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EXPLAINING THE GREAT DIVERGENCE:

MEDIUM AND MESSAGE

ON THE EURASIAN LAND MASS, 1700-1850

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Abstract

Between 1700 and 1850, per-capita income doubled in Europe while falling in the rest of Eurasia. Neither geography nor economic institutions can explain this sudden divergence. Here the consequences of differences in communications technology are examined. For the first time, there appeared in Europe a combination of a *standardized* medium (national vernaculars with a phonetic alphabet) and a *non-standardized* message (competing religious, political and scientific ideas). The result was an unprecedented fall in the cost of combining ideas and burst of productivity-raising innovation. Elsewhere, decreasing standardization of the medium and increasing standardization of the message blocked innovation.

JEL codes: N1, O3

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In 1712, an ironmonger named Thomas Newcomen and a plumber named John Calley installed a stem-powered engine to pump water from a coal mine near Dudley Castle in Staffordshire, about 200 km north-west of London. Although to James Watt, some fifty years later, the technology of their atmospheric steam engine already appeared quite primitive, the machine was arguably the most important innovation of the past 500 years. It marked the first use of heat to generate mechanical power (Rolt and Allen, 1977). The machine combined three ideas developed shortly before by physicists of different nationalities: first, a vacuum used to move a piston (Otto von Guericke, a German), second, condensed steam to generate a partial vacuum (Denis Papin, a Frenchman) and third, a separate boiler to generate steam (Thomas Savery, an Englishman). Yet the two inventors had no scientific training. Moreover, they had developed their invention in Dartmouth, a remote port on the southwest coast of England. Both were devout Baptists, members of a non-conformist religious sect who insisted that their children be able to read and write.

At the beginning of the eighteenth œntury, when Newcomen and Calley began their experiments, average income levels were quite similar across the Eurasian land mass. Estimates by Maddison (2001) suggest that in 1700, Europe had a per-capita GDP of about 870 dollars at 1990 prices. Average incomes elsewhere at that time were 550 dollars in India, 600 dollars in China and 565 dollars in the rest of Eurasia. Yet barely a century and a half later, in 1870, European incomes were almost three times the level of the rest of Eurasia -- a gap remarkably similar to that which exists today.

If one looks for possible explanations of the divergence between Europe and the rest of Eurasia that occurred over the century and a half after 1700, a good starting point is the example of Newcomen and Calley. Their invention, the atmospheric steam engine, was but one of roughly 115 important innovations developed in this interval that have been noted by historians of technology. All were developed in Europe, and their diffusion prior to 1850 was limited essentially to Europe and its offshoots (Dudley and Witt, 2003). Why was this so? Why did China, which had contributed the most important innovations over the previous two millennia, stop innovating around 1300? Why did what Lal (1998) has called the 'closing of the Muslim mind' occur at about the same time? And why did India make no important contributions to technology after the first millennium AD?

An examination of the literature on economic progress written over the past half century, reveals two types of answers to these questions. One group of authors has emphasized geography. McNeill (1963, 114) attributed the rise of the West to its resource base and to political competition that encouraged innovation. Jones (1987, 226; 2002) suggested that this competition is explained by the mountain chains and marshes of Europe that formed barriers sufficient to prevent a single state from dominating the entire territory. Diamond (1997, 409-412) too emphasized the importance of geography, noting Europe's abundant rainfall and the favorable effects of its indented coastline and high mountains on political competition. For Landes (1998), Europe's temperate climate was important in allowing its residents to accumulate a surplus above the subsistence level. Pomeranz (2000) emphasized Europe's stocks of coal and its access to the resources of the Americas.

A second group of analysts has given precedence to institutions. North (1981, 17) argued that the structure of a society's political and economic institutions determines the performance of its economy and its rate of technical change. His argument is straightforward. Institutions determine the degree to which property rights are protected and contracts enforced, that is, the cost of transacting. The lower are transaction costs, the greater will be the degree of specialization and the division of labor (North, 1990, 27). Josselin and Marciano (1997) suggested that in constraining the growth of the public sector, a country’s legal system can have a considerable impact on its development. Comparing societies across Eurasia, Lal (1998, 173) attributed the success of the West to cultural factors: cosmological beliefs, political decentralization and "the inquisitive Greek spirit."

Which camp is right? There can be little doubt that favorable geographic conditions are a necessary condition for economic progress. A minimum of heat and water would appear indispensable, as a cursory examination of living standards in Siberia and the Sahara indicates. However, it is questionable whether geography’s influence on inventiveness operates through its effects on the degree of political competition. China has a relatively short coastline and few important barriers to internal movement. In general, political power has been highly centralized. Yet as Mokyr (1990, 209-218) has shown, over the two millennia prior to the modern era, China had the highest rate of innovation of any society (hydraulic engineering, the iron plow, the seed drill, cast iron, the spinning wheel, the loom, the waterwheel, clocks, the compass, paper, printing, and porcelain).

Regarding institutions, once again there would appear to be some minimal level of respect of property rights and enforcement of contracts that is essential for sustained innovation. However, it does not necessarily follow that societies run by merchants will be more inventive than societies run by bureaucrats. During the period from 1700 to 1850, the Netherlands, where property rights were strictly enforced, contributed not a single innovation of note, whereas France, with a spottier record in protecting commercial interests, developed a number of important innovations. Nevertheless, institutions do seem to matter. Mokyr (1990, 233-236) notes that in China, the state was favorable to innovation before 1400 but withdrew its support during the Ming and Qing periods.

