological frontiers does not affect the results.[19]

An additional concern is that the results may reflect the effect of the Out-of-Africa (OOA) hypothesis on economic development (Ashraf and Galor, 2013). In particular, the OOA hypothesis suggests that economic development across countries in the Old World is positively associated with the pre-

[19] This does not imply that local technological frontiers played no role. In particular, technology might have diffused from the global to the local technological frontiers and then to the countries. But this implies that the *relevant* distance from the source of innovation is still the global technological frontier, since imitation can only happen from the local frontier once enough time has passed for the innovation to diffuse or be created there.

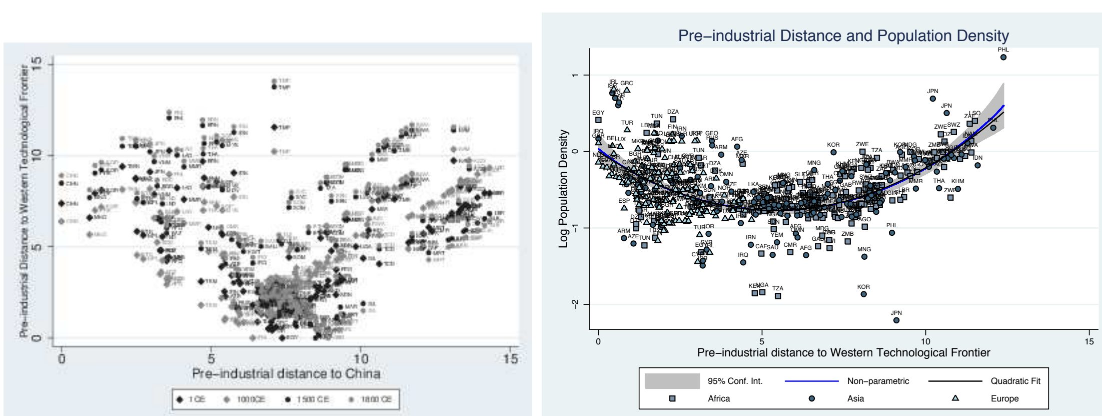
industrial distance to the Cradle of Humankind (East Africa). If the distance to the technological frontier is correlated with the distance to East Africa, then its omission may bias the results. Reassuringly, as established in column (6) accounting for the pre-industrial distance to East Africa does not alter the results.

Moreover, accounting jointly for all these other potential channels does not alter the results. This suggests that the U-shaped effect of the pre-industrial distance to the frontier on economic development does not capture the effect of these other theories. Finally, as established in Appendix F, including the New World, splitting the sample by regions, including the minimum distance to either frontier, or analyzing the alternative theories at the sectorial level does not alter the qualitative results either.

5.3 Historical Evidence II: Population Density (Panel-Data Analysis)

This section further explores the existence of a non-monotonic relation between the pre-industrial distance to the technological frontier and economic development across countries. In particular, using data on countries' population density during the pre-industrial era, and exploiting changes in the location of the western pre-industrial technological frontier in the Old World, the analysis explores the effect of distance to the frontier on economic development across countries. Importantly, changes in countries' distances to the pre-industrial frontiers across time, permit the analysis to exploit within-country variations to explore the existence of a U-shaped relation, while mitigating potential concerns due to the confounding effects of time-invariant country-specific characteristics. As illustrated in Figure 7(a), which depicts the location of Old World countries in the two-dimensional space defined by their distance to China and the western technological frontier in the years 1CE, 1000CE, 1500CE, and 1800CE, there exist large variations in distances to these frontiers both between and within countries across time.

Figure 7: Changes in the Location of the Frontier and Pre-industrial Population Density



(a) Countries' locations relative to China and the Western Technological Frontier in 1CE, 1000CE, 1500CE, and 1800CE.

(b) Distance to the Technological Frontier and Pre-industrial Population Density.

Table 4 explores the existence of a U-shaped relation between distance to the technological frontier and population density across countries during the pre-industrial era. In particular, column (1) uses Pooled OLS to establish that population density between 1CE and 1800CE had a U-shaped relation with the distance to the pre-industrial technological frontier across countries. The analysis in column (1) accounts for the distance to China as well as the geographical controls included in Table 1. The results suggest that the Least Desirable Distance, LDD, is economically and statistically significant, located at 5.9 weeks of travel from the pre-industrial frontier.

Table 4: Distance from the Pre-industrial Frontier and Pre-industrial Population Density

	Log Population Density in 1CE, 1000CE, 1500CE, and 1800CE							
	Pooled OLS					FE		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Pre-industrial distance to frontier	-0.41***	-0.39***	-0.33***	-0.24**	-0.18**	-0.38***	-0.15***	-0.13**
	(0.10)	(0.08)	(0.07)	(0.10)	(0.08)	(0.07)	(0.05)	(0.05)
Sq. Pre-industrial distance to frontier	0.04***	0.04***	0.03***	0.02**	0.02***	0.05***	0.02***	0.02***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.00)	(0.00)
Pre-industrial distance to China	-0.06	-0.18***	-0.14**	-0.14**	-0.03			
	(0.04)	(0.07)	(0.07)	(0.07)	(0.09)			
Pre-industrial distance to major trade routes					-0.35*			
					(0.19)			
Pre-industrial distance to East Africa					-0.01			
					(0.06)			
Colonial status					0.32**			0.10
					(0.16)			(0.12)
Pre-industrial distance to local frontier					0.00			-0.13*
					(0.10)			(0.08)
Caloric Suitability					-0.00			0.00
					(0.00)			(0.00)
LDD	5.90***	4.37***	6.12***	5.78***	4.59***	3.89***	4.16***	3.61***
	(0.53)	(0.44)	(0.68)	(1.24)	(0.98)	(0.40)	(0.69)	(0.81)
Country FE	No	No	No	No	No	Yes	Yes	Yes
Geographical Controls	Yes	Yes	Yes	Yes	Yes	No	No	No
Region FE	No	Yes	Yes	Yes	Yes	No	Yes	Yes
Period FE	No	No	Yes	Yes	Yes	No	Yes	Yes
Region × Period FE	No	No	No	Yes	Yes	No	Yes	Yes
Time Since Neolithic Revolution	No	No	No	No	Yes	No	No	Yes
Adjusted-R^2	0.49	0.59	0.74	0.76	0.78	0.21	0.86	0.86
Observations	463	463	463	463	463	463	463	463

Notes: This table establishes the statistically and economically significant U-shaped relation between distance to the frontier and population density across countries in the pre-industrial era. Column names denote the estimator used: (POLS) pooled OLS estimator, (FE) fixed effects estimator. Additional controls as in Table 1. Least desirable distance (LDD) is the number of weeks that minimizes the quadratic relation with respect to the pre-industrial distance to the technological frontier. It is equal to $-\beta_{Distance}/(2 \cdot \beta_{Sq.Distance})$. Heteroskedasticity robust standard error estimates clustered at the country level are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests.

Additionally, as established in columns (2)-(4), accounting for the potential effects of time-invariant characteristics of regions that shared a common history, religion, or language (Findlay and O'Rourke, 2007), as well as any period-specific unobserved heterogeneity, and any period-region-specific omitted factors does not qualitatively alter the results. Indeed, after accounting for historical region, period and period-region fixed effects, as well as countries' geographical characteristics, the estimated LDD remains statistically and economically significant, and is estimated to be located at 5.8 weeks of travel from the frontier.

Column (5) additionally accounts for the potential confounding effects of other sources of comparative development. In particular, it accounts for the potential confounding effect of (i) trade by controlling for a country's distance to a major trade route; (ii) population diversity as determined during the Out-of-Africa migration of modern humans by controlling for a country's pre-industrial distance to East Africa; (iii) the transition to agriculture by controlling for the number of years since a country experienced the Neolithic Revolution; (iv) European expansion by controlling for a country's colonial status in a period; (v) local technological spillovers by controlling a country's pre-industrial distance to a local technological frontier in a period; and (vi) agricultural productivity by controlling for the country's average caloric suitability in a period. Reassuringly, the U-shape and LDD remain statistically and economically significant.

Columns (6)-(8) further explore the potential effect of omitted time-invariant country-specific characteristics on the analysis. In particular, changes across time in the location of the western pre-industrial technological frontier in the Old World, permit the research to account for country fixed effects. Reassuringly, accounting for country fixed effects and thus for time-invariant country-specific characteristics does not alter the qualitative results. Moreover, additionally accounting for period and period-region fixed effects (column 7), as well as other time-varying pre-industrial characteristics of a country (column 8), does not affect the qualitative results either. Thus, these findings suggest that the U-shape is not reflecting omitted time-varying and time-invariant characteristics at the country and regional level. Figure 7(b) depicts the relation between a country's distance to the frontier and its population density in the pre-industrial era as estimated in column 8.

Equation 7 suggests that changes across time in countries' economic development should be associated with changes in their distance to the frontier and its square. Importantly, by taking differences in equation 7, the analysis accounts for any time-invariant country-specific heterogeneity. Table 5 further explores the predictions of the theory using this strategy. Column (1) establishes that countries' population density has an economically and statistically significant U-shaped relation with their distance to the technological frontier. As established in columns (2) and (3), this result is robust to accounting for region, period, and region-period fixed effects, as well as changes in the number of years since a country experienced the Neolithic Transition, changes in a country's caloric suitability, changes in a country's colonial status, and changes in a country's distance to a local technological frontier.

A potential concern with these findings, is that they are driven by a specific period or frontier. Although period, region and period-region fixed effects ought to account for any unobserved heterogeneity at the region, period, or period-region levels, columns (4)-(6) further mitigate this concern. While the analysis in columns (1)-(3) employed the first-difference of equation 7 to explore the relation, the analysis in columns (4)-(6) uses long-differences for the 1-1800CE era. In particular, column (4) explores the change in population density between 1000CE and 1800CE, column (5) between 1CE and 1500CE, and column (6) between 1CE and 1800CE. Reassuringly, the analysis in all three columns suggests that there exists a statistically and economically significant U-shaped relation between population density and the distance to the frontier across countries.

Table 5: Distance from the Pre-industrial Frontier and Pre-industrial Population Density

	Change in Log Population Density					
	All Periods			1000CE-1800CE	1CE-1500CE	1CE-1800CE
	(1)	(2)	(3)	(4)	(5)	(6)
ΔPre-industrial distance to frontier	-0.18***	-0.08*	-0.07*	-0.08	-0.23***	-0.32***
	(0.03)	(0.04)	(0.04)	(0.06)	(0.09)	(0.09)
ΔSq. Pre-industrial distance to frontier	0.01***	0.01***	0.01***	0.01**	0.03***	0.03***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.01)	(0.01)
ΔYears Since Transition to Agriculture			-0.72***			
			(0.13)			
ΔCaloric suitability			0.00			
			(0.00)			
ΔColonial status			0.03			
			(0.12)			
ΔPre-industrial distance local frontier			-0.06			
			(0.06)			
LDD	5.92***	4.40***	4.04***	3.87***	3.67***	4.66***
	(0.45)	(0.99)	(1.21)	(1.46)	(0.75)	(0.64)
Region FE	No	Yes	Yes	Yes	Yes	Yes
Period FE	No	Yes	Yes	No	No	No
Region × Period FE	No	Yes	Yes	No	No	No
Adjusted-R^2	0.43	0.44	0.43	0.43	0.47	0.43
Observations	343	343	343	343	343	343

Notes: This table establishes the statistically and economically significant U-shaped relation between distance to the frontier and population density across countries in the pre-industrial era. (i) Columns (1)-(3) use a panel of changes in countries' log population density and distances to the frontier (First Differences). Columns (4)-(6) use long differences (two periods columns (4)-(5), column (6) three periods). (ii) Least desirable distance (LDD) is the number of weeks that minimizes the quadratic relation with respect to the pre-industrial distance to the technological frontier. It is equal to $-\beta_{Distance}/(2 \cdot \beta_{Sq.Distance})$. (iv) Heteroskedasticity robust standard error estimates clustered at the country level are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests.

5.4 Alternative Tests of the Theory

This section explores additional predictions of the theory. In particular, the theory predicts that countries located farther than the Least Desirable Distance (LDD) from the technological frontier should grow faster, and increasing their distance to the technological frontier should boost economic development during the pre-industrial era. Additionally, the theory predicts a cumulative positive effect of being distant from the technological frontier, reflecting its beneficial effect on the emergence of institutional and cultural characteristics conducive to innovation and entrepreneurship.

Table 6 explores the first prediction that countries that are distant from the pre-industrial technological frontier tend to grow faster, and that increases in their distance boosts their economic performance. Column (1) establishes that the pre-industrial distance to the technological frontier in a period is positively associated with future increases in population density during the following period. Additionally, column (2) establishes that distant countries that became even more distant from the frontier, benefited of a boost to population density growth. These results account for the potential confounding effects of region, period and region-period unobservable heterogeneity.

A potential concern with the results of columns (1) and (2) is that they reflect the confounding

Table 6: Distance from the Pre-industrial Frontier and Pre-industrial Population Density Growth

	Change in Log Population Density					
	Western Frontier				Local Frontier	Closest Frontier
	(1)	(2)	(3)	(4)	(5)	(6)
Lagged Pre-industrial distance to frontier	0.04**	0.04**	0.04**	0.04**	0.08***	0.03*
	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
ΔPre-industrial distance to frontier		-0.03		-0.03	-0.27***	-0.04
		(0.04)		(0.04)	(0.08)	(0.04)
(Lag ×Δ)Pre-industrial Distance to frontier		0.01**		0.01**	0.10***	0.01**
		(0.01)		(0.01)	(0.02)	(0.01)
Region FE	Yes	Yes	Yes	Yes	Yes	Yes
Period FE	Yes	Yes	Yes	Yes	Yes	Yes
Region × Period FE	Yes	Yes	Yes	Yes	Yes	Yes
Other Controls and Interactions	No	No	Yes	Yes	Yes	Yes
Adjusted-R^2	0.43	0.44	0.43	0.43	0.47	0.43
Observations	343	343	343	343	343	343

Notes: This table establishes that during the pre-industrial era, countries located far from the technological frontier had higher economic growth as captured by growth in population density. Moreover, countries that became more distant from the frontier got an additional boost to their economic growth. Columns (1)-(4) use the distance to the western technological frontier. Column (5) and (6) show similar effects using a country's distance to a local or to the closest technological frontier. All columns account for region, time and region×time fixed effects. Additionally, columns (3)-(6) account for lagged values and changes in countries' caloric suitability and colonial status. Heteroskedasticity robust standard error estimates clustered at the country level are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests.

effects of other time-varying country characteristics. In order to mitigate this concern, columns (3) and (4) replicate the analysis, but account additionally for the lag, difference and interaction of the set of country's time-varying characteristics included in Table 4. Reassuringly, the results remain unchanged. Furthermore, the analysis uncovers qualitatively similar effects of the increases in the distance to the local or to the closest frontier (columns 5 and 6).

Table 7 further explores the predicted benefits of being far from the frontier. In particular, it analyzes the association between the time (measured in centuries) that a country spent more than one standard deviation farther away than the average country from pre-industrial technological frontiers, i.e., at the More Desirable Distances (MDD). The theory predicts that the more time a country was located at the MDD the higher its economic development. Column (1) establishes that after accounting for country, period, and region-period fixed effects, the time spent at the MDD is positively associated with population density. The results suggest that for each century a country was located at the MDD, its population density increased by 3%. Additionally, accounting for a country's colonial status, its distance to a local technological frontier, its caloric suitability, and the time since the Neolithic Revolution does not affect the results (column 2).

A potential concern with these results is that countries located at the MDD in one period, may be located close to another frontier in a different period. Thus, the positive effect of being located at the MDD may be reflecting the confounding positive effect of being close to the frontier in different periods. In order to mitigate this concern, columns (3)-(7) constrain the sample to countries that are

Table 7: Persistent Effect of Distance from the Pre-industrial Technological Frontier on Pre-industrial Population Density

	Log Population Density in Period						
	Full Sample		Distance From Frontier Always ≥				
			1 Std	2 Std			
					Distance to China Always ≥		
					1 Std	2 Std	3 Std
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Time at MDD	0.03**	0.03**	0.03**	0.04**	0.03**	0.03**	0.03**
	(0.02)	(0.02)	(0.01)	(0.02)	(0.01)	(0.01)	(0.01)
Colonial Status		0.06	0.20**	0.23*	0.24	0.16	0.16
		(0.12)	(0.09)	(0.12)	(0.16)	(0.13)	(0.13)
Pre-industrial distance local frontier		-0.09	0.28***	0.39***	0.39***	0.42***	0.42***
		(0.08)	(0.09)	(0.08)	(0.07)	(0.07)	(0.07)
Caloric Suitability		-0.00	-0.00	-0.00	-0.00	-0.00	-0.00
		(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region × Time FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time Since Neolithic Revolution	No	Yes	Yes	Yes	Yes	Yes	Yes
Adjusted-R^2	0.85	0.85	0.90	0.91	0.94	0.95	0.95
Observations	463	463	298	178	161	110	106

Notes: This table establishes the positive cumulative effect of being relatively far from the technological frontier during the pre-industrial era. In particular, years at MDD measures the number of centuries a country had been located at more than 9 weeks of travel (more than one standard deviation further away than the average country) from pre-industrial technological frontiers. Columns (3)-(7) additionally impose that the country is never too close to a western frontier, nor is located close to the eastern frontier (China). All columns account for country, time and region×time fixed effects. Heteroskedasticity robust standard error estimates clustered at the country level are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests.

always more than 1 or 2 standard deviations away from the technological frontiers.[20] As established in columns (3) and (4), constraining the sample to countries located always more than 1 or 2 standard deviations away from the technological frontier does not affect the results. Moreover, focusing on countries that are additionally far away from China, thus accounting for the potential confounding effect of diffusion from the Eastern technological frontier does not alter the results either.

Finally, Table 8 establishes the robustness of the results to the measure of the time a country was located at the MDD. In particular, instead of using the time spent at the MDD, which might potentially be subject to measurement error, it employs the MDD Index that counts the number of pre-industrial technological frontiers for which the country was located at the MDD. Reassuringly, the results remain qualitatively similar and imply that for each pre-industrial technological frontier for which a country was at the MDD, its population density increased by 18%.

[20]Constraining the sample to include only countries that are always more than 3 standard deviations (i.e., 9 weeks) away from the technological frontier in every period results in a much smaller sample size. Reassuringly, the results remain qualitatively similar.

Table 8: Persistent Effect of Distance from the Pre-industrial Technological Frontier on Pre-industrial Population Density

	Log Population Density in Period						
	Full Sample		Distance From Frontier Always ≥				
			1 Std	2 Std			
					Distance to China Always ≥		
					1 Std	2 Std	3 Std
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
MDD Index	0.21***	0.22***	0.20***	0.22***	0.18**	0.18**	0.18**
	(0.07)	(0.07)	(0.07)	(0.07)	(0.07)	(0.07)	(0.07)
Colonial Status		0.06	0.19**	0.23*	0.24	0.09	0.09
		(0.12)	(0.09)	(0.12)	(0.16)	(0.12)	(0.12)
Pre-industrial distance local frontier		-0.10	0.26***	0.35***	0.35***	0.39***	0.39***
		(0.08)	(0.08)	(0.07)	(0.06)	(0.06)	(0.06)
Caloric suitability		-0.00	0.00	-0.00	-0.00	-0.00	-0.00
		(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Country FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Period FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region × Period FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time Since Neolithic Revolution	No	Yes	Yes	Yes	Yes	Yes	Yes
Adjusted-R^2	0.85	0.85	0.90	0.92	0.94	0.96	0.96
Observations	463	463	298	178	161	110	106

Notes: This table establishes the positive cumulative effect of being far from the technological frontier during the pre-industrial era. In particular, MDD measures the number of technological frontiers for which a country had been located at more than 9 weeks of travel (more than one standard deviation further away than the average country). Columns (3)-(7) additionally impose that the country is never too close to a western frontier, nor is located close to the eastern frontier (China). All columns account for country, time and region×time fixed effects. Heteroskedasticity robust standard error estimates clustered at the country level are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests.

6 Distance to the Pre-industrial Technological Frontier and Contemporary Economic Development

This section explores the persistent effects of the distance to the pre-industrial technological frontier on contemporary economic development. In particular, it establishes the existence of a U-shaped relation between countries' contemporary GDP per capita and their distance to the UK, which was the technological frontier around 1800. Moreover, the analysis demonstrates a cumulative positive effect of being far from the technological frontiers during the pre-industrial era on contemporary economic development across countries. In particular, the analysis demonstrates the persistent effect of distance from the pre-industrial frontier on contemporary GDP per capita, innovation and entrepreneurial activity across countries. Thus, the results suggest that distance from the frontier may have beneficial effects on innovation and entrepreneurship as proposed by the theory.

Table 9 explores the persistence of the non-monotonic effect of distance from the (last) pre-industrial technological frontier on contemporary economic development across countries. In particular, it analyzes whether countries' pre-industrial distance to the UK has a U-shaped association with contemporary technological sophistication (2000CE) and income per capita (average 2000-2015CE).

Table 9: Distance from the Pre-industrial Technological Frontier and Contemporary Development

	Contemporary Development							
	Technological Sophistication				Log[GDP per capita (2000-2015CE)]			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Pre-industrial distance to frontier	-0.16***	-0.14***	-0.14***	-0.14***	-1.03***	-0.65***	-0.64***	-0.61***
	(0.01)	(0.03)	(0.03)	(0.03)	(0.09)	(0.14)	(0.16)	(0.17)
Sq. Pre-industrial distance to frontier	0.01***	0.01***	0.01***	0.01***	0.07***	0.05***	0.05***	0.05***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.01)	(0.01)	(0.01)	(0.01)
Pre-industrial distance CHN			0.00	0.01			0.01	0.04
			(0.01)	(0.01)			(0.05)	(0.07)
Pre-industrial distance to Addis Ababa				0.01				0.13
				(0.03)				(0.14)
Sq. Pre-industrial distance to Addis Ababa				-0.00				-0.01
				(0.00)				(0.01)
European Colony (includes Turkey)				-0.07				-0.45
				(0.05)				(0.37)
LDD	7.32***	7.06***	7.02***	6.97***	7.25***	6.25***	6.21***	6.15***
	(0.28)	(0.37)	(0.39)	(0.42)	(0.27)	(0.40)	(0.50)	(0.54)
Geographical Controls	No	Yes	Yes	Yes	No	Yes	Yes	Yes
Time Since Neolithic Revolution	No	Yes	Yes	Yes	No	Yes	Yes	Yes
Continental FE	No	Yes	Yes	Yes	No	Yes	Yes	Yes
Adjusted-R^2	0.60	0.71	0.71	0.70	0.57	0.77	0.77	0.77
Observations	97	97	97	97	112	112	112	112

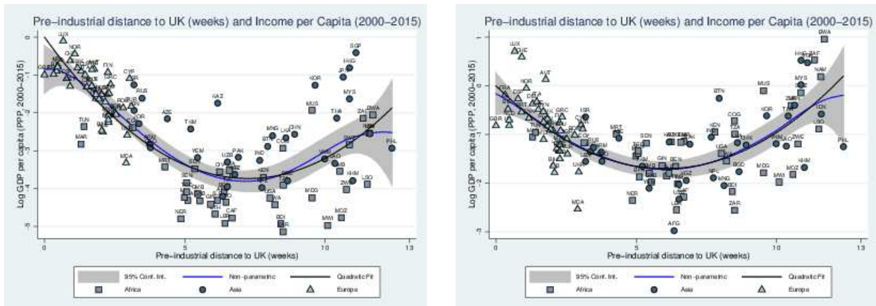
Notes: This table establishes the U-shaped association between the distance to the pre-industrial technological frontier and contemporary development as measured by technological sophistication in 2000CE and income per capita (average 2000-2015CE) across countries. The analysis accounts for country's geographical characteristics, the time since the country experienced the Neolithic Revolution, continental fixed effects, colony fixed effects, and pre-industrial distances to China and East Africa (and their squares). Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests.

Columns (1) and (5) establish that there exist unconditional U-shaped associations between the distance to the pre-industrial frontier and both measures of contemporary development across countries. Even though the estimates are based on two different measures and samples, the estimated Least Desirable Distance (LDD), at 7.3 weeks of travel from the UK, is similar in both columns. Figure 8(a) depicts the quadratic relation as well as the results of a non-parametric regression between income per capita and distance to the pre-industrial frontier. The figure suggests that the quadratic specification is a good approximation to the underlying association.

Clearly, these U-shaped relations may be biased due to omitted variables. In order to mitigate this potential concern, columns (2)-(4) and (6)-(8) explore their robustness to accounting for the effect of various potential confounders. Reassuringly, the U-shaped relation and the existence of the LDD are robust to accounting for a country's geographical characteristics; the number of years since a country experienced the Neolithic Revolution; continental fixed effects; the pre-industrial distance to China and its square; the effect of European colonization; and the pre-industrial distance to East Africa and its square. Figure 8(b) depicts the U-shaped relation and semi-parametric regression associated with the specification in column (8). The results suggest that the LDD is located at 6 weeks of travel from the pre-industrial technological frontier. Moreover, additionally accounting for geographical characteristics associated with the emergence of pre-modern states, risk attitudes, and cooperation;

religious composition of the population; institutional quality; a country's share of population with European ancestry; legal origins; and the distance to the contemporary technological frontier does not alter the qualitative nature of the results.[21]

Figure 8: Distance to Pre-Industrial Technological Frontier (UK) and Income per capita (2000-2015CE)



(a) Unconditional Relation (b) Conditional Relation

Table 10: Persistent Effect of Distance from the Pre-industrial Technological Frontier on Contemporary Development

	Log[GDP per capita (2000-2015CE)]								
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Time at MDD	0.07***	0.07***	0.08***	0.07**	0.07**	0.08***	0.08***	0.05*	0.07**
	(0.02)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)
Regional FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Geographical Controls	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time Since Neolithic Revolution	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Colony FE	No	No	Yes	No	Yes	Yes	Yes	Yes	Yes
Volatility Controls	No	No	No	Yes	No	No	No	No	No
Religious Shares	No	No	No	No	Yes	No	No	No	No
Constraints on Executive	No	No	No	No	No	Yes	No	No	No
Population Share with European Ancestry	No	No	No	No	No	No	Yes	No	No
Legal Origin FE	No	No	No	No	No	No	No	Yes	No
Distance to USA	No	No	No	No	No	No	No	No	Yes
Adjusted-R^2	0.70	0.76	0.76	0.77	0.76	0.76	0.76	0.79	0.76
Observations	105	105	105	105	105	105	105	105	105

Notes: This table establishes the positive cumulative effect of being far from the technological frontier during the pre-industrial era on contemporary income per capita (average 2000-2015CE). The analysis accounts for regional fixed effects, country's geographical characteristics, the time since the country experienced the Neolithic Revolution, colony fixed effects, geographical determinants of statehood, cooperation and risk preferences, religious composition of the population, constraints on the executive, European ancestry, legal origins, and distance to the contemporary technological frontier. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests.