This paper argues that while both geography and institutions are important in determining a society's rate of innovation, there is a further set of phenomena intermediate between the two that is crucial. Following the path set out by Innis (1950, 1951), we will look at the characteristics of a society's communication system. In particular, we will inquire whether there exists a relation between economic progress and the extent to which the written and spoken language (the *medium*) and its content (the *message*) are standardized. As Holler and Thisse (1996, 180) observe, little research has been done on the pure coordination problems involved in developing social standards. Here, it is shown that while geography plays an important role in determining the parameters by which people interact within a society, the social equilibrium of the resulting game is not necessarily unique. Accordingly, shocks from outside or within a society can jolt it from one equilibrium to another, thereby altering the rate of social innovation.

Section I sets out the facts to be explained, namely the unprecedented rate of innovation in Europe during the century and a half after 1700. Section II points out some remarkable differences in the systems of communication of the four main cultural regions of Eurasia at the beginning of this period. One dimension is the degree of standardization of the *medium* of communication while the other is the extent of standardization of the *message* that is transmitted. Each cultural region had chosen a distinct pattern, most likely for reasons of geography. Finally, Section III examines the consequence of these differences for the willingness to cooperate in developing innovations. The Great Divergence between east and west is explained by two developments in the early modern period that resulted from the introduction of movable type in Europe. The first was the emergence of standardized written versions of the vernacular languages that allowed information to be shared ad low cost. The second was a series of revolutions, as rising literacy within European societies shifted them from a non-cooperative to a cooperative equilibrium. In the other regions of Eurasia, the introduction of movable type was less appropriate because of characteristics of the writing systems and was therefore delayed.

I. The Stylized Facts of Innovation, 1700-1850

This section sets out the facts to be explained. First is the divergence in per-capita income levels across Eurasia during the century and a half after 1700. Second is the unprecedented number of technological innovations during this period. Finally, there is the location of these innovations, confined essentially to three Western nations.

(a) The Great Divergence

Table 1 displays the levels of per-capita GDP between 1700 and 1870 across Eurasia, based on Maddison's (2001) estimates. Note that the figures for Europe include the United Kingdom, Ireland and the former USSR, while those for East Eurasia exclude Japan. As mentioned in the introduction, the initial gap in living standards was not very great. In 1700, the Eurasian income level was about two-thirds that of Europe, a gap that falls within the range of measurement error.[1] However, over the following century and a half, average incomes stagnated or fell in the major regions of Eurasia while rising sharply in the West. By 1870, Europe's per-capita income was almost three times that of the rest of Eurasia. Although the size of this gap fluctuated over the following decades, by the end of the twentieth century, it was still roughly three to one.

[Insert Table 1 about here.]

(a) Innovations, 1700-1849

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[1] Pomeranz (2000) offered evidence that there was no gap at all in per-capita income between Europe and China in 1750.

If per-capita incomes rose after 1700 in Europe while stagnating elsewhere in Eurasia, the principal reason was that Europeans learned before their East-Eurasian counterparts how to increase systematically the level of production output per unit of labor input. Underlying these productivity increases was an unprecedented wave of technological innovation. Historians of technology have long been interested in the individual innovations and when they were developed. Table 2 brings together the research of four studies, each by an author of a different nationality, namely Cardwell (1991), Daumas (1979), Mokyr (1990) and Paulinyi (1989). If one counts only those contributions to technology mentioned by two or more of these authors, one obtains a list of 115 innovations.

[Insert Table 2 about here.]

(b) The Location of Innovations, 1700-1849

It is interesting to note exactly when and where these innovations occurred. As Figure 1 indicates, for the first half century after 1700, almost all of the innovations were from the regions that today comprise the United Kingdom. Over the following fifty years, while the pace of innovations in Britain accelerated, both France and the United States also began to produce significant numbers of innovations. This pattern continued over the half century after 1800. In all, these three countries accounted for 91 percent of the world's significant technological innovations during the full century and a half after 1700. The few remaining developments were scattered among Germany, Switzerland and northern Italy. It is remarkable that Scandinavia, southern and central Europe and the entire remainder of the Eurasian land mass played no role in these developments. Not a single innovation of note came from outside the core countries in northwestern Europe and North America.

[Insert Figure 1 about here.]

When one looks at how these new technologies diffused prior to 1850, one also finds a limited number of participants. The Industrial Revolution that these innovations triggered spread first from Great Britain to France and Belgium, then to the United States, Germany, Switzerland and northern Italy. With the exception of Belgium, during the initial century and a half, no innovation also meant no industrialization.

II. The Impact of Geography on Medium and Message

Let us examine communication systems across the Eurasian land mass in 1700. Our first concern will be to discover the extent to which the medium and the message were standardized. We will compare four societies – the Middle East, India, China and Europe. We will then explore whether geography's influence on these societies' destiny has been exerted through the development of their communication systems.