Table 10 further explores the potential persistent effects of distance from the pre-industrial technological frontier on contemporary economic development across countries. It exploits variations in the location of the western pre-industrial frontier in the Old World to analyze the effect of the time a country spent far from the pre-industrial technological frontier. In particular, column (1) establishes

[21]These results can be obtained from the author upon request.

the positive association between the time (measured in centuries) that a country spend more than one standard deviation farther away than the average country from pre-industrial technological frontiers, i.e., at the More Desirable Distances (MDD). The results suggest that after accounting for regional fixed effects, each additional century at the MDD is associated with a 7% increase in contemporary income per capita. Moreover, accounting for other geographical characteristics of a country, the number of years since it experienced the Neolithic revolution and its colonial experience does not qualitatively alter the results (columns 2-3).

A potential concern with these results is that they may be capturing the potential confounding effects of other sources of economic development. In particular, the time spent at the MDD may be correlated with geographical characteristics associated with risk attitudes, trust, cooperation and pre-modern states (Durante, 2009; Depetris-Chauvin and Özak, 2015b; Bentzen et al., 2016), which may have independently affected development. Similarly, changes in the distance to the pre-industrial technological frontier may be correlated with the religious composition of a country, which in turn may independently affect its development. Moreover, the results may be biased if a country's distance to the pre-industrial technological frontier is associated with the quality of its institutions, the share of its population that descends from Europeans, its legal origins, or its distance to the contemporary technological frontier. Reassuringly, as columns (4)-(9) establish, accounting for these characteristics does not alter the estimated positive association between the time spent at the MDD and contemporary economic development.

Additionally, the analysis explores the potential persistent effects of distance from the pre-industrial technological frontier on contemporary innovation across countries. In particular, the theory predicts that periods of remoteness from the technological frontier during the pre-industrial era promoted the emergence of a culture and institutions that were conducive to innovation and entrepreneurship, and thus to economic development. Table 11 explores this prediction by analyzing the association between a country's time spent at the MDD and its contemporary propensity to innovative, as measured by its average patenting activity per capita in the 2000-2015CE period. Column (1) establishes that after accounting for unobserved regional heterogeneity, an additional century of remoteness from the technological frontier during the pre-industrial era is associated with a 15% increase in the number of patents per capita. Additionally accounting for geographical characteristics, the time since the Neolithic Revolution, the effects of colonization, and the geographical characteristics associated with risk attitudes, trust, cooperation and pre-modern states increases the statistical and economic significance of the effect. Specifically, after accounting for all these confounders, the results suggest that an additional century of remoteness from the technological frontier during the pre-industrial era is associated with an increase of 17% in contemporary patenting activity (columns 2-5).

A potential concern with these results is that they capture foreign patenting activity. In order to mitigate this concern, columns (6) replicates the analysis for the domestic patenting activity of residents only. In particular, it establishes that there is a statistically and economically significant positive association between the time spent at the MDD and domestic patenting activity by residents of a country. After accounting for the same set of controls as in column (5), the analysis suggests that an additional century of remoteness from the technological frontier during the pre-industrial era

Table 11: Persistent Effect of Distance from the Pre-industrial Technological Frontier on Contemporary Patenting Activity

	Log[Patents per Capita (2000-2015CE)]					
	All					Residents
	(1)	(2)	(3)	(4)	(5)	(6)
Time at MDD	0.15**	0.14**	0.14**	0.17***	0.17***	0.20***
	(0.07)	(0.06)	(0.06)	(0.06)	(0.06)	(0.06)
Regional FE	Yes	Yes	Yes	Yes	Yes	Yes
Geographical Controls	No	Yes	Yes	Yes	Yes	Yes
Time Since Neolithic Revolution	No	No	No	Yes	Yes	Yes
Colony FE	No	No	No	Yes	Yes	Yes
Volatility Controls	No	No	No	No	Yes	Yes
Adjusted-R^2	0.60	0.70	0.70	0.74	0.78	0.80
Observations	84	84	84	84	84	84

Notes: This table establishes the positive cumulative effect of being far from the technological frontier during the pre-industrial era on domestic patenting activity (average patents per capita 2000-2015CE). The analysis accounts for regional fixed effects, country's geographical characteristics, the time since the country experienced the Neolithic Revolution, colony fixed effects, and geographical determinants of statehood, cooperation and risk preferences. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests.

is associated with an increase of 20% in contemporary domestic patenting activity by residents. This result supports the proposed theory that distance from the frontier during the pre-industrial era was conducive to the emergence of a culture and institutions that promote innovation and entrepreneurship.

Table 12: Persistent Effect of Distance from the Pre-industrial Technological Frontier on Contemporary Domestic Patenting Activity (Robustness)

	Log[Patents per capita by Residents (2000-2015CE)]							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Time at MDD	0.18***	0.17***	0.17***	0.17**	0.18***	0.12**	0.26***	0.18**
	(0.05)	(0.06)	(0.06)	(0.07)	(0.05)	(0.06)	(0.05)	(0.07)
Regional FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Geographical Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time Since Neolithic Revolution	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Colony FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Volatility Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Religious Shares	No	Yes	No	No	No	No	No	Yes
Constraints on Executive	No	No	Yes	No	No	No	No	Yes
Main Colonizer FE	No	No	No	Yes	No	No	No	Yes
Population Share with European Ancestry	No	No	No	No	Yes	No	No	Yes
Legal Origin FE	No	No	No	No	No	Yes	No	Yes
Distance to USA	No	No	No	No	No	No	Yes	Yes
Adjusted-R^2	0.80	0.79	0.80	0.77	0.80	0.84	0.81	0.82
Observations	81	81	81	81	81	81	81	81

Notes: This table establishes the robustness of the positive cumulative effect of being far from the technological frontier during the pre-industrial era on domestic patenting activity (average patents per capita 2000-2015CE) by residents. In particular, it establishes the robustness of the result to accounting for religious composition, institutional quality, colonizer's identity, European ancestry, legal origins, and distance to contemporary frontier. All columns account for the full set of controls in Table 11. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests.

A major potential concern with this result is that it may capture the confounding effect of omitted cultural or institutional characteristics of the country. In particular, the time spent at the MDD may be correlated with the religious composition of a country, and thus with a major cultural determinant of economic behavior (Andersen, Bentzen, Dalgaard and Sharp, 2016). Similarly, given the European expansion in the post-1500 era, the time spent at the MDD may be correlated with the culture or institutions brought by European migrants. Moreover, the results may be biased if the time spent at the MDD is correlated with a country's distance to the contemporary technological frontier.

In order to mitigate these concerns, Table 12 explores the robustness of the positive association between the time spent at the MDD and domestic patenting activity by residents to accounting for the potential effects of these confounders. Column (1) replicates the analysis of column (6) in Table 11 for the sample of countries for which all additional controls are available. The result remains statistically and economically significant and suggests that an additional century of remoteness from the technological frontier during the pre-industrial era is associated with an increase of 18% in contemporary domestic patenting activity by residents. Reassuringly, accounting for a country's religious composition, and thus for any cultural effects of religion (column 2); its level of constraints on the executive (column 3); fixed effects for the identity of its main colonizer, and thus for any unobserved cultural, institutional or ancestral characteristics associated with its main colonizer (column 4); the share of its population that descends from European ancestors, and thus for the extent of European influence in the country's culture, institutions and human capital (column 5); fixed effects for the origin of its legal system, and thus for any unobserved heterogeneity due to its legal tradition (column 6); or its distance to the contemporary technological frontier does not qualitatively affect the results. Moreover, accounting simultaneously for all these potential confounders has no effect on the estimated relation.

Another concern with these results is that not all innovative activity results in new patents. Thus, the results may underestimate the potential positive effect of the time spent at the MDD on innovation. On the other hand, patents may not translate directly into economic activity and thus development. In order to mitigate this concern, Table 13 analyzes the effect of the time spent at the MDD on entrepreneurship. In particular, innovative activity that results in the creation of new business opportunities should potentially be accompanied by the arrival of new firms in the economy. Reassuringly, the results in Table 13 suggest that there exists an economically and statistically significant positive association between the time spent at the MDD and the density of new firms. Moreover, this association is robust to accounting for regional fixed effects and countries' characteristics like geography, the time since the Neolithic Revolution, colonial fixed effects, religious composition, institutional quality, colonizer fixed effects, European ancestry, legal origin fixed effects, and the distance to the contemporary technological frontier. In particular, after accounting for the potential effect of all these confounders, the analysis suggests that an additional century of remoteness from the technological frontier during the pre-industrial era is associated with an increase of 19% in the number of new firms per 1,000 people.[22]

[22] Tables F.10, F.11 and F.12 provide additional support to the proposed thesis. They establish that there exists a U-shaped association between patenting and entrepreneurial activity and the distance to the last pre-industrial technological frontier.

Table 13: Persistent Effect of Distance from the Pre-industrial Technological Frontier on Contemporary Entrepreneurial Activity

	Log[New Firms per 1,000 people (2000-2015CE)]						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Time at MDD	0.16***	0.19**	0.18**	0.19**	0.18**	0.17**	0.19**
	(0.06)	(0.08)	(0.08)	(0.08)	(0.08)	(0.08)	(0.09)
Regional FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Geographical Controls	No	Yes	Yes	Yes	Yes	Yes	Yes
Time Since Neolithic Revolution	No	No	Yes	Yes	Yes	Yes	Yes
Colony FE	No	No	No	Yes	Yes	Yes	Yes
Volatility Controls	No	No	No	No	Yes	Yes	Yes
Religious Shares	No	No	No	No	No	Yes	Yes
Constraints on Executive	No	No	No	No	No	Yes	Yes
Main Colonizer FE	No	No	No	No	No	No	Yes
Population Share with European Ancestry	No	No	No	No	No	No	Yes
Legal Origin FE	No	No	No	No	No	No	Yes
Distance to USA	No	No	No	No	No	No	Yes
Adjusted-R^2	0.41	0.56	0.55	0.55	0.54	0.54	0.65
Observations	85	85	85	85	85	85	85

Notes: This table establishes the positive cumulative effect of being far from the technological frontier during the pre-industrial era on the number of new firms registered per 1,000 people of ages 15-64 (average 2000-2015CE). In particular, it establishes the robustness of the result to accounting for regional fixed effects, all geographical controls in Table 11, time since the country experienced the Neolithic Revolution, colony fixed effects, geographical determinants of statehood, risk attitudes and cooperation, religious composition, institutional quality, colonizer's identity, European ancestry, legal origins, and distance to contemporary frontier. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests.

7 Conclusions

This research explores the effects of distance to the pre-industrial technological frontiers on comparative economic development in the course of human history. It proposes that during the pre-industrial era, while a country's remoteness from the frontier diminished imitation, it fostered the emergence of a culture conducive to innovation, knowledge creation and entrepreneurship, which may have persisted into the modern era. The emergence of these cultural values generated a positive force that counteracted the conventional negative effects of distance. Thus, the theory proposes that the interaction of these opposing forces resulted in a U-shaped relation between economic development and the distance to the frontier in the pre-industrial era. In line with this prediction, the analysis establishes both theoretically and empirically that distance to the frontier had a persistent non-monotonic effect on a country's pre-industrial level of economic development. In particular, advancing a novel measure of the travel time to the technological frontiers, the analysis establishes a robust persistent U-shaped relation between distance to the frontier and pre-industrial economic development across countries. Moreover, it demonstrates that countries, which throughout the last two millennia were relatively more distant from these frontiers, have higher contemporary levels of innovation and entrepreneurial activity, suggesting that distance from the frontier may have fostered the emergence of a culture conducive to innovation, knowledge creation, and entrepreneurship.

Although technological progress may have diminished the role of geographical distance in the contemporary period, the theory suggests that cultural and institutional differences from the contemporary technological frontier may be similarly conducive to innovation and entrepreneurship in the modern era. Thus, these forces may be driving the innovative and entrepreneurial activities in locations where cultural and institutional differences may prevent technological diffusion from the contemporary technological frontier. In particular, health care innovations that could substantially lower costs and increase access are being generated in countries that are culturally and institutionally different from the West. For example, the development and simplification of cataract surgery with lens implantation at the community level, small incision cataract surgery, intraocular lenses, and sutureless surgical procedures has been pioneered by a group of doctors in the Tilganga Eye Center in Nepal. Similarly, General Electric's strategy of reverse innovation, in which products are developed in markets dissimilar to the frontier and then distributed globally, have generated innovations like the portable ultrasound and ECG (Immelt et al., 2009).

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APPENDIX NOT FOR PUBLICATION (available online only)

A Human Mobility Index and Seafaring

This section explains the construction of the Human Mobility Index with Seafaring (HMISea) and the distance measures based on it. Additionally, it performs validation tests for these measures. Unlike previous approaches, the analysis measures geographic distances during the pre-industrial era by the travel time between locations. This approach can be justified by fact that during the pre-industrial era, travel time were the most important determinants of transportation costs (O'Rourke and Williamson, 2001). The analysis constructs the HMISea in two steps: First, the analysis constructs the Human Mobility Index (HMI), which estimates the time required to travel on each square kilometer on land during the pre-industrial era. Second, it estimates the time required to cross each square kilometer of sea during the pre-industrial era.

The Human Mobility Index (HMI) estimates the potential time to cross each square kilometer on land based on data on infantry movement (Hayes, 1994). In particular, Hayes (1994) estimates the maximal sustainable speeds of dismounted infantry movement under different temperature, relative humidity, slope, and terrain conditions: he determined the maximum sustainable metabolic rates for soldiers of weight 70 kilograms, 23 years of age, and 1.7 meters height, each carrying a load of 20 kilograms, which he then used to estimate the maximum sustainable speed for each terrain characteristic. Hayes focused on the levels of metabolic rates and speeds that can be sustained for long periods of time without causing the soldier to become a victim of heat-exhaustion. The different meteorological, terrain, and risk conditions considered by him are:

- temperature: 5°-35°C in 5° increments
- relative humidity: 5, 25, 50, 75 and 95%
- cloud cover: night, cloudy, partially cloudy, clear sky
- slope: -50% to 50% in 10% steps, except in the range -20% to 20% where 5% steps were used
- terrain: black top, dirt road, and loose sand
- heat exhaustion risk: high, medium, and low

Using Hayes (1994) data, this paper estimates the relationship between the highest sustainable speed and the geographical variables considered by him. The estimated relationship can be applied to the geographical conditions in each cell of 1 square kilometer in the world to estimate the minimum travel time to cross it.

In order to estimate the time of travel on each square kilometer on land, the analysis uses the estimated relationship under clear sky, high risk conditions, and loose sand. In particular, Hayes' data suggest that the high risk of heat stress assumption generates *ceteris paribus* the highest sustainable speeds among any configuration of meteorological and terrain conditions. On the other hand, the clear sky assumption generates the slowest speeds sustainable under high risk of heat exhaustion. Additionally, among the types of terrains Hayes analyzes, loose sand seems closer to the types one would expect humans to have encountered earlier in history. Thus, using these assumptions HMI tries to approximate conditions present in the pre-industrial era. Using this configuration of sky cover conditions, heat exhaustion risk levels, and terrain types, the analysis computes the maximum sustainable speed on each square kilometer in the world, which determines the (minimum) time required to cross it, given its slope, its temperature, and its relative humidity.[23]

[23]While it would be possible to use data for a particular day or month or year, the analysis uses the average yearly

In order to construct the Human Mobility Index (HMI), the analysis computes the average slope in each cell i of one square kilometer ($30'' \times 30''$) in the world using the GLOBE data set (GLOBE Task Team and others, 1999) as

$$slope_i = \frac{1}{\bar{l}}\left(\frac{1}{8}\sum_{k=1}^{8}(h_i - h_{j_k})\right)$$

where the term in parenthesis is the average change in elevation when moving out of the cell i and $\bar{l}$ is the distance between the centers of the cells. Additionally, the analysis uses the average temperature in each cell i according to Hijmans et al. (2005) and the average relative humidity from New et al. (2002). Given that New et al. (2002) present their data in cells of size $10' \times 10'$, the analysis assigns to each cell i of size $30'' \times 30''$, the value of the $10' \times 10'$ cell in which it is contained without any transformation.

The HMI cost surface can be used to calculate distances between any two points on the same continental mass to estimate the minimum travel time between them, for periods before the advent of seafaring technology or for distances among places in which seafaring is either unfeasible or regarded as inferior to mobility by land. Although this might be useful for helping to answer certain types of questions, the lack of the possibility to cross major bodies of water might limit the usefulness of these analyses and the types of questions that can be answered. For this reason, the analysis extends the HMI cost surface in order to incorporate the possibility of travel across larger bodies of water.

The history of ancient seafaring can be characterized by three major events: (i) the introduction of boats with paddles (ca. 11000-5,000 BCE), (ii) the invention of the sail (ca. 3,500 BCE), and (iii) the invention of navigational devices (ca. 100 CE). Table A.1 shows some of the major developments in the history of seafaring from 11000 BCE to 1,200 CE. Although many improvements and innovations were accumulated during this period, the data suggests that the gains that these permitted in terms of speed and wider applicability were limited (Braudel, 1972). Özak (2010) constructs a data set that compiles estimations, made by historians and from primary sources, of the travel speed that ships attained in various voyages that took place between the years 500 BCE and 1500 CE. This data suggests that the average speed remained relatively stable during this period.[24] The main differences in speed stem, unsurprisingly, not from the period in which the voyage took place, but its purpose and location. In particular, the climatic conditions, currents, and winds characteristic of each sea are reflected on the speeds attained.

Based on this information, the analysis sets the speed required to cross a cell i in a sea by averaging the speeds of the voyages that passed through that sea. If no information is available, although the historical record indicates that sea travel was common in that sea before the Era of Exploration, the analysis assigns to it the value of the closest sea for which information is available. Table A.2 shows the assigned speeds and implied crossing times. Combining the HMI cost surface and the Seafaring travel time generates the HMISea cost surface, which can be used to determine minimal travel time among locations employing pre-industrial technologies.

In order to test the reliability of these estimates, the analysis constructs optimal travel time between various regions and compare these estimates or the paths they generate with a sample of historical data on trade, news diffusion, and cultural distances.

temperatures and relative humidities for each square kilometer, since the research is not in trying to capture the conditions of a specific voyage, but of the average conditions of travel.

[24]Furthermore, if one takes the speed of the earliest steam ships as an upper bound, these estimates suggest that not much speed gain could be achieved in this era. Historians like Braudel (1972) and O'Rourke and Williamson (2001) argue that innovation in seafaring mostly increased dependability and lowered the risk of travel, but did not increase speed by much, before the advent of the steam engine and the internal combustion engine.

A.1 Historical Trade Routes

This section validates the new measure by comparing paths among capitals in the Old World with the location of historical trade, banking, pilgrimage and postal routes as compiled by Ciolek (2004). In particular, Ciolek (2004) compiles and georeferences around 4,500 stopping places of networks that allow for the movement of goods, people, and information from the year 500 BCE to 1,820 CE in the Old World (OWTRAD).[25] The analysis establishes that an artificial transportation network based on minimum travel paths among capitals in the Old World predicts the location of the historical OWTRAD network.

The analysis constructs the paths that minimize total travel time among pairs of capitals in the Old World (OPHMISea) and explores how well these paths explain the location of the historical locations identified by Ciolek (2004). In particular, it compares the transportation network among capitals generated using HMISea, OPHMISea, with the historical network compiled by Ciolek (2004). Importantly, with the exception of some capitals, the historical (OWTRAD) and artificial (OPHMISea) networks do not share any nodes in common. So, one should not expect the historical nodes to be geographically close to the paths on this artificial network, unless the OPHMISea network is capturing travel conditions during this era.

Figures A.1-A.3 overlay the network (OPHMISea) on the OWTRAD nodes. The figures show that there is a non-depreciable set of nodes, which are not capitals, that are very close to the optimal paths. In order to have a better measure as to how these locations are geographically distributed with respect to the optimal paths, the analysis computes the minimum distance from each location to the artificial network OPHMISea. Table A.3 and A.4 present some statistics of the distribution of these distances.

Clearly, it is difficult to know if these distances are "close" in a meaningful sense. Furthermore, one could argue that the artificial network is located close to the historical nodes by pure chance. In order to mitigate these concerns, the analysis compares the distances between OPHMISea and OWTRAD, with the distances to random linear networks (RLN). In particular, the analysis created 5,000 random linear networks (RLN) between the same capitals used to create the OPHMISea network and computed the minimum distance between each RLN and OWTRAD. These distributions of distances to RNL provide a measure of "closeness" between the OPHMISea and OWTRAD networks or whether it is all driven by chance. For each set of 5,000 RLN's the analysis imposed a different number of edges that each capital should have.

As can be seen in table A.3 the OPHMISea network performs rather well compared to the RLN's. In particular, all the statistics presented in table A.3 are lower for the OPHMISea network than for any of the RLN's, sometimes by two orders of magnitude. Additionally, table A.4 shows that less than 10% of OWTRAD nodes are over 90 kms from the OPHMISea network. On the other hand, over 50% of those nodes are at a distance higher than 360 kms for the RLN's, even when these are fully connected. These results suggest that the OPHMISea network and the OWTRAD nodes are close in a meaningful sense. Furthermore, they hint that distances measured by using HMISea and the paths they generate are closely related to travel and trade conditions in the pre-industrial.

[25] The data is available at `http://www.ciolek.com/owtrad.html`.

Table A.1: A timeline of seafaring.

Year	Event	Civilization	Note
11000 BCE	Evidence of trade		Obsidian imported into Greece from the island of Melos
6000 BCE	People settle the island of Crete		
5000 BCE	Dugout boats and wodden paddle in China		Neolithic dugout boats and wooden paddles have been excavated at Hemudu and Xiaoshan in China's Zhejiang province
4500 BCE	Oak canoes are used on the Seine		The oldest wooden boats ever found in Europe. The largest of the canoes is nearly 5 meters (16 ft)
4000 BCE	Boats in Egypt	Egyptian	"Egyptians build boats made from planks joined together; previuosly, boats were dogout canoes and possible rafts of reeds bound together or skins stretched over a framework"
3500 BCE	Invention of sails	Sumerians Egyptians	
3000 BCE	Evidence of sailing activities		"Boats built in Egypt or Mesopotamia are paddled or sailed with a simple square sail; rowing has not yet been discovered; egyptians boats are essentially papyrus rafts at this time, although shaped with upturned ends"
2900 BCE	Earliest contacts between Egypt and Crete	Egyptian	"Bowls found on crete appear to have been made in Egypt, suggesting seagoing trade between the two; it is likely that the Minoan ships were even more venturous, trading all over the mediterranean by this period"
2650 BCE	Import of timber from Lebanon	Egyptian	"A command from the Egyptian pharao Snefru to bring ""40 ships filled with cedar logs"" to Egypt from Lebannon is the first written record of the existence of boats and shipping"
2500 BCE	Wooden Boats and invention of oars	Egyptian	"Boats in Egypt are now made of wood, instead of being papyrus rafts with unturned ends; oars have probably been invented by this time"
2500 BCE	Shipping		"Clay tablets record imports of stone to southern Mesopotamia form either Magan or Makran (both ports on the Persian Gulf); Magan developed a reputation as a port, and the stone was probably transported by boat to the mouth of the Euphrates at the head of the gulf and then up the Tigris-Euphrates river system"
2400 BCE	Fleet of transports to ferry troops to some Asiatic coast	Egyptian	Pharaoh Sahure orders for his pyramid a representation of the levant coast; this is the earliest known depiction of seagoing ships that has been preserved and the earliest recorde use of ships for military purposes (they were undoubtely used in war earlier)
2000 BCE	Multi-planked boats in China	Xia Dynasty	
2000 BCE	Mentuhotep sends a ship to the Red Sea	Egyptian	
2000-1500 BCE	Heyday of Minoan maritime activity	Minoan	

Table A.1: A timeline of seafaring (continued).

Year	Event	Civilization	Note
1500 BCE	Expedition to Punt	Egyptian	
1400 BCE	Seagoing ships in the Mediterraean		Seagoing ships in the Mediterraean are built by first joining planks together to make a hull
1100 BCE	Wenamon's voyage	Egyptian	To bring wood from Lebanon
1100 BCE	Voyage of the Argo	Greek	To go to Colchis (Georgia today)
970 BCE	Trade with India	Phoenician	
1000-700 BCE	Phoenician colonize the west	Phoenician	From Tyre (where a port was built) to Utica to Cadiz
800 BCE	Invention of the Penteconter	Greek	"Penteconters are believed to have been between 28 and 33 meters long, approximately 4 meters wide and capable of reaching a top speed of 9 knots (18km/h)"
700 BCE	Invention of the two-banked galleys (Bireme)	Phoenician	
550 BCE	Invention of the trireme	Greek	"This type was employed by ancient Greece, Rome, and other Mediterranean maritime nations. The Athenian trireme had 54 oarsmen in the lowest or thalamite bank, 54 in the second or zygite bank, and 62 in the uppermost or thranite bank. Such a galley would have a length of about 39 m (about 128 ft) and a maximum width of perhaps 4.6 m (15 ft) at the waterline. The boat would sink about 1.2 m (about 4 ft) into the water."
500 BCE	Canal linking the Mediterranean with the Indian Ocean	Persian	This canal was 145km (90 miles) long and 45m (150ft) wide
425 BCE	Trade by sea with China	Chinesse Babylonian Greek	"Babylonians sailed to the South China Sea. Meanwhile, Chinese silk was sent to Greece by sea."
398 BCE	Invention of the quinquereme	Greek	
350 BCE	Peryplus of Niarchus	Greek	"The Periplus (pilot book) of Niarchus, an officer of Alexander the Great, describes the Persian coast. Niarchus commissioned thirty oared galleys to transport the troops of Alexander the Great from northwest India back to Mesopotamia, via the Persian Gulf and the Tigris, an established commercial route."
200 BCE	Construction of Magic Canal in China	Chinese	That enables a ship to sail from Canton (or anywhere else on the China Sea) to the latitude of present day Beijing
200 BCE	Construction of the largest naval vessel in the classical age	Egyptian	"Built by Ptolemy IV of Egypt. It had 4000 rowers in 40 banks, and carried as many as 3250 others as a crew and fighting marines (was a catamaran over 120 m-400 ft- long)"

Table A.1: A timeline of seafaring (continued).