(a) Medium and Message in 1700

(i) The Middle East

In 1700, states with a majority of Muslims stretched across the southern part of the Eurasian land mass from the Balkans to the Malaysian peninsula, interrupted only by the Indian subcontinent, where they nevertheless formed an important minority. If one looks at the medium of communication over this territory, one finds a wide variety of spoken languages, some Altaic (for example Turkish) some Semitic (for example, Arabic) and some Indo-European (for example, Persian). Most of the spoken dialects had no written counterpart. For written communication, educated people used one of three vehicular languages, Arabic, Turkish or Persian. Writing was with the Arabic consonantal script, of which there were several important variants.[2] The diacritical notation used for the short vowels was not standardized and was generally omitted in ordinary books and private documents (Bauer, 1996, 562). Within the Ottoman Empire, there were no printing presses in Arabic before the nineteenth century.

[2] Note that three of the 28 symbols used for consonants in Arabic also double to represent long vowels (Bauer, 1996, 561).

What messages were transmitted across this territory? In the Ottomans and Persian states, there was tight control over information that was allowed to circulate. For the most part, censure came from the *ilmiye*, those learned in Islam. The Koran and the Hadith, the sayings attributed to the Prophet, had been standardized by the ninth century. Outside the sphere of religion, there was also little tolerance for dissent. The Ottoman state was a centralized autocracy in which both the officials (the *devshirme*) and the soldiers (Janissaries) were slaves of the sultan.

(ii) India

Some 200 different languages were spoken on the Indian subcontinent. As in the Muslim world outside India, they belonged to several different language families. The largest group was made up of those who spoke Indo-European languages. In 1700, Sanskrit was still in use as a vehicular language for religious texts and poetry. However, modern vernaculars such as Bengali and Hindi were beginning to develop their own literatures. Most languages that had writing systems used semi-phonetic alphabets known as alphasyllabaries that were descended from Aramaic, the ancestor of classical Arabic. Each consonant-vowel combination in a syllable was written as a unit consisting of a consonantal symbol plus a vowel diacritical. [3] In 1700, the printing press had still not been introduced into India. Consequently, literacy rates were low.

The Mughal Empire that controlled most of the Indian subcontinent in 1700 promoted the Muslim faith and used the Persian Arabic script for its own records. However, since Muslims were only about ten percent of the total population, the emperors had shown considerable tolerance of other religions, notably, Hindu and Sikh.[4] As mentioned, in the modern period, the major Indian languages were developing their own literatures. Writers in Persian, Urdu and Hindi were all patronized by the Mughal court.[5]

(iii) China

[3] Bright (1996, 384).
[4] Aurangzeb, who reigned from 1658 to 1707, was an exception to this general rule of Moghal tolerance, but the religious repression of his reign could not be maintained by his successors.

[5] Again, Aurangzeb is an exception. It should be noted however, that after military defeat in 1739 by the Persians, the Mughal empire broke up into numerous autonomous kingdoms.

By 1700, most Chinese spoke one of the mutually intelligible dialects of Mandarin. Although Mandarin and the six non-Mandarin dialects spoken in the southeast were not mutually understandable, all used the same logographic writing system consisting of thousands of ideograms. Indeed, since the symbols represented words rather than phonemes, they could easily be adapted to any spoken language, including Korean and Japanese. Printing using xylography from wooden blocks was becoming increasingly popular. Despite the thousands of symbols to be mastered, literacy rates were higher in China than anywhere else in Eastern Eurasia.

For the previous half century, China had been ruled by a foreign dynasty, the Qing, who had conquered the country from its base to the northeast, in Manchuria. As under the preceding dynasty of the Ming, there was little tolerance for new ideas. Those who questioned Confucian norms under the Ming had been jailed and executed. Now the Manchus favored a return to an earlier form of Confucian thought that was considered untainted by influences from Daoism and Buddhism. Although there was an active printing industry, the imperial bureaucracy imposed tight control over what could be printed. Between 1774 and 1778, for example, the emperor Qianlong would have all books that could be deemed critical of the Manchus destroyed. Not surprisingly, there was little political debate. Intellectuals confined themselves for the most part with discussions of texts dating from the Han period that had ended some 1500 years earlier.

(iv) Europe

Like the Chinese, most Europeans in 1700 used a standardized writing system. However, unlike the systems of any of the other cultural regions in Eurasia, the Latin alphabet was fully phonetic, with separate symbols to represent vowels. As a result, it had been readily adapted to the dialects of the major printing centers that had by now become standardized national vernaculars. Equally important, the Latin alphabet was the only writing system in Eurasia that had been adapted to movable metallic type. With inexpensive reading matter using a compact set of phonetic characters available in the vernacular, Europe had been able to outdistance the rest of Eurasia in effective literacy rates. By 1700, in northern Europe, roughly half of the adult population was able to read and write (Graff, 1991).

Unlike China and the Muslim world, but like India, there was considerable tolerance of religious diversity in many parts of Europe by 1700. Although France had expelled its Protestants after 1685, Great Britain had extended full rights to Protest dissenters after the Glorious Revolution of 1688. Moreover, censorship was much less severe in Europe than in other parts of Eurasia. Great Britain had abolished censorship in 1688. Books and newspapers printed in French in the Netherlands circulated widely in France. Finally, Europe was the only area in Eurasia where multi-party political competition was to be found. The Glorious Revolution had introduced the principle of government responsible to an elected legislature in Great Britain. Over the course of the eighteenth century, first Britain's American offshoot, the United States, and then France would also adopt this principle.

(b) Geography and Standardization

Let us now try to generalize from this brief survey of communication systems across Eurasia. Our discussion suggests two dimensions of languages that should be considered. One dimension, shown on the vertical axis of Figure 2, is the degree of standardization of the *medium* of communication. We saw that the degree of medium standardization was relatively low both in India and in the Muslim territories of the Ottoman Empire and Iran. In each region, there were multiple non-phonetic scripts and distinct vehicular and vernacular languages. We also saw that in the two remaining regions, China and Europe, the degree of medium standardization was high. Both of these cultural areas had a uniform writing system accessible to people from their vernacular languages.

[Insert Figure 2 about here.]

How might these differences in the degree of standardization of the communications medium be explained? India and the Middle East, the two regions of low standardization, are centrally located in Eurasia, with only low to moderate geographic obstacles to external invasion. Over the two millennia prior to 1700, the Middle East had experienced many successive waves of conquerors: the Persians, the Macedonians, the Romans, the Arabs, the Mongols and the Turks. India was somewhat better protected geographically but nevertheless its rich northern plains had been raided many times, from the Indo-European invasion in the middle of the second millennium BC to the Turko-Afghan conquest of the early sixteenth century. Since each set of conquerors had brought along its own language and writing system, the result was an accumulation of written and spoken languages.

As for Europe and China, their eccentric geographic positions sheltered them to a great extent from outside conquest. A millennium had now elapsed since the last successful invasion of Western Europe from outside the region. Even that attack, by Muslims from North Africa in the eighth century, had been stopped at the Pyrenees. Parts of China had several times been conquered by peoples from beyond its northern borders. However, on each occasion, the invaders had either been assimilated or expelled without leaving any permanent cultural heritage. In addition, by 1700 both Europe and China had adapted printing to their vernacular languages. As a result, there were large sub-regions in Europe and China where a significant fraction of the population could communicate with one another easily using a common written and spoken medium.

A second dimension to be examined is the degree of standardization of the *message* that was transmitted over the media in a given region. This variable is measured on the horizontal axis in Figure 2. By this new criterion, the pairs of similar regions have changed. In 1700, China was similar to the Muslim world in that a strong central regime was able to monopolize the medium with a uniform cultural message. In the former, the Confucian system of thought prevailed, in the latter the Muslim religion. At the same time, by this new criterion, India resembled Europe in that in religion, literature and politics, there was considerable competition.

Once again, geography offers a possible explanation for the way the regions of Eurasia are grouped. On the one hand, in both China and the Middle East, there were few major *internal* barriers to the movement of troops. Thus a single regime can conquer a vast territory and impose a uniform message. On the other hand, in both Europe and India, there were considerable internal barriers to troop movements. As Diamond (1997, 409-412) has observed, sub-regions with long coastlines and internal mountain ranges, such as the Deccan plateau in India or the Italian peninsula in Europe, generally tend to be able to preserve their autonomy at low cost. Internal geography, then, would explain the differences in the degree of standardization of the message within each major cultural region.

Thus we see that in the causal hierarchy, a region's communication system would appear to be intermediate between geography and political-economic institutions. Language, written and spoken, changes less rapidly than geography but is subject to more inertia than a region's economic and political system.

III. The Innovation Game

Our discussion began in Section I by comparing of rates of innovation across the Eurasian land mass during the Industrial Revolution. It then turned in Section II to a description of the characteristics of communications systems in Eurasia's main regions in the year 1700, just before the wave of innovations that characterized the Industrial Revolution. The obvious question is whether there is any relationship between these two sets of phenomena. We begin this section by examining how innovations occur, noting that for the creation of new ideas it is essential to bring together hitherto unrelated units of information. We then turn to the question of cooperation, studying the conditions under it will emerge. Finally, we bring together the characteristics of communication systems into the discussion to learn which societies were more likely to favor cooperation in the exchange of information and therefore to innovate in the years after 1700.

(a) The Nature of Innovation

In *The Act of Creation*, Koestler (1964) argued that innovation occurs when existing ideas are combined in hitherto untried ways. Recently, Weitzman (1998) has formalized this process in a model of 'recombinant' growth. Innovation involves the successful crossing of old ideas to replace existing ways of doing things. If this approach is valid, then the rate of innovation in a society should be an increasing function of the frequency with which existing ideas are brought together for the first time. Now the greater the degree of standardization of the *medium*, the more likely it is that individuals with different sets of knowledge can successfully exchange ideas when they come together. In addition, the greater the degree of standardization of the *message*, the *less* likely it is that new crossings of existing knowledge will occur. Thus a society's rate of innovation will depend on the degree of standardization of *both* the medium and the message of its communication system, the former having a positive effect and the latter a negative effect.

(b) Three games

Consider a game between two randomly selected agents to develop a collective good, namely a technology. Think, for example of a partnership made up of Newcomen and Calley to develop a pumping device based on steam. In essence, the technology is a club good as defined by Buchanan (1965). Both players benefit whatever the contribution of each to the development costs. In addition, third parties may be excluded from at least a part of the benefits at moderate cost. Let Q be the quantity of output. Let n be the fraction of the two agents who contribute to production, where $0 \leq n \leq 1$, with K the cost to the individual of cooperating in this way. Each player can either defect or cooperate. If both players defect, then output will be zero. If one player defects while the other cooperates, then we will assume that they succeed only in reproducing the existing technology. However, if both cooperate, combining their ideas, they will be able to produce a new technology that is superior to the present one.