Year	Event	Civilization	Note
200 BCE	Invention of the dry dock	Egyptian	"Ptolemy's ship was built in a channel that was connected to the sea; when the ship was completed, the channel was filled with water and launched it "
200 BCE	Introduction of three-masted vessels	Greek	"A foremast called an artemon, the main, and a mizzenmast at the rear"
120 BCE	Eudoxus sails to India	Greek	
12 BCE	Construction of Canal in Netherlands	Roman	Nero Claudius Drusus joins the Flevo Lacus (the largest lake in Netherlands) to the Rhine with a canal that also uses the Yssl River for part of the passage
0	Use of a small triangular topsail above the mainsail	Roman	
0	Earliest known despiction of a ship's rudder	Chinesse	
45 CE	Construction of Canal in Germany	Roman	Gnaesus Domitius Corbulo digs a ship's canal joining the Rhine with the Meuse River
62 CE	St. Paul's voyage to Rome	Roman	
70 CE	The Grand Canal of China is started	Chinesse	965 Km (600 mi) long
100 CE	Use of grid for location	Chinesse	Zhang Heng develops the method of using a grid to locate points on a map
130 CE	Creation of device for orientation	Chinesse	Zhang Heng combines a water clock with an armallary to produce a device that keeps track of where stars are expected to be in the sky
270 CE	First form of compass	Chinesse	"The first form of compass is probably used for finding south, earlier applications of magnetic lodestones were more magical than practical"
520 CE	Paddle wheel boats	Roman	"The first paddle wheel boats are designed, to be powered by oxen walking in circles, as in a mill; it is unlikely that these were built"
1020 CE	Earliest known evidence that seagoing wooden ships are bieng built in the modern way		"A vessel wrecked off Serce Limani (Turkey), the construction started with a keel and framework to which planked is added"
1080 CE	First known reference to use of magnetic compass for navigation	Chinesse	Chinese scientist Shen Kua's Dream pool essays contains the first reference
1170 CE	Regulations and navigation for navigation in China	Chinesse	"Were described by Zhu Yu, son of a former high port official and then governor of Guangzhou. Large ships carried several hundred men, the smaller ones more than a hundred. They navigated by the coasts, the stars, the compass, and seabed sampling."

Table A.1: A timeline of seafaring (continued).

Year	Event	Civilization	Note
1180 CE	Sternpost rudder		“The sternpost rudder, possibly borrowed from the chinese, replaces the steering oars that have been used in Europe and the near East since antiquity”
1190 CE	First known western reference to the magnetic compass		in De naturis rerum by Alexander Neckam)

Table A.2: Speeds on sea.

Sea	Number of Voyages	Average Speed	Min. Speed	Max. Speed	Std. Deviation	Speed on Cell i	Time Required (hours)
Arabian Sea	9	6.99	4.82	9.45	1.46	7.56	0.13
Atlantic Ocean	8	11.6	3.47	28.94	7.35	12.55	0.08
Bay of Bengal	2	7.92	6.39	9.45	1.53	8.57	0.12
Black Sea	2	12.6	10.72	14.47	1.88	13.62	0.07
Gulf of Thailand	2	5.43	5.02	5.83	0.41	5.87	0.17
Indian Ocean	13	6.97	5.02	9.45	1.44	7.54	0.13
Malacca Strait	5	6.89	5.02	9.45	1.56	7.46	0.13
Mediterranean	87	9.62	2.14	17.23	4.06	10.4	0.1
North Sea	3	8.13	7.03	9.09	0.85	8.79	0.11
Persian Gulf	2	6.16	4.82	7.5	1.34	6.66	0.15
Red Sea	3	5.8	3.06	7.23	1.94	6.28	0.16
South China Sea	3	4.52	2.7	5.83	1.33	4.89	0.2
Bay of Bizcay	NA	NA	NA	NA	NA	12.55	0.08
Phillipine Sea	NA	NA	NA	NA	NA	4.89	0.2
Sea of Japan	NA	NA	NA	NA	NA	4.89	0.2
East China Sea	NA	NA	NA	NA	NA	4.89	0.2
Gulf of Tonkin	NA	NA	NA	NA	NA	4.89	0.2
Taiwan Strait	NA	NA	NA	NA	NA	4.89	0.2

Table A.2: Speeds on sea (continued).

Sea	Number of Voyages	Average Speed	Min. Speed	Max. Speed	Std. Deviation	Speed on Cell i	Time Required (hours)
Mozambique Channel	NA	NA	NA	NA	NA	7.54	0.13
English Channel	NA	NA	NA	NA	NA	12.55	0.08
Baltic Sea	NA	NA	NA	NA	NA	8.79	0.11
Caspian Sea	NA	NA	NA	NA	NA	13.62	0.07

Source: Özak (2010)

Table A.3: Distribution of distance from historical locations to Optimal Paths and Random Linear Networks.

Network	Distance from OWTRAD Nodes to Network.				
	Edges[†]	Average	Std	Median	Max (Max)[§]
OPHMISea		35	56	15	610
RLN4	4	2405	2824	480	9421(9431)
RLN6	6	2399	2827	454	9417(9431)
RLN8	8	2394	2828	437	9414(9431)
RLN16	16	2385	2830	406	9403(9431)
RLN32	32	2379	2829	384	9388(9431)
RLN64	64	2374	2829	370	9375(9429)
LN128[‡]	128	2371	2827	363	9366(9366)

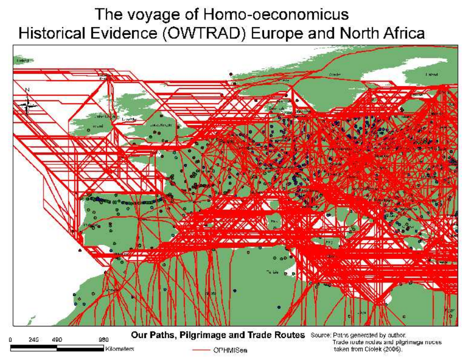
[†] Number of capitals to which each capital is randomly connected. [‡] All capitals are connected to each other.
[§] Average maximum and in parenthesis maximum over all maxima.
Distance in Kilometers. Calculations by author.

Table A.4: Deciles of the distribution of distance from historical locations to Optimal Paths and Random Linear Networks.

Network	Distance from OWTRAD Nodes to Network (Deciles).								
	1	2	3	4	5	6	7	8	9
OPHMISea	1	3	6	10	15	24	35	52	90
RLN4	3	9	18	36	480	2755	3787	5747	7120
RLN6	2	6	12	24	454	2742	3779	5747	7120
RLN8	2	4	9	18	437	2733	3773	5746	7120
RLN16	1	2	4	9	406	2709	3756	5746	7119
RLN32	0	1	2	4	384	2692	3741	5745	7119
RLN64	0	0	1	2	370	2681	3729	5745	7118
LN128†	0	0	0	1	363	2675	3724	5745	7117

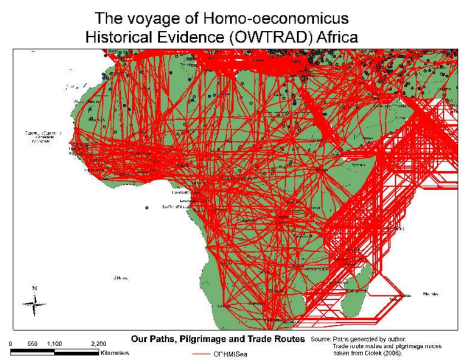
Distance in Kilometers. Calculations by author. † All capitals are connected to each other.

Figure A.1: Optimal Paths for HMISea, trade and pilgrimage routes data for Europe and North Africa.



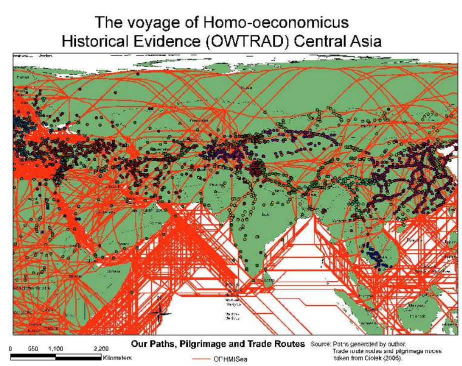
Source: Computations by author and data by Ciolek (2004).

Figure A.2: Optimal Paths for HMISea, trade and pilgrimage routes for Africa and the Middle East.



Source: Computations by author and data by Ciolek (2004).

Figure A.3: Optimal Paths for HMISea, trade and pilgrimage routes for Asia and the Middle East.



Source: Computations by author and data by Ciolek (2004).

A.2 Diffusion of News from Venice

This section validates the new measure by showing that HMISea estimated travel time are good predictors of actual recorded historical travel time. In particular, using historical data on the diffusion of news to Venice it shows that HMISea travel distances to Venice are highly positively correlated with recorded historical travel time.

In particular, in his *magnum opus*, Braudel (1972) analyzes the connections between history and geographical space using the Mediterranean as his example. One aspect analyzed by him is the effect of geography on communication and transportation costs. Using data by Sardella (1948) on the record of arrival of letters and news to the Signoria of Venice between 1497 and 1532 and on evidence of the Venetian *avvisi* available at the Public Record Office in London, he constructs some measures of the speed with which news travelled to and from Venice. Table A.6 reproduces Braudel's data.[26] He summarized this information about the speed of the transmission of news in 1500, 1686-1700 and 1733-1765 by means of iso-chronic lines in three graphs that are reproduced in Figure A.4. As can be seen there, and as Braudel (1972) himself argues, the maps are roughly identical, showing the persistence of the effect of technological limitations on the speed of communication.[27] These maps are not perfect, in the sense that they are only approximations since, as Braudel argues, the speed with which news traveled in the period was very volatile and depended both on climatic conditions and on the price paid to the courier. Furthermore, the iso-chronic lines can only be imperfectly asserted at places with which there is communication. Still, they serve as a another source for comparison of the proposed cost surfaces and the travel time generated by them.

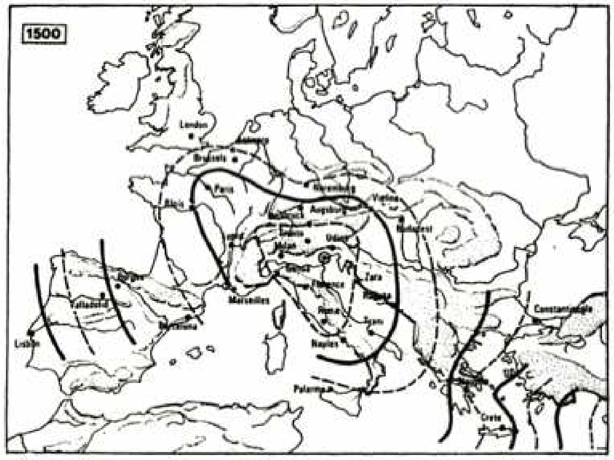
The analysis compares Braudel's iso-chronic lines with the travel time generated by HMI and HMISea. In particualr, using both HMI and HMISea the analysis computes the optimal paths to get from any cell i in the Old World to Venice. Using georeferencing methods, figures A.5(a)-A.5(c) overlay the graphs generated by Braudel on the surface of optimal accumulated times of travel to Venice and the iso-chronic lines generated by HMI. Each red iso-chronic line represents half a week time of travel, which, under the assumption that news was transported in twelve-hour working days, can be interpreted as representing a one week accumulated travel time. Figures A.6(a)-A.6(c) repeat this same analysis using the HMISea data.

Although the iso-chronic lines look similar in certain regions, it is difficult to ascertain the adequacy of the measures compared to the estimates visually. For this reason, table A.6 reproduces the data on the number of days required to travel from Venice to various cities as presented by Braudel (1972) and on the computations using HMI and HMISea. For example, Braudel found that news from Antwerp to Venice took a minimum of 8 days, normally 16 days and on average 20 days, while both HMI and HMISea measures require 7 days of continuous travel, or 15 twelve-hour working days or 22 eight-hour working days. Looking at the average travel time over all the cases presented by Braudel, one can infer that on average, the HMI is similar to the "normal" time estimate of Braudel, while the transformation of HMI into 8 hour days makes it similar to Braudel's maximum time estimate and the 12 hour days makes it similar to the average time measured by him. On the other hand, HMISea is similar to the minimum times reported by Braudel, while the 12 and 8 hour conversions of HMISea are similar to the normal and average times found by him. Table A.7 compares again the different measures with Braudel's estimates confirming the similarity between HMI and the "normal" time estimates, and between HMISea and the minimum travel time of news under the 24-hour continuous

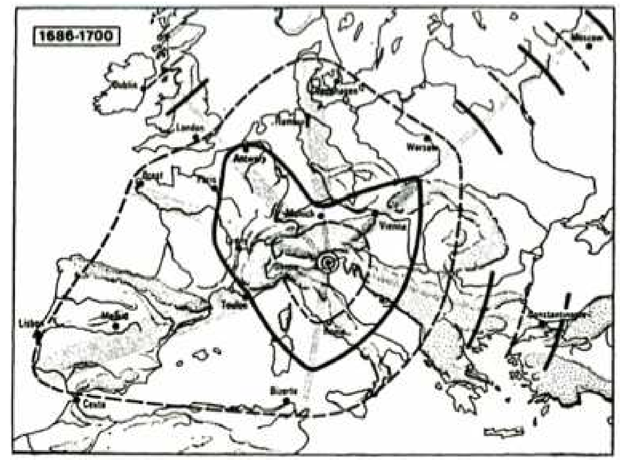
[26] The data is also aggregated in Braudel's presentation and analysis. There does not seem to exist a disaggregated version of the data, which would allow for a much better and interesting comparison, since one could control for the effect of price or urgency on travel speeds.

[27] In particular, Braudel (1972) argues that "[t]he differences from one map to another may seem very marked in certain directions. They are the result of the varying frequency of communications, depending on the urgency of the circumstances. Generally speaking, communication seems to be as slow on the third map as on the first, while the second shows noticeable shorter delays. But it cannot be regarded as definite proof." (p.367)

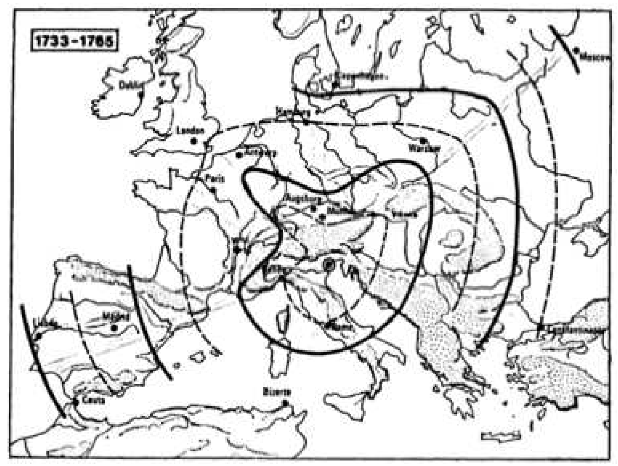
Figure A.4: Diffusion of news from Venice.



(a) 1500 CE



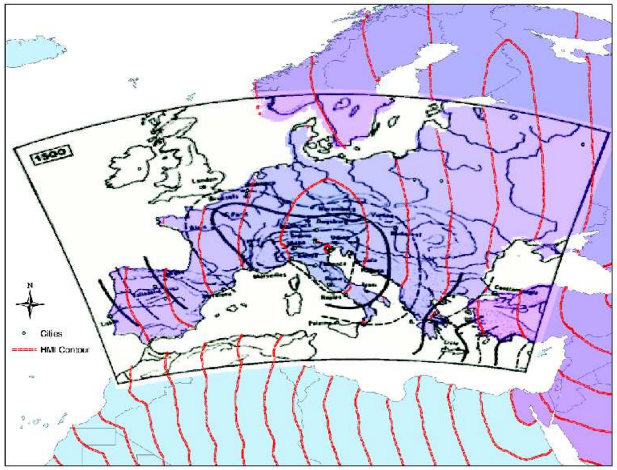
(b) 1686-1700CE



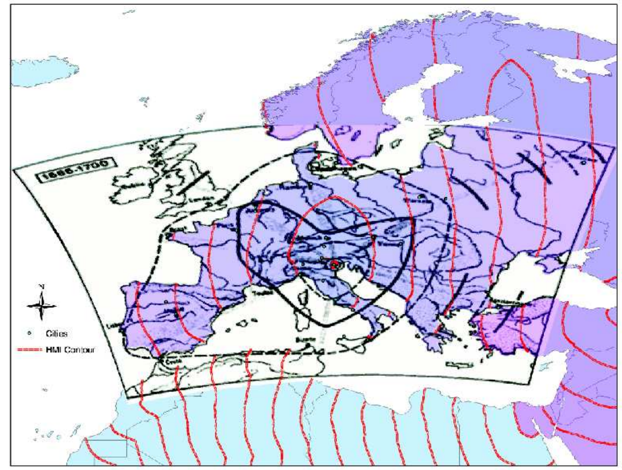
(c) 1733-1765CE

Source: Braudel (1972) Iso-chronic lines, representing intervals of one week, show all the locations that lie at the same travel time from Venice.

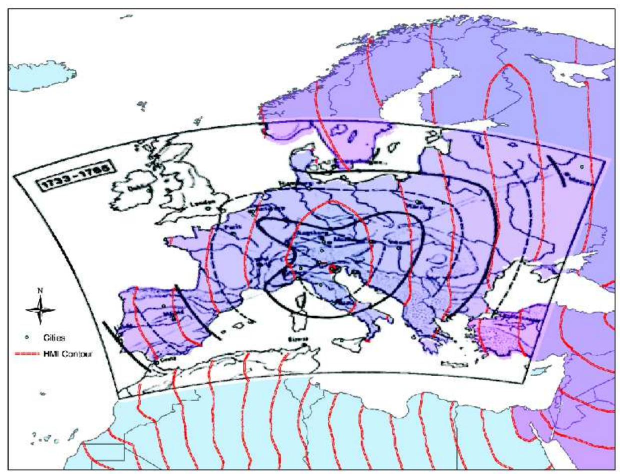
Figure A.5: Distance from Venice (HMI).



(a) 1500 CE



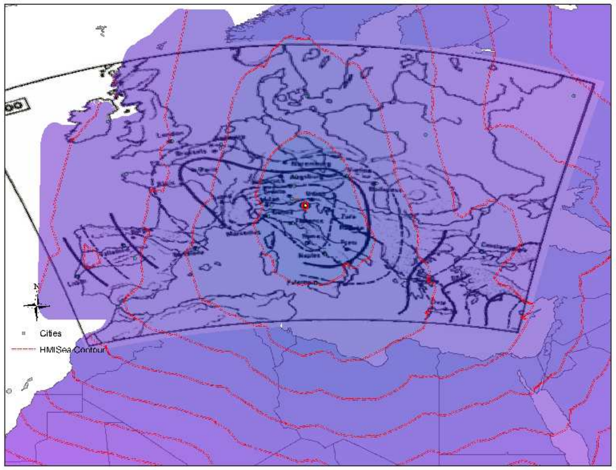
(b) 1686-1700CE



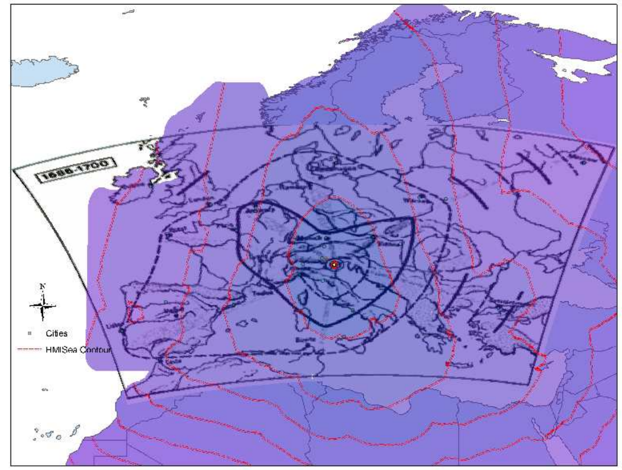
(c) 1733-1765CE

Georeferencing done by author. Original data by Braudel (1972). Red Iso-chronic lines, representing intervals of half week in HMI accumulated costs of travel to Venice. Under the assumption of a 12 hour travel per day, these iso-chronic lines can be interpreted as representing one week travel time.

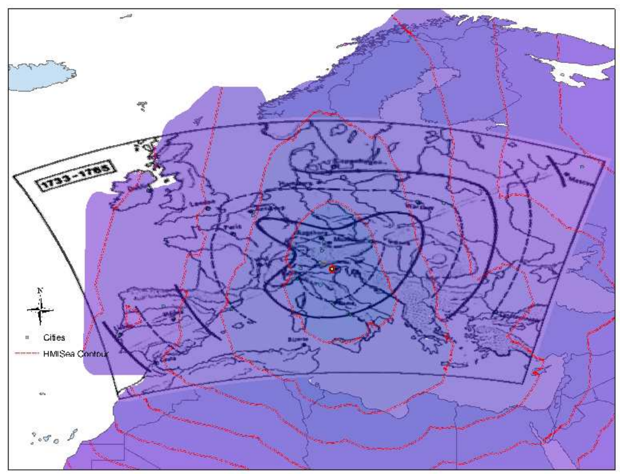
Figure A.6: Distance from Venice (HMISea).



(a) 1500 CE



(b) 1686-1700CE



(c) 1733-1765CE

Georeferencing done by author. Original data by Braudel (1972). Red Iso-chronic lines, representing intervals of half week in HMISea accumulated costs of travel to Venice. Under the assumption of a 12 hour travel per day, these iso-chronic lines can be interpreted as representing one week travel time.

Table A.6: Distance to Venice from various cities as measured by the number of days travelled.

City	Braudel (1972)						HMI			HMISea		
	Total Cases	Normal Cases	Maximum	Average	Normal	Minimum	HMI	HMI days of 12 hours	HMI days of 8 hours	HMISea	HMISea days of 12 hours	HMISea days of 8 hours
Alexandria	266	19	89	65	55	17	43	86	129	10	20	30
Antwerp	83	13	36	20	16	8	7	15	22	7	15	22
Augsburg	110	19	21	11	12	5	2	4	6	2	4	6
Barcelona	171	16	77	22	19	8	10	19	29	6	13	19
Blois	345	53	27	14	10	5	9	18	27	9	18	26
Brussels	138	24	35	16	10	9	7	15	22	7	15	22
Budapest	317	39	35	18	19	7	6	12	18	5	11	16
Burgos	79	13	42	27	27	11	14	28	42	11	23	34
Calais	62	15	32	18	14	12	9	19	28	9	18	27
Candia	56	16	81	38	33	20	NA	NA	NA	8	15	23
Cairo	41	13	10	7	8	3	41	83	124	12	24	36
Constantinople	365	46	81	37	34	15	15	30	45	9	18	27
Corfu	316	39	45	19	15	7	NA	NA	NA	4	9	13
Damascus	56	17	102	80	76	28	34	69	103	12	24	37
Florence	387	103	13	4	3	1	1	3	4	1	3	4
Genoa	215	58	15	6	6	2	3	6	10	3	6	9
Innsbruck	163	41	16	7	6	4	1	2	3	1	2	3
Lisbon	35	9	69	46	43	27	20	40	59	13	26	39
London	672	78	52	27	24	9	NA	NA	NA	10	20	30
Lyons	812	225	25	12	13	4	6	12	18	6	12	18
Marseilles	26	7	21	14	12	8	6	12	18	5	9	14
Milan	871	329	8	3	3	1	3	5	8	3	5	8
Naples	682	180	20	9	8	4	NA	NA	NA	2	5	7
Nauplia	295	56	60	36	34	18	12	24	36	7	13	20
Nuremberg	39	11	32	20	21	8	2	5	7	2	5	7
Palermo	118	23	48	22	25	8	NA	NA	NA	4	7	11
Paris	473	62	34	12	12	7	8	17	25	8	17	25
Ragusa	95	18	26	13	14	5	NA	NA	NA	5	9	14
Rome	1053	406	9	4	4	2	2	5	7	2	4	6
Trani	94	14	30	12	12	4	NA	NA	NA	2	5	7
Trento	205	82	7	3	3	1	1	2	3	1	2	3
Udine	552	214	6	2	2	2	1	1	2	1	1	2
Valladolid	124	15	63	29	23	12	15	30	45	12	24	36
Vienna	145	32	32	14	13	8	4	7	11	3	7	10
Zara	153	28	25	8	6	1	3	7	10	1	3	4
Average	275	146	31	15	10	6	10	20	31	6	12	18
STD	265	132	23	14	11	5	12	23	35	4	8	11

Table A.7: Distance to Venice from various cities (Comparison).

	Braudel (1972)		HMI			HMISea			
City	Average/Minimum	Normal/Minimum	Average/HMI	Normal/HMI	HMI/Minimum	Average/HMISea	Normal/HMISea	HMISea/Minimum	HMISea/HMI
Alexandria	382	323	152	128	252	643	544	59	24
Antwerp	250	200	274	219	91	274	219	91	100
Augsburg	220	240	589	642	37	589	642	37	100
Barcelona	274	237	229	197	120	343	297	80	67
Blois	311	222	154	110	202	160	114	194	96
Brussels	178	111	220	137	81	220	137	81	100
Budapest	257	271	308	325	83	335	353	77	92
Burgos	245	245	194	194	126	239	239	102	81
Calais	149	116	192	149	78	201	156	74	95
Candia	188	163	NA	NA	NA	500	434	38	NA
Cairo	233	266	17	19	1376	59	67	395	29
Constantinople	246	226	248	227	99	412	378	60	60
Corfu	271	214	NA	NA	NA	445	351	61	NA
Damascus	285	271	233	222	122	655	622	44	36
Florence	400	300	302	227	132	302	227	132	100
Genoa	300	300	188	188	159	211	211	142	89
Innsbruck	175	150	627	538	28	627	538	28	100
Lisbon	170	159	233	217	73	352	329	48	66
London	299	266	NA	NA	NA	266	236	113	NA
Lyons	300	325	204	221	147	204	221	147	100
Marseilles	175	150	234	200	75	298	256	59	78
Milan	300	300	110	110	272	110	110	272	100
Naples	225	200	NA	NA	NA	364	324	62	NA
Nauplia	199	188	298	281	67	547	516	36	54
Nuremberg	250	262	859	902	29	859	902	29	100
Palermo	275	312	NA	NA	NA	628	713	44	NA
Paris	171	171	141	141	121	141	141	121	100
Ragusa	260	280	NA	NA	NA	286	308	91	NA
Rome	266	266	169	169	157	200	200	133	85
Trani	300	300	NA	NA	NA	487	487	62	NA
Trento	300	300	310	310	97	310	310	97	100
Udine	133	133	288	288	46	390	390	34	74
Valladolid	241	191	195	155	123	242	192	99	81
Vienna	174	162	382	355	46	425	394	41	90
Zara	800	600	235	176	341	557	418	144	42
Average	270	252	179	178	118	306	269	113	80
STD	92	73	108	103	107	151	136	68	24

travel interpretation. If a 12 or 8-hour interpretation is taken, then HMISea is similar to Braudel's "normal" and average time estimates. These results suggest that historical minimal travel distances are similar to the estimates generated by the use of HMISea.

Table A.5: Correlation between Braudel's estimates, HMI and HMISea.

	Maximum	Average	Normal	Minimum	HMI
HMI	0.61	0.72	0.71	0.60	1
HMISea	0.65	0.68	0.65	0.71	0.77

A.3 Cultural Distances

This section validates the new measure by showing that they predict well cultural distances determined during the pre-industrial era. Cultural differences among societies are determined historically by their level of interaction, which depend, at least partially, on the initial differences in culture among those societies and their technological possibilities of interaction. Three measures that have been frequently used in order to measure cultural differences are genetic, religious, and linguistic distances between populations (Cavalli-Sforza, 1973; Cavalli-Sforza and Bodmer, 1971; Cavalli-Sforza et al., 1994; Fearon, 2003; Alesina et al., 2003; Giuliano et al., 2006; Ramachandran et al., 2005; Prugnolle et al., 2005; Liu et al., 2006). Özak (2010) analyzes how well various measures of geographical distance explain the cultural differences between populations as measured by genetic (Spolaore and Wacziarg, 2009), religious (Mecham et al., 2006), and linguistic (Fearon, 2003) distances. It shows that HMISea has a high explanatory power, is always statistically significant, and is positively correlated with these measures of cultural distance. I do not replicate all the analyses here, but show some representative results.

In particular, tables A.8 and A.9 analyze the relationship between genetic distance as measured by the FST and Nei distances to various geographic distances considered in Özak (2010). As established in those tables, the coefficient on HMISea always has the correct sign and is statistically significant. Additionally, it has a high explanatory power as measured by the adjusted R-squared. Notice that compared to the other measures it performs rather well, especially if compared to geodesic distances.

Similar results are obtained when using different measures of culture (Özak, 2010). These results further support the applicability of HMISea for measuring distances during the pre-industrial era. Furthermore, given its high positive correlation with various measures of cultural distance, one could use it as a proxy of cultural distance for regions in which only very coarse measures exist.

Table A.8: F_{ST} genetic distance in 1500 and Mobility Measures.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	OLS	OLS	OLS	OLS	OLS	OLS	OLS	OLS	OLS	OLS	OLS	OLS
	Dependent variable: F_{ST} genetic distance in 1500											
HMI Cost (weeks)	0.560***				0.557***				0.880***			
	(0.032)				(0.059)				(0.081)			
HMISea Cost (weeks)		0.469***				0.508***				0.797***		
		(0.027)				(0.063)				(0.076)		
RIX distance (1000's km)			0.235***				0.341***				0.405***	
			(0.013)				(0.048)				(0.042)	
Geodesic Distance				1.038***				0.692***				1.279***
				(0.085)				(0.115)				(0.124)
Standardized β	0.619	0.505	0.487	0.503	0.615	0.547	0.706	0.335	0.972	0.858	0.839	0.620
Continental FE	NO	NO	NO	NO	YES	YES	YES	YES	NO	NO	NO	NO
Country FE	NO	NO	NO	NO	NO	NO	NO	NO	YES	YES	YES	YES
Adjusted R-squared	0.383	0.255	0.237	0.254	0.613	0.594	0.595	0.572	0.651	0.502	0.517	0.435
Observations	9454	9454	9454	9454	9454	9454	9454	9454	9454	9454	9454	9454

Two-way clustered robust standard errors in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests.

Table A.9: *Nei* genetic distance in 1500 and Mobility Measures.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
	OLS	OLS	OLS	OLS	OLS	OLS	OLS	OLS	OLS	OLS	OLS	OLS
	Dependent variable: *Nei* genetic distance in 1500											
HMI Cost (weeks)	0.096***				0.112***				0.142***			
	(0.005)				(0.010)				(0.013)			
HMISea Cost (weeks)		0.081***				0.101***				0.130***		
		(0.004)				(0.011)				(0.012)		
RIX distance (1000's km)			0.040***				0.064***				0.065***	
			(0.002)				(0.008)				(0.007)	
Geodesic Distance				0.161***				0.091***				0.195***
				(0.015)				(0.022)				(0.021)
Standardized β	0.626	0.517	0.487	0.464	0.733	0.647	0.785	0.262	0.932	0.830	0.804	0.562
Continental FE	NO	NO	NO	NO	YES	YES	YES	YES	NO	NO	NO	NO
Country FE	NO	NO	NO	NO	NO	NO	NO	NO	YES	YES	YES	YES
Adjusted R-squared	0.393	0.267	0.238	0.215	0.587	0.558	0.550	0.495	0.640	0.507	0.516	0.421
Observations	9454	9454	9454	9454	9454	9454	9454	9454	9454	9454	9454	9454

Two-way clustered robust standard errors in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests.

B Variable Definitions, Sources and Summary Statistics

This section presents the definition, sources, and summary statistics for the variables used in the different analyses in the main body of the paper. Since I have tried to use the largest sample possible for each analysis, there are multiple samples. I present the summary statistics for each set of variables used in each table in the main body in a different table.

B.1 Outcome Variables

- **Technological Sophistication in 1500 and 2000CE**: Average and sectoral levels of technological sophistication as reported by Comin et al. (2010). Technological sophistication is measured on the extensive margin by documenting whether a particular set of technologies was used or known by the residents of the region where a contemporary country is located.

- **Population Density in 1, 1000, 1500 and 1820CE**: Population density (in persons per square km) in 1500CE as reported by McEvedy and Jones (1978), divided by total land area, as reported by the World Bank's World Development Indicators.

- **GDP per capita**: GDP per capita is gross domestic product divided by midyear population. GDP is the sum of gross value added by all resident producers in the economy plus any product taxes and minus any subsidies not included in the value of the products. It is calculated without making deductions for depreciation of fabricated assets or for depletion and degradation of natural resources. Data are in constant 2005 U.S. dollars and represent the average for each country for the years 2000-2015 from the World Bank's World Development Indicators.

- **Patents per capita**: Patents per capita is the number of patents divided by midyear population. Patents are worldwide patent applications filed through the Patent Cooperation Treaty procedure or with a national patent office for exclusive rights for an invention–a product or process that provides a new way of doing something or offers a new technical solution to a problem. A patent provides protection for the invention to the owner of the patent for a limited period, generally 20 years. Resident patent applications are those for which the first-named applicant or assignee is a resident of the State or region concerned. Data represent the average for each country for the years 2000-2015 from the World Bank's World Development Indicators.

- **New Firms per 1,000 people**: New business density (new registrations per 1,000 people ages 15-64). New businesses registered are the number of new limited liability corporations registered in the calendar year. Data represent the average for each country for the years 2000-2015 from the World Bank's World Development Indicators.

B.2 Controls

- **Absolute latitude**: The absolute value of the latitude of a country's approximate geodesic centroid, as reported by the CIA's World Factbook.

- **Mean Elevation**: The mean elevation of a country in km above sea level, calculated using geospatial elevation data reported by the G-ECON project (Nordhaus et al., 2006) at a 1-degree resolution. The interested reader is referred to the G-ECON project web site for additional details.

- **Mean distance to nearest waterway**: The distance, in thousands of km, from a GIS grid cell to the nearest ice-free coastline or sea-navigable river, averaged across the grid cells of a country. This variable was originally constructed by Gallup et al. (1999) and is part of Harvard University's CID Research Datasets on General Measures of Geography.

- **Percentage of population living in tropical, subtropical and temperate zones**: The percentage of a country's population in 1995 that resided in areas classified as tropical by the Köppen-Geiger climate classification system. This variable was originally constructed by Gallup et al. (1999) and is part of Harvard University's CID Research Datasets on General Measures of Geography.

- **Percentage of population in country at risk of contracting falciparum malaria**: The percentage of a country's population in 1995 that were at risk of contracting falciparum malaria as reported by Gallup and Sachs (2001).

- **Land Suitability**: Average probability within a region that a particular grid cell will be cultivated as computed by Ramankutty et al. (2002).

- **Caloric Suitability**: Pre-1500CE Caloric suitability and its change due to the Columbian Exchange is the average potential caloric output in a country as reported in Galor and Özak (2016).

- **Island nation dummy**: An indicator for whether or not a country shares a land border with any other country, as reported by the CIA's World Factbook online.

- **Landlocked dummy**: An indicator for whether or not a country is landlocked, as reported by the CIA's World Factbook online.

- **Coast length**: Length, in thousands of km, of a country's coastline. This variable was originally constructed by Gallup et al. (1999) and is part of Harvard University's CID Research Datasets on General Measures of Geography.

- **Share of Area within 100kms of Sea**: Share of a country's area within 100kms of Sea. Author's computations.

- **Ecological Diversity**: Herfindahl index of share's of a country's area in various ecologies. Author's computations following the method of Fenske (2014) and Depetris-Chauvin and Özak (2015a).

- **Neolithic Transition Timing**: The number of thousand years elapsed (as of the year 2000) since the majority of the population residing within a country's modern national borders began practicing sedentary agriculture as the primary mode of subsistence (Putterman, 2008). See the Agricultural Transition Data Set website
`http://www.econ.brown.edu/fac/louis_putterman/agricultural%20data%20page.htm`
for additional details on primary data sources and methodological assumptions.

- **Total land area**: The total land area of a country, in millions of square kilometers, as reported for the year 2000 by the World Bank's World Development Indicators online.

- **Major religion shares**: Share of major religion in each country as reported in La Porta et al. (1999).

- **Legal Origins**: Dummy variables for origin of legal system as identified in La Porta et al. (1999).

- **Pre-Industrial Distance to Trade Route**: Number of weeks of travel from a country's capital to the closest trade route. Author's computations based on Ciolek (2004).
- **Volatility (temperature and precipitation)**: Volatility of temperature and precipitation constructed using v3.2 of the Climatic Research Unit (CRU) database following the method of Durante (2010).
- **Diversification (temperature and precipitation)**: Spatial Correlation of temperature and precipitation shocks constructed using v3.2 of the Climatic Research Unit (CRU) database following the method of Durante (2010).

Table B.1: Summary statistics for variables used in regressions for tables 1-3.

Variable	**Mean**	**Std. Dev.**	**Min.**	**Max.**	**N**
Technological Sophistication in Agriculture	0.768	0.317	0	1	82
Technological Sophistication in Communications	0.558	0.381	0	1	82
Technological Sophistication in Transportation	0.348	0.267	0	1	82
Technological Sophistication in Military	0.485	0.372	0	1	82
Technological Sophistication in Industry	0.787	0.273	0	1	82
Technological Sophistication (Average)	0.589	0.286	0.1	1	82
Technological Sophistication (Average, Mig. Adj.)	0.6	0.272	0.157	0.995	82
Pre-industrial distance NLD	5.393	3.595	0	12.067	82
Sq.Pre-industrial distance NLD	41.854	41.96	0	145.602	82
Pre-industrial distance CHN	8.24	3.48	0	14.306	82
Sq.Pre-industrial distance CHN	79.861	57.093	0	204.669	82
Lagged Average Technology	0.845	0.179	0.6	1	82
European Colony	0.561	0.499	0	1	82
Pre-industrial distance local frontier	3.155	2.492	0	9.731	82
Pre-industrial distance trade route	0.58	0.949	0	3.824	82
Pre-industrial distance Addis Ababa	5.853	2.146	0	10.887	82
Latitude in degrees	24.183	23.572	-29.317	60.133	82
Squared Latitude	1133.7	1081.724	0.111	3616.018	82
Island dummy	0.073	0.262	0	1	82
Landlocked Dummy	0.244	0.432	0	1	82
Area	0.909	2.1	0.028	16.573	82
% Land Area in Tropics or Subtropics	0.325	0.416	0	1	82
% Land Area in Tropics	0.259	0.383	0	1	82
% Land Area in Temperate Zone	0.335	0.435	0	1	82
Elevation	581.591	475.914	10.255	2205.34	82
% Population at risk of Malaria	0.446	0.446	0	1	82
Average Crop Yield (pre-1500CE)	2862.571	1083.604	556.341	5227.940	82

Table B.2: Summary statistics for variables used in regressions for table 4-8.

Variable	Mean	Std. Dev.	Min.	Max.	N
Pre-industrial distance trade route	0.49	0.84	0	3.82	463
Landlocked Dummy	0.28	0.45	0	1	463
Latitude in degrees	25.72	22.72	-29.32	60.13	463
Years (BP) since transition to agriculture	4.5	2.48	-0.75	10.3	463
% Land Area in Tropics or Subtropics	0.29	0.41	0	1	463
% Land Area in Tropics	0.24	0.38	0	1	463
% Land Area in Temperate Zone	0.35	0.44	0	1	463
Area	0.70	1.81	0	16.57	463
% Population at risk of Malaria	0.4	0.45	0	1	463
Island dummy	0.06	0.24	0	1	463
Pre-industrial distance to frontier	4.9	3.03	0	12.38	463
Regions identified by Findlay and O'Rourke (2007)	4.5	2.79	1	8	463
Log Population Density	1.03	1.54	-3.17	4.46	463
Pre-industrial distance CHN	8.04	3.26	0	14.31	463
MDD Index (far only)	0.18	0.55	0	3	463
Pre-industrial distance closest frontier	4.14	2.68	0	11.5	463
European Colony (includes Turkey)	0.15	0.36	0	1	463
Pre-industrial distance Addis Ababa	5.49	2.12	0	10.89	463
Pre-industrial distance local frontier	2.98	2.37	0	9.73	463
Elevation	602.77	548.03	10.26	2964.04	463
Average Crop Yield (pre-1500CE)	2876.57	1186.62	0	5227.94	463
Caloric Suitability	2945.4	1189.23	0	5671.33	463
Time at MDD	0.84	2.62	0	17.99	463

C A model of technology imitation and creation in a world with many frontiers

This section complements the presentation of the model presented in the main body of the text. The world consists of a set of economies $\mathcal{E} \subseteq \mathbb{R}^n$ and n technological leaders. Assume that all economies in $\mathcal{E}$ are identical except for their geographical distance $\mathbf{d} = (d_1, \ldots, d_n)$ from these leaders, and thus identify each economy with this distance vector $\mathbf{d}$. Each economy $\mathbf{d} \in \mathcal{E}$, is populated by overlapping generations of two-period lived individuals. Population is constant and is normalized so that its size is 1. Each individual is endowed with one unit of time when young and one unit of time when old. For simplicity, assume that young individuals can only engage in activities of imitation or creation of technology, and do not engage in consumption. On the other hand, old individuals can only engage in production and consumption activities, where their production possibilities are determined by their own technology, which is generated by their decisions when young and the technology left by their parents.[28]

Individuals born in period $t-1$ inherit a level of technology A_{t-1} from their parents. They increase their stock of technology, which will be available for production in period t, using two types of intermediate inputs. The first intermediate input, $\tilde{I}$, is produced by imitation from the technological

[28]These assumptions are made for convenience and in order to simplify the analysis. Changing them would not alter the main qualitative results since the underlying mechanism does not depend on them. For example, one could allow young individuals to produce and consume or old individuals to engage in additional research activities, without affecting the main results.

Table B.3: Summary statistics for variables used in regressions for tables 9-13.

Variable	**Mean**	**Std. Dev.**	**Min.**	**Max.**	**N**
Log GDP per capita (PPP, year 2000)	8.19	1.39	5.42	10.89	111
Executive Constraints (Decision Rules): 1 (low) - 7 (high)	0.54	18.2	-88	7	113
Technological Sophistication (Average)	0.44	0.2	0.17	0.87	97
Landlocked Dummy	0.29	0.46	0	1	116
Distance to USA (population weighted)	10.52	2.52	6.52	16.47	116
Catholics as %Population (1980)	21.92	30.11	0	97.3	117
Muslims as %Population (1980)	25.09	34.35	0	99.8	117
Protestants as %Population (1980)	10.87	20.33	0	97.8	116
Legal origin - British	0.26	0.44	0	1	117
Legal origin - French	0.35	0.48	0	1	117
Legal origin - Socialist	0.3	0.46	0	1	117
Legal origin - German	0.05	0.22	0	1	117
Legal origin - Scandinavian	0.03	0.18	0	1	117
Years (BP) since transition to agriculture	5.27	2.34	0.36	10.5	117
Absolute latitude	30.05	17.73	0.33	60.13	116
Asia	0.29	0.46	0	1	117
Africa	0.35	0.48	0	1	117
Europe	0.36	0.48	0	1	117
Subsahara	0.32	0.47	0	1	117
Island dummy	0.1	0.3	0	1	117
Pre-industrial distance to frontier	5.42	3.53	0	12.38	117
Sq. Pre-industrial distance to frontier	41.77	43.03	0	153.23	117
Regions identified by Findlay and O'Rourke (2007)	4.5	2.85	1	8	117
Pre-industrial distance CHN	7.93	3.26	0	14.31	117
Colonizer	6.85	4.65	0	14	117
European Colony (includes Turkey)	0.56	0.5	0	1	117
Pre-industrial distance Addis Ababa	5.56	2.13	0	10.89	117
Elevation	622.74	591.16	10.26	2964.04	117
Precipitation (mm/month)	81.09	53.25	2.94	255.27	117
Precipitation Spatial Correlation	0.81	0.2	0	0.99	117
Precipitation Volatility	36.9	20.3	2.79	116.07	117
Temperature (Daily Mean)	16.29	8.44	-5.16	28.3	117
Temperature Spatial Correlation	0.86	0.21	0	1	117
Temperature Volatility	1.21	0.56	0.37	2.4	117
Average Crop Yield (pre-1500CE)	3047.52	1119.8	0	5227.94	117
Share of Area within 100kms of Sea	0.36	0.36	0	1	117
Coast Length	2734.77	9731.16	0	93321.81	117
Ecological Diversity	0.55	0.29	0	0.91	117
Percentage of population of European descent	0.35	0.46	0	1	113
Time at MDD	1.93	3.91	0	17.99	116
Log[New Firms per 1,000 people (2000-2015CE)]	0.1	1.73	-5.34	3.19	93
Log[Patents per capita by Residents (2000-2015CE)]	-10.99	2.41	-16.84	-5.95	87
Log[Patents per Capita (2000-2015CE)]	-9.95	2.08	-15.59	-5.76	85
Log[GDP per capita (2000-2015CE)]	8.85	1.31	6.35	11.39	112

frontiers, while the second, $\tilde{R}$, is produced through independent creation. Productivity in each activity depends not only on the amount of labor the individual inputs, but also on the amount of labor their parents allocated when they were young. This captures the idea of intertemporal spillovers in imitation and creation of technologies, where the productivity of the current generation depends on the allocations of previous generations.

In particular, let l_t denote the amount of labor an individual born in period $t-1$ devotes to independent creation. To simplify the analysis assume that the intertemporal sector specific spillovers take the form $S_R(\mathbf{l_{t-1}}) = l_{t-1}^{\alpha'}$ and $S_{Ij}(\mathbf{i_{jt-1}}) = i_{jt-1}^{\beta'}$. Thus, she produces a quantity $\tilde{R}_t = a l_{t-1}^{\alpha'} l_t^{\alpha} A_{t-1}$ of independent knowledge, where $a > 0$, $\alpha', \alpha \in (0,1)$. She devotes the rest of her time, $(1-l_t)$, to creating intermediate knowledge through imitation from the frontiers. Let i_{jt} denote the amount of time she devotes to imitating from frontier j, so that, $\sum_j i_{jt} = 1 - l_t$. Additionally, assume that the intermediate knowledge from each frontier is generated using similar technologies, namely

$$\tilde{I}_{jt} = b(d_j) i_{jt-1}^{\beta'} i_{jt}^{\beta} A_{t-1}, \qquad j = 1, \ldots, n \tag{9}$$

where $\beta', \beta \in (0,1)$, $b : \mathbb{R}_+ \to \mathbb{R}_{++}$ is continuous, decreasing, and twice differentiable. The function $b(d)$ captures the negative effect of distance on the productivity of imitation. So, from the point of view of the young individual, the only difference between frontiers is their distance. She combines the intermediate knowledge she gained from the frontiers through a constant elasticity of substitution production function to produce her aggregate knowledge from imitation

$$\tilde{I}_t = \left(\sum_{j=1}^{n} \lambda_{2j} \tilde{I}_{jt}^{\rho_2} \right)^{\frac{1}{\rho_2}} \tag{10}$$

where $\sum_{j=1}^{n} \lambda_{2j} = 1$, $\lambda_{2j} \in [0,1]$, $0 \leq \rho_2 \equiv \frac{\eta_2 - 1}{\eta_2} \leq 1$, and $\eta_2 \geq 1$ is the constant elasticity of substitution of knowledge between any two frontiers. The new knowledge she gains from imitation and independent creation are aggregated through another constant elasticity of substitution production function to produce total new knowledge. This new knowledge is added to the existing stock of technology, so that

$$A_t - A_{t-1} = \left[\lambda_1 \tilde{R}_t^{\rho_1} + (1-\lambda_1) \tilde{I}_t^{\rho_1} \right]^{\frac{1}{\rho_1}} \tag{11}$$

where $\lambda_1 \in (0,1)$, $0 \leq \rho_1 \equiv \frac{\eta_1 - 1}{\eta_1} \leq 1$, and $\eta_1 \geq 1$ is the constant elasticity of substitution between imitation and creation. Letting $R_t = \tilde{R}_t / A_{t-1}$ and $I_t = \tilde{I}_t / A_{t-1}$, the growth rate of technology can be written as

$$g_t = \frac{A_t - A_{t-1}}{A_{t-1}} = \left[\lambda_1 R_t^{\rho_1} + (1-\lambda_1) I_t^{\rho_1} \right]^{\frac{1}{\rho_1}}. \tag{12}$$

Let $u(c_t)$, be the utility an individual born in period $t-1$ derives from consumption, where $u'(c) > 0$, $u''(c) < 0$. She chooses $l_t \in [0,1]$ and $i_{jt} \in [0,1]$ for $j = 1, \ldots, n$, in order to maximize her lifetime expected utility, i.e. she solves the following problem

$$\max_{(l_t, (i_{jt})_{j=1}^n) \in [0,1]^{n+1}} \quad u(c_t) \quad \text{subject to} \quad c_t = (1+g_t) A_{t-1}, \; l_t + \sum_{j=1}^{n} i_{jt} = 1. \tag{13}$$

I assume the following two conditions are satisfied by the parameters of the production functions:

$$(\alpha'+\alpha)\rho_1 < 1, \qquad (\beta'+\beta)\rho_1 < 1, \tag{ES}$$

$$\frac{\rho_1\beta\left[\frac{\alpha'}{\alpha}-\frac{\beta'}{\beta}\right]x}{\big(1-(\alpha'+\alpha)\rho_1\big)(1-x)+\big(1-(\beta'+\beta)\rho_1\big)x} = 1 \text{ for some } x\in(0,1). \tag{U}$$

Condition (ES) ensures that the marginal productivity of labor of young and old individuals is "jointly" decreasing in the production of intermediate products. Condition (U) gives a measure of the strength of intertemporal spillovers across sectors, and imposes limits on the differences in labor productivities across them. Clearly, $\alpha'/\alpha > \beta'/\beta$ is a necessary condition for (U) to hold, which implies intertemporal spillovers are more important in creation than imitation. Additionally, it implies that if in the production of each intermediate input the same quantities of current and past labor are used, then the marginal rate of technical substitution between current and past labor is larger in I than in R. So, as the distance d increases, the lower productivity of labor in imitation generates a substitution out of imitation and into research.

Clearly, the individual will allocate her time in all activities until the marginal product of labor is equal in all of them. The marginal productivities are given by

$$\frac{\partial g_t}{\partial R_t}\frac{\partial R_t}{\partial l_t} = \lambda_1\alpha\left(\frac{g_t}{R_t}\right)^{1-\rho_1}\frac{R_t}{l_t} \tag{14}$$

$$\frac{\partial g_t}{\partial I_t}\frac{\partial I_t}{\partial I_{jt}}\frac{\partial I_{jt}}{\partial i_{jt}} = (1-\lambda_1)\lambda_{2j}\beta\left(\frac{g_t}{I_t}\right)^{1-\rho_1}\left(\frac{I_t}{I_{jt}}\right)^{1-\rho_2}\frac{I_{jt}}{i_{jt}} \tag{15}$$

Thus, it must be that for all $j, j' = 1,\ldots,n$

$$\frac{\partial g_t}{\partial R_t}\frac{\partial R_t}{\partial l_t} = \frac{\partial g_t}{\partial I_t}\frac{\partial I_t}{\partial I_{jt}}\frac{\partial I_{jt}}{\partial i_{jt}}, \qquad \text{and} \qquad \frac{\partial g_t}{\partial I_t}\frac{\partial I_t}{\partial I_{jt}}\frac{\partial I_{jt}}{\partial i_{jt}} = \frac{\partial g_t}{\partial I_t}\frac{\partial I_t}{\partial I_{j't}}\frac{\partial I_{j't}}{\partial i_{j't}}.$$

In particular, from (15) the last condition is

$$\frac{\partial I_t}{\partial I_{jt}}\frac{\partial I_{jt}}{\partial i_{jt}} = \lambda_{2j}\beta\left(\frac{I_t}{I_{jt}}\right)^{1-\rho_2}\frac{I_{jt}}{i_{jt}} = \lambda_{2j'}\beta\left(\frac{I_t}{I_{j't}}\right)^{1-\rho_2}\frac{I_{j't}}{i_{j't}} = \frac{\partial I_t}{\partial I_{j't}}\frac{\partial I_{j't}}{\partial i_{j't}},$$

which can be rewritten as the ratio of labor used in imitation in j to j', namely

$$i_t^{j,j'} \equiv \frac{i_{jt}}{i_{j't}} = \frac{\lambda_{2j}}{\lambda_{2j'}}\left(\frac{I_{jt}}{I_{j't}}\right)^{\rho_2} = \frac{\lambda_{2j}}{\lambda_{2j'}}\left(\frac{b(d_j)}{b(d_{j'})}(i_{t-1}^{j,j'})^{\beta'}(i_t^{j,j'})^{\beta}\right)^{\rho_2}.$$

This implies that in a steady state the ratio of labor used in imitation from j and j' is

$$i^{j,j'} \equiv \frac{i_j}{i_{j'}} = \left(\frac{\lambda_{2j}}{\lambda_{2j'}}\right)^{\frac{1}{1-\rho_2(\beta'+\beta)}}\left(\frac{b(d_j)}{b(d_{j'})}\right)^{\frac{\rho_2}{1-\rho_2(\beta'+\beta)}} \tag{16}$$

Clearly, $i^{j,j'}$ is decreasing in d_j and increasing in $d_{j'}$, so that increases in the distance to frontier j causes an increase in the relative amount of labor allocated to all other frontiers. This implies that in a steady state the ratio of knowledge imitated from frontiers j and j' is

$$\frac{I_j}{I_{j'}} = \left(\frac{\lambda_{2j}}{\lambda_{2j'}}\right)^{\frac{(\beta'+\beta)}{1-\rho_2(\beta'+\beta)}}\left(\frac{b(d_j)}{b(d_{j'})}\right)^{\frac{1}{1-\rho_2(\beta'+\beta)}}, \tag{17}$$

which is also decreasing in d_j and increasing in $d_{j'}$. This implies that

$$\frac{I}{I_j} = \left[\lambda_{2j} + \sum_{j' \neq j} \lambda_{2j} \left(\frac{I_j}{I_{j'}}\right)^{-\rho_2}\right]^{\frac{1}{\rho_2}}.$$

The ratio of marginal productivities of labor in a steady state imply that for each $j = 1, \ldots, n$, the ratio of labor allocated to imitating from j to labor used for independent creation satisfies

$$\frac{i_j}{l} = \underbrace{\frac{(1-\lambda_1)}{\lambda_1}\frac{\beta}{\alpha}}_{\Lambda} \lambda_{2j} \left(\frac{I}{R}\right)^{\rho_1} \left(\frac{I}{I_j}\right)^{-\rho_2}. \tag{18}$$