The basic structure of this coordination problem has been studied by Heckathorn (1996). The new element here is to allow for both scale economies and network effects.[6] Let c be the fixed cost of production and let e represent a network effect. The production function is assumed to take the form:

$$Q = \frac{c + 1 - e}{c + 1/n - en}. \qquad (1)$$

It may be seen that if $n = 0$, then $Q = 0$, while if n=1, then $Q = 1$. There are some interesting special cases. First, if there are neither scale economies nor network effects, that is, c=e=0, the production function is linear in n. Second, if $c > 0$ while $e = 0$, the function is concave in n. Finally, if c=0, while e>0, production is convex in n.

The implications of this function for the players may be seen from Table 3. If neither player cooperates, then both players receive the Penalty (P) payoff of 0. If both players cooperate, then each receives the Reward payoff of 1-K. If one player defects while the other cooperates, then the defecting player receives the Temptation payoff of

$$T = \frac{c+1-e}{c+2-e/2}. \tag{2}$$

Meanwhile, in the latter case, the cooperating player receives the Sucker payoff of

$$S = \frac{c+1-e}{c+2-e/2} - K. \tag{3}$$

[Insert Table 3 about here.]

This coordination problem allows us to reinterpret the information concerning the degree of standardization of the communication systems across Eurasia in 1700. The characteristics of each society's information technology now determine the game that will be played by its citizens, as shown in Figure 3. Once again, consider the degree of standardization of the *medium* of communication. The greater the number of people who are able to read and write in the same language, the greater will be the network externalities within the society. Thus the vertical axis indicating standardization of the medium may be interpreted as measuring the importance of network effects, e.

[Insert Figure 3 about here.]

[6] This same function is used to analyze political revolutions in Dudley (2000).

Now turn once again to the degree of standardization of the *message*. We have suggested that low internal barriers to troop movements, as in China and the Middle East, will enable a single ruler to control an entire region. To maintain power, such a regime will tend to regulate the information that is transmitted, thereby standardizing the message. Once this system has been established, the fixed costs of entering with an alternative message become very high. Accordingly, in Figure 3, the horizontal axis indicating the degree of standardization of the message may be interpreted as measuring the fixed cost of processing information, c.

Consider those points in Figure 3 where the values of c and e are such that the Reward payoff (R) is equal to the Temptation payoff (T). For K=2/3, the result is the line rt. Above this line, the Reward payoff is greater than the Temptation payoff. As a result, if each player is assured that the other will cooperate, there is no incentive for her to defect. Thus we have the game of Assurance, an example of which appears in Table 4(a). Below the line rt, since the Reward payoff is less than the Temptation payoff, it is in each player's interest to defect if she believes that the other will cooperate. This game is the Prisoner's Dilemma, illustrated in Table 4(b).

[Insert Table 4 about here.]

Now consider those points in Figure 3 where the values of c and e are such that the Sucker payoff (S) is equal to the Punishment payoff (P). The resulting line, sp, is also a boundary between two games. Above the line, the Sucker payoff is less than the Punishment payoff. Accordingly, if one player believes the other player will defect, her best strategy is also to defect. This is the space of the Prisoner's Dilemma. Below the line, since the Sucker payoff is greater than the Punishment payoff, it is now in the interest of a player to cooperate if she believes the other will defect. Accordingly, this area corresponds to the game of Chicken, an example of which is presented in Table 4(c).

(c) Cooperation and Innovation

We have suggested that cooperation between economic agents, as in the example of Newcomen and Calley, is a prerequisite for successful innovation. Let us then reexamine the information systems of Figure 3 in order to determine which configurations are most likely to foster cooperation between agents. Consider first the zone marked Chicken into which the Middle East falls. As the example in Table 4(c) shows, joint cooperation is never a Nash equilibrium in this game. As a result, the rate of innovation should be extremely low in this region.

Next examine the section of Figure 3 that is close to the origin, in the zone marked Prisoner's Dilemma. We see that India falls into this zone. In the one-shot game illustrated in Table 4(b), the only Nash equilibrium is joint defection. Should people interact frequently, the threat of retaliation will tend to induce cooperation. However, since the degree of standardization of both medium and message is low, agents who interact frequently will be rare in such a society. There should therefore be a low rate of innovation.

The region of the Prisoner's Dilemma zone farther from the origin, where Chinese society is situated, would also seem at first glance to be unfavorable to innovation. However, the common medium will lead to more frequent interaction than in the case of India. If such a society is left undisturbed for long periods, it should be able to generate novelty. However, should foreign conquest disrupt patterns of social interaction, the rate of innovation would be expected to decline.

The final region in Eurasia, Europe, falls into the Assurance zone. As Table 4(a) shows, there are two Nash equilibria in this game. Joint defection is one possibility, as in the Prisoner's Dilemma. However, a sufficiently strong shock could shift the society into the alternative equilibrium of joint cooperation. The political revolutions that occurred in England in 1642 and 1688, the American Revolution of 1776 and the Revolution in France that began in 1789 might be interpreted in this way. Conscious of their collective identity as a nation with sovereign power, the citizens of these countries were arguable more willing to cooperate with one another than previously when they had simply considered themselves as subjects of the same monarch.