Replacing in the time endowment condition, this implies that the steady state allocation of labor to creation satisfies

$$l^* = \frac{1}{1 + \Lambda \left[\sum_{j=1}^{n} \lambda_{2j} \left(\frac{I_j}{I}\right)^{\rho_2}\right] \left(\frac{I}{R}\right)^{\rho_1}} = \frac{1}{1 + \Lambda \left(\frac{I}{R}\right)^{\rho_1}}. \tag{19}$$

From equation (18) and the production functions for technology, it follows that for $j = 1, \ldots, n$

$$i_j = \frac{\Lambda \lambda_{2j} \left(\frac{I}{R}\right)^{\rho_1} \left(\frac{I_j}{I}\right)^{\rho_2}}{1 + \Lambda \left(\frac{I}{R}\right)^{\rho_1}}, \qquad I_j = b(d_j)^{\frac{1}{1-\rho_2(\beta'+\beta)}} \left(\frac{\Lambda \left(\frac{I}{R}\right)^{\rho_1} \frac{\lambda_{2j}}{I^{\rho_2}}}{1 + \Lambda \left(\frac{I}{R}\right)^{\rho_1}}\right)^{\frac{\beta'+\beta}{1-\rho_2(\beta'+\beta)}}, \tag{20}$$

and

$$I^{\rho_2} = \left(\sum_{j=1}^{n} \lambda_{2j} b(d_j)^{\frac{\rho_2}{1-\rho_2(\beta'+\beta)}}\right) \left(\frac{\Lambda \left(\frac{I}{R}\right)^{\rho_1} \frac{\lambda_2}{I^{\rho_2}}}{1 + \Lambda \left(\frac{I}{R}\right)^{\rho_1}}\right)^{\frac{\rho_2(\beta'+\beta)}{1-\rho_2(\beta'+\beta)}},$$

which is equivalent to

$$I = \left(\frac{\Lambda \left(\frac{I}{R}\right)^{\rho_1}}{1 + \Lambda \left(\frac{I}{R}\right)^{\rho_1}}\right)^{(\beta'+\beta)} \left(\sum_{j=1}^{n} \lambda_{2j}^{\frac{1}{1-\rho_2(\beta'+\beta)}} b(d_j)^{\frac{\rho_2}{1-\rho_2(\beta'+\beta)}}\right)^{\frac{1-\rho_2(\beta'+\beta)}{\rho_2}}. \tag{21}$$

All these are functions of $\mathbf{d}$ and the ratio of imitation to creation I/R, which is itself determined by following condition,

$$\frac{I}{R} = \frac{\left(\Lambda \left(\frac{I}{R}\right)^{\rho_1}\right)^{\beta'+\beta}}{\left(1 + \Lambda \left(\frac{I}{R}\right)^{\rho_1}\right)^{(\beta'+\beta)-(\alpha'+\alpha)}} \frac{\left(\sum_{j=1}^{n} \lambda_{2j}^{\frac{1}{1-\rho_2(\beta'+\beta)}} b(d_j)^{\frac{\rho_2}{1-\rho_2(\beta'+\beta)}}\right)^{\frac{1-\rho_2(\beta'+\beta)}{\rho_2}}}{a}. \tag{22}$$

The right hand side is a strictly concave function of I/R with a slope that is infinite at $I/R = 0$ and goes to zero as $I/R \to \infty$. Thus, there exists a unique $(I/R)^*(\mathbf{d}) > 0$ that satisfies this equation, which is decreasing in each d_j $j = 1, \ldots, n$. This implies that l^* and R^* are increasing in d_j. So, the steady state growth rate of economy $\mathbf{d}$ is

$$g^*(\mathbf{d}, \lambda_\mathbf{2}) = R^*(d) \left[\lambda_1 + (1 - \lambda_1) \left(\frac{I}{R}(\mathbf{d}, \lambda_\mathbf{2}) \right)^{\rho_1} \right]^{\frac{1}{\rho_1}}, \tag{23}$$

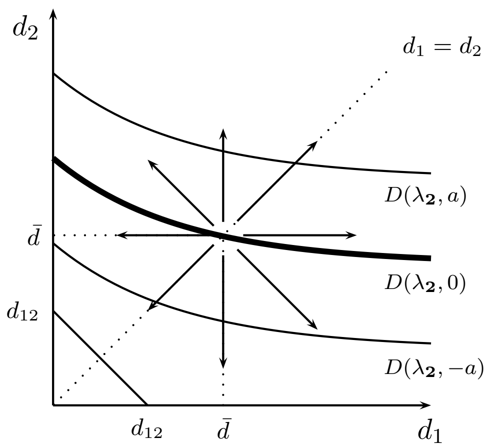
where $\lambda_\mathbf{2} = (\lambda_{2j})_{j=1}^n$. From the previous results, the first factor is increasing and the second one is decreasing in all the components of $\mathbf{d}$. This implies

$$\begin{aligned}
\frac{\partial g^*}{\partial d_j} =& \frac{\partial R^*}{\partial d_j} \frac{g^*}{R^*} + (1 - \lambda_1) \frac{\partial (I/R)^*}{\partial d_j} R^* \left(\frac{g^*}{R^*} \right)^{1-\rho_1} \\
=& \frac{g^*}{R^*} \left[\frac{\partial R^*}{\partial d_j} + (1 - \lambda_1) \frac{\partial (I/R)^*}{\partial d_j} \frac{(R^*)}{\lambda_1 + (1 - \lambda_1) \left((I/R)^* \right)^{\rho_1}} \right],
\end{aligned}$$

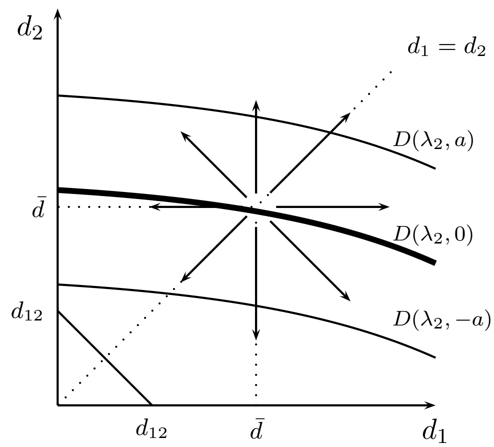
where the variations in the distance to frontier j, d_j, generate a trade-off between imitation and creation that affect the growth rate of the economy.

Clearly, economies that are equidistant from all frontiers, effectively have only one frontier, and thus behave as if they existed in a world with a unique frontier. For these economies, $\mathbf{d} = d \cdot \mathbf{e}$ and $g^*(\mathbf{d}, \lambda_\mathbf{2}) = G(d)$, where $\mathbf{e}$ is the n dimensional vector of ones, $d \in \mathbb{R}_+$, and $G(d)$ is the steady state growth rate in a world with a unique frontier for an economy at distance d from it. In appendix D I prove that assumptions (ES) and (U) imply that in a world with a unique frontier, $G(d)$ is U-shaped with the lowest growth rate attained at a distance $\bar{d} > 0$. Since any $d \in \mathbb{R}_+$ can be written as $d = \bar{d} + z$, $z \in \mathbb{R}$, this implies that equidistant economies' growth rates are given by $g^*\Big((\bar{d} + z) \cdot \mathbf{e}, \lambda_\mathbf{2} \Big) = G(\bar{d} + z)$, so that the growth rate for these economies is also U-shaped.

Figure C.1: Isogrowth maps in a world with two frontiers.



(a) Convex $b(d)$



(b) Concave $b(d)$

$D(\lambda_2, 0)$ is the set of economies that have the lowest growth rate. The arrows show the direction of increase in the growth rate. d_{12} is the distance between frontier 1 and 2.

This implies that a similar non-monotonicity holds for all other economies as well. To see this, let a z-isogrowth curve be the set of economies that grow at rate $G(\bar{d} + z)$, i.e.

$$D(\lambda_\mathbf{2}, z) = \left\{ \mathbf{d} \in \mathcal{E} \mid g^*(\mathbf{d}, \lambda_\mathbf{2}) = G(\bar{d} + z) \right\}. \tag{24}$$

Clearly, $[D(\boldsymbol{\lambda_2}, z)]_{z\in\mathbb{R}}$ defines a partition of $\mathcal{E}$.[29] Thus, $D(\boldsymbol{\lambda_2}, 0)$ is the $(n-1)$-manifold that splits $\mathcal{E}$ in two regions, such that for any $z_1 < z_2 < 0 < z_3 < z_4$, if $\mathbf{d}_i \in D(\boldsymbol{\lambda_2}, i)$, $i = 0, 1, 2, 3, 4$, it follows that $g^*(\mathbf{d}_1, \boldsymbol{\lambda_2}) > g^*(\mathbf{d}_2, \boldsymbol{\lambda_2}) > g^*(\mathbf{d}_0, \boldsymbol{\lambda_2})$ and $g^*(\mathbf{d}_0, \boldsymbol{\lambda_2}) < g^*(\mathbf{d}_3, \boldsymbol{\lambda_2}) < g^*(\mathbf{d}_4, \boldsymbol{\lambda_2})$. But, this implies that for any economy $\mathbf{d} \in D(\boldsymbol{\lambda_2}, z)$ where $z \geq 0$, $\partial g^*(\mathbf{d}, \boldsymbol{\lambda_2})/\partial d_j > 0$ for all $j = 1, \ldots, n$. Furthermore, for each frontier j, given the distances to the other $n-1$ frontiers, $\mathbf{d}_{-j}$, the steady state growth rate $g^*(\mathbf{d}, \boldsymbol{\lambda_2}) = G_j(d_j)$ is also U-shaped and has a minimum at some $\bar{d}_j(\mathbf{d}_{-j}) > 0$.

These results imply that the steady state profile of growth rates looks like a valley with the economies belonging to $D(\boldsymbol{\lambda_2}, 0)$ at its bottom. Figure 2 shows the isogrowth maps in a world with two frontiers. Panel (a) assumes $b(d)$ is convex, while panel (b) assumes $b(d)$ is concave. The distance $\bar{d}$ is the least desirable distance from the technological frontier and is located where the 45-degree line intersects $D(\boldsymbol{\lambda_2}, 0)$.

Notice that conventional wisdom is a special case of this theory in which either (i) $\bar{d} = \infty$, so that $D(\boldsymbol{\lambda_2}, z) = \emptyset$ for all $z \geq 0$, or (ii) the observable world is too small, so that $D(\boldsymbol{\lambda_2}, 0)$ is not observable. In either case, there would not exist a valley and a non-monotonicity cannot exist (see also appendix E).

D A model with a unique frontier

This section presents a version of the model presented in section 3 for the case of a unique frontier, $n = 1$. The proofs are collected in appendix G

The world consists of a set of economies $\mathcal{E} = [0, \tilde{d}]$, where $\tilde{d}$ is large enough,[30] and a technological leader economy. Assume that all economies in $\mathcal{E}$ are identical except for their geographical distance, d, to the technological leader and thus identify each economy with this distance d. Each economy $d \in \mathcal{E}$, is populated by overlapping generations of two-period lived individuals. Population is constant and is normalized so that its size is 1. Each individual is endowed with one unit of time when young and one unit of time when old. For simplicity, assume that young individuals can only engage in activities of imitation or creation of technology, and do not engage in consumption. On the other hand, old individuals can only engage in production and consumption activities, where their production possibilities are determined by their own technology, which is generated by their decisions when young and the technology left by their parents.

Individuals born in period $t-1$ inherit a level of technology A_{t-1} from their parents. They increase their stock of technology, which will be available for production in period t, using two types of intermediate inputs. The first intermediate input, I, is produced by imitation from the technological frontier, while the second, R, is produced through independent creation. Let l_t denote the amount of labor an individual born in period $t-1$ devotes to independent creation. She produces a quantity $\tilde{R}_t = a l_{t-1}^{\alpha'} l_t^{\alpha} A_{t-1}$ of independent knowledge, where $a, \alpha', \alpha > 0$. She devotes the rest of her time, $(1-l_t)$, to imitation and generates $\tilde{I}_t = b(d)(1-l_{t-1})^{\beta'}(1-l_t)^{\beta} A_{t-1}$, where $\beta', \beta > 0$, $b(d)$ is continuous, decreasing, convex, and twice differentiable. The function $b(d)$ captures the negative effect of distance on the productivity of imitation. In order to capture the idea of intertemporal spillovers, I assume the

[29] Since economies for which I/R is equal have the same growth rate, it follows that

$$D(\boldsymbol{\lambda_2}, z) = \left\{ \mathbf{d} \in \mathcal{E} \,\middle|\, \left(\sum_{j=1}^{n} \lambda_{2j}^{\frac{1}{1-\rho_2(\beta'+\beta)}} b(d_j)^{\frac{\rho_2}{1-\rho_2(\beta'+\beta)}} \right)^{\frac{1-\rho_2(\beta'+\beta)}{\rho_2}} = b(\bar{d}+z) \right\}.$$

[30] For the theoretical analysis the total number of economies and their spatial distribution is unimportant, as long as the set $\mathcal{E}$ is big (long) enough. In particular, I assume that $\tilde{d} = \inf\{d > 0 \mid G(d) \geq G(0)\}$, where $G(\cdot)$ is defined in equation (28). On the other hand, the number of economies and their distribution across space is very important for the empirical analysis, since it can affect the statistical significance and the sign of the parameters.

productivity of each individual in the production of these intermediate goods depends on her parents' decisions in the past.

These intermediate products are aggregated through a constant elasticity of substitution production function to produce new knowledge, which is added to the existing stock of technology, so that

$$A_t - A_{t-1} = \Big[\lambda \tilde{R}_t^{\rho} + (1-\lambda)\tilde{I}_t^{\rho}\Big]^{\frac{1}{\rho}} \tag{25}$$

where $\lambda \in (0,1)$, $0 \leq \rho \equiv \frac{\eta-1}{\eta} \leq 1$, and $\eta \geq 1$ is the constant elasticity of substitution between imitation and creation. Letting $R_t = \tilde{R}_t/A_{t-1}$ and $I_t = \tilde{I}_t/A_{t-1}$, the growth rate of technology can be written as

$$g_t = \frac{A_t - A_{t-1}}{A_{t-1}} = \Big[\lambda R_t^{\rho} + (1-\lambda)I_t^{\rho}\Big]^{\frac{1}{\rho}}. \tag{26}$$

Let $u(c_t)$, be the utility an individual born in period $t-1$ derives from consumption, where $u'(c) > 0$, $u''(c) < 0$. She chooses $l_t \in [0,1]$ in order to maximize her lifetime expected utility, i.e. she solves the following problem

$$\max_{l_t \in [0,1]} \quad u(c_t) \qquad \text{subject to} \qquad c_t = (1+g_t)A_{t-1} \tag{27}$$

I assume the following two conditions are satisfied by the parameters of the production functions:

(ES) $(\alpha' + \alpha)\rho < 1$, $(\beta' + \beta)\rho < 1$.

(U) $\dfrac{\rho\beta\left[\frac{\alpha'}{\alpha} - \frac{\beta'}{\beta}\right]x}{\Big(1-(\alpha'+\alpha)\rho\Big)(1-x) + \Big(1-(\beta'+\beta)\rho\Big)x} = 1$ for some $x \in (0,1)$.

The interpretation of these conditions was given in the text.

D.1 Equilibrium

Given $A_0(d) > 0$ and $l_0(d) \geq 0$, an *equilibrium* for economy d is a sequence $\{l_t^*(d)\}_{t=0}^{\infty}$ such that for each $t \geq 1$, l_t^* solves the optimization problem (27). A *stationary equilibrium* for economy d is an equilibrium such that $l_t^* = l^*$ for all $t \geq 0$. An *equilibrium profile* is a sequence of functions, $\{\{l_t^*(d)\}_{t=0}^{\infty}\}_{d \in \mathcal{E}}$, such that for each $d \in \mathcal{E}$ the sequence $\{l_t^*(d)\}_{t=0}^{\infty}$ is an equilibrium for economy d. Similarly, a *stationary equilibrium profile* is an equilibrium profile such that each economy $d \in \mathcal{E}$ is in a stationary equilibrium. Given the stationary equilibrium profile $\{\{l^*(d)\}_{t=0}^{\infty}\}_{d \in \mathcal{E}}$, the *profile of stationary growth rates* is the function $G : \mathcal{E} \to \mathbb{R}$ that assigns to each economy d its growth rate in a stationary equilibrium, i.e.

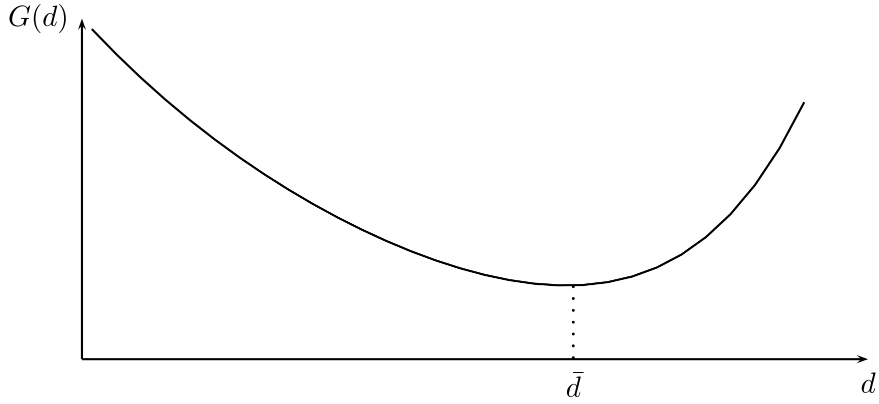
$$G(d) = \Big[\gamma l^*(d)^{(\alpha'+\alpha)\rho} + \delta(1 - l^*(d))^{(\beta'+\beta)\rho}\Big]^{\frac{1}{\rho}}. \tag{28}$$

It is not difficult to see that for any $d \in \mathcal{E}$, if $l_0 = 0$, then $l_t = 0$ for all $t \geq 1$ is the unique (stationary) equilibrium. Similarly, if $l_0 = 1$, then $l_t = 1$ for all $t \geq 1$ is the unique (stationary) equilibrium. Since these two cases are not very interesting, as they are not stable to errors made by the individuals, and seem rather artificially generated by the choice of production functions, I shall assume in what follows that $l_0(d) \in (0,1)$ for all $d \in \mathcal{E}$. In the appendix I prove that:

Theorem D.1. *Given $A_0(d) > 0$ and $l_0(d) \in (0,1)$, each economy d has a* unique *equilibrium. Additionally, each economy has a* unique, asymptotically stable, and sub-optimal *stationary equilibrium.*

Finally, there exists an economy $\bar{d}$, such that the profile of stationary growth rates is a decreasing function of d for all economies $d \leq \bar{d}$ and is an increasing function of d for all economies $d > \bar{d}$.

Figure D.1: The relationship between distance and economic growth in the model.



This shows the non-monotonic effect of distance on growth rates in the stationary equilibrium: Initially, for $d \in [0, \bar{d}]$ the growth rates fall as the distance from the technological frontier increases, but once $d > \bar{d}$ growth rates increase. Thus, there is a U-shaped relation between the distance from the frontier and the rate of growth of an economy, as shown in Figure D.1. Notice that if $\tilde{d} \leq \bar{d}$, i.e. the world is too "small", then conventional wisdom holds true.

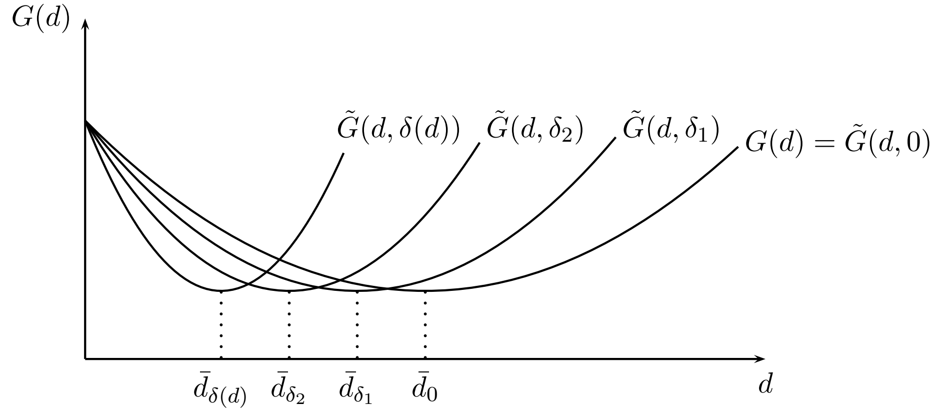
It is not difficult to prove that this U-shaped relation between distance from the frontier and economic growth translates into a U-shaped relation between distance and income levels *irrespective* of the shape of the initial profile of technology levels (see appendix). This implies that in this model there is no tendency towards convergence among economies. Furthermore, the economy at $\bar{d}$ will be the least developed economy in the long-run, making the distance $\bar{d}$ the *least desirable distance (LDD)* from the technological frontier.

D.2 The Effect of Cultural Barriers to Diffusion

The analysis conducted so far has focused on the effects of geographical distance on the substitution of imitation and creation of new technologies.[31] But as mentioned in the introduction, cultural differences, among others, act as barriers to the adoption and imitation of technologies. A simple extension of the previous model can introduce this additional complexity by considering an additional measure of distance between economies $\delta \in \mathbb{R}_+$, so that every economy $d \in \mathcal{E}$ is identified by a pair (d, δ) and the productivity of imitation is determined by $\tilde{b}(d, \delta)$. Assume that $\tilde{b}(\cdot, \cdot)$ is continuous, decreasing in both parameters, twice differentiable and such that for any $d \in \mathcal{E}$, $\tilde{b}(d, 0) = b(d)$. It is easy to prove that for any $\delta > 0$ and for any economy $d \in \mathcal{E}$ there exists a unique economy $d_\delta \geq d$ such that $\tilde{b}(d, \delta) = b(d_\delta)$. This implies that for any fixed $\delta > 0$ the profile of stationary growth rates $\left\{\tilde{G}(d, \delta)\right\}_{d \in \mathcal{E}}$ is a contraction of the profile $\{G(d)\}_{d \in \mathcal{E}}$ in the sense that $\tilde{g}(d, \delta) = g(d_\delta)$ for each $d \in \mathcal{E}$. Additionally, if $\delta_1 < \delta_2$, then $d_{\delta_1} < d_{\delta_2}$, which implies that $\left\{\tilde{G}(d, \delta_2)\right\}_{d \in \mathcal{E}}$ is a stronger contraction of $\{G(d)\}_{d \in \mathcal{E}}$ than $\left\{\tilde{G}(d, \delta_1)\right\}_{d \in \mathcal{E}}$, so that $\bar{d}_{\delta_1} > \bar{d}_{\delta_2}$.

[31] This is not completely accurate, since the meaning of the distance d is open to interpretation. A priori any measure of distance that satisfies the conditions assumed above must generate the same results. So, this same model can explain why large institutional or cultural distances increase innovative efforts during the modern era, as exemplified by the case studies in Immelt et al. (2009).

Figure D.2: The effect of cultural distance on the relationship between growth and geographical distance.



Since cultural distances in general increase with geographical distances, one should expect δ to be an increasing function of d. Assuming that $\delta = \delta(d)$ is a continuous and increasing function of d it is not difficult to prove, using an analysis similar to the previous one, that this causes an additional contraction of the stationary equilibrium. Figure D.2 shows these effects graphically.

Clearly, these results imply that the estimates of the distance d from the frontier will be affected if one controls for other distances that affect the productivity of imitation.

E Monte Carlo Simulations

This section uses Monte Carlo simulations in order to assess how conventional theory and the theory presented in this paper can be differentiated econometrically. To do so, it follows two avenues: First, using the theory presented in section 3 it creates artificial worlds in which either conventional theory or the proposed theory hold. It adds random shocks to the implied steady state growth rates and uses samples of economies, located in similar patterns as the actual Old World countries, or at the actual location of Old World countries, to run regressions similar to equation 7. Second, it creates artificial development data and studies how differences in the relation between distance to one or two frontiers affect the regression analysis. Of particular interest is the effect of the inclusion of the distance to one or two possible frontiers on the value and statistical significance of the various estimates, especially of the LDD. The objective of this analysis is to determine whether the quadratic coefficients, which capture the non-monotonicity, and the LDD's generated by them, have the right signs and statistical significance as predicted by the theory.

E.1 Model-based artificial economies

This section presents the results of generating artificial economies based on the model presented in section 3 when there are two technological frontiers (n=2). The main objective of these simulations is to serve as a guide on how to test econometrically the difference between a world in which conventional wisdom holds, i.e. $\bar{d} = \infty$ or $\sup_{\mathbf{d} \in \mathcal{E}} \|\mathbf{d}\| < \bar{d}$, from one when the theory put forward in this paper holds and is observable. In order to do so, for each world $\mathcal{E}$ I choose a set of parameters and a function $b(d)$ such that given the actual locations of countries in the Old World, there exists at least one set of parameters $a, \alpha, \alpha', \beta, \beta', \rho_1, \rho_2, \lambda_1, \lambda_2 \in [0, 1]$ that satisfy assumptions (ES) and (U), and the theoretical value of $\bar{d}$ is less than the maximum of the distances from China and the Netherlands to the countries in the Old World. This implies that $\mathcal{E} = \left\{(d_1, d_2) \in \mathbb{R}^2_+ \mid d_1 \leq \max d_{CHN} \leq 15, d_2 \leq \max d_{NLD} \leq 15\right\}$. Additionally, it ensures that for at least one parametrization the U-shape holds in theory and could in principle be observable/estimable.[32]

Notice that if λ_2 is too small or too big, so that one frontier has a much larger importance, then the world will behave almost like a world with one frontier, where the non-monotonicity is easy to determine.[33] Simulations showed that λ_2 does not have to deviate a lot from 0.5 for the world to behave basically like a one-frontier economy. For this reason, and since a priori there is no reason to assume frontiers might differ in their importance, I assume that $\lambda_2 = 0.5$. Similarly, I assume $\lambda_1 = 0.5$ so as to not assign a major relative importance to creation vis-à-vis adoption. Clearly, neither parameter is essential for assumptions (ES) and (U) for any set of the other parameters.

In addition, it is necessary to choose a functional form for $b(d)$. I follow of the literature on technological diffusion (see e.g. Keller, 2004) and assume that $b(d) = b_0 \exp(-b_1 d)$. Since b_0's size only matters relative to a, I set $a = 0.55$ and $b_0 = 1$. Additionally, I choose $b_1 = 0.05$, which implies that for given levels of inputs, the elasticity of the output from imitation with respect to the distance to the frontier is -0.05.

The remaining set of parameters are related to the CES and Cobb-Douglas production functions. The set of all possible parameter values is $[0, 1]^6$, which I discretize. In particular, I let $\rho_1, \rho_2, \alpha, \alpha', \beta, \beta' \in \{0.1, 0.3, 0.5, 0.7, 0.9\}$. This generates a set of 15,625 worlds $\mathcal{E}$. Of these, I discard all economies such that $\alpha + \alpha' > 1$ and $\beta + \beta' > 1$. This leaves me with a set of 5624 worlds. Each world has a set of economies located on a lattice that belongs to $[0, 15]^2$ where every point on the lattice is at a distance of 0.25 from its neighbors to the north, south, east and west.

For every world $\mathcal{E}$ I compute the steady state growth rate for all economies. The perfect sample to identify the non-monotonicity and estimate the LDD is the set of countries equidistant from the frontiers, i.e. those located on the 45-degree line in figure 2. Figure 3 shows the growth surface of one such world and the profile of growth rates along the equidistant economies. Additionally, since for each world I know if condition (U) is satisfied or not, I need to establish if the U-shape would be identifiable. For this, I consider only the set of equidistant economies. I estimate a quadratic relation between the growth rate in these economies and their distance to the frontier. The regression correctly identifies the model if it rejects the U-shape when the world does not have a U-shape (or it is not observable), or, when it fails to reject the U-shape when the world has one.

Figure E.1 presents the distribution of worlds' probability of correctly identifying the U-shape. In figure E.1(a) I present the frequency distribution of worlds' probability of correctly identifying the non-monotonicity, when they satisfied assumption (U). As can be seen there, in most worlds that have a U-shape, the econometric test with the sample of equidistant economies fails to identify this non-monotonicity. In particular, only in 12.5% of the worlds is the non-monotonicity correctly identified when the U-shape is actually present.

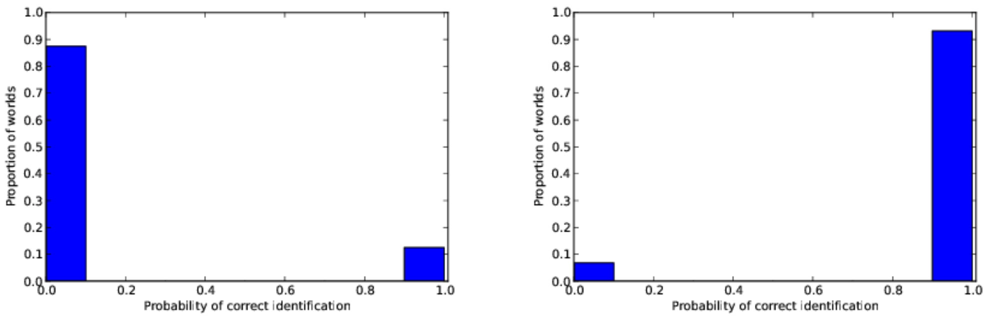
On the other hand, figure E.1(b) presents the frequency distribution of worlds' probability of correctly identifying the lack of non-monotonicity, when they did not satisfy condition (U). In this case, for most worlds, the econometric test does reject the U-shape, when it is not present. In particular, in 93.7% of the worlds the U-shape is correctly rejected. These results suggest that not rejecting a non-monotonicity, when one uses the sample of equidistant countries would be a strong indicator of the existence of the U-shape.

Unfortunately, in the empirical analysis I do not have observations for the sample of equidistant economies. In order to overcome this problem, I use Monte Carlo simulations based on the sample of

[32] Simulations with other parameter values generated similar results to the ones presented here. The main difficulty is generating observability, since condition (U) can be satisfied by many parameter values generating a theoretically true U-shape, which cannot be identified.

[33] In that case, only one of the distances will have a non-monotonicity, while the other will always be not statistically significant.

Figure E.1: Identification of U-shape on sample to equidistant economies.



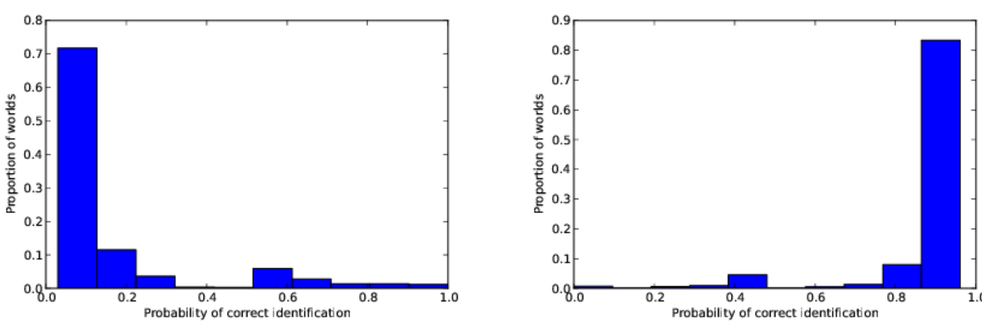
(a) Worlds with theoretical U-shape. Test incorrectly rejects U-shape.

(b) Worlds without theoretical U-shape. Test correctly rejects U-shape.

economies in the artificial world that are located where the countries in the Old World would be.[34] For this sample I generate 1000 artificial copies of each possible world, and add a normally distributed random shock to the steady state growth rate of each economy in the sample. The random shock has mean zero and a standard deviation equal to the standard deviation of steady state growth rates across all economies in the artificial world.

Using these samples of artificial worlds, I estimate a quadratic relation between the steady state growth rate in an economy and the distances to both frontiers. For each simulation I test if one or both LDD's are statistically significant and smaller than the maximum distance to their frontier. Since I know if the world has a U-shape I can determine the probability of correctly identifying the U-shape for each artificial world.

Figure E.2: Identification of U-shape on sample of Old World economies.



(a) Worlds with theoretical U-shape. Test incorrectly rejects U-shape.

(b) Worlds without theoretical U-shape. Test correctly rejects U-shape.

Figure E.2 summarizes the result of these experiments. In figure E.2(a) I show the frequency distribution of worlds' probability of correctly identifying the U-shape, when the world has a U-shape. As can be seen there, in most worlds that have a U-shape, the econometric test incorrectly rejects the null hypothesis that the LDD of *at least one* frontier is finite and less than the maximum distance

[34]This is one of the main constraints in the choice of values for a and b_1 above.

to it. In particular, the average probability of not rejecting the U-shape with respect to at least one frontier is 16.2%, while the median is 7.0%. Furthermore, for worlds in which the sample of equidistant countries correctly identifies the U-shape when it exists, the median probability of correctly identifying the U-shape with the sample of Old World countries is 26.0%.

On the other hand, figure E.2(b) shows that in most worlds that do not have a U-shape, the test correctly rejects the hypothesis that the LDD of *both* economies is statistically significant and less than the maximum distance to it. The average probability of correctly identifying the model in these worlds is 88.6% and the median probability is 94.0%. Additionally, for the worlds in which the sample of equidistant countries correctly rejects the U-shape when it does not exist, the median probability of correctly rejecting the U-shape with the sample of Old World countries is 95.0%.

The results of these Monte Carlo simulations suggest that the probability of incorrectly finding a U-shape when the world does not have one is low. Furthermore, in general, the test tends to reject the null hypothesis of existence of a U-shape in both samples, even when the U-shape exists. Thus, when the world does not have a U-shape, the probability of making an error of type II by not rejecting the U-shape, is less than 5%. On the other hand, for a world where the U-shape exists, the probability of making an error of type I is quite large (over 80%). Thus, these results suggest that the test has a high power for the question being asked. Furthermore, and as the next section will further show, not rejecting the null hypothesis of a U-shaped relation seems a strong indicator that there exists a U-shape.

E.2 General artificial economies

In this subsection I take a less parametric approach by looking at the more general implications of the theory, without considering the specific CES functional forms used in this paper. In particular, using the distances to the Netherlands and China I construct for each country various artificial income processes based on different assumptions about the relation between income and distance:

$$\begin{aligned}
y_i^1 &= a + b_1 \mathbb{I}_{i1} d_{i1} + b_2 \mathbb{I}_{i2} d_{i2} + \epsilon_i \\
y_i^2 &= a + b_1 d_{i1} + b_2 d_{i2} + \epsilon_i \\
y_i^3 &= a + b_1 d_{i1} + b_{12} d_{i1}^2 + \epsilon_i \\
y_i^4 &= a + b_1 d_{i1} + b_{12} d_{i1}^2 + b_2 d_{i2} + \epsilon_i
\end{aligned}$$

where y_i^s is country i's income under the data generating process s, $\mathbb{I}_{ij}$ is an indicator function with value 1 if the country i's income is affected by frontier $j = 1, 2$; $a \in \mathbb{R}$, $b_1, b_2 < 0$, $b_{12} > 0$, and $\epsilon_i \sim \mathcal{N}(\mu, \sigma^2)$. I assume that $\mathbb{I}_{i1} = 1 - \mathbb{I}_{i2}$, frontier 1 is the Netherlands and frontier 2 is China, and that the $\mathbb{I}_{i1} = 1$ if the country does not lie in Asia and zero otherwise. Processes y^1 and y^2 represent the conventional wisdom, where income is a monotonically decreasing function of the distance to the technological frontier. Processes y^3 and y^4 capture the idea of a U-shaped relation between economic development and distance.

Having generated a cross country sample for each income process, I run various econometric specifications in order to estimate the effect of distance on income. The specifications I consider are:

$$\begin{aligned}
R_1 : \ y_i &= \alpha + \beta_1 d_{i1} + \beta_{12} d_{i1}^2 \\
R_2 : \ y_i &= \alpha + \beta_1 d_{i1} + \beta_{12} d_{i1}^2 + \beta_2 d_{i2} \\
R_3 : \ y_i &= \alpha + \beta_1 d_{i1} + \beta_{12} d_{i1}^2 + \beta_2 d_{i2} + \beta_{22} d_{i2}^2 \\
R_4 : \ y_i &= \alpha + \beta_1 d_{i1} + \beta_{12} d_{i1}^2 + \beta_{13} \mathbb{I}_{i2} d_{i1} \\
R_5 : \ y_i &= \alpha + \beta_1 d_{i1} + \beta_{12} d_{i1}^2 + \beta_{13} \mathbb{I}_{i2} d_{i1} + \beta_{14} \mathbb{I}_{i2} d_{i1}^2
\end{aligned}$$

Repeating this process T times gives a distribution of the parameters of the different econometric specifications for each income process. I use these results in order to compare the sign pattern and statistical significance generated by these econometric specifications between a world where the conventional wisdom holds, with one where the theory proposed in this paper does.

Tables E.1-E.3 present the results under the following parametric assumptions: $a = 1$, $b_1 = b_2 = -0.5$, $b_{12} = 0.05$, $T = 5000$, $\mu = 0$, and $\sigma^2 = 0.5$.[35] As can be seen from the tables, if income is generated according to conventional wisdom (y^1 or y^2), the inclusion of the distance to the second frontier renders the inflection point at the LDD$_1$ statistically insignificant, with the wrong sign or outside the sample, reflecting perfectly the fact that there does not exist a U-shaped relation between distance and income per capita. On the other hand, if income is generated according to the models presented in this paper (y^3 or y^4), then the inclusion of the distance to a second frontier *does not* affect the sign or statistical significance of the estimate of the LDD, which remains within the sample range. Thus, inclusion of the distance to the second technological frontier should allow one to differentiate between both worlds.

Furthermore, comparison of the sign patterns and statistical significances from the estimated parameters in the different specifications R_1-R_5 for the artificial processes $y^1 - y^4$ with the ones from the technological sophistication in 1500CE data, shows that the technology data resembles (more closely) the pattern from y^3-y^4, i.e. the data generated by the models in this paper.

[35] Varying the parameters generated in similar results.

Table E.1: Results of Monte Simulations.

	Econometric Specification R_1				
	y^1	y^2	y^3	y^4	Tech. Soph.
β_1	—	—	—	—	—
	-0.56***	-0.77***	-0.50***	-0.77***	-0.12***
	(0.06)	(0.06)	(0.06)	(0.06)	(0.03)
β_{12}	+++	+++	+++	+++	+++
	0.02***	0.03***	0.05***	0.08***	0.01***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.00)
LDD_1	+++	+++	+++	+++	+++
	12.88***	15.31***	4.99***	5.09***	5.46***
	(2.06)	(2.18)	(0.17)	(0.11)	(0.37)

Notes: (i) Column y^s denotes that the dependent variable is income process s. In column Tech. Soph. the level of technological sophistication in 1500CE from Comin et al. (2010). (ii) LDD_1 is least desirable distance (LDD) to frontier 1. It is equal to $-\beta_1/(2*\beta_{12})$. (iii) Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests. Sign patterns denoted by + and -. The number of pluses or minuses denotes the statistical significance of each estimate.

Table E.2: Results of Monte Simulations (continued).

	Econometric Specification R_2					Econometric Specification R_3				
	y^1	y^2	y^3	y^4	Tech. Soph.	y^1	y^2	y^3	y^4	Tech. Soph.
β_1	—	—	—	—	—	—	—	—	—	—
	-0.43***	-0.50***	-0.50***	-0.50***	-0.14***	-0.72***	-0.50***	-0.50***	-0.50***	-0.14***
	(0.06)	(0.06)	(0.06)	(0.06)	(0.02)	(0.07)	(0.07)	(0.07)	(0.07)	(0.03)
β_{12}	+		+++	+++	+++	+++		+++	+++	+++
	0.01*	0.00	0.05***	0.05***	0.01***	0.03***	-0.00	0.05***	0.05***	0.01***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.00)	(0.01)	(0.01)	(0.01)	(0.01)	(0.00)
β_2	—	—		—	—	—	—		—	
	-0.24***	-0.50***	-0.00	-0.50***	-0.04***	-0.88***	-0.50***	0.00	-0.50***	-0.03
	(0.02)	(0.02)	(0.02)	(0.02)	(0.01)	(0.09)	(0.09)	(0.09)	(0.09)	(0.04)
β_{22}						+++				
						0.04***	-0.00	-0.00	-0.00	-0.00
						(0.01)	(0.01)	(0.01)	(0.01)	(0.00)
LDD_1			+++	+++	+++	+++		+++	+++	+++
	7.74	-98.30	4.99***	4.99***	7.62***	12.97***	-19.05	4.98***	4.98***	7.36***
	(1167.05)	(5207.55)	(0.17)	(0.17)	(0.82)	(1.61)	(3368.26)	(0.23)	(0.23)	(1.13)
LDD_2						+++				
						10.93***	27.95	6.74	28.02	-19.02
						(0.46)	(3000.25)	(102.25)	(3002.76)	(87.50)

Notes: (i) Column y^s denotes that the dependent variable is income process s. In column Tech. Soph. the level of technological sophistication in 1500CE from Comin et al. (2010). (ii) LDD_i is least desirable distance (LDD) to frontier $i = 1, 2$. It is equal to $-\beta_1/(2{*}\beta_{12})$. (iii) Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests. Sign patterns denoted by + and -. The number of pluses or minuses denotes the statistical significance of each estimate.

Table E.3: Results of Monte Simulations (continued).

	Econometric Specification R_4					Econometric Specification R_5				
	y^1	y^2	y^3	y^4	Tech. Soph.	y^1	y^2	y^3	y^4	Tech. Soph.
β_1	—	—	—	—	—	—	—	—	—	—
	-0.59***	-0.82***	-0.50***	-0.82***	-0.14***	-0.44***	-1.02***	-0.50***	-1.02***	-0.12***
	(0.06)	(0.06)	(0.06)	(0.06)	(0.02)	(0.07)	(0.07)	(0.07)	(0.07)	(0.03)
β_{12}	+		+++	+++	++		+++	+++	+++	
	0.01*	0.01	0.05***	0.06***	0.01**	-0.00	0.03***	0.05***	0.08***	0.00
	(0.01)	(0.01)	(0.01)	(0.01)	(0.00)	(0.01)	(0.01)	(0.01)	(0.01)	(0.00)
β_{13}	+++	+++		+++	++		+++		+++	
	0.28***	0.47***	0.00	0.47***	0.04**	-0.06	0.93***	0.00	0.93***	0.02
	(0.02)	(0.02)	(0.02)	(0.02)	(0.01)	(0.08)	(0.08)	(0.08)	(0.08)	(0.03)
β_{14}					+++	—		—		
						0.04***	-0.05***	-0.00	-0.05***	0.00
						(0.01)	(0.01)	(0.01)	(0.01)	(0.00)
LDD_1			+++	+++	+++		+++	+++	+++	+
	33.47	116.87	5.00***	7.36***	9.38***	-25.36	20.00***	5.00***	6.67***	12.11*
	(188.45)	(4477.99)	(0.20)	(0.24)	(2.46)	(2079.03)	(4.34)	(0.20)	(0.17)	(5.24)
$\text{LDD}_1\mathbb{I}_2$							+++		+++	
						0.52	9.36***	4.12	9.36***	-3.17
						(1.42)	(0.90)	(24.49)	(0.90)	(6.98)

Notes: (i) Column y^s denotes that the dependent variable is income process s. In column Tech. Soph. the level of technological sophistication in 1500CE from Comin et al. (2010). (ii) LDD_i is least desirable distance (LDD) to frontier $i = 1, 2$. It is equal to $-\beta_1/(2*\beta_{12})$. (iii) Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests. Sign patterns denoted by + and -. The number of pluses or minuses denotes the statistical significance of each estimate.

F Additional Results and Tables

This section reproduces some of the tables in the text, presenting the estimated coefficients for all controls, and presents some additional results that were not included in the paper in order to save space.

F.1 Historical Evidence I: Technological Sophistication

Table F.1 establishes the robustness of the results in table 2 to the inclusion of the quadratic distance to China. As can be seen there the results are unchanged and the estimates of the LDD remain qualitatively unchanged.

As explained above, the analysis in the main body of the paper focuses on the Old World. I exclude the New World and Oceania from the analysis, since their development experiences were mainly affected by other forces both pre-1500 and post-1500, which prevent a clean analysis of the effect of geographical distance from the frontier. In particular, pre-1500 Diamond (1997) suggested the extinction of megafauna, continental size, lack of domesticable plants, among others had a major impact on the differential development of these three regions. Additionally, post-1500 population replacement with its cultural, technological, and political effects, played a major role in these two continents. Furthermore, the lack of interaction among the three regions raises major difficulties for the analysis based on geographical distances. In particular, geodesic distances clearly underestimate the distance between the New and Old World, while there is no straight forward way to generalize my measures to include them for the pre-contact period. I tackle the problem in two ways in order to assess if the results presented before are driven by the exclusion of the New World.

First, I use the HMISea measure to find the distance between New World countries and the Netherlands and China using the Bering strait as crossing point that allowed both continents to be in contact. With this assumption I do not mean that both continents were in contact through this path, especially post 15000BCE. Still, it creates measures of distance between the technological frontiers in the Old World and countries in the New World, which maintain the ordering one should expect in terms of distance. In particular, we should consider countries in the New World to be farther away from the frontiers in the Old World than any country in the Old World. Additionally, countries in the New World also maintain a distance ordering that seems reasonable.[36] Using these distance measures, column (1) in table F.2 analyzes the relation between technological sophistication in 1500 CE and distance from the frontiers in the Old World across countries. The results remain qualitatively unchanged and do not reject the existence of a U-shape with a finite (in-sample) LDD.

A second approach one can take is to assume that the New and Old Worlds have their own frontiers from which the countries within it interact (i.e. $\lambda_{2j} = 0$ for frontiers outside the landmass or $\lim_{d_j \to \infty} b(d_j) = 0$), e.g. Mexico or Peru in the New World. This is equivalent to running additional independent regressions for the New World. Clearly, this implies that the results for the Old World presented in the main body of the paper do not change, since this amounts to a seemingly unrelated regression analysis. Columns (2)-(6) in table F.2 analyze the relation between countries' distance from Mexico and Peru on technological sophistication in the New World. The results of columns (2) and (3) show that there exists a robust U-shaped relation with the distance to Mexico, while columns (4) and (5) shows a non-robust inverse U-shaped relation with the distance to Peru. In column (6) when I control for the distance to both Mexico and Peru, I find that there exists a (weak) U-shaped relation with the distance to Mexico, and an non-monotonic increasing with the distance from Peru. These results do not reject the theory proposed in this paper, but are based on a very small sample, which

[36] This is the case unless we consider all countries in the New World to be equally distant from the frontiers in the Old World. But this would imply that we should not include them in our analysis, since there is no variation that could be exploited. This would take us back to the analysis in the main body of the paper.

excludes the caribbean islands, and on two negatively correlated distance measures.

As a final check I joined both subsamples and explored the association when all countries are assumed to be able to imitate from all 4 frontiers (Column 7). Additionally, I explored the association assuming each country can imitate only from the frontiers on its continental mass. In order to do so, for each country I assigned a distance of zero for each frontier not on the same landmass. The results are shown in column (8) of table F.2. The results are basically the same, with a U-shaped relation to at least one frontier in both the Old and New Worlds. The results of table F.2 suggest that the results presented in the main body of the paper are not driven by the exclusion of the New World from the analysis. But it also shows that its inclusion is not straightforward and subject to many caveats and problems. Furthermore, this analysis cannot be extended to the panel-data framework used in the main body of the paper, which exploits changes in the locations of the Western frontier.

In table 3 I had shown that controlling for the effects of local technological frontiers, trade, European colonization, and the advantages of backwardness could not explain the existence of the U-shape in average technology. Tables F.3-F.7 establish the robustness of these results at the sectorial level for each of these channels, supporting the analysis presented in section 5.

The Monte Carlo simulations of appendix E show that in a world with two frontiers, if conventional wisdom holds and countries' development depends only on the closest frontier, the inclusion of both distances would not generate a U-shape. Moreover, inclusion of the minimal distance should render the quadratic terms insignificant. In table F.8 I analyze the effect of including the minimum distance to either frontier as one of the regressors. The results show that the U-shape is not generated by misspecification of the relevant distance. Inclusion of the distance to the closest frontier does not change the qualitative results in the text. The U-shaped relation remains statistically and economically significant. This result and the theoretical model suggest that technology from both frontiers are not perfect substitutes. Thus, the existence of the U-shape supports the theory presented in the paper.

Table F.1: Sectorial Technology in 1500 CE and Pre-industrial Distance from the Technological Frontier
Robustness to Non-monotonicity in Distance to Second Frontier

	Technological Sophistication in 1500CE						
	(Agr)	(Comm)	(Trans)	(Mil)	(Ind)	(Av.)	(Av.M.)
Pre-industrial distance NLD	-0.13***	-0.09	-0.13***	-0.21***	-0.12*	-0.13***	-0.13***
	(0.05)	(0.05)	(0.05)	(0.07)	(0.06)	(0.03)	(0.03)
Sq.Pre-industrial distance NLD	0.01**	0.00	0.01**	0.01**	0.01**	0.01***	0.01***
	(0.00)	(0.00)	(0.00)	(0.01)	(0.00)	(0.00)	(0.00)
Pre-industrial distance CHN	-0.01	-0.08	-0.04	-0.05	-0.01	-0.04	-0.04
	(0.06)	(0.09)	(0.04)	(0.07)	(0.04)	(0.04)	(0.04)
Sq.Pre-industrial distance CHN	-0.00	0.00	-0.00	-0.00	-0.00	0.00	0.00
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
LDD NLD	8.32***	12.22	8.18***	7.54***	5.63***	7.73***	7.41***
	(2.24)	(7.33)	(2.40)	(2.41)	(1.29)	(1.62)	(1.52)
LDD CHN	-3.98	13.47**	-72.17	-110.37	-8.29	124.61	61.21
	(40.90)	(5.75)	(619.56)	(2049.80)	(56.15)	(1456.00)	(325.44)
Continental FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Geographical Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time Since Neolithic Revolution	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Adjusted-R^2	0.64	0.80	0.73	0.68	0.67	0.86	0.86
Observations	84	84	84	84	84	84	84

Notes: This table establishes the statistically and economically significant U-shaped relation between the distance to the frontier and sectorial technological sophistication in 1500CE across countries. Each column analyzes a specific sector: agriculture (Agr.), communications (Comm.), transportation (Trans.), military (Mil.), industry (Ind.), average (Av.) and migration adjusted average (Av.M.) across sectors. All columns include the same set of controls as column (5) in Table 1. Least desirable distance (LDD) is the number of weeks that minimizes the quadratic relation with respect to the pre-industrial distance. It is equal to $-\beta_{Distance}/(2 \cdot \beta_{Sq.Distance})$. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests.

Table F.2: Technology in 1500 CE and Pre-industrial Distance from the Technological Frontier
Robustness to New World Sample

	Technological Sophistication in 1500CE							
	World	New World					World	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Pre-industrial	-0.05**						-0.06***	
distance NLD	(0.02)						(0.02)	
Sq.Pre-industrial	0.00***						0.00**	
distance NLD	(0.00)						(0.00)	
Pre-industrial	-0.03***						-0.05	
distance CHN	(0.01)						(0.03)	
Pre-industrial		-0.04***	-0.04**		-0.01	-0.04	-0.02	
Distance MEX		(0.01)	(0.01)		(0.01)	(0.02)	(0.01)	
Sq. Pre-industrial		0.00***	0.00**			0.00	0.00	
Distance MEX		(0.00)	(0.00)			(0.00)	(0.00)	
Pre-industrial			-0.01	0.05**	0.04	0.01	-0.02	
Distance PER			(0.01)	(0.02)	(0.02)	(0.03)	(0.01)	
Sq. Pre-industrial				-0.00*	-0.00	-0.00		
Distance PER				(0.00)	(0.00)	(0.00)		
Pre-industrial								-0.07***
Distance Frontier								(0.02)
Sq. Pre-industrial								0.00***
Distance Frontier								(0.00)
Pre-industrial								-0.03*
Distance Frontier 2								(0.02)
Sq. Pre-industrial								0.00
Distance Frontier 2								(0.00)
LDD NLD	15.80***						15.35***	
	(2.89)						(3.38)	
LDD MEX		7.03***	6.75***			6.60***	7.07	
		(1.14)	(1.14)			(1.28)	(7.20)	
LDD PER				7.15***	8.19**	2.57		
				(1.49)	(3.23)	(10.54)		
LDD Frontier 1								8.61***
								(0.94)
LDD Frontier 2								34.63
								(59.33)
Continental FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Geographical Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time Since Neolithic Revolution	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Adjusted-R^2	0.88	0.83	0.81	0.72	0.72	0.79	0.88	0.89
Observations	104	22	22	22	22	22	104	104

Notes: This table establishes robustness of the results in Table 1 to the inclusion of countries in the New World. Estimation by OLS. Pre-industrial distance to Netherlands/China/Mexico/Peru is the minimum total travel time (in weeks) along the optimal path between a country's capital and the Netherlands/China/Mexico/Peru (see text for construction). Column 1 replicates the analysis in Table 1 to the expanded sample. Columns 2-6 explore the existence of a U-shaped relation in the sample of New World countries. Column 7 and 8 explore the relation in the expanded sample allowing for imitation from all 4 frontiers (column 7) or only with continental frontiers (column 8). Additional controls include latitude and latitude squared of the country's capital, Pre-1500CE caloric suitability, percentage of land area in tropics and subtropics, mean elevation above sea level, land area, island and landlocked dummies, and malaria (falciparum) burden. Least desirable distance (LDD) is the number of weeks that minimizes the quadratic relation with respect to the pre-industrial distance. It is equal to $-\beta_{Distance}/(2 \cdot \beta_{Sq.Distance})$. Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests.

Table F.3: Technological sophistication and distance to the technological frontier in 1500CE. Is the U-shape generated by local technological frontiers?