Conclusion

This paper has returned to the question posed by Kuznets (1966) in his pioneering compilation of the statistics of modern economic growth: why over certain periods have income levels risen more rapidly in some societies than in others? With the help of Madisson's (2001) recent extension of the Kuznets methodology, we were able to focus on a per-capita-income gap that opened up between Europe and the rest of Eurasia in the century and a half after 1700 and has persisted to this day. To explain this income divergence, we suggested, we must understand why the unprecedented number of important technological innovations developed over the time interval from 1700 to 1849 were *all* invented in the West.

Since the data for the period under study do not allow us to test statistically a formal growth model, we have been obliged to confine ourselves to a search for historical patterns. We have focused on a typology of characteristics of a society's communication system. Allowing the degree of standardization of both the *medium* and the *message* to be either high or low, we saw that there were four possible types of society. We then examined the impact of the communication system on the outcome of a two-player coordination game. Only one of the four types of society was able to sustain high rates of cooperation, and then only if it was somehow able to reach the "good" rather than the "bad" equilibrium.

Our discussion suggests a possible explanation for the economic success of the West between 170 and 1850. It was the only one of Eurasia's four main cultural regions to have both a *standardized medium* and a *non-standardized message*. As a result, existing ideas could be combined at low cost to generate novelty. The two cooperating Baptists, Newcomen and Calley, and their seminal innovation, the atmospheric engine, are but one example of over a hundred developments that transformed Western society in the years before 1850.

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Table 1. Per-capita GDP in 1990 dollars

Region	1700	1870	1998
Europe	***870***	***1521***	***10939***
East Eurasia	***571***	***543***	***2936***
China	600	530	3117
India	550	533	1746
Others	565	565	3734
Eurasia	647	846	4464

Source: Maddison (2001)

Table 2

115 significant innovations, 1700-1849

Country	1700-1749	1750-1799	1800-1849
France	Loom coded with perforated paper (Bouchon, 1725) Loom coded with punched cards (Falcon, 1728)	Automatic loom (Vaucanson, 1775) Single-action press (Didot, 1781) Two-engine steamboat (Jouffroy d'Abbans, 1783) Hot-air balloon (Montgolfier, 1783) Parachute (Lenormand, 1783) Press for the blind (Haüy, 1784) Chlorine as bleaching agent (Berthollet, 1785) Sodium carbonate from salt (Leblanc, 1790) Visual telegraph (Chappe, 1793) Vacuum sealing (Appert, 1795) Illuminating gas from wood (Lebon, 1799)	Automatic loom with perforated cards (Jacquard, 1805) Wet spinning for flax (de Girard, 1815) Single-helix propeller (Sauvage, 1832) Three-color textile printing machine (Perrot, 1832) Water turbine with adjustable vanes (Fourneyron, 1837) Photograpy (Daguerre, 1838) Multiple-phase combing machine (Heilmann, 1845) Measuring machine (Whitworth, 1845)
Germany	Porcelain (Böttger, 1707)	Lithography (Senefelder, 1796)	
Great Britain	Seed drill (Tull, 1701) Iron smelting with coke (Darby, 1709) Atmospheric engine (Newcomen, 1712) Pottery made with flint (Astbury, 1720) Quadrant (Hadley, 1731) Hot blast furnace (Nielson, 1733) Flying shuttle (Kay, 1733) Glass-chamber process for sulphuric acid (Ward, 1736) Spinning machine with rollers (Wyatt, 1738) Stereotyping (Ged, 1739) Lead-chamber process for sulphuric acid (Roebuck, 1746)	Crucible steel (Huntsman, 1750) Rib knitting attachment (Strutt, 1755) Achromatic refracting telescope (Dollond, 1757) Breast wheel (Smeaton, 1759) Bimetallic strip chronometer (Harrison, 1760) Spinning jenny (Hargreaves, 1764) Creamware pottery (Wedgewood, 1765) Cast-iron railroad (Reynolds, 1768) Engine using expansive steam operation (Watt 1769) Water frame (Arkwright, 1769) Efficient atmospheric steam engine (Smeaton, 1772) Dividing machine (Ramsden, 1773) Cylinder boring machine (Wilkinson, 1775) Carding machine (Arkwright, 1775) Condensing chamber for steam engine (Watt, 1776)	Machines for tackle block production (Brunel, 1800) Illuminating gas from coal (Murdock, 1802) Paper-making machine (Robert, 1803) Steam locomotive (Trevithick, 1804) Winding mechanism for loom (Radcliffe, 1805) Arc lamp (Davy, 1808) Food canning (Durand, 1810) Compound steam engine (Woolf, 1811) Rack locomotive (Blenkinson, 1811) Mechanical printing press (Koenig, 1813) Steam locomotive on flanged rails (Stephenson, 1814) Safety lamp (Davy, 1816) Circular knitting machine (M. I. Brunel, 1816) Planing machine (Roberts, 1817) Large metal lathe (Roberts, 1817) Gas meter (Clegg, 1819)