	Technological Sophistication in 1500CE						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	(Agr)	(Comm)	(Trans)	(Mil)	(Ind)	(Av.)	(Av.M.)
Pre-industrial distance NLD	-0.16***	-0.06	-0.12***	-0.22***	-0.11**	-0.13***	-0.13***
	(0.05)	(0.06)	(0.04)	(0.08)	(0.05)	(0.03)	(0.03)
Sq.Pre-industrial distance NLD	0.01**	0.00	0.01**	0.01**	0.01**	0.01***	0.01***
	(0.00)	(0.00)	(0.00)	(0.01)	(0.00)	(0.00)	(0.00)
Pre-industrial distance CHN	-0.04	-0.02	-0.04***	-0.06**	-0.02	-0.04***	-0.03***
	(0.03)	(0.02)	(0.02)	(0.02)	(0.01)	(0.01)	(0.01)
Pre-industrial distance local frontier	0.05	-0.01	-0.02	0.03	-0.03	0.00	0.01
	(0.04)	(0.04)	(0.03)	(0.04)	(0.06)	(0.02)	(0.02)
LDD NLD	9.30***	8.66	8.09***	7.79***	5.54***	7.70***	7.35***
	(2.12)	(5.41)	(2.00)	(1.90)	(1.07)	(1.33)	(1.20)
Continental FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Geographical Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time Since Neolithic Revolution	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Adjusted-R^2	0.65	0.80	0.74	0.68	0.67	0.86	0.86
Observations	84	84	84	84	84	84	84

Notes: Estimation by OLS. See table 1 for list of additional controls. (i) Least desirable distance is the number of weeks that minimizes the quadratic relation with respect to the pre-industrial distance to the Netherlands. It is equal to $-\beta_{Distance}/(2 \cdot \beta_{Sq.Distance})$. (ii) Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests.

Table F.4: Technological sophistication and distance to the technological frontier in 1500CE. Is the U-shape generated by trade?

	Technological Sophistication in 1500CE						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	(Agr)	(Comm)	(Trans)	(Mil)	(Ind)	(Av.)	(Av.M.)
Pre-industrial distance NLD	-0.14***	-0.06	-0.12***	-0.21***	-0.12*	-0.13***	-0.13***
	(0.05)	(0.05)	(0.04)	(0.08)	(0.06)	(0.03)	(0.03)
Sq.Pre-industrial distance NLD	0.01**	0.00	0.01**	0.01**	0.01**	0.01***	0.01***
	(0.00)	(0.00)	(0.00)	(0.01)	(0.00)	(0.00)	(0.00)
Pre-industrial distance CHN	-0.03	-0.02	-0.04**	-0.05*	-0.03**	-0.03**	-0.03**
	(0.03)	(0.03)	(0.01)	(0.02)	(0.01)	(0.01)	(0.01)
Pre-industrial distance trade route	0.02	-0.03	-0.05	-0.03	0.01	-0.02	-0.01
	(0.07)	(0.05)	(0.04)	(0.05)	(0.03)	(0.03)	(0.03)
LDD NLD	9.37***	7.72	7.31***	7.33***	5.98***	7.40***	7.12***
	(2.91)	(5.24)	(1.43)	(1.67)	(0.97)	(1.27)	(1.15)
Continental FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Geographical Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time Since Neolithic Revolution	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Adjusted-R^2	0.64	0.80	0.74	0.68	0.67	0.86	0.86
Observations	84	84	84	84	84	84	84

Notes: Estimation by OLS. See table 1 for list of additional controls. (i) Least desirable distance is the number of weeks that minimizes the quadratic relation with respect to the pre-industrial distance to the Netherlands. It is equal to $-\beta_{Distance}/(2 \cdot \beta_{Sq.Distance})$. (ii) Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests.

Table F.5: Technological sophistication and distance to the technological frontier in 1500CE. Is the U-shape generated by European colonization?

	Technological Sophistication in 1500CE						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	(Agr)	(Comm)	(Trans)	(Mil)	(Ind)	(Av.)	(Av.M.)
Pre-industrial distance NLD	-0.13***	-0.08	-0.13***	-0.22***	-0.13*	-0.14***	-0.13***
	(0.05)	(0.05)	(0.05)	(0.07)	(0.07)	(0.03)	(0.03)
Sq.Pre-industrial distance NLD	0.01**	0.00	0.01**	0.01**	0.01**	0.01***	0.01***
	(0.00)	(0.00)	(0.00)	(0.01)	(0.01)	(0.00)	(0.00)
Pre-industrial distance CHN	-0.03	-0.02	-0.05***	-0.05***	-0.03**	-0.03***	-0.03***
	(0.03)	(0.02)	(0.01)	(0.02)	(0.01)	(0.01)	(0.01)
European Colony	0.07	-0.13	0.02	-0.10	-0.10	-0.05	-0.05
	(0.11)	(0.08)	(0.10)	(0.12)	(0.16)	(0.06)	(0.06)
LDD NLD	8.85***	8.92**	8.31***	7.67***	6.06***	7.71***	7.33***
	(2.30)	(4.01)	(1.94)	(1.80)	(1.09)	(1.24)	(1.13)
Continental FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Geographical Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time Since Neolithic Revolution	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Adjusted-R^2	0.64	0.81	0.73	0.69	0.68	0.86	0.86
Observations	84	84	84	84	84	84	84

Notes: Estimation by OLS. See table 1 for list of additional controls. (i) Least desirable distance is the number of weeks that minimizes the quadratic relation with respect to the pre-industrial distance to the Netherlands. It is equal to $-\beta_{Distance}/(2 \cdot \beta_{Sq.Distance})$. (ii) Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests.

Table F.6: Technological sophistication and distance to the technological frontier in 1500CE. Is the U-shape generated by technological backwardness?

	Technological Sophistication in 1500CE						
	(1) (Agr)	(2) (Comm)	(3) (Trans)	(4) (Mil)	(5) (Ind)	(6) (Av.)	(7) (Av.M.)
Pre-industrial distance NLD	-0.14**	-0.05	-0.12**	-0.20**	-0.13*	-0.13***	-0.12***
	(0.05)	(0.05)	(0.05)	(0.08)	(0.07)	(0.04)	(0.04)
Sq.Pre-industrial distance NLD	0.01**	0.00	0.01*	0.01**	0.01**	0.01***	0.01***
	(0.00)	(0.00)	(0.00)	(0.01)	(0.00)	(0.00)	(0.00)
Pre-industrial distance CHN	-0.04	-0.02	-0.04***	-0.05*	-0.03*	-0.03**	-0.03**
	(0.03)	(0.02)	(0.01)	(0.02)	(0.02)	(0.01)	(0.01)
Lagged Average Technology	0.01	0.18	0.08	0.07	-0.11	0.05	0.04
	(0.21)	(0.20)	(0.11)	(0.23)	(0.17)	(0.11)	(0.10)
LDD NLD	9.22***	7.66	7.94***	7.41***	6.28***	7.57***	7.10***
	(2.46)	(4.73)	(1.99)	(1.90)	(1.42)	(1.37)	(1.23)
Continental FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Geographical Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time Since Neolithic Revolution	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Adjusted-R^2	0.68	0.82	0.72	0.67	0.66	0.86	0.86
Observations	82	82	82	82	82	82	82

Notes: Estimation by OLS. See table 1 for list of additional controls. (i) Least desirable distance is the number of weeks that minimizes the quadratic relation with respect to the pre-industrial distance to the Netherlands. It is equal to $-\beta_{Distance}/(2 \cdot \beta_{Sq.Distance})$. (ii) Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests.

Table F.7: Technological sophistication and distance to the technological frontier in 1500CE. Is the U-shape generated by Out-of-Africa?

	Technological Sophistication in 1500CE						
	(1) (Agr)	(2) (Comm)	(3) (Trans)	(4) (Mil)	(5) (Ind)	(6) (Av.)	(7) (Av.M.)
Pre-industrial distance NLD	-0.14***	-0.07	-0.13***	-0.21***	-0.12*	-0.14***	-0.13***
	(0.05)	(0.05)	(0.04)	(0.07)	(0.06)	(0.03)	(0.03)
Sq.Pre-industrial distance NLD	0.01	0.00	0.01*	0.01*	0.01**	0.01**	0.01**
	(0.00)	(0.00)	(0.00)	(0.01)	(0.00)	(0.00)	(0.00)
Pre-industrial distance CHN	-0.05*	-0.05*	-0.05***	-0.06**	-0.03	-0.05***	-0.04***
	(0.03)	(0.02)	(0.02)	(0.02)	(0.02)	(0.01)	(0.01)
Pre-industrial distance Addis Ababa	0.02	0.03	0.01	0.01	-0.00	0.01	0.01
	(0.02)	(0.02)	(0.01)	(0.02)	(0.01)	(0.01)	(0.01)
LDD NLD	11.16**	25.67	8.92***	8.36***	5.90***	8.89***	8.40***
	(4.37)	(53.88)	(2.86)	(2.84)	(1.50)	(2.22)	(1.95)
Continental FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Geographical Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time Since Neolithic Revolution	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Adjusted-R^2	0.64	0.81	0.73	0.68	0.67	0.86	0.86
Observations	84	84	84	84	84	84	84

Notes: Estimation by OLS. See table 1 for list of additional controls. (i) Least desirable distance is the number of weeks that minimizes the quadratic relation with respect to the pre-industrial distance to the Netherlands. It is equal to $-\beta_{Distance}/(2 \cdot \beta_{Sq.Distance})$. (ii) Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests.

Table F.8: Technological sophistication and distance to the technological frontier in 1500CE. Robustness to minimal distance to frontiers.

	Technological Sophistication in 1500CE						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Pre-industrial distance NLD	-0.11	-0.01	-0.13**	-0.13	-0.12*	-0.10**	-0.09**
	(0.08)	(0.09)	(0.06)	(0.10)	(0.06)	(0.05)	(0.05)
Sq.Pre-industrial distance NLD	0.01	0.00	0.01*	0.01	0.01**	0.01*	0.01*
	(0.00)	(0.01)	(0.00)	(0.01)	(0.00)	(0.00)	(0.00)
Pre-industrial distance CHN	-0.02	-0.01	-0.05***	-0.03	-0.02*	-0.03**	-0.02*
	(0.03)	(0.02)	(0.02)	(0.02)	(0.01)	(0.01)	(0.01)
Distance Closest Frontier	-0.02	-0.05	0.00	-0.07	-0.00	-0.03	-0.03
	(0.04)	(0.05)	(0.03)	(0.04)	(0.03)	(0.02)	(0.02)
LDD NLD	9.15***	52.46	8.31***	7.56***	5.84***	7.65***	7.14***
	(2.62)	(2414.37)	(1.93)	(2.70)	(1.06)	(1.56)	(1.39)
Continental FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Geographical Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time Since Neolithic Revolution	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Adjusted-R^2	0.64	0.80	0.73	0.69	0.67	0.86	0.86
Observations	84	84	84	84	84	84	84

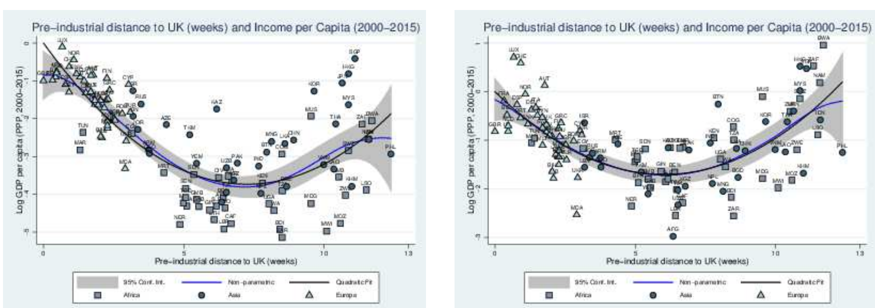
Notes: This table establishes that the statistically and economically significant U-shaped relation between distance to the western frontier and technological sophistication is robust to the inclusion of the minimal distance to either frontier. Estimation by OLS. See table 1 for list of additional controls. (i) Least desirable distance (LDD) is the number of weeks that minimizes the quadratic relation with respect to the pre-industrial distance to the Netherlands. It is equal to $-\beta_{Distance}/(2\cdot\beta_{Sq.Distance})$. (ii) Heteroskedasticity robust standard error estimates are reported in parentheses; *** denotes statistical significance at the 1% level, ** at the 5% level, and * at the 10% level, all for two-sided hypothesis tests.

F.2 Persistence

Table F.9: Distance from the Pre-industrial Technological Frontier and Contemporary Development

	Log[GDP per capita in 2000CE]							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Pre-industrial distance to frontier	-1.15***	-0.72***	-0.79***	-0.73***	-0.71***	-0.71***	-0.67***	-0.65***
	(0.09)	(0.13)	(0.13)	(0.15)	(0.17)	(0.17)	(0.17)	(0.18)
Sq. Pre-industrial distance to frontier	0.08***	0.05***	0.06***	0.06***	0.06***	0.06***	0.06***	0.05***
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Pre-industrial distance CHN					0.01	0.01	0.07	0.07
					(0.06)	(0.06)	(0.07)	(0.08)
European Colony (includes Turkey)							-0.70**	-0.83**
							(0.32)	(0.40)
Pre-industrial distance to Addis Ababa								0.19
								(0.17)
Sq. Pre-industrial distance to Addis Ababa								-0.02
								(0.01)
LDD UK	7.20***	6.77***	6.46***	6.30***	6.25***	6.25***	6.08***	6.09***
	(0.26)	(0.36)	(0.31)	(0.39)	(0.48)	(0.48)	(0.50)	(0.54)
Geographical Controls	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time Since Neolithic Revolution	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Continental FE	No	No	No	Yes	Yes	Yes	Yes	Yes
Adjusted-R^2	0.62	0.73	0.76	0.75	0.75	0.75	0.76	0.76
Observations	111	111	111	111	111	111	111	111

Figure F.1: Distance to Pre-Industrial Technological Frontier (UK) and Income per capita (2000CE)



(a) Unconditional Relation (b) Conditional Relation

Table F.10: Persistent Effect of Distance from the Pre-industrial Technological Frontier and Contemporary Patenting Activity

	Log[Patents per Capita (2000-2015CE)]					
	All					Residents
	(1)	(2)	(3)	(4)	(5)	(6)
Pre-industrial distance to frontier	-0.55**	-0.25	-0.25	-0.57**	-0.59**	-0.66**
	(0.26)	(0.24)	(0.24)	(0.26)	(0.28)	(0.29)
Sq. Pre-industrial distance to frontier	0.05**	0.03	0.03	0.06**	0.06**	0.06**
	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
LDD	5.41***	3.89**	3.89**	5.09***	5.10***	5.54***
	(1.35)	(1.78)	(1.78)	(0.79)	(0.80)	(0.79)
Regional FE	Yes	Yes	Yes	Yes	Yes	Yes
Geographical Controls	No	Yes	Yes	Yes	Yes	Yes
Time Since Neolithic Revolution	No	No	No	Yes	Yes	Yes
Colony FE	No	No	No	Yes	Yes	Yes
Volatility Controls	No	No	No	No	Yes	Yes
Adjusted-R^2	0.60	0.68	0.68	0.72	0.76	0.79
Observations	85	85	85	85	85	85

Table F.11: Persistent Effect of Distance from the Pre-industrial Technological Frontier and Contemporary Patenting Activity (Robustness)

	Log[Patents per Capita by Residents (2000-2015CE)]							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Pre-industrial distance to frontier	-0.66**	-0.75**	-0.69**	-1.16***	-0.67**	-0.26	-0.62	-0.47
	(0.31)	(0.30)	(0.31)	(0.37)	(0.32)	(0.40)	(0.37)	(0.84)
Sq. Pre-industrial distance to frontier	0.06**	0.07**	0.06**	0.09***	0.06**	0.02	0.06**	0.05
	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.06)
LDD	5.64***	5.72***	5.73***	6.40***	5.65***	6.06***	5.43***	5.14
	(0.65)	(0.61)	(0.61)	(1.14)	(0.64)	(2.01)	(1.58)	(3.89)
Regional FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Geographical Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time Since Neolithic Revolution	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Colony FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Volatility Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Religious Shares	No	Yes	No	No	No	No	No	Yes
Constraints on Executive	No	No	Yes	No	No	No	No	Yes
Colonizer FE	No	No	No	Yes	No	No	No	Yes
Population Share with European Ancestry	No	No	No	No	Yes	No	No	Yes
Legal Origin FE	No	No	No	No	No	Yes	No	Yes
Distance to USA	No	No	No	No	No	No	Yes	Yes
Adjusted-R^2	0.79	0.79	0.80	0.78	0.79	0.83	0.79	0.80
Observations	81	81	81	81	81	81	81	81

Table F.12: Persistent Effect of Distance from the Pre-industrial Technological Frontier and Contemporary Entrepreneurial Activity

	Log[New Firms per 1,000 people (2000-2015CE)]						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Pre-industrial distance to frontier	-0.70***	-0.64**	-0.61*	-0.59*	-0.71*	-0.87**	-0.94
	(0.24)	(0.28)	(0.34)	(0.35)	(0.42)	(0.39)	(0.60)
Sq. Pre-industrial distance to frontier	0.07***	0.07***	0.07**	0.06**	0.07**	0.09***	0.10**
	(0.02)	(0.02)	(0.03)	(0.03)	(0.03)	(0.03)	(0.05)
LDD	5.16***	4.75***	4.67***	4.57***	4.89***	5.04***	4.58***
	(0.91)	(0.94)	(1.12)	(1.20)	(1.09)	(0.80)	(1.34)
Regional FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Geographical Controls	No	Yes	Yes	Yes	Yes	Yes	Yes
Time Since Neolithic Revolution	No	No	Yes	Yes	Yes	Yes	Yes
Colony FE	No	No	No	Yes	Yes	Yes	Yes
Volatility Controls	No	No	No	No	Yes	Yes	Yes
Religious Shares	No	No	No	No	No	Yes	Yes
Constraints on Executive	No	No	No	No	No	Yes	Yes
Colonizer FE	No	No	No	No	No	No	Yes
Population Share with European Ancestry	No	No	No	No	No	No	Yes
Legal Origin FE	No	No	No	No	No	No	Yes
Distance to USA	No	No	No	No	No	No	Yes
Adjusted-R^2	0.45	0.56	0.55	0.55	0.54	0.56	0.66
Observations	85	85	85	85	85	85	85

G Proofs

The following intermediate results prove Theorem D.1.

Proposition G.1. *For each economy d and each $l_0 > 0$ there exists a unique equilibrium in which $l_t^* \in (0,1)$ for all $t \geq 1$.*

Proof. The first order condition of the problem in equation (27) is

$$u'(c_t) g_t^{\frac{1-\rho}{\rho}} \Big[\alpha\gamma_t l_t^{\alpha\rho-1} - \beta\delta_t(1-l_t)^{\beta\rho-1}\Big] A_{t-1} = 0,$$

where

$$g_t = \gamma_t l_t^{\alpha\rho} + \delta_t(1-l_t)^{\beta\rho}, \qquad \gamma_t = \lambda a^\rho l_{t-1}^{\alpha'\rho}, \qquad \delta_t = (1-\lambda)\Big(b(d)\Big)^\rho (1-l_{t-1})^{\beta'\rho}.$$

Thus, the solution to the individual's problem must satisfy the equation

$$F_1(l_t) \equiv \alpha\gamma_t l_t^{\alpha\rho-1} - \beta\delta_t(1-l_t)^{\beta\rho-1} = 0. \tag{29}$$

Notice that this equation is continuous for $l_t \in (0,1)$, and

$$\lim_{l_t\to 0} F_1(l_t) = +\infty \qquad \text{and} \qquad \lim_{l_t\to 1} F_1(l_t) = -\infty.$$

Since

$$F_1'(l_t) = \alpha(\alpha\rho-1)\gamma_t l_t^{\alpha\rho-2} + (\beta\rho-1)\beta\delta_t(1-l_t)^{\beta\rho-2} < 0$$

the intermediate value theorem implies that there exists a unique value $l_t^* \in (0,1)$ that solves the individual's problem. To see that the solution is interior, i.e. $l_t^* \in (0,1)$, it suffices to notice that the first order condition converges to $+\infty$ as $l_t \to 0$ and to $-\infty$ as $l_t \to 1$.

Additionally,

$$\begin{aligned}
\frac{\partial^2 c_{st}}{\partial l_t^2} =& g_t^{\frac{1-2\rho}{\rho}} \Big\{(1-\rho)\Big[\alpha\gamma_t l_t^{\alpha\rho-1} - \beta\delta_t(1-l_t)^{\beta\rho-1}\Big]^2 \\
& -g_t\Big[\alpha(1-\alpha\rho)\gamma_t l_t^{\alpha\rho-2} + \beta(1-\beta\rho)\delta_t(1-l_t)^{\beta\rho-2}\Big]\Big\} A_{t-1} \\
=& g_t^{\frac{1-2\rho}{\rho}} \Big\{(1-\rho)\alpha^2\gamma_t^2 l_t^{2\alpha\rho-2} + (1-\rho)\beta^2\delta_t^2(1-l_t)^{2\beta\rho-2} - 2(1-\rho)\alpha\beta\gamma_t\delta_t l_t^{\alpha\rho-1}(1-l_t)^{\beta\rho-1} \\
& - \alpha(1-\alpha\rho)\gamma_t^2 l_t^{2\alpha\rho-2} - \beta(1-\beta\rho)\delta_t^2(1-l_t)^{2\beta\rho-2} \\
& -\alpha(1-\alpha\rho)\gamma_t\delta_t l_t^{\alpha\rho-2}(1-l_t)^{\beta\rho} - \beta(1-\beta\rho)\gamma_t\delta_t l_t^{\alpha\rho}(1-l_t)^{\beta\rho-2}\Big\} A_{t-1} \\
=& g_t^{\frac{1-2\rho}{\rho}} \Big\{\Big[(1-\rho)\alpha - (1-\alpha\rho)\Big]\alpha\gamma_t^2 l_t^{2\alpha\rho-2} + \Big[(1-\rho)\beta - (1-\beta\rho)\Big]\beta\delta_t^2(1-l_t)^{2\beta\rho-2} \\
& - 2(1-\rho)\alpha\beta\gamma_t\delta_t l_t^{\alpha\rho-1}(1-l_t)^{\beta\rho-1} \\
& -\alpha(1-\alpha\rho)\gamma_t\delta_t l_t^{\alpha\rho-2}(1-l_t)^{\beta\rho} - \beta(1-\beta\rho)\gamma_t\delta_t l_t^{\alpha\rho}(1-l_t)^{\beta\rho-2}\Big\} A_{t-1} \\
=& - g_t^{\frac{1-2\rho}{\rho}} \Big\{(1-\alpha)\alpha\gamma_t^2 l_t^{2\alpha\rho-2} + (1-\beta)\beta\delta_t^2(1-l_t)^{2\beta\rho-2} \\
& + 2(1-\rho)\alpha\beta\gamma_t\delta_t l_t^{\alpha\rho-1}(1-l_t)^{\beta\rho-1} \\
& +\alpha(1-\alpha\rho)\gamma_t\delta_t l_t^{\alpha\rho-2}(1-l_t)^{\beta\rho} + \beta(1-\beta\rho)\gamma_t\delta_t l_t^{\alpha\rho}(1-l_t)^{\beta\rho-2}\Big\} A_{t-1} < 0.
\end{aligned}$$

So, the second order condition of the problem in equation (27) is satisfied since

$$u''(c_{st})\left(\frac{\partial c_{st}}{\partial l_t}A_{t-1}\right)^2 + u'(c_{st})\frac{\partial^2 c_{st}}{\partial l_t^2} < 0. \qquad \blacksquare$$

Additionally,

Proposition G.2. *For each economy d there exists a unique stationary equilibrium such that $l_t^* = l^* \in (0,1)$ for all $t \geq 0$.*

Proof. In what follows, any variable without a time subscript t denotes its steady state value. In particular, redefine

$$\gamma = \lambda a^\rho, \qquad \delta = (1-\lambda)\Big(b(d)\Big)^\rho, \qquad g = \gamma l^{(\alpha'+\alpha)\rho} + \delta(1-l)^{(\beta'+\beta)\rho}.$$

The proof is similar to the previous one. In a stationary equilibrium the first order condition implies

$$u'(c)g^{\frac{1-\rho}{\rho}}\Big[\alpha\gamma l^{(\alpha'+\alpha)\rho-1} - \beta\delta(1-l)^{(\beta'+\beta)\rho-1}\Big]A_{t-1} = 0. \tag{30}$$

which is satisfied if, and only if,

$$F(l,d) \equiv \alpha\gamma l^{(\alpha'+\alpha)\rho-1} - \beta\delta(1-l)^{(\beta'+\beta)\rho-1} = 0 \tag{31}$$

Again notice that

$$\lim_{l\to 0} F(l,d) = +\infty \qquad \text{and} \qquad \lim_{l\to 1} F(l,d) = -\infty,$$

and

$$\frac{\partial F(l,d)}{\partial l} = \alpha\Big((\alpha'+\alpha)\rho - 1\Big)\gamma l^{(\alpha'+\alpha)\rho-2} + \beta\Big((\beta'+\beta)\rho-1\Big)\delta(1-l)^{(\beta'+\beta)\rho-2} < 0. \tag{32}$$

Thus, by the intermediate value theorem, there exists a unique value $l^* \in (0,1)$ that satisfies the first order condition in a stationary state. $\blacksquare$

Proposition G.3. *The unique stationary equilibrium of economy d is not Pareto efficient.*

Proof. To see this consider the problem faced by a central planner

$$\max_{l\in[0,1]} \quad u(c^o) \tag{33a}$$

$$c^o = \left\{\left[\lambda\left(al^{\alpha'+\alpha}\right)^\rho + (1-\lambda)\Big(b(d)(1-l)^{\beta'+\beta}\Big)^\rho\right]^{\frac{1}{\rho}} + 1\right\}A_{t-1} \tag{33b}$$

The first order condition of the problem is given by

$$u'(c^o)g^{\frac{1-\rho}{\rho}}\Big[(\alpha'+\alpha)\gamma l^{(\alpha'+\alpha)\rho-1} - (\beta'+\beta)\delta(1-l)^{(\beta'+\beta)\rho-1}\Big] = 0,$$

so that the unique solution is determined by the condition

$$(\alpha'+\alpha)\gamma l^{(\alpha'+\alpha)\rho-1} - (\beta'+\beta)\delta(1-l)^{(\beta'+\beta)\rho-1} = 0. \tag{34}$$

Clearly, equations (31) and (34) have different solutions, so that the solution to the planner's problem $l^o \neq l^*$. Using a similar argument as in the previous proof one can show that the left-hand side of equation (34) is strictly decreasing in l, converges to $+\infty$ as $l \to 0$ and to $-\infty$ as $l \to 1$, so that there exists a unique solution l^o to equation (34). Similarly, one can show that the second order condition is satisfied, and that $l^o \in (0,1)$. $\blacksquare$

Proposition G.4. *The unique stationary equilibrium is asymptotically stable.*

Proof. The dynamics of the economy are determined by the condition given in equation (29). The stationary equilibrium is asymptotically stable if

$$\left|\frac{\partial l_t}{\partial l_{t-1}}\right|_{l_t=l_{t-1}=l^*} < 1.$$

From previous results

$$F_1'(l_t) = \alpha(\alpha\rho - 1)\gamma_t l_t^{\alpha\rho-2} + (\beta\rho - 1)\beta\delta_t(1-l_t)^{\beta\rho-2} < 0.$$

Thus, the Implicit Function Theorem implies that $l_t \equiv l_t(l_{t-1})$ is a continuous function of l_{t-1}. Letting $F_2(l_{t-1})$ denote the same condition as a function of l_{t-1}, so that

$$F_2(l_{t-1}) = \alpha\gamma l_{t-1}^{\alpha'\rho} l_t^{\alpha\rho-1} - \beta\delta(1-l_{t-1})^{\beta'\rho}(1-l_t)^{\beta\rho-1}$$

and

$$F_2'(l_{t-1}) = \alpha\alpha'\rho\gamma l_{t-1}^{\alpha'\rho-1} l_t^{\alpha\rho-1} + \beta\beta'\rho\delta(1-l_{t-1})^{\beta'\rho-1}(1-l_t)^{\beta\rho-1} > 0.$$

Clearly,

$$\frac{\partial l_t}{\partial l_{t-1}} = -\frac{F_2'(l_{t-1})}{F_1'(l_t)} > 0.$$

In a stationary state

$$\begin{aligned}
F_1'(l^*) =& \alpha(\alpha\rho - 1)\gamma {l^*}^{(\alpha'+\alpha)\rho-2} + (\beta\rho-1)\beta\delta_t(1-l_t)^{\beta\rho-2}, \\
F_2'(l^*) =& \alpha\alpha'\rho\gamma {l^*}^{(\alpha'+\alpha)\rho-2} + \beta\beta'\rho\delta(1-l^*)^{\beta\rho-2},
\end{aligned}$$

so that

$$-F_1'(l^*) - F_2'(l^*) = \alpha(1-(\alpha'+\alpha)\rho)\gamma {l^*}^{(\alpha'+\alpha)\rho-2} + (1-(\beta'+\beta)\rho)\beta\delta_t(1-l_t)^{\beta\rho-2} > 0.$$

This implies that

$$\left|\frac{\partial l_t}{\partial l_{t-1}}\right|_{l_t=l_{t-1}=l^*} = \left|-\frac{F_2'(l_{t-1})}{F_1'(l_t)}\right|_{l_t=l_{t-1}=l^*} < 1$$

and the stationary equilibrium is asymptotically stable. ■

From the previous results and using the Implicit Function Theorem, one has that

Proposition G.5. *The stationary equilibrium allocation l^* is a continuous, increasing and differentiable function of d, i.e. $l^* = l^*(d)$, such that $\frac{\partial l^*(d)}{\partial d} > 0$. Additionally, it is a convex function of d ($\frac{\partial^2 l^*(d)}{\partial d^2} > 0$) if any of the following holds:*

(i) $[1 + (\beta' + \beta)]\rho \leq 1$,

(ii) $\Big(1 - (\alpha' + \alpha) + (\beta' + \beta)\Big) \leq 0$,

(iii) $\Big((\beta' + \beta) - (\alpha' + \alpha)\Big) \geq 0$, *and* $[1 - (\alpha' + \alpha) + 2(\beta' + \beta)]\rho \leq 1$.