		Steam jacket for steam engine (Watt, 1776) Spinning mule (Crompton, 1779) reciprocating compound steam engine (Hornblower, 1781) Sun and planet gear (Watt, 1781) Indicator of steam engine power (Watt, 1782) Rolling mill (Cort, 1783) Cylinder printing press for calicoes (Bell, 1783) Jointed levers for parallel motion (Watt, 1784) Puddling (Cort, 1784) Power loom (Cartwright, 1785) Speed governor (Watt, 1787) Double-acting steam engine (Watt, 1787) Threshing machine (Meikle, 1788) Single-phase combing machine (Cartwright, 1789) Machines for lock production (Bramagh, 1790) Single-action metal printing press (Stanhope, 1795) Hydraulic press (Bramah, 1796) High-pressure steam engine (Trevithick, 1797) Slide lathe (Maudslay, 1799)	Metal power loom (Roberts, 1822) Rubber fabric (Hancock, 1823) Horizontal water wheel (Burdin, 1824) Electromagnet (Sturgeon, 1824) Locomotive with fire-tube boiler (Stephenson, 1829) Self-acting mule (Roberts, 1830) Lathe with automatic cross-feed tool (Whitworth, 1835) Planing machine with pivoting tool-rest (Whitworth, 1835) Even-current electric cell (Daniell, 1836) Electric telegraph (Cooke & Wheatstone, 1837) Riveting machine (Fairbairn,1838) Transatlantic steamer (I. K. Brunel, 1838) Assembly-line production (Bodmer, 1839) Multiple-blade propeller (Smith, 1839) Steam hammer (Nasmyth, 1842) Iron, propellor-driven steamship (I. K. Brunel, 1844) Multiple-spindle drilling machine (Roberts, 1847)
Italy			Electric battery (Volta, 1800)
Switzer-land		Massive platen printing press (Haas, 1772) Stirring process for glass (Guinand, 1796)	
United States		Continuous-flow production (Evans, 1784) Cotton gin (Whitney, 1793) Machine to cut and head nails (Perkins, 1795) Interchangeable parts (Whitney, 1797)	Single-engine steamboat (Fulton, 1807) Milling machine (Whitney, 1818) Ring spinning machine (Thorp, 1828) Grain reaper (McCormick, 1832) Binary-code telegraph (Morse, 1845) Sewing machine (Howe, 1846) Rotary printing press (Hoe, 1847)

Sources: Daumas (1979), Cardwell (1972/1991), Mokyr (1990), Paulinyi (1989)

Table 3
Matrix of payoffs to player 1

	Player 2's strategy	
Player 1's strategy	Cooperate	Defect
Cooperate	Reward (R): $1-K$	Sucker (S): $\frac{c+1-e}{c+2-e/2}-K$
Defect	Temptation (T): $\frac{c+1-e}{c+2-e/2}$	Penalty (P): 0

Table 4
Examples of three games with production of information

Player 1's strategy:	Player 2's strategy:	
	Cooperate	Defect
Cooperate	(0.33, 0.33)	(-0.38, 0.29)
Defect	(0.29, -0.38)	(0, 0)

(a) Assurance (c=0, e=0.5)

Player 1's strategy:	Player 2's strategy:	
	Cooperate	Defect
Cooperate	(0.33, 0.33)	(-0.17, 0.5)
Defect	(0.5, -0.17)	(0, 0)

(b) Prisoner's dilemma (c=0, e=0)

Player 1's strategy:	Player 2's strategy:	
	Cooperate	Defect
Cooperate	(0.33, 0.33)	(0.08, 0.75)
Defect	(0.75, 0.08)	(0, 0)

(c) Chicken (c=2, e=0)

K=2/3
Nash equilibria are underlined.