Proof. Equation (32) and the Implicit Function Theorem imply that l^* is a continuous and differentiable function of d, such that

$$\frac{\partial l^*}{\partial d} = -\frac{\frac{\partial F(l^*,d)}{\partial d}}{\frac{\partial F(l^*,d)}{\partial l^*}}.$$

On the other hand,

$$\frac{\partial F(l^*,d)}{\partial d} = -\rho\beta\delta\frac{b'(d)}{b(d)}(1-l^*)^{(\beta'+\beta)\rho-1} > 0,$$

so that

$$\frac{\partial l^*}{\partial d} = -\frac{\frac{\partial F(l^*,d)}{\partial d}}{\frac{\partial F(l^*,d)}{\partial l^*}} = -\frac{\rho\frac{b'(d)}{b(d)}l^*(1-l^*)}{\Big(1-(\alpha'+\alpha)\rho\Big)(1-l^*)+\Big(1-(\beta'+\beta)\rho\Big)l^*} > 0. \qquad (35)$$

Furthermore, the optimal allocation is a convex function of d under the additional assumptions. To see this, notice that

$$\begin{aligned}
\frac{\partial^2 F(l^*,d)}{\partial l^2} =&\alpha\Big(1-(\alpha'+\alpha)\rho\Big)\Big(2-(\alpha'+\alpha)\rho\Big)\gamma l^{*\,(\alpha'+\alpha)\rho-3} \\
&-\beta\Big(1-(\beta'+\beta)\rho\Big)\Big(2-(\beta'+\beta)\rho\Big)\delta(1-l^*)^{(\beta'+\beta)\rho-3}, \\
\frac{\partial^2 F(l^*,d)}{\partial d^2} =&-\beta\delta\left(\rho\frac{b'(d)}{b(d)}\right)^2(1-l^*)^{(\beta'+\beta)\rho-1} - \beta\delta\rho\frac{b''(d)b(d)-b'(d)^2}{b(d)^2}(1-l^*)^{(\beta'+\beta)\rho-1} \\
=&\beta\delta\rho\left\{(1-\rho)\left(\frac{b'(d)}{b(d)}\right)^2 - \frac{b''(d)}{b(d)}\right\}(1-l^*)^{(\beta'+\beta)\rho-1} > 0, \\
\frac{\partial^2 F(l^*,d)}{\partial l\partial d} =&\rho\beta\Big((\beta'+\beta)\rho-1\Big)\delta\frac{b'(d)}{b(d)}(1-l^*)^{(\beta'+\beta)\rho-2} > 0,
\end{aligned}$$

and

$$\begin{aligned}
\frac{\partial^2 l^*}{\partial d^2} =& -\frac{\left(\frac{\partial^2 F(l^*,d)}{\partial d\partial l}\frac{\partial l^*}{\partial d}+\frac{\partial^2 F(l^*,d)}{\partial d^2}\right)\frac{\partial F(l^*,d)}{\partial l^*} - \frac{\partial F(l^*,d)}{\partial d}\left(\frac{\partial^2 F(l^*,d)}{\partial l^{*2}}\frac{\partial l^*}{\partial d}+\frac{\partial^2 F(l^*,d)}{\partial l^*\partial d}\right)}{\left(\frac{\partial F(l^*,d)}{\partial l^*}\right)^2} \\
&>0 \iff \\
&-\left(\frac{\partial^2 F(l^*,d)}{\partial d\partial l}\frac{\partial l^*}{\partial d}+\frac{\partial^2 F(l^*,d)}{\partial d^2}\right)\frac{\partial F(l^*,d)}{\partial l^*} + \frac{\partial F(l^*,d)}{\partial d}\left(\frac{\partial^2 F(l^*,d)}{\partial l^{*2}}\frac{\partial l^*}{\partial d}+\frac{\partial^2 F(l^*,d)}{\partial l^*\partial d}\right) \\
&=2\frac{\partial^2 F(l^*,d)}{\partial d\partial l}\frac{\partial F(l^*,d)}{\partial d} - \frac{\partial^2 F(l^*,d)}{\partial d^2}\frac{\partial F(l^*,d)}{\partial l^*} + \frac{\partial F(l^*,d)}{\partial d}\frac{\partial^2 F(l^*,d)}{\partial l^{*2}}\frac{\partial l^*}{\partial d} \\
&=2\Big(1-(\beta'+\beta)\rho\Big)\left(\rho\beta\delta\frac{b'(d)}{b(d)}\right)^2(1-l^*)^{2(\beta'+\beta)\rho-3} \\
&\quad+\alpha\Big(1-(\alpha'+\alpha)\rho\Big)\beta\gamma\delta\rho\left\{(1-\rho)\left(\frac{b'(d)}{b(d)}\right)^2-\frac{b''(d)}{b(d)}\right\}l^{*\,(\alpha'+\alpha)\rho-2}(1-l^*)^{(\beta'+\beta)\rho-1} \\
&\quad+(\beta\delta)^2\rho\Big(1-(\beta'+\beta)\rho\Big)\left\{(1-\rho)\left(\frac{b'(d)}{b(d)}\right)^2-\frac{b''(d)}{b(d)}\right\}(1-l^*)^{2(\beta'+\beta)\rho-3}
\end{aligned}$$

$$
\begin{aligned}
&-\alpha\beta\Big(1-(\alpha'+\alpha)\rho\Big)\Big(2-(\alpha'+\alpha)\rho\Big)\gamma\delta\rho\frac{b'(d)}{b(d)}l^{*\,(\alpha'+\alpha)\rho-3}(1-l^*)^{(\beta'+\beta)\rho-1}\frac{\partial l^*}{\partial d}\\
&+\rho(\beta\delta)^2\frac{b'(d)}{b(d)}\Big(1-(\beta'+\beta)\rho\Big)\Big(2-(\beta'+\beta)\rho\Big)(1-l^*)^{2(\beta'+\beta)\rho-4}\frac{\partial l^*}{\partial d}\\
=&2\Big(1-(\beta'+\beta)\rho\Big)\left(\rho\beta\delta\frac{b'(d)}{b(d)}\right)^2(1-l^*)^{2(\beta'+\beta)\rho-3}\\
&+\Big(1-(\alpha'+\alpha)\rho\Big)(\beta\delta)^2\rho\left\{(1-\rho)\left(\frac{b'(d)}{b(d)}\right)^2-\frac{b''(d)}{b(d)}\right\}l^{*\,-1}(1-l^*)^{2(\beta'+\beta)\rho-2}\\
&+(\beta\delta)^2\rho\Big(1-(\beta'+\beta)\rho\Big)\left\{(1-\rho)\left(\frac{b'(d)}{b(d)}\right)^2-\frac{b''(d)}{b(d)}\right\}(1-l^*)^{2(\beta'+\beta)\rho-3}\\
&-\Big(1-(\alpha'+\alpha)\rho\Big)\Big(2-(\alpha'+\alpha)\rho\Big)(\beta\delta)^2\rho\frac{b'(d)}{b(d)}l^{*\,-2}(1-l^*)^{2(\beta'+\beta)\rho-2}\frac{\partial l^*}{\partial d}\\
&+\rho(\beta\delta)^2\frac{b'(d)}{b(d)}\Big(1-(\beta'+\beta)\rho\Big)\Big(2-(\beta'+\beta)\rho\Big)(1-l^*)^{2(\beta'+\beta)\rho-4}\frac{\partial l^*}{\partial d}>0
\end{aligned}
$$

because

$$
\begin{aligned}
&2\Big(1-(\beta'+\beta)\rho\Big)\rho(1-l^*)\\
&+\Big(1-(\alpha'+\alpha)\rho\Big)(1-\rho)l^{*\,-1}(1-l^*)^2\\
&+\Big(1-(\beta'+\beta)\rho\Big)(1-\rho)(1-l^*)\\
&-\Big(1-(\alpha'+\alpha)\rho\Big)\Big(2-(\alpha'+\alpha)\rho\Big)\frac{b(d)}{b'(d)}l^{*\,-2}(1-l^*)^2\frac{\partial l^*}{\partial d}\\
&+\frac{b(d)}{b'(d)}\Big(1-(\beta'+\beta)\rho\Big)\Big(2-(\beta'+\beta)\rho\Big)\frac{\partial l^*}{\partial d}\\
=&\Big(1-(\alpha'+\alpha)\rho\Big)(1-\rho)l^{*\,-1}(1-l^*)^2\\
&+\Big(1-(\beta'+\beta)\rho\Big)(1+\rho)(1-l^*)\\
&+\frac{\rho\Big(1-(\alpha'+\alpha)\rho\Big)\Big(2-(\alpha'+\alpha)\rho\Big)l^{*\,-1}(1-l^*)^3}{\Big(1-(\alpha'+\alpha)\rho\Big)(1-l^*)+\Big(1-(\beta'+\beta)\rho\Big)l^*}\\
&-\frac{\rho\Big(1-(\beta'+\beta)\rho\Big)\Big(2-(\beta'+\beta)\rho\Big)l^*(1-l^*)}{\Big(1-(\alpha'+\alpha)\rho\Big)(1-l^*)+\Big(1-(\beta'+\beta)\rho\Big)l^*}\\
=&\frac{(1-\rho)\Big(1-(\alpha'+\alpha)\rho\Big)^2l^{*\,-1}(1-l^*)^3+(1-\rho)\Big(1-(\alpha'+\alpha)\rho\Big)\Big(1-(\beta'+\beta)\rho\Big)(1-l^*)^2}{\Big(1-(\alpha'+\alpha)\rho\Big)(1-l^*)+\Big(1-(\beta'+\beta)\rho\Big)l^*}\\
&+\frac{(1+\rho)\Big(1-(\alpha'+\alpha)\rho\Big)\Big(1-(\beta'+\beta)\rho\Big)(1-l^*)^2+(1+\rho)\Big(1-(\beta'+\beta)\rho\Big)^2l^*(1-l^*)}{\Big(1-(\alpha'+\alpha)\rho\Big)(1-l^*)+\Big(1-(\beta'+\beta)\rho\Big)l^*}\\
&+\frac{\rho\Big(1-(\alpha'+\alpha)\rho\Big)\Big(2-(\alpha'+\alpha)\rho\Big)l^{*\,-1}(1-l^*)^3}{\Big(1-(\alpha'+\alpha)\rho\Big)(1-l^*)+\Big(1-(\beta'+\beta)\rho\Big)l^*}
\end{aligned}
$$

$$
\begin{aligned}
&- \frac{\rho\Big(1-(\beta'+\beta)\rho\Big)\Big(2-(\beta'+\beta)\rho\Big)l^*(1-l^*)}{\Big(1-(\alpha'+\alpha)\rho\Big)(1-l^*)+\Big(1-(\beta'+\beta)\rho\Big)l^*} \\
=&\frac{\Big(1-(\alpha'+\alpha)\rho\Big)\Big(1+\rho-(\alpha'+\alpha)\rho\Big)l^{*\,-1}(1-l^*)^3+2\Big(1-(\alpha'+\alpha)\rho\Big)\Big(1-(\beta'+\beta)\rho\Big)(1-l^*)^2}{\Big(1-(\alpha'+\alpha)\rho\Big)(1-l^*)+\Big(1-(\beta'+\beta)\rho\Big)l^*} \\
&+\frac{\Big(1-(\beta'+\beta)\rho\Big)\Big(1-\rho-(\beta'+\beta)\rho\Big)l^*(1-l^*)}{\Big(1-(\alpha'+\alpha)\rho\Big)(1-l^*)+\Big(1-(\beta'+\beta)\rho\Big)l^*}>0
\end{aligned}
$$

if $[1+(\beta'+\beta)]\rho \leq 1$. Otherwise, notice that the last inequality holds if

$$
\begin{aligned}
&\Big(1-(\alpha'+\alpha)\rho\Big)\Big(1+\rho-(\alpha'+\alpha)\rho\Big)l^{*\,-1}(1-l^*)^3+2\Big(1-(\alpha'+\alpha)\rho\Big)\Big(1-(\beta'+\beta)\rho\Big)(1-l^*)^2 \\
&+\Big(1-(\beta'+\beta)\rho\Big)\Big(1-\rho-(\beta'+\beta)\rho\Big)l^*(1-l^*)>0 \iff \\
&\Big(1-(\alpha'+\alpha)\rho\Big)\Big(1+\rho-(\alpha'+\alpha)\rho\Big)(1-l^*)^2+2\Big(1-(\alpha'+\alpha)\rho\Big)\Big(1-(\beta'+\beta)\rho\Big)l^*(1-l^*) \\
&+\Big(1-(\beta'+\beta)\rho\Big)\Big(1-\rho-(\beta'+\beta)\rho\Big)l^{*\,2} \\
=&\Big(1-(\alpha'+\alpha)\rho\Big)\Big(1+\rho-(\alpha'+\alpha)\rho\Big) \\
&+2l^*\Big(1-(\alpha'+\alpha)\rho\Big)\Big[\Big(1-(\beta'+\beta)\rho\Big)-\Big(1+\rho-(\alpha'+\alpha)\rho\Big)\Big] \\
&+\Big[\Big(1-(\alpha'+\alpha)\rho\Big)\Big(1+\rho-(\alpha'+\alpha)\rho\Big)+\Big(1-(\beta'+\beta)\rho\Big)\Big(1-\rho-(\beta'+\beta)\rho\Big) \\
&-2\Big(1-(\alpha'+\alpha)\rho\Big)\Big(1-(\beta'+\beta)\rho\Big)\Big]l^{*\,2} \\
=&\Big(1-(\alpha'+\alpha)\rho\Big)\Big(1+\rho-(\alpha'+\alpha)\rho\Big)-2\rho l^*\Big(1-(\alpha'+\alpha)\rho\Big)\Big(1-(\alpha'+\alpha)+(\beta'+\beta)\Big) \\
&\rho^2\Big(1-(\alpha'+\alpha)+(\beta'+\beta)\Big)\Big((\beta'+\beta)-(\alpha'+\alpha)\Big)l^{*\,2}>0
\end{aligned}
$$

since,

(i) if $\Big(1-(\alpha'+\alpha)+(\beta'+\beta)\Big)\leq 0$, then $\Big((\beta'+\beta)-(\alpha'+\alpha)\Big)<0$, so that the inequality holds;

(ii) if $\Big((\beta'+\beta)-(\alpha'+\alpha)\Big)\geq 0$, and $[1-(\alpha'+\alpha)+2(\beta'+\beta)]\rho\leq 1$, then $\Big(1-(\alpha'+\alpha)+(\beta'+\beta)\Big)>0$ and the inequality holds, as

$$
\begin{aligned}
&\Big(1-(\alpha'+\alpha)\rho\Big)\Big(1+\rho-(\alpha'+\alpha)\rho\Big)-2\rho l^*\Big(1-(\alpha'+\alpha)\rho\Big)\Big(1-(\alpha'+\alpha)+(\beta'+\beta)\Big) \\
&\rho^2\Big(1-(\alpha'+\alpha)+(\beta'+\beta)\Big)\Big((\beta'+\beta)-(\alpha'+\alpha)\Big)l^{*\,2} \\
>&\Big(1-(\alpha'+\alpha)\rho\Big)\Big(1+\rho-(\alpha'+\alpha)\rho\Big)-2\rho\Big(1-(\alpha'+\alpha)\rho\Big)\Big(1-(\alpha'+\alpha)+(\beta'+\beta)\Big) \\
&\rho^2\Big(1-(\alpha'+\alpha)+(\beta'+\beta)\Big)\Big((\beta'+\beta)-(\alpha'+\alpha)\Big)l^{*\,2} \\
=&\Big(1-(\alpha'+\alpha)\rho\Big)\Big(1-\rho-(\beta'+\beta)\rho+[(\alpha'+\alpha)-(\beta'+\beta)]\rho\Big) \\
&\rho^2\Big(1-(\alpha'+\alpha)+(\beta'+\beta)\Big)\Big((\beta'+\beta)-(\alpha'+\alpha)\Big)l^{*\,2}>0.
\end{aligned}
$$

■

Proposition G.6. *If $\alpha'/\alpha > \beta'/\beta$, $\lim_{d\to\infty} |b'(d)/b(d)| < \infty$, and*

$$\bar{l} \equiv \frac{1-(\alpha'+\alpha)\rho}{\rho\left\{\beta\left[\frac{\alpha'}{\alpha}-\frac{\beta'}{\beta}\right]+(\beta'+\beta)-(\alpha'+\alpha)\right\}} \in (0,1),$$

then there exists an economy $\bar{d} \geq 0$ such that the profile of stationary growth rates is decreasing on $\mathcal{D} = [0, \bar{d}]$ and increasing on $\mathcal{E} \setminus \mathcal{D}$.

Proof. Clearly $G(d)$ is continuous and differentiable. The derivative of equation (28) with respect to d is

$$\begin{aligned} G'(d) = &\left\{ g^{\frac{1-\rho}{\rho}} \left[(\alpha'+\alpha)\gamma l^{*\,(\alpha'+\alpha)\rho-1} - (\beta'+\beta)\delta(1-l^*)^{(\beta'+\beta)\rho-1} \right] \right\} \frac{\partial l^*}{\partial d} \\ &+ g^{\frac{1-\rho}{\rho}} \frac{b'(d)}{b(d)} \delta (1-l^*)^{(\beta'+\beta)\rho} \end{aligned} \tag{36}$$

Notice that

$$\lim_{d\to\infty} g^{\frac{1-\rho}{\rho}} \frac{b'(d)}{b(d)} \delta(1-l^*)^{(\beta'+\beta)\rho} = 0.$$

From the first order condition (31), equation (35), and the assumption that $\alpha'/\alpha > \beta'/\beta$ it follows that

$$\begin{aligned} G'(d) = &- \frac{\rho \frac{b'(d)}{b(d)} g^{\frac{1-\rho}{\rho}} \beta \left[\frac{\alpha'}{\alpha} - \frac{\beta'}{\beta}\right] \delta l^* (1-l^*)^{(\beta'+\beta)\rho}}{\Big(1-(\alpha'+\alpha)\rho\Big)(1-l^*) + \Big(1-(\beta'+\beta)\rho\Big) l^*} + g^{\frac{1-\rho}{\rho}} \frac{b'(d)}{b(d)} \delta (1-l^*)^{(\beta'+\beta)\rho} \\ = & g^{\frac{1-\rho}{\rho}} \frac{b'(d)}{b(d)} \delta(1-l^*)^{(\beta'+\beta)\rho} \left[1 - \frac{\rho\beta\left[\frac{\alpha'}{\alpha}-\frac{\beta'}{\beta}\right] l^*}{\Big(1-(\alpha'+\alpha)\rho\Big)(1-l^*) + \Big(1-(\beta'+\beta)\rho\Big) l^*} \right] \end{aligned}$$

The second term in brackets is a strictly decreasing function of l^*, and is equal to 1 if $l^* = 0$. Since, l^* is increasing in d, for the existence of U-shape it is necessary that the second term be negative at $l^* = 1$, which is ensured by condition (U). Define $\bar{d}$ as the value of d such that second term is equal to zero if it exists, and $\bar{d} = \infty$ if no such d exists.[37] Thus, $G'(\bar{d}) = 0$, and $G'(d) \gtreqless 0$ if and only if $d \gtreqless \bar{d}$. ∎

H The Effect of Initial Technology Levels

I have previously shown that the initial levels of technology on each economy have been irrelevant to the determination of the path of growth rates and their stationary levels.[38] Clearly, this does not hold

[37]Notice that this definition of $\bar{d}$ allows for the possibility of $\bar{d} < 0$. This implies that the growth rate is an increasing function of distance.

[38]Unlike other models in the literature I do not focus on the effects of the *technological distance to the frontier* on the allocation of resources between imitation and creation (Acemoglu and Zilibotti, 2001; Acemoglu et al., 2006, 2010). Clearly, both types of distances affect these allocations and both types of models are complementary. One could generalize the model in this paper in order to include both distances by defining the technological distance $a(d) = \frac{\bar{A}}{A(d)}$, where $\bar{A}$ is the technological level in the frontier and by replacing $b(d)$ for $b(d) \cdot a(d)$ (or more generally for $b(d, a(d))$). Although the formal inclusion of both types of distances makes the solution method more cumbersome, since the technological distance varies each period, one can show that the results of this paper's model remain qualitatively unchanged as long as certain initial conditions hold. For example, if the derivative of $b(d, a(d))$ with respect to d is negative at the initial conditions, then there will exist a U-shaped relation between d and $g(d)$.

for income levels, since in period t the income in economy d is

$$y_t(d) = \left(\prod_{i=1}^{t} G_i(d)\right) A_0(d). \tag{37}$$

If the economy starts in the stationary equilibrium, then this amounts to

$$y_t^*(d) = (G(d))^t A_0(d). \tag{38}$$

This is an increasing function of $G(d)$, and since $y_t^*(d)$ is exponential in t, for any positive profile $\{A_0(d)\}_{d\in\mathcal{E}}$ there always exists a value $t' \geq 0$, so that for all $t \geq t'$ the profile of incomes $y_t^*(d)$ is qualitatively similar to the profile of growth rates. Now, since in equilibrium $G_t(d) \to G(d)$ as $t \to \infty$, it is not difficult to show that there exists $t'' \geq 0$ such that for all $t \geq t''$ the profile of incomes $\{y_t(d)\}_{d\in\mathcal{E}}$ is qualitatively similar to the profile of stationary growth rates $\{G(d)\}_{d\in\mathcal{E}}$. Let's write this more formally:

Proposition H.1. *Let the initial technology profile $\{A_0(d)\}_{d\in\mathcal{E}}$ be positive and $t^* = \max\{t', t''\}$. Then for all $t \geq t^*$ the income profiles $\{y_t(d)\}_{d\in\mathcal{E}}$ and $\{y_t^*(d)\}_{d\in\mathcal{E}}$ are such that for all economies $d \in [0, \bar{d}]$ incomes are falling as d increases. On the other hand, for all economies $d > \bar{d}$ incomes are rising as d increases.*

Proof of theorem H.1. Consider an economy $d \leq \bar{d}$ and define $y_t^u(d) = \sup_{d'\in(d,\bar{d}]}\{y_t^*(d')\}$. Notice that $y_t^u(d)$ is finite and bounded for any d and $t < \infty$, since

$$y_t^u(d) \leq G(0)^t \sup_{d'\in[0,\bar{d}]}\{A_0(d)\}.$$

Let $T(d) = \inf\{t \in \mathbb{R}_+ \mid y_t^*(d) \geq y_t^u(d)\}$. The fact that $G(d) > G(d')$ for all $d' \in (d, \bar{d}]$, implies $T(d) < \infty$. Furthermore, define $y_t^l(d) = G(d)^t \inf_{d'\in[0,\bar{d}]}\{A_0(d)\}$ and $T^l(d) = \inf\left\{t \in \mathbb{R}_+ \mid y_t^l(d) \geq y_t^u(d)\right\}$. Then $T(d) \leq T^l(d) < \infty$. It is not difficult to see that $T^l(d)$ is continuous, so that there exists $T_1^l = \sup_{d\in 0[,\bar{d}]}\left\{T^l(d)\right\}$. Let $T_1 = \sup\{T(d)\} \leq T_1^l < \infty$, so that for any $t \geq T_1$ incomes are a decreasing function of d. Similarly, for $d > \bar{d}$ let $y_t^u(d) = \sup_{d'\in[\bar{d},d)}\{y_t^*(d')\}$. By a similar argument as before one can show there exist T_2 and T_2^l, finite, such that incomes are increasing in d in every period $t > T_1$. Letting $t' = \max\{T_1, T_2\}$ one obtains the desired result.

The proof for the non-stationary case is similar and is omitted. ■

Thus, the U-shaped relation between growth and distance from the frontier translates into a U-shaped relation between income levels and distance from the frontier for big enough t. Notice that this result does not depend on any specific form of the profile of initial technologies and implies that there will not exist a tendency for convergence among economies and might generate reversal of fortunes for certain initial conditions.

Appendix References

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