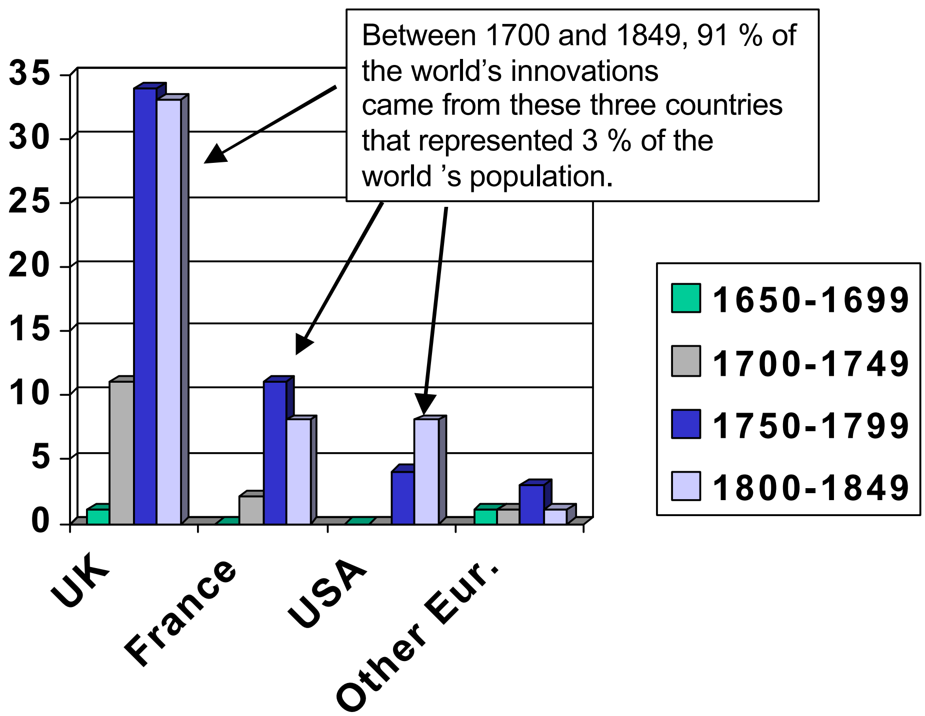

Fig. 1 Innovations by country, 1650-1849

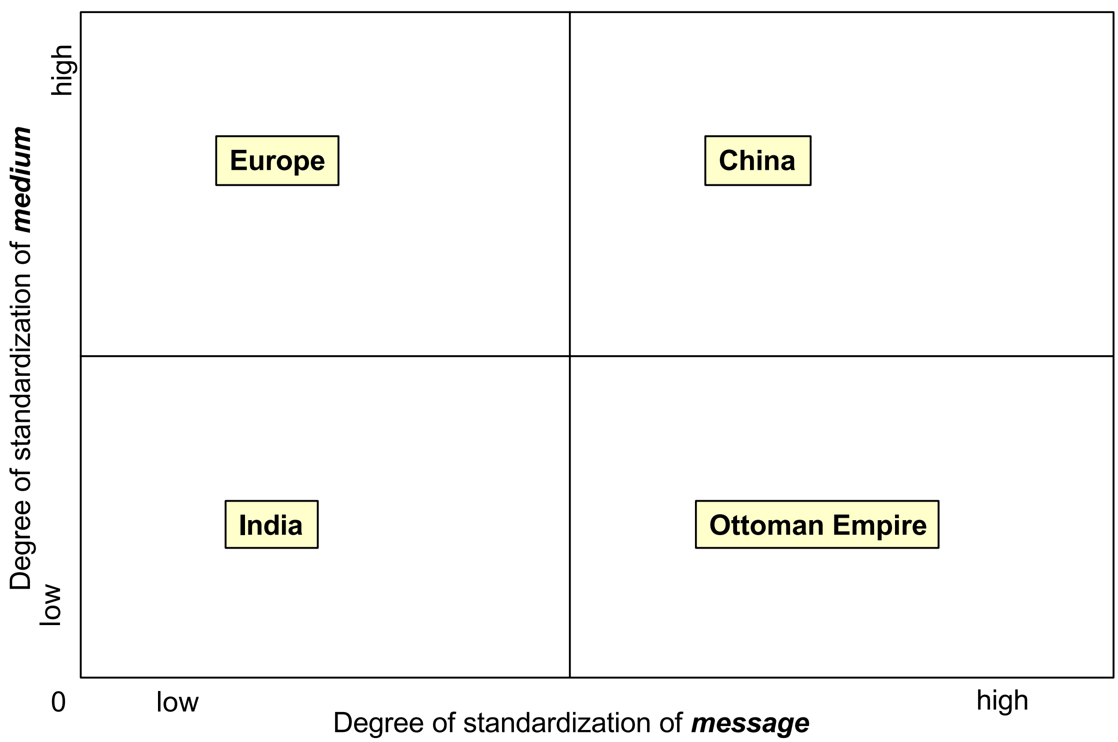

Figure 2. Medium and message in Eurasia, c. 1700

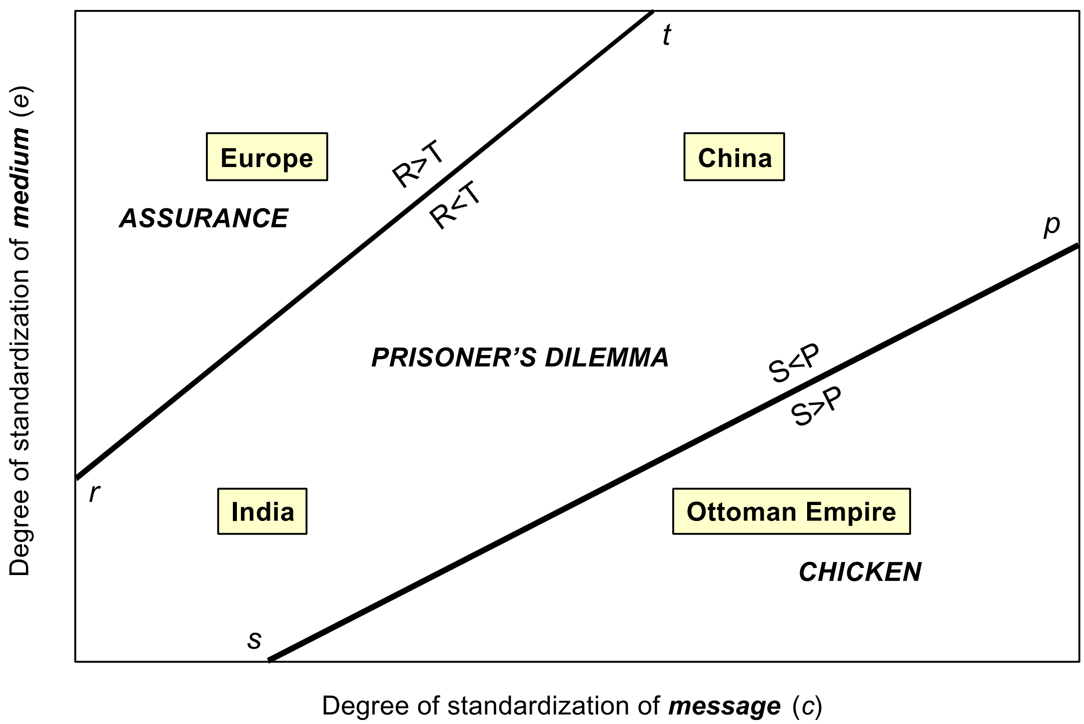

Figure 3. Coordination games in Eurasia, c. 1